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29th JANUARY – 1ST FEBRUARY 2018, MELBOURNE

ZEMCH NETWORK

Edited by

Hing-wah Chau & Cynthia dos S. Hentschke

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ZEMCH Network

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PREFACE

ZEMCH is the acronym of “Zero Energy Mass Custom Home” reflecting social, economic and environmental sustainability in the built environment. To cluster diverse ZEMCH knowledge accumulated throughout the globe, ZEMCH International Conference has been held annually since 2012 in collaboration with 689 ZEMCH Network international partners from over 40 counties. This year sees the 6th ZEMCH conference operation hosted by the University of Melbourne in Australia. The ZEMCH 2018 International Conference attracted 110 abstracts, with 67 papers finally making it through the rigorous peer review process.

Homes need to be socially, economically, and environmentally sustainable in response to societal pressures on our common future. The current concept of ‘Sustainable Development’ was advocated by the World Commission on Environment and Development in 1987, and was posited as *‘a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet needs and aspirations’.* In 1992, this notion was given additional impetus at the United Nations Conference on Environment and Development (or the Earth Summit) held in Rio de Janeiro, where an initial international treaty on environment was produced; however, this had neither limits on greenhouse gas emissions nor legal enforcement provisions for individual nations. In 1997, the text of the Kyoto Protocol to the United Nations Framework Convention on Climate Change was adopted eventually at the 3rd Conference of the Parties held in Kyoto, Japan. As of April 2008, 178 countries had signed and ratified the Protocol; in consequence, most industrialized nations and some central European countries agreed to legally binding reductions of greenhouse gas emissions averaging 6 to 8% less than 1990 levels between 2008 and 2012.

In response to growing global warming issues and the constant increase of energy prices, house-builders and housing manufacturers today are becoming more responsive to the delivery of net zero energy and net zero greenhouse gas emission, more sustainable homes than ever. The business model adopted within the built environment operation tends to be risk averse, following traditional ways of doing business and a closed system mode of operation. Such approaches often hinder enterprises from adopting unfamiliar, but necessary, innovations to realise the delivery and operation of socially, economically and environmentally sustainable homes. In theory, homebuilders and housing manufactures are sensitive to societal needs and demands. Yet, in reality, traditional builders generally tend to follow business as usual routines and do not undertake the research to determine whether or not to adopt unfamiliar design challenges, and innovative building materials and systems. Nonetheless, to build zero carbon mass custom homes that aim to satisfy the wants and needs of individual consumers, as well as society, may require the adoption of innovations. Then, how can such conventional house-builders and housing manufacturers be adapted to new business operations required for the delivery of zero carbon mass custom homes, whose design, production and marketing approaches may not be akin to those to which they are accustomed?

‘Mass customisation’ is a paradoxical concept. The current notion was anticipated in 1970 by Alvin Toffler, in his book, ‘Future Shock.’ In 1987, the term was eventually coined by Stanley M. Davis in his book titled ‘Future Perfect.’ Furthermore, in 1993, Joseph B. Pine II profoundly systematised the general methods of mass-customising products and services in his book ‘Mass Customization.’ This was followed in 2009, with Frank T. Piller’s and Mitchell M. Tseng’s edited ‘Handbook of Research in Mass Customization and Personalization’ which compiled the

R&D activities and outputs delivered by various industries globally. Nonetheless, the idea of customisation can be dated back to the 1950s, as the gravity became explicit in Walter Gropius' book entitled 'Scope of Total Architecture.' The essence of mass customisation applied to housing was speculated as he emphasized the need for 'standardising and mass-producing not entire houses, but only their component parts which can then be assembled into various types of houses.' The period coincided with the post World War Two construction boom and the need to rebuild and repair many buildings globally, where it was also known as 'prefabrication' or 'prefab'. Today this term has been renamed 'offsite manufacture' or OSM. Technological innovations have great potential for future mass customisation technologies and designs.

In fact, house is a system of energy and environment, which contains a number of parts and components. The selection of housing design elements need to be made carefully with due consideration of the project's initial and operational cost, quality, and time. Moreover, the location factor cannot be less of a consideration as it encompasses geographical and topographical conditions and local regulations. Location and orientation of house help secure the optimum use or prevention of solar radiation and wind and this affects the building's operational energy consumption and generation which correlate with greenhouse gas emissions and energy costs.

The total number of possible ordered pairs (or combination) of given standard housing components can be quantified. In this approach, the mass customization (MC) has been systematised and visualised simply by making use of a conceptual analogue model as follows: $MC = f(P, S)$. In this model, the service sub-system (S) concerns communication platforms that lead the users to participate in customizing their design output while the product sub-system (P) covers production techniques that aim to encourage the standardization of housing components for mass production and dissemination. Standardisation of building components seems to be a limited hindrance to design customisation if communication platforms are well developed. Design-consulting staff and appropriate communication interfaces are required to facilitate user choice of standard design components. These fundamental design service factors can also be integrated into a comprehensive model: $S = f(l, p, t)$. In this model, the service sub-system (S) is supported by the existence of the location (l), personnel (p) and tool (t) factors and they are necessarily interrelated. In general, building components can be divided into three categories: volume, exterior and interior. These can be considered the main elements of the product sub-system (P) which can be explained by the following conceptual model: $P = f(v, e, i, o)$. The volume (v) components are used to configure the building's internal space that determines the size and location of each room while the exterior (e) and interior (i) components serve to co-ordinate decorative and functional elements that customize a building. In addition, (o) denotes other optional features such as building amenity and security systems, inclusive design components and renewable energy technologies. In general, envelope and ventilation heat losses are associated with building volume and exposures, while thermal transmittance links up with materials applied to exterior and interior components. Energy monitors may fall into the category of optional features.

Most of the net zero-utility-cost housing manufacturers typically in Japan have begun to install a number of renewable energy technologies as standard features rather than options based on their value-added, high cost-performance marketing strategy. The strategy itself is far from new having been applied to a variety of end user products around the globe. For instance, although today's automobiles can be produced with lower production costs than those in the past, their selling price does not seem to be affected dramatically by higher productivity. New cars are still generally regarded as expensive; nevertheless, the list of items now offered as standard in new cars, such as air conditioning, in car entertainment systems, airbags, remote-control keys,

power steering, power windows and adjustable mirrors, were offered only as expensive options in older models. Clearly, the quality of newer models is much higher than that of older models. The same is true for the housing industry in Japan. Quality-oriented production contributes towards the delivery of high cost-performance housing, in which high-tech modern conveniences that are installed as optional in conventional homes, are available as standard equipment (*Se*). In this context, the product subsystem (*P*) can further be modified into the following conceptual model: $P = f\ (v,\ e,\ i,\ o) + Se$. In fact, Japanese housing manufacturers mass-produce net zero-utility-cost customizable homes in which a variety of housing amenities and renewable energy technologies such as solar PV, air source heat pump, micro combined heat and power systems are installed as standard features, rather than optional extras. Despite the reduction of equipment choices, volumetric, exterior and interior design components still remain substantial options from which the users can choose so as to customize the end product.

To deliver a marketable and replicable net zero energy/emission mass custom homes or ZEMCH, the strategic balance between the optional and standard features seems to be critical. The optional features may be provided with the aim to enhance design quality (or customisability) that helps contribute to satisfying desires and expectations of individual stakeholders. The standard equipment, on the other hand, needs to be installed in buildings as it aims to exceed product quality whose levels can be adjusted in conjunction with societal demands and requirements.

ZEMCH 2018 International Conference encompasses a wide spectrum of hopes and fears around the design, production and marketing approaches to the ZEMCH delivery and operation, and showcases some exemplars budding out in different climates around the globe. All papers included in this proceedings were peer reviewed in accordance with the full review process of the Department of Education and Training (DET), Australian Government. It is the cooperative effort of many authors and qualified reviewers. The editors and organising committee wish to thank all the authors and the reviewers.

Sara Wilkinson, Lu Aye and Masa Noguchi
Co-chairs
(On behalf of the ZEMCH2018 Organising Committee)
29th January 2018

CONTENTS

SUSTAINABLE DESIGN STRATEGIES IN HOT, ARID CLIMATE

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Abstract: *Recently, the United Arab Emirates has been faced with a rapidly growing economy and has become intensively resource dependent. Consequently, it has topped a list of countries with the largest ecological footprint. At the same time there has been a movement towards sustainable design in the past few decades, mainly due to its significance in reducing the harmful impact of buildings on the environment. In line with UAE movement towards a green community, the author investigated the science of "Biomimicry" thoroughly and explored its power and strength in greening the community. Thus, it is important to highlight "Biomimicry" or "Biomimetic Architecture" philosophy as a powerful key to eliminating our ecological footprint. This has been widely used in contemporary architecture to seek solutions for sustainable design by examining natural species forms and systems as a source of inspiration to solve architectural problems. The author have selected the 'butterfly' as the natural concept, highlighted a number of inspired strategies, implemented them on a residential unit in Dubai and assessed the case study by using simulation software Ecotect. This paper aims to investigate the effectiveness of different strategies on overall thermal comfort and energy performance. Finally, the study reveals some key findings that may help architects and buildings to enhance design solutions for a sustainable future in hot arid climate.*

Keywords: *Greening Buildings, Biomimicry, Dubai, Environmental Impact, Thermal Comfort*

1 Introduction

NASA, NREL, Architecture 2030 and many other non-profit organizations is emerging rapidly to improve the built environment and wellbeing, in general it focuses in transforming the built environment from a major contributor of greenhouse gases emissions to be part of the solution to the global warming and climate change challenges, COP21(2016). On the international level, the philosophy of sustainability had an attempt to reduce the impact of the built environment through significant efforts and actions to change the way it's designed and constructed via enhancing building efficiency, changing the construction materials and practices to reduce the overall impacts on the biosphere, Jaber & Samer (2011). As part of the global challenge, UAE have launched several green building codes and ratting systems such as ESTIDAMA pearl rating systems and Dubai Safat green buildings standards with respect to the national UAE 2021 vision initiatives to promote a high performance built environment through the whole life cycle of the building, Khaleej Times (2016). By now it is known that energy use in buildings has a large contribution to the global CO2 emissions and since that the UAE climate is categorized as hot arid, it is anticipated that there is a huge demand for air conditioning and consequently will increase the building stock contribution in the climate change phenomenon, Al-Masri and Abu-Hijileh (2012). In the building industry there are several approaches being made in the design characteristics to achieve a sustainable innovation, by architects, materials manufactures, building products developer and other members within the building industry. In addition to that, passive innovative solutions have been implanted, as well as associated active systems technologies to minimize the building negative impacts on the environment, Xianting et al. (2017). In general, sustainability innovations assist the designers and architects to broaden their purpose beyond shaping shelters for their clients. However, there are still some shortcomings in the deliverable products on the practical and economical levels, Hwang and Tan (2012). This paper is intended to draw the reader attention to safeguarded approach named "biomimetic design". This approach is composed of deep understanding to the biological ecosystem and applications of well-tested solutions that was invented by natural beings and evolved overtime. Biomimicry is a growing paradigm that helps designers into their new role as sustainability interventionists, Kennedy et al. (2015). The author has chosen the "Butterfly" biological system as an inspiration source to enhance the building envelope and let it act as a thermal barrier to regulate the interior temperature and consequently improve the thermal comfort and wellbeing.

1.1 Background

For over twenty years' sustainable architecture was known as a set of principles that could be applied to the design in-order to overcome the global climate change crises due to excess consumption energy, water security, occupant's comfort and wellbeing, Holstov, ET, al, (2015). Biomimetic innovation has grown over that last two decades and has been implanted in multidisciplinary aspects beyond architecture such as lightweight concept cars that were influenced by the boxfish, satellite plates were inspired by the folding patterns of hornbeam leaves and many and many other examples that confirm that biomimicry is a useful tool for in the industrial design field Volstad and Boks (2012). Simply scientist have studied the natural organisms and highlighted some opportunities to engage biomimicry science in creative problem solving in many aspects. However, this paper will only focus on architectural aspects. "Biomimetic Architecture" philosophy has been widely used in contemporary architecture seeking solutions for sustainable development and it endorses a deeper understanding of nature and ecology rules and in order to enable the building to be responsive and adaptable to the harsh climate condones, Al-Obaidi et al. (2017). Biomimetic is the abstraction of good design from

nature, Williams (2004). For instance, the Renaissance architects studied the eggshell strength to enable the construction of a lighter and thinner dome since 1700. Another example the East-gate shopping centre and office block, was inspired by the termite mound that has an outstanding power in controlling the temperature in extreme environment, another example, Pawlyn (2016). These examples, confirms that biomimetic in architecture is not new; in fact, the concept of biomimetic is a revolutionary in its implications for human systems of production.

In 1960, the term "biomimetic" was coined by American inventor, Otto Schmitt to describe way of transferring the knowledge from biology to technology, Kennedy et al. (2015). Within the framework of this paper the application of biomimicry aims to describe ways of transferring the knowledge from biological ecosystems to architectural design in terms of form and process. Hence, “Biomimetic Architecture” is a part of larger multidisciplinary approach known as “Biomimicry” that examines nature forms and systems as a source of inspiration to solve architectural problems. Accordingly, “Biomimicry” can be considered as the key to harmonize nature in human life and man-made structures, Holstov et al. (2015). In the early beginnings biology was a sources of inspiration via mimicking and imitating forms of plants and animals and integrates them superficially to their built structures; this was purely demonstrated in ancient buildings, Aziz and El Sherif, (2015). With reference to Blok and Gremmen (2016), “Biomimicry isn’t itself a product but a process, drawing on natural organisms and processes in order to spark innovation” while Nicholas et al. (2015) states the beautiful thing about biomimicry is it isn’t simply “stealing” ideas from nature; it is gaining inspiration and appreciating the source from which it came”. However, Dicks (2016) draws attention to three levels of biomimicry in building: Organism level, Behaviour level and Ecosystem level; and there are five different elements under each level which are: form, material, construction, process and function. In parallel to that, there are uncountable examples that applied bio inspired structures. As whole, it is vital to highlight that practitioners must consider form, process and ecosystem levels of biomimetic design, which means it's deliverable is not a replication of nature but involves learning from nature systems that has been tested and evolved overtime, Kennedy et al. (2015). Biomimicry promotes the best solutions via identifying the successful adaptations found in the natural environment and use them as a pre thinking source for better inform design solutions, Holstov et al. (2015). Thus, application of biomimicry aims to describe ways of transferring the knowledge from biological to architectural design in terms of form and process. Taking biomimicry into consideration within the design process and apply it appropriately in order to ensure lower costs throughout the lifecycle of buildings and allow the human civilization to flourish and grow within the limitation of the ecosystem without compromising the future generation’s needs, Mathews (2011). Based on that, the “Butterfly” was selected as a source of inspiration to apply retrofitting strategies on existing buildings to attain a certain level of human comfort and energy efficiency. The Butterfly was chosen because it has a very unique anatomy, scales morphology that originates its special survival techniques and its interaction behavior in the ecosystem.

1.2 Purpose statement

Building performance can potentially be improved if the building envelope is designed and constructed with an ability to adapt to its environment, Holstov, ET, al, (2015). Therefore, this paper will highlight the effectiveness of integrating some survival strategies learned from the nature in retrofitting buildings to reduce its harmful impacts on the environment. The author will study the Butterfly anatomy, form, process and ecosystem levels, then apply them on the case study in order to confirm that biomimetic architecture is a powerful tool to enhance the building performance.

2 Methodology

In order to approach Biomimicry as a design process, it is vital to primarily understand the form, process and ecosystem levels of the natural being. Therefore, the author has studied butterfly organism form, shape, appearance and more details in order to appreciate its powerful survival and adaptable strategies and accordingly use them as an inspiration to retrofit the studied case study. Residential unit located in Dubai Silicon Oasis has been chosen to implement the lessons learned from the butterfly with the aim of reducing energy consumption and enhancing human comfort. The proposed unit will be assessed by energy software named “Ecotect”. The assessment will specifically evaluate some sustainable cooling strategies and their effect on energy efficiency with reference to ASHRAE standards.

Paper will begin by presenting a brief description about Dubai weather data and site analysis. Followed by general characteristics of physical appearance and functional behaviour of the natural anatomy. After that, set of lessons learned will be applied on the case study to modify its building envelope and consequently it is anticipated that these changes will play a significant role in enhancing the building efficiency. Finally, the author will recommend the best sustainable cooling strategy that can be applied in hot, arid climate.

3 Climate

Dubai, UAE is known for its hot and dry climate, where the mean temperature is estimated to be 27 °C that is beyond the comfort level. The maximum Dry Bulb Temperature hits its peak during the summer and is estimated to be around 45° (Fig. 1) and relative humidity even may exceed 86%. Moreover, mean annual illumination level is estimated to be around 64,000 Lux and mean annual cloud coverage is estimated to be around 18% and (Fig. 2) shows the wind direction, which is mainly concentrated in the northwest side of the city throughout the whole year.

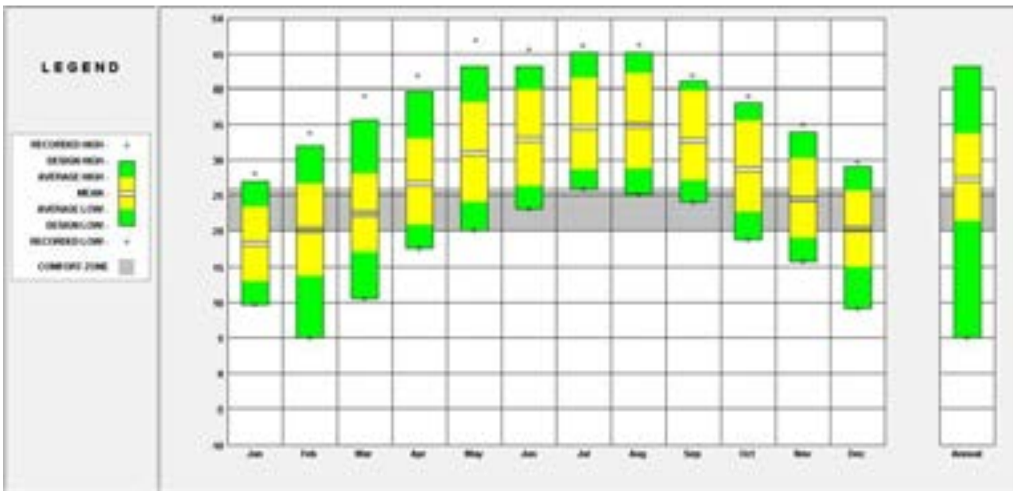


Figure 1: Temperature range of Dubai, source: Climate consultant software (2012)

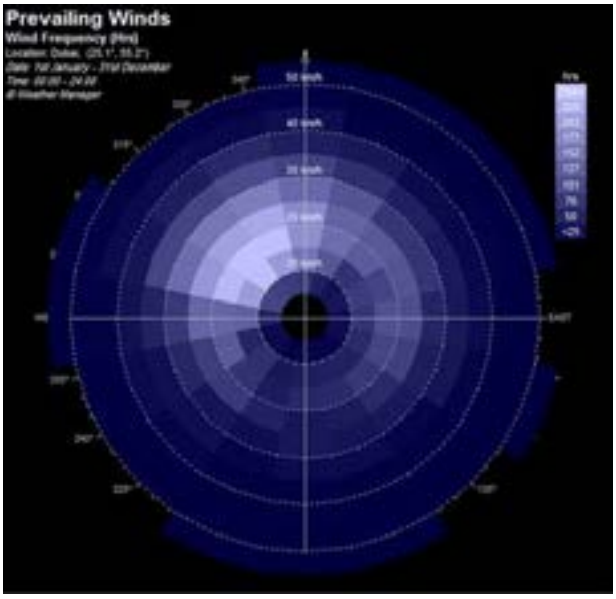


Figure 2: Wind direction of Dubai, source: Climate consultant software (2012)

4 Butterfly anatomy

4.1 Butterfly physical characteristics

It’s important to understand and analyse the butterfly physical characteristics in order to highlight the main features that can be inspired from its physical setting such as: exoskeleton, respiratory system, wings structure/topography and wing ground and cover scales (Fig. 3). Butterfly behaviour plays a considerable role in adapting to their surroundings environment and these adaptations are forming set of strategies and mechanisms. For instance, the colour and brightness of the wings were different when exposing scales to different medias due to the changes in water vapour, Yang, et al. (2011). Moreover, the temperature fluctuating has a considerable impact on the life development rate as well as their flying journeys, thus butterflies store heat to warm their bodies and then be able to fly, actually the hollow central exoskeleton reduces overall weight for better flight journeys, Zografou, et al. (2015).

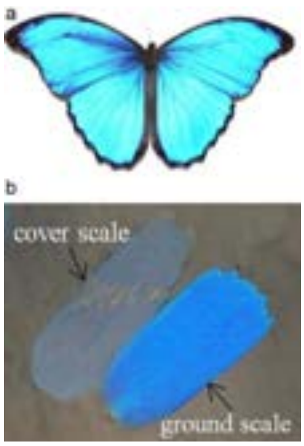


Figure 3: Butterfly (a), wing scales (b), source: Yang, ET, al. (2011)

In fact, butterflies' wings act like a battery because it stores the energy and use it when needed. Similarly, the solar panels store the solar energy and use it during the absence of the sun. These strategies create influence and inspire architects to propose some innovative and responsive building envelope as it acts as a transition barrier between interior and exterior environment Kennedy et al. (2015). Furthermore, the scales covering the wings has an overlapping arrangement that enrich the waterproofing and self-cleaning procedures of the wings, Whipple (2013).

4.2 Inspired design strategies

With reference to the physical characteristics explained in the butterfly and associated adaptation mechanisms for the surroundings, (Fig. 4) will concisely demonstrate links between the anatomy of the butterfly and lessons learned that can be perceived as an inspiration by architects within sustainable building industry.

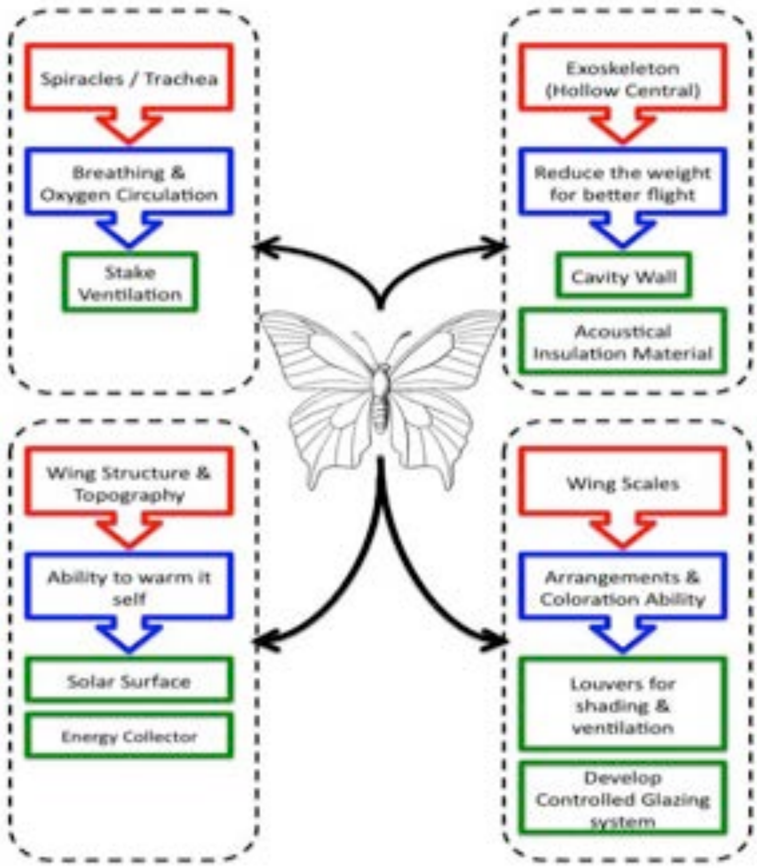


Figure 4: Environmental strategies and lessons learned [Red: Anatomy part, Blue: Survival techniques and Green: Architectural Design strategy, source: Author (2013)

5 Case study description

The site lies in Dubai Silicon Oasis, a residential area that varies from single unit houses to multi storey residential and commercial buildings. The area has reasonable levels of supplied services including infrastructure, communal buildings, schools and some daily-needs support buildings. It is also well connected to transportation routes to all other parts of Dubai. The area is still growing and this is an opportunity to inject sustainable ideas into its buildings. The selected two story housing unit is one in this mass housing neighbourhood, the ground floor elevation is 3.00 meters high, consisting of the main

house entrance, living room, toilet, kitchen and a small office. The second floor elevation is 3.00 meters high and contain a master bedroom, two bedrooms - one with balcony - a common bathroom and a home theatre (Fig. 5). The roof area is designated for services. The building is constructed from concrete blocks with the facade material being a grey-painted plaster wall. Windows are dark coloured single glazed on metal frame and (WWR) window to wall ratio 34%, however the recommended is 15% as per UAE green buildings regulation, Awadh and Abu-Hijleh (2013). Furthermore, the front side of the house faces south while the back of the house is shaded by two multi-storey buildings that is facing it and relatively close to the Dubai Silicon Oasis authorities.

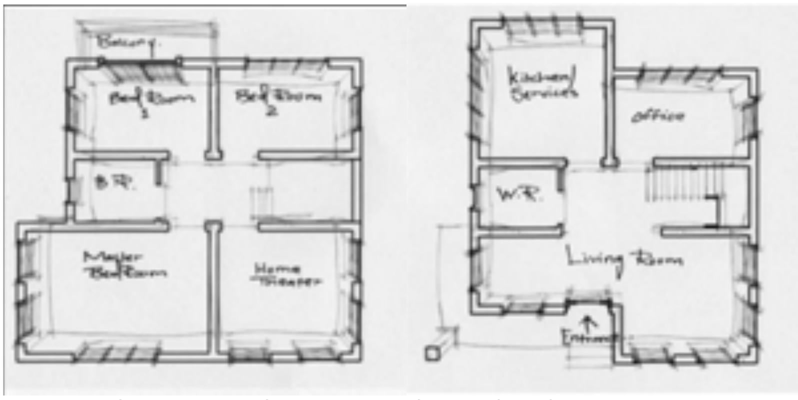


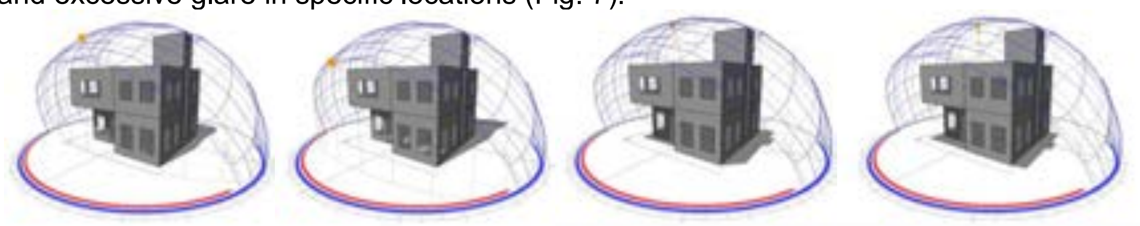
Figure 5: Schematic sketch of the ground floor plan (Left) and first floor plan (Right), source: Author (2013)

6 Case study analysis

With reference to case study details and climatic contextual conditions, the main goal of this paper to enhance building energy efficiency and human comfort via set of survival strategies learned from the butterfly. It is important to understand the solar path, daylight factor and hourly heat gain and losses in order to evaluate the impact of introducing different strategies to the case study.

6.1 Monthly sun path diagram and solar rays

In order to achieve the main goal of this paper, this section will utilise a seasonal sun path diagram for particular months that experience seasonal changes annually (Fig. 6). It will also show the solar ray effect on the building, which may cause overheating issues and excessive glare in specific locations (Fig. 7).



January @ 13:00 March @ 13:00 May @ 13:00 June @ 13:00

Figure 6: Sun path diagram for January, March, May and July, source: Ecotect (2013)

January @ 13:00 March @ 13:00 May @ 13:00 June @ 13:00

Figure 7: Solar rays diagram for January, March, May and July, source: Ecotect (2013)

6.2 Daylight factor

The daylight factor is very important in illustrating the ratio of internal to external light levels. Accordingly, two different spaces were chosen to show variations in the daylight factor with reference to orientation. The first space is a living room facing south; it presented a daylight factor of over 22.4%. The second space is a bedroom facing north, it presented with a daylight factor of over 18.4% which is lower than the first space with reference to orientation, yet both are a source of discomfort due to excessive heat levels (Fig. 8).

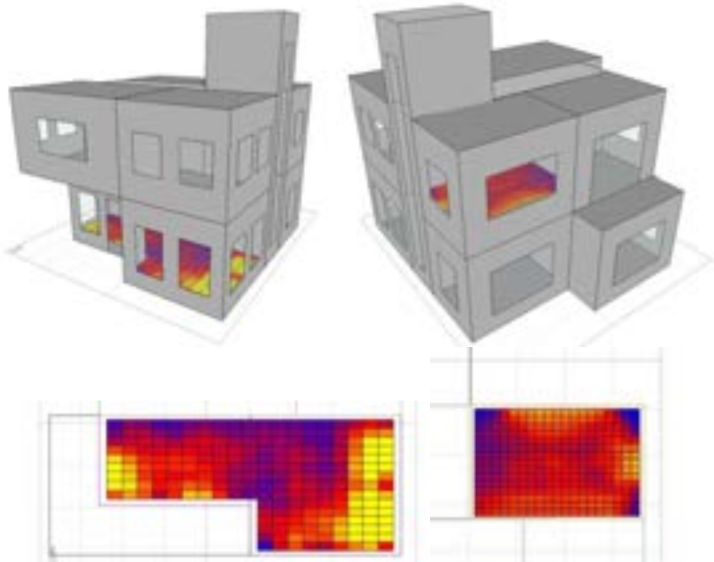


Figure 8: Daylight factor on the south (Left) and on the north (Right), source: Ecotect (2013)

6.3 Hourly heat gains losses

This graph represents hourly heat gain and HVAC load (Fig. 9), which is highlighted by the bright line. The building envelope is a key element of any energy efficient design. The recommendation is to enhance overall building performance by using proper insulation materials with the consequence that the HVAC load will be trimmed down.

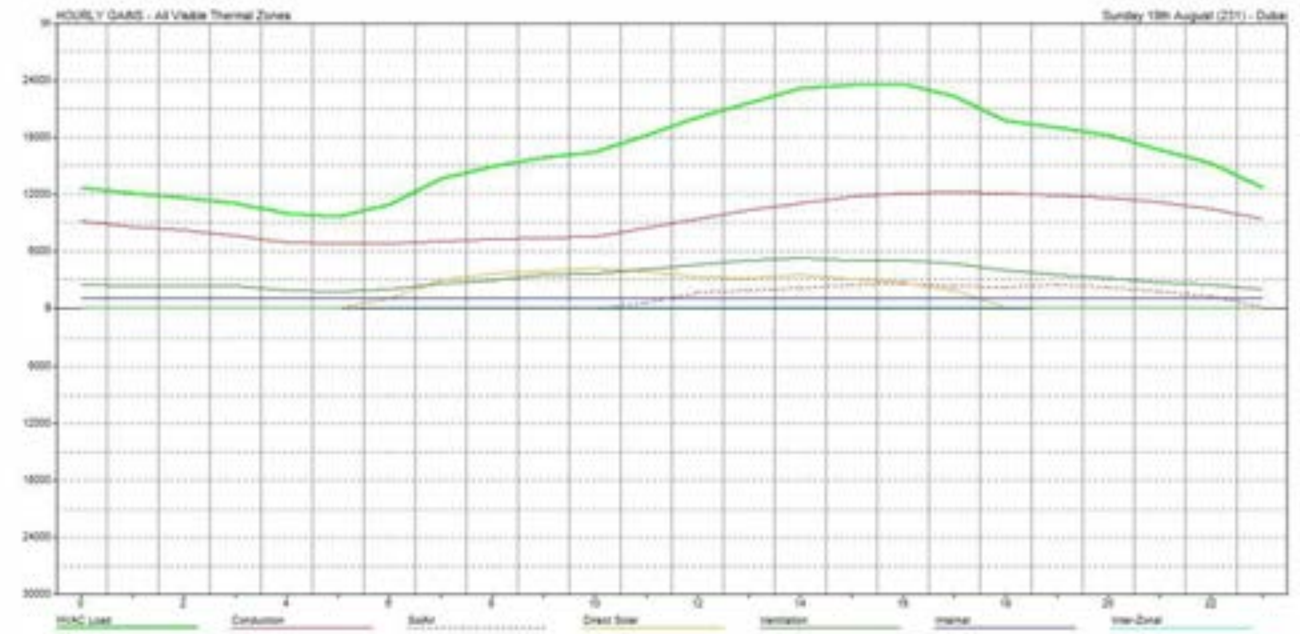


Figure 9: Hourly gains/losses graph for all visible zones, source: Ecotect (2013)

7 Applying strategies

7.1 Enhancing the building envelop

The building envelope plays a major role in attaining the best possible comfort with the least energy consumption within a building. The former is only achievable by enhancing thermal insulation and creating a lightweight cavity wall as in the butterfly exoskeleton (Fig. 10).

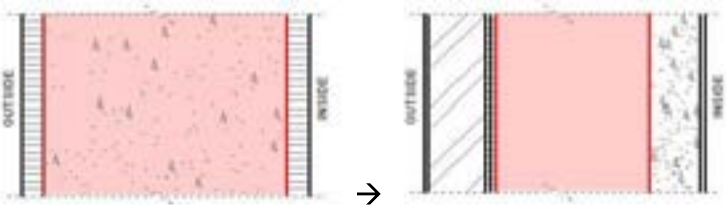


Figure 10: Wall improvement, source: Ecotect (2013)

Furthermore, the glazing was enhanced and the author propose to replace single glazed windows with triple glazed windows separated with cavities filled with argon gas to minimise penetration of excessive light and heat to indoor spaces. In addition, it must be acknowledged that minimising lower U-value for walls, Warnner and Roos (2008), roof, floor and fenestration will lead to dramatic changes in terms of reducing overall energy consumption and the HVAC load in particular, Taleb (2016).

7.2 Shading innovation via louvers

The morphology of the butterfly features special overlapping scales that are similar to louvers (Fig. 3). In parallel we can see (Fig. 6) illustrated a relatively high daylight factor level, something that is associated with human discomfort. From that perspective, the southern living room was fitted with louvers and a further daylight factor analysis was made (Fig. 11). The daylight factor was reduced by 16.4% after adding louvered shading. It was also examined that reducing south facing windows contributed to reducing overall energy consumption while also encouraging cross ventilation.

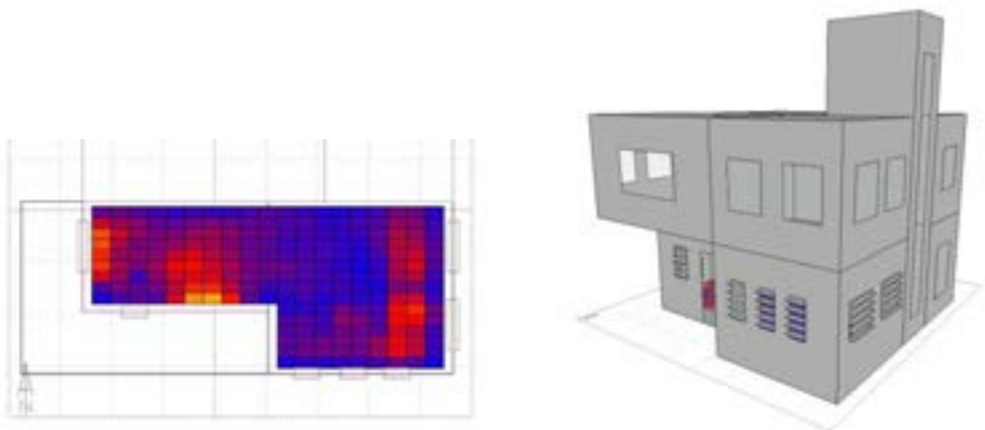


Figure 11: Living room after louvered shading improvement, source: Ecotect (2013)

7.3 Harnessing solar thermal

The butterfly is categorised as a cold-blooded insect, which uses its wing scales as a solar absorber to get warm and continue to fly. Similarly, buildings can integrate renewable resources to reduce overall energy demand from the grid and subsequently

reduce electricity bills. For that purpose, PV panels are recommended in climatic conditions that experience solar energy almost all year round. For this case study, the PV panels are most effective on the south elevation and after browsing the current state of PV technology an advanced mono-crystalline AC solar panel from BenQ, 2012 was selected. This features PV modules with reliable micro inverter technology to maximize PV benefits, increasing performance by 25%. The power output is 240 W, inverter efficiency is 95.5%, it has a rectangular shape of 0.992 x 1.651 m and along with the system a highly efficient – 70% - battery is needed to store the energy (Al-Saffar, 2012). In order to calculate the total electricity generated by a single PV panel per annum, solar irradiance in Dubai is needed. The calculation of total electricity generated by the PV panels is equal to 9.75 MW/h.

After knowing the total energy generated from PV panes, occupants may decide how many PV modules are needed to cover a noticeable percentage of energy to reduce costs and to promote sustainable design and the usage of renewable energies. Furthermore, water heating can be undertaken by using solar energy through the installation of a good quality flat plate collector connected to a water heater for domestic use.

8 Conclusion

The built environment contributes to both environmental and social problems globally. There are huge levels of energy consumption and greenhouse gas emissions as a result of human actions within the built environment. It is becoming increasingly clear that a shift must be made immediately in how the built environment is created and maintained. Throughout the paper the biomimicry concept has been in a conflict debate, some authors argued that the idea of biomimicry is all about mimicking the life and appreciating the complex relationships in the natural system, Pawlyn (2016), Aziz and El Sherif, (2015) and Holstov, ET, al, (2015). However, other authors claimed that biomimicry is an inspiration idea that can enhance the suggested solutions by architects and designers Blok and Gremmen (2016) and Nicholas et al. (2015).

Using this framework, the study suggests learning some lessons and strategies from nature to achieve energy efficient buildings with high comfort expectations. Architects and designers may integrate these strategies within building design at the early design stage or retrofit existing buildings and convert them to sustainable one because these environmental solutions are tested by nature and evolved overtime Kennedy et al. (2015). Furthermore, it is essential to highlight that integrating passive and active strategies will increasingly enhance the overall building performance. Subsequent to the butterfly understanding and specially the uniqueness of the wing scales and its ability to store energy and use it when needed for flying journeys. One of the proposed solutions was implementing the PV panels which is conceptually inspired by the butterfly anatomy within the frame of this study. Finally, it must be noted that the study reveals the importance of integrating design strategies inspired by nature and renewable energy sources, aiming to reach an energy efficient building. Further studies can be done on the same bases but to reach to zero-energy buildings.

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INCLUSIVE DESIGN: OUTCOMES FROM KNOWLEDGE TRANSLATION OF RESEARCH FINDINGS

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Abstract: *This paper presents key approaches which are significant for architects/designers who are responding to mental health design briefs, and to ensure inclusive design in our built and urban environments. There is a large body of existing literature affirming the links between good design practice, mental wellbeing, and inclusive design. However, definitive design strategies are absent or vague and generalised, limiting their application. This paper reports the findings from a design project which translated and implemented knowledge derived from an exploratory qualitative data collection and analysis undertaken in order to develop strategies for designing built environments delivering mental health services. This data collection involved a series of semi-structured interviews with mental health service users, their carers, therapists/counsellors, architects, and design experts/researchers. A case study examination of existing built therapeutic spaces was also undertaken. Through analysis, this data produced a series of design recommendations to guide the design of best practice built environments delivering mental health services. The design project which is the subject of this paper followed this data collection, and the project is an evidence informed reflection on the articulation of built environments delivering mental health services. This project uncovered three key conclusions regarding inclusive design, including: the importance of understanding metaphors significant to mental health service users; the importance of integrating unique spatial perceptions of service user groups; and strategies to aid the synthesis of design recommendations in built space.*

Keywords: *Mental Health, Built Environment, Research Translation, Healthcare Design*

1 Introduction

There is a considerable body of existing literature affirming links between mental wellbeing and good design practice. Evaluations of specific design interventions have shown that good design of a hospital's environment leads to better clinical outcomes and less stress for the users; both patients and staff (Marberry, 2006; Ulrich, Zimring, Quan, & Joseph, 2004; Ulrich et al., 2008). Research also links environmental aspects, such as landscaping or natural elements, to the reduction of stress and the promoting of recovery from illness (Laumann, Garling, & Morten Stormark, 2001). Researchers have found, through empirical investigations, that restorative environments have the potential to reduce stress and anxiety and promote wellness (Ke-Tsung, 2003; Ulrich, 2006), and these "restorative influences of environments manifest themselves in emotional, physiological and cognitive responses of humans" (Ke-Tsung, 2003, p. 209). Importantly, it is acknowledged that the external "built environment represents a modifiable feature to which [patients] are exposed and is therefore important for public health research" (Messer, Maxson, & Miranda, 2012, p. 858), yet a need remains for research identifying mechanisms by which the built environment adversely and positively impacts health in order to develop appropriate interventions (Srinivasan, O'Falton, & Dearry, 2003).

Researchers note their belief that the environment is of significance for those in treatment for mental health conditions as service users[1] "are not always consciously aware of the patterns of behaviour and the subtle interplay between experiences and environmental features," (Myin-Germeys, Birchwood, & Kwapil, 2011, p. 245) yet this has strong influence on mental wellbeing (Myin-Germeys et al., 2011). Further, studies have also linked various aspects of the environment to the onset of symptoms (Collip et al., 2011; Ellett, Freeman, & Garety, 2008) and demonstrate that where opportunities for environmental engagement with the world or environment do not exist, this results in a reduction in mental wellbeing (Blanchard, Kring, Horan, & Gur, 2010; Messinger et al., 2011).

The counselling environment is regarded within clinical literature as having an effect on a patient's sense of wellbeing (Gross, Sasson, Zarhy, & Zohar, 1998). Service users' experience of such spaces can have a highly emotional dimension (Pressly & Heesacker, 2001) which is suggestive that environmental design should be investigated as a potential means to influence therapeutic efficacy. Further, individuals have differing abilities to censor or supress their environments (Dijkstra, Pieterse, & Pruyn, 2008) and a stressed patient has reduced capacity to exclude environmental distractions (Samuelson & Lindauer, 1976), suggesting the environment of a counselling room may have more impact for these individuals who often arrive in a distressed state. "As many counselling clients arrive for their first session in distress, it may be valuable to assess their level of emotional and physical comfort in the room, and discuss their first impressions, in order to minimise any assumptions engendered by the room" (Pearson & Wilson, 2012, p. 50) This is suggestive that the counselling workspace may be influential in patient anxiety levels and therapeutic efficacy.

The body of literature identified acknowledges limitations regarding the measuring and empirical evidence of the role of the built environment in increased mental wellbeing (Evans & McCoy, 1998). As acknowledged by Ke-Tsung and others, there is a gap in the literature and more research is required in order to test ways in which theories of

[1] The term 'service user' is used throughout this paper to refer to the individual who avails themselves of mental health services.

restorative environments and design supportive of mental wellbeing could be manifest in design practice (Ke-Tsung, 2003). It is recognised by Ulrich, Parsons and Kaplan that further investigation is needed regarding the validation of concepts used as guides to assess the environmental aspects of a space conducive to supporting mental wellbeing, for example the tangible valuation of the aesthetic and psychological benefits of 'attractive visual landscapes' (Kaplan, 1987; Parsons, 1991; Ulrich, 1986). Within studies, built features or elements of the environment are often broadly defined, examined variables including 'territoriality' for example (Messer et al., 2012). More broadly, the fluid definitions found of 'mental health' may be related to the paucity of definition of spatial features or design guidelines. Researchers in this area note that "the health measures… may have been too global in content to reflect the influence of the more specific design factors" (Duffy & Willson, 1985, p. 44). Difficulty here lies in defining the environments or modifications in commensurate terms, which increases difficulty in quantifying the effects of environments on individuals (Dilani, 2015). The existing literature suggests that further research is required in the areas relating to specific design outcomes, in order to provide tangible design strategies. Suggested methodologies to mitigate limitations include defining research concepts clearly and in relation to a specific user group and context/situation, thus allowing the quantification process and design suggestions to become more clear.

Throughout the past decade, social work and mental health practice has been confronted with increased expectations to measure outcomes of service delivery (Osborne, 2002). This is also seen in architectural discourse, where measurable outcomes of built environments in relation to wellbeing are increasingly sought (Ulrich, 2006). Terms such as 'evidence-based practice' (Uggerhoj, 2011) and 'empirical research' have become commonplace in research seeking to understand health and social work services, and their associated built environments. This "age of accountability"(Austin, Dal Santo, & Lee, 2012, p. 173) has placed increased pressures on managers and practitioners at human service organisations to specify service objectives, and quantify outcomes of these objectives, involving significant investment of time and resources. This focus has led to an emphasis on developing new knowledge in a scientific approach (Uggerhoj, 2011) that is also closely related to local needs (Julkunen, 2011). However, researchers have noted how reports from such research have focused predominantly on outputs, such as how many clients/patients are served in a given timeframe, and less on outcomes, such as level of improvement of service user experience (Austin et al., 2012). Further, "even when outcome data is available, it is rarely presented in a form that practitioners can either understand or utilise to improve their practice"(Austin et al., 2012, p. 175).

Practice research is an emergent form of academic research, particularly within mental health and social work fields, whereby theory is built not only from academia but from practice also. Practice research begins with a curiosity about practice and processes, critically examining these with the aims of developing new ideas through experience and collaboration. This approach privileges the generation of knowledge with close affective ties to the professional practice itself. To meaningfully develop this knowledge, practice research "recognises that this is best done by practitioners in partnership with researchers, where [researchers] have as much, if not more, to learn from practitioners as practitioners have to learn from researchers. It is an inclusive approach" (Epstein et al., 2015). There is growing interest to incorporate the service user voice, alongside those of carers, into the research process, and the development of evidence-based strategies which can improve service user outcomes and experience. Practice research may capture input and data from practitioners, researchers, service users and educators collectively to engage in processes of inquiry, where each party "become partners in

research instead of only consumers of it" (Uggerhoj, 2011, p. 46). In this manner, social work practitioners, and other collaborating parties, can meaningfully, and enthusiastically, engage in research that has implications for their own practice, and impacts for service user outcomes and experience (Epstein & Blumenfield, 2001). This participatory approach also has also been linked to the social and economic sustainability of the mental health services provided (Epstein et al., 2015).
This paper reports the findings from research seeking to understand service user perceptions of spatiality and how architecture might contribute to improved therapeutic experiences for service users. As an outcome of this research, a design project translated and implemented knowledge derived from the exploratory qualitative data collection and analysis undertaken. This served as a means to develop and refine strategies for designing built environments delivering mental health services.

2 Methods

The research involved an exploratory qualitative design that utilised a triangulated strategy. The method of data collection was a series of semi-structured interviews with five participant groups in a triangulated approach. Interviews were undertaken with twelve service users;[2] twelve therapists/counsellors;[3] three carers of a loved one with a mental illness;[4] four architects/designers who work in design for mental health;[5] and five design specialists who work in the field of research on design for mental health. The semi-structured interviews were both exploratory and experiential, allowing in-depth qualitative data collection encompassing perspectives from each interview participant group. These interview groups were selected in order to understand service user experience of built environments delivering therapy, and how the physical design was impacting the delivery of this service; samples sizes were deemed appropriate for an exploratory qualitative study (Nastasi, 2014). This data was analysed through a thematic network (Attride-Stirling, 2001) using NVivo software package, and a series of key themes identified, conceptualising significant notions vital to interrogate and develop understanding of service user spatial perceptions, and strategies for built environments delivering therapy. The data was then re-interpreted using the thematic network as a lens, to more deeply interrogate the data, in order to draw conclusions on spatial perceptions and built environment design recommendations which could be supportive of therapy and mental wellbeing. This study is the first Australian study to align the perceptions of service users, therapists, carers, researchers and designers, and to explore similarities and differences between each of these constituent groups.

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[2] Recruited from different mental health service providers across Australia and worldwide. The initial respondents were recruited by contacting established mental health service provider organisations in Melbourne and Perth. These organisations referred peer support workers who had previously self harmed as potential participants for the research. The research project was then explained to the potential participants and an interview arranged if they chose to participate. Additional respondents were recruited through the mental health service provider Eastern Health.
[3] Recruited from different mental health service providers across Australia and worldwide. The practicing therapists and counsellors were recruited through the researcher contacting the practices directly and advertising the research and inviting participation.
[4] The carers were recruited in two ways: firstly through an advertisement circulated through newsletters sent out by Mind (a provider of carer support and education services) and Safe in Oz (a provider of support and education for those supporting individuals with mental health conditions) and secondly, through referral by other interview respondents, principally the service users themselves.
[5] The architects and therapeutic design specialists were recruited directly through contact by the researcher, using her existing contacts from her experience in architectural practice, and extending this to those considered experts in the field by the architectural profession.

Cases of existing built environments delivering mental health services were also analysed and compared with interview data, to develop supportive design strategies. Ten cases were selected using two methods. Firstly, practicing therapists/counsellors who were participating in the research were asked if their own practice rooms could be included. Secondly, notable exemplar cases from within Australia and New Zealand, as arose during the literature review phase of this research project, were selected for inclusion, also. Architectural instruments used in documenting the selected cases included those in Table 1.

Table 1: Architectural instruments used in documenting selected cases

Cases aspect	Method of documenting/architectural instruments used
Lighting levels/colour	Annotated photographs
Colour schemes	Annotated photographs, finishes schedules
Material palate	Textural variety measures including annotated photographs, finishes schedules
Layout	Annotated photographs, annotated drawings
Furniture	Annotated photographs, annotated drawings
Room size/area/ceiling height	Measurements, annotated drawings
Additional props	Annotated photographs, annotated drawings
Atmosphere	Researcher's own notes examining her feelings/impressions of the environment
Access/egress	Annotated photographs, annotated drawings, researcher's own notes examining her feelings/impressions of the environment
Noise levels	Researcher's own notes examining her feelings/impressions of the environment
Nature content	Annotated photographs, annotated drawings

A cases analysis tool was developed which focused on the translation of the factors arising in the interviews into the language of designing spaces. To develop this analysis, a synthesis of techniques was employed, including application of the interview data, the researcher's observations (including the aspects noted in Table 1 above) and the photographs taken. The cases analysis tool includes aspects for examination grouped according to the interview respondents who discussed the particular aspects.

3 Knowledge translation

Following the development of the design recommendations, an evidence informed reflection on how to realize built therapeutic environments was undertaken. Two sketch design proposals were developed. These are examples of how the knowledge gained and design recommendations uncovered might be translated and implemented in the built environment. These proposals are predominantly illustrated through perspective views and visualisations (not technical drawings). This format privileges the service user perspective. This format is also a useful means to disseminate findings and illustrate how design recommendations could be integrated into existing (or proposed) therapeutic environments by practitioners; a need identified by research participants. Direction was sought from participants as to how to disseminate findings in a useable format. Here the inclusion of participant perspectives, in a practice research approach, informed an understanding of the best strategies for how to integrate, deploy and disseminate the design recommendations derived.

Three key areas of significance emerged: the importance of understanding metaphors significant to service users; the importance of integrating unique spatial perceptions of service user groups; and strategies to aid the synthesis of sensory encounter in built interior space. These are each discussed below, with illustrations exploring their integration in architectural space.

3.1 Understanding metaphors significant to service users

In relation to understanding architectural encounters which are of particular significance to service users, and inclusive design, a series of metaphors were uncovered. Most significant is the metaphor of a uni-directional progression/sequence of spaces manifesting therapeutic progress of the service users (Figs.1 and 2). As one explains:
It's kind of yucky to walk out the same way you came in if you are distressed. There should be a distressed door [an exit to use when feeling distressed after a counselling session], where you can't be seen, and can leave that's different to the entry (Service user, 2015, Personal communication).

Fig. 1: Uni-directional journey visualization

Fig. 2: Uni-directional journey visualization

It seems there is a metaphor of progress made spatially, and to back track and repeat earlier steps is not conducive to or representative of therapeutic development, and reminds the service users of how they felt prior to the session, which to the service users feels as though they are not making positive progress (Fig.3). A practicing therapist reflects on this:

So you step out of the counselling space and if it is somewhere where you have just been, it doesn't totally make sense [to reverse your journey] and I can see why someone could feel like it is a little bit of a backtrack, and you are just back where you started… if a certain behaviour environment represents something to someone, we need to listen to that and understand that it is really beneficial (Therapist, 2015, Personal communication).

Fig. 3: Waiting area visualisation; experienced only once in a uni-directional journey

Another practicing therapist reflects on the metaphorical journey of a counselling session:

Having a space that you could then leave through [after counselling] would associate more with letting go of the session, and creating that mental boundary or that mental break between what just happened in the session and resuming your day to day daily life (Therapist, 2015, Personal communication).

Spatial metaphors are also evident in notions of or trace within interior environments (Fig.4). Service users discuss how notions of trace of previous inhabitants leads the service user to be more aware of the previous occupation of the space, and thus they are confronted with the comprehending of another service user voicing their own issues/problems in that same space. These issues linger in the space, and the service user then feels that they are dealing with the issues of another person in addition to their own, which is overwhelming and increases stress and anxiety. Thus, weathering and trace are indicators of this, and should be minimised where possible, in order to reduce the psychological load on the service users.

Fig.4: Counselling workspace visualisation; signs of trace minimised

Ensuring a minimisation of trace is key to ensure the service user need only be concerned with their own thoughts, issues, and the present therapy session, rather than being aware and overwhelmed with the service users who have inhabited the space before, and the traumas imagined to be associated with them. This is the space acting as through metaphor in a significant way; the space is a carrier of past issues, a vessel of another's trauma discussed in the room and made physical through trace. This physicality of another's distress is confronting to the service user, infringes upon their sense of psychological safety, and reduces their therapeutic engagement. Using the notion of inclusive design as a lens, the metaphors revealed by the interview data took on a deeper significance. This allowed for a greater comprehension of how metaphors are coded in the built environment and interpreted by service users. The physicality of interaction was the mechanism by which the metaphors were manifest and perceived by the service users, leading to specific design recommendations related to trace and materiality in built environments.

3.2 Integrating unique spatial perceptions of service user groups

Concepts of spatial agency were discussed by service users in relation to their spatial perceptions of built environments. Agency was discussed by service users as an amalgamation of feelings of increased control and reduced anxiety, allowing them to feel empowered enough to derive a sense of agency. Built environments would erode feelings of agency through mitigating opportunities for control, and exacerbating stress. Psychological aspects of safety allow the service user to open up more, to engage, and to feel more in control. Presence of nature serves to reduce stress; this is significant in the counselling workspace and in corridor spaces, enabling a continuation of connection to nature throughout the experience (Fig.5 and 6). Furniture selection which reduces imbalance of power between the therapist and the service user also reduces stress. Particular lighting conditions, layout, views, surveillance and trace could increase stress, reduce feelings of control, and erode any sense of agency service users felt they possessed. There were characteristic similarities in the way service users discussed manipulations of spatial arrangements or spatial expression as a means to derive a sense of agency (Liddicoat, 2015). Particularly significant was the manipulating spatial arrangements in personally significant spaces. This was a confronting activity for service users, yet ultimately a process which could provoke and heal simultaneously, and assist in the development of agency.

Fig.5: Connection to nature in circulation spaces visualisation

Fig.6: Connection to nature in circulation spaces visualisation

Notions of trace were also connection to perceptions of spatial agency. Evidence of past inhabitation by other service users made manifest their ‘issues’ physically in the therapeutic space. The imprints left behind by these other service users, now absent, were interpreted by the service user present in the space as unresolved issues lingering. This added to the weight of their own thoughts and feelings, and increased the psychological chaos and anxiety experienced. Space as production zone for agency refers to the manner in which these service users relate to space in a manner which articulates their own psychological states. Personal space and proxemics become vehicles for the spatial expression of transferences, both positive and negative. However, this can be interrupted by the presence of another service user and their ‘issues’ in the room, made manifest through their traces. The manipulation of non-fixed

physical features to derive empowerment and sense of agency is directly interrupted when the space, and those non-fixed physical features, display the traces of another.

Space acting as symbolism was also a significant aspect of the service users' spatial perceptions of built environments. Space as symbolism refers to spatial arrangements as external texts to be decoded and interpreted by the service users. Space as symbolism was often manifest in relation to aspects of control. It seems notions of control were strong examples of external texts being interpreted by the service users. This was discussed in relation to building layouts, security measures, segregation, abilities to personalise, and flexible spaces. Interior environments were commonly perceived as either eroding their sense of control, or undermining their abilities to exert control. This was then interpreted as indicating that they, themselves, were not worthy, were insignificant, and exacerbated negative stigma related to mental health. Therapeutically, this resulted in a lower sense of self and identity, and unwillingness to engage in therapeutic processes due to feeling psychologically unsafe in spaces where one was not in control. Further, where a service user felt they had no control in the space, this also related to an imbalance in power relations perceived, manifest in physical ways such as layouts, furniture/chair choices/selection, and therapist personalisation of space. Subtle articulations of physical space, such as an intervening desk between therapist and service user, could bring on these powerful spatial metaphors, suggesting a characteristic sensitivity and emotional overtone interpreted together with the physical space. Interior environments could also be interpreted as minimising or exacerbating imbalances of power. Any articulation of space which symbolised an erosion of power or control for the service user, for example surveillance windows in doors, or duress alarms, caused psychological engagement to cease. Further, having few opportunities for physical engagement reduced psychological engagement. This illustrates how the human sensorium and its connections to interior environments are significant in relation to perceptions of spatiality and mental wellbeing.
The perception of stigma in the built environment was discussed by service users, and could result in detrimental therapeutic effects. Aspects such as visible security measures, internal rooms, peninsula beds, excessive use of concrete, lack of natural elements, all were read and interpreted by service users as a kind of punishment. Here they are being told they are abnormal, dangerous, insignificant and, for some, worthy of imprisonment. This served to increase stress and anxiety, and reduced engagement in therapeutic processes. The service users felt psychologically unsafe when experiencing such interior environments, and thus were less willing to communicate, or to feel validated, and reinforce a sense of identity.

When re-interpreting the interview data through the notion of inclusive design as a lens, the mechanisms by which spatial agency is developed or restricted becomes apparent. Inclusive design also offered insights into how stigma and various symbolic aspects were communicated by features, layout and materials of the built environment. Here, engaging with the notion of inclusive design serves as a catalyst to unpacking perceptions of spatiality, and understanding the modes in which mental wellbeing might be influenced through built space. This also emphasizes participatory design methodologies as a means to best realise supportive mental health environments and integrate the needs and spatial perceptions of service users.

3.3 Synthesis of sensory encounter in built environments

The provision of a series of additional spaces which form part of built environments delivering therapy is a strategy emphasised by this paper. These three additional spaces aid the synthesis of sensory encounter in built environments, which is supportive of therapeutic effect. These spaces, termed by the author as a ‘de-escalation space’, an ‘urge room’ and a ‘natural mind-space’, are detailed below. The suggestions of a de-escalation space and a natural mind-space arose through discussions in the fieldwork data collection and are non-existent in terms of what is currently delivered in mental health service facilities/built environments. This paper suggests the inclusion of these spaces, as part of a built environment, in order to further support therapeutic efficacy and inclusive design.

3.3.1 De-escalation space

A space to occupy post- counselling as part of a journey of de-escalation was found to be of particular significance to individuals who self harm (see Fig.7). After the intensity of a counselling session, for individuals who self harm the transition to the outside world afterward was found to be very difficult:
The therapy sessions are often really intense, I don’t know about other people but my sessions might go for two hours, and I’d be totally numb afterwards and have to go straight out into the world, when I feel so vulnerable and it was so frightening, sometimes I’d just get so anxious about it, I’d be self harming in my car on the way home (Service user, 2015, Personal communication).

Fig.7: De-escalation space visualisation

Having a space to occupy alone post counselling was raised by several service users as being of potential benefit to them:
If you could sit on your own and self soothe and rebalance yourself before you leave; otherwise I just dissociate and I think how did I get here! I must have gotten in my car and driven home but I've dissociated, which I do really easily after a session, and I have no idea how I've gotten home, and that's dangerous! Somewhere in private before you go, it'd stop you dissociating, and mediate between the really intense heavy session, and going home (Service user, 2015, Personal communication).

Service users who were interviewed mentioned feeling very vulnerable after their counselling session and needed a space to occupy quietly and privately to rebalance themselves and move from the intensity of the counselling session to the noise and pressure of the 'outside world'. Some mentioned that within the counselling workspace they felt shut off from the world and needed a private space to sit in and maybe have a cry and prepare themselves for moving back into the world they had felt shut off from moments before. One service user noted that even knowing that a private room was available for this de-escalation would help: "you may not go into the room, but knowing it is there [would bring comfort]" (Service user, 2015, Personal communication).

A practicing therapist also reflects and supports the idea of a de-escalation space for service users after a counselling session:

Emerging straight into the world is confronting; I would liken it to getting up in the morning, and you have been in another state like sleep, and you need to adjust and bring yourself back to the world outside and bringing yourself back to whatever that might need to be. So, I think you are at a different rate, whether it be consciousness, or reengaging back into where you were previously, I think that can take time, and it can also take an awareness of how you can bring yourself back to that space (Therapist, 2015, Personal communication).

One practicing therapist also discusses the notion of a de-escalation space for service users to occupy post counselling, revolving around bodily movement:

Possibly beyond that [counselling space] a space for someone to take a short walk, like a small hallway, for someone who the way they gather themselves… [is to] take a short walk back and forth… the physicality of walking is calming… it does offer the opportunity for your mind to go to find the answer. The rhythmic nature is also important (Therapist, 2015, Personal communication).

This is suggestive that the transition between a counselling session and the world beyond is difficult and needs to be supported by environment and design, such as through a de-escalation space. The value of a de-escalation space is its support to aid reconnection with the self and re-integration with the 'outside world'.

3.3.2 Urge room

The notion of an urge room in inpatient care was suggested by service users. This is essentially a space where they might go when confronted with the urge to act out or self harm, and this space would help to quell these desires through its design. This is described thus:

Bright coloured pods, a confined space, where I could go would help - I blast the senses to occupy myself, to bring me back to the present. A sensory stimulus pod! That can rock! To soothe yourself. I mean, that's why I watch a movie really loud [when I have the urge to self harm], or play my music real loud, to bring me back and stop distress. Rocking - it's relaxing, and it's disabling, it's rhythmic and brings you back to your body (Service user, 2015, Personal communication).

High sensory stimulation is paramount in this room to assist the service user to remain present. Music is also noted as useful in this endeavour: "[Music] would be great for soothing, to be more present, it's a good distraction and coping strategy. Music is good for escapism, it can transport you" (Service user, 2015, Personal communication).

The urge room was suggested by users predominantly as a space which would be a useful addition in an in-patient facility. Here service users felt they did not have a suitable space where they could 'blast the senses' as they needed and relieve potential

urges to self harm in this way, as they might have opportunities to do in their own home environment (Service users, 2015, Personal communication). The urge room thus needs to be easily accessible to in-patient bedrooms, however its placement within the overall sequencing of spaces is otherwise flexible. Service users also discussed how an urge room might manifest in different ways; some discussed their own vehicles as safe spaces where they could quell urges to self injure through the tightness of the vehicle interior, playing music loudly, and similar, without fear of disturbing others or drawing attention. The vehicle here is a kind of urge room, where the service users can self-soothe in private. This suggests that an urge room can also be mobile, and may not manifest as a room in a traditional sense. This may manifest as a mass-produced item/prop for use in spaces delivering mental health services, customisable to the needs of the facility and their service user demographic/needs.

3.3.3 Natural mind-space

A natural mind-space is a natural, physical space which is accessed visually and occupied only by the mind (see Fig.8). This provides escape and mental respite, yet also promotes a sense of control, and permits the service users to engage more comfortably in therapy as they feel more psychologically safe:
Having that view out to a landscape, it's been important through my whole stages of treatment, yeah the whole way, but I didn't realise until I didn't have that safe view from a window, and I think that is probably part of the reason I didn't continue in some ways, because as I said it was so confrontational, I had nowhere to look, I felt totally judged and I just didn't feel safe (Service user, 2015, Personal communication).

Fig.8: Natural mind-space visualisation

It seems that this landscape is not important to occupy physically, and that visual access provides the sense of escape or mental respite which is desired:
I would look out the window and even in the counselling I would need a window to feel safe… It gives me a psychological connection to a bigger space, to a world outside what I am dealing with (Service user, 2015, Personal communication).

Practicing therapists also acknowledge that "landscapes and views to nature allows you [the service user] a sense of escape" (Therapist, 2015, Personal communication). Theoretical research in this area explains that nature containing elements and content will reduce stress (Ulrich, 1999). Studies in healthcare environments generate strong

evidence of the stress-reducing benefits of real or simulated views of nature or natural elements, and this manifests in positive emotional, psychological and physiological changes (Hartig, Book, Garvill, Olsson, & Garling, 1995). This relates to how visual access to nature may allow service users a sense of safety, as nature helps to reduce stress and anxiety and thus promotes a sense of comfort. Research cites connection to nature positively influencing staff, resulting in improved service user experience (Ulrich, 1999) (see Figs.9, 10). Research also cites the inclusion of natural content as supportive to service users of diverse cultural backgrounds (Sloan Devlin & Arneill, 2003). Further, the use of sustainable, natural materials is emphasised, as these natural elements were also viewed as supportive. The architectural encounters which are significant to service users, such as urge rooms, de-escalation and natural mind-spaces, can be more readily conceptualised when examined through the lens of inclusive design.

Fig.9: Inclusion of nature/natural elements in communal spaces

Fig.10: Inclusion of nature/natural elements in staff spaces

Fig 11: Inclusion of nature/natural elements in staff spaces

4 Conclusion

This paper began with an investigation into inclusive design strategies for designing mental health service environments. Through an exploratory qualitative analysis undertaken, the perceptions of spatiality of service users, and the architectural encounters which might be supportive of their therapy, were explored. Through presentation of a design scheme responding to this data collection and analysis, this paper has detailed three key conclusions regarding the modes in which mental wellbeing might be influenced through built space and inclusive design. These included the importance of understanding metaphors significant to service users; the importance of integrating unique spatial perceptions related to spatial agency; and strategies to aid the synthesis of sensory encounter in built interior space. What becomes clear through this investigation is that executing supportive designed environments begins with an understanding of the needs and spatial perceptions of service users, together with other stakeholders. Participatory design methodologies are emphasized to best realise mental health environments that are not merely a housing of therapy, but an active agent in therapy processes, and psychological engagement, for service users. These conclusions are key to realising social and economic sustainability with regard to societal mental health issues and mental health service environments. Participatory and practice research informed design methodologies are also key to assist the delivery of built environments which accommodate people with different needs and sensitivities, such as mental health service users.

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OCCUPANT ENERGY USE BEHAVIOR AND SATISFACTION IN OFFICES IN QATAR

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Abstract: *Uncertainties about the occupant behavior adversely affect the building performance predictability of the simulation models. In the absence of field data on occupant energy use and behavior in Qatar, we conducted an environmental satisfaction and energy use survey in seven office buildings in Qatar. We noted high turn-off rates of 87% and 85% for computers and monitors in offices respectively. Building occupants were highly satisfied with their work environments with respect to most of the environmental parameters excepting acoustics. Access to operable controls such as windows, thermostats improved the satisfaction. Subjects in private offices were more satisfied with their working environments. In general, we noted the self-declared productivity of respondents to be high. Noise level dissatisfaction was the uppermost in high partitioned cubicle offices and satisfaction was high in open plan offices. These findings can provide vital design directions for new offices and environmental systems in Qatar.*

Keywords: *Occupant Behavior, Energy Use, Office Buildings, Energy Conservation, Occupant Satisfaction.*

1 Introduction

Qatar's per capita energy consumption is one of the highest, aggregating to 222 MWh as of 2013 (World Bank, 2016). It is increasing phenomenally. Buildings contribute majorly about 80% to this energy consumption. Some of the primary influencing factors are building design, use of heating, ventilation and air conditioning (HVAC) systems, operation and maintenance, building envelope characteristics, etc. In addition to these, building occupants' behaviour also influences the overall energy consumption. Uncertainties about the occupant behavior adversely affect the building performance predictability of the simulation models. Temporal, spatial and stochastic nature of occupant occupancy/ behavior makes it hard to account for in energy simulations. A large number of studies evaluated the impact of occupant behavior on total energy consumption levels, mainly through their action and interaction with the building environment (Hong & Lin, 2012; Webber, Roberson, McWhinney, Brown, Pinckard, & Busch, 2006; Masoso & Grobler, 2010). Some of the studies focused on building lighting, where the light switching patterns of occupants based on the room and outside conditions were investigated (Masoso & Grobler, 2010; Lindelöf & Morel, 2006).

Changes in the indoor environment that disturb the thermal comfort equilibrium drive occupants to take several actions to restore comfort. Several researchers studied human adaptation in offices and proposed adaptive models (Nicol, 2004; de Dear & Brager, 2002; Indraganti, Ooka, Rijal, & Brager, 2014; CEN:15251, 2007). The adaptive actions might change the net energy use in the building.

Elaborate research is available on thermal comfort and indoor air quality in the West, Asia and parts of Africa (ASHRAE, 2010; Nicol, 2004; CEN:15251, 2007; Indraganti, Ooka, Rijal, & Brager, 2014; Ogbonna & Harris, 2008). However, user satisfaction is also essential. One's ability/ opportunity to interact with the building also affects the user satisfaction. It was noted that buildings in USA, Canada and Finland fell far short of air quality and thermal comfort performance goals set by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards (ASHRAE, 2010) vis-à-vis occupant satisfaction (Huizenga, Abbaszadeh, Zagreus, & Arens, 2006a). Occupant satisfaction with respect to the indoor environment is less understood and reported in this part of the world.

Very few studies from the Middle East focused on the occupant behavior in buildings. Al-Mumin et al. (2003) looked at the occupant's behavior and activity patterns in 30 residences in Kuwait. This study questioned the default assumptions of Western lifestyle for Kuwaitis. It reported 21% increase in annual energy consumption on replacing the default values with occupancy patterns observed in the field study.

However, there is little information on the occupant energy use behavior in offices in the Middle East. Therefore, we conducted a field study in offices in Qatar. This survey aimed at recording (1) the energy use behavior of the occupants and (2) to understand the level of satisfaction in occupants with respect to the environment.

2 Methods

We surveyed a total of seven buildings in Qatar. An energy use and occupant satisfaction survey was carried out in two stages. The first stage was a paper based on field survey in five office buildings in Doha in winter. The latter was an online survey done in summer in two more buildings. The offices surveyed were both government and private companies' offices. Two separate questionnaire sets were used. We administered the former on the building facility managers, and the latter directly on the building occupants. The building managers provided general information on the building and their operation. The latter was aimed at directly collecting information on the users' behavior. A total of 322 occupants responded, 48 of them through an on-line survey.

The building manager's survey had questions in five sections as following:
(1) Building background relating to the tenancy, age and type of the structure, number of occupants, hours in use per week, floor area, and the level of occupancy,
(2) Building materials used for walls and roofing systems,
(3) Energy sources for space cooling and heating, percentage of spaces heated or cooled,
(4) Space and water heating and cooling systems, types of equipment and maintenance,
(5) Lighting systems in use and the percentage of areas lighted when the office is in operation and when the office is closed.
The occupant survey had four sections. These are:
(1) User identifiers: such as gender, nationality, office, nature of work, type of office space occupied, type of windows, etc.,
(2) Involvement indicators such as access to controls, time spent in the office,…etc
(3) Information on appliances such as their availability and attitudes towards energy use,
(4) Satisfaction queries such as overall environmental satisfaction, environmental satisfaction relating to thermal, air-movement, indoor air quality, noise and sound levels, and self-declared productivity.

2.1 Building Description

We surveyed three government and four private companies' office buildings in Doha. These are 3 – 12 years old. Private offices operated for six days a week while the public offices for five days. Two of the private buildings were owner occupied and operated while the rest were tenant occupied. One of the buildings is 52 stories, while the rest were 2-6 stories high, with partially vacant spaces in all of them. Very few of them have operable windows. Interestingly, 50-99% of the building area is under electrical lighting during the office hours, and about 49% beyond the office hours, in all the buildings. The following Table 1 summarizes the details about the facilities in the buildings surveyed.

Table 1 Summary of the facilities in the buildings surveyed

No.	Description	High rise building	Other buildings
1	Source of energy for lighting, HVAC, water heating and refrigeration	Electricity	Electricity
2	Centralized space heating equipment	Not installed	Not installed
3	Stand alone space heaters	Available in a few offices	Available in a very few offices
4	Period of HVAC usage	Yearlong	Yearlong
5	Type of space cooling equipment	Central chillers and split-system heat pumps	Residential type central air-conditioners with individual air-conditioners
6	Hot water supply	Small-distributed water heating systems (30 – 100 li)	Small-distributed water heating systems (30 li)
7	Refrigeration	Individual refrigerators	Individual refrigerators
8	Day lighting	Multi-paned windows and tinted window glass	Multi-paned windows and single layered glass
9	Artificial lighting control for specular reflectors and electronic ballasts	Energy management and control system	Energy management and control system
10	HVAC Energy control and monitoring	Energy management and control system	HVAC maintenance

2.2 Occupant profile

We collected 71 (22%) responses from females and 251 (78%) from males. About 43% of the subjects are engaged in technical jobs while 3 -15% of them are in managerial/ supervisory, administrative support, educational and other jobs each. Their distribution is similar across the offices.

3 Results and discussion

The subjects had association with their offices for over different lengths of time: 22% for less than 1 year, 26% for 1- 2 years, 27% 2 - 5 years and 21% for more than five years. While 93% of the subjects worked for five days a week, less than 1% subjects reported to have worked for 2 – 7 days/ week. Interestingly, 69% subjects worked for 10 hours/ day while 4 – 5% worked for 7 – 9 hours/ day and less than 1% each worked for 1- 6 hours/day in the office. On the contrary, a California study observed that the occupants were away from their offices 25–30% of the nominally occupied hours of the day (Bauman & McClintock, May, 1993).

3.1 Work spaces and access to temperature control

We identified five types of works spaces: private, shared enclosed, high partitioned, low partitioned cubicles and open offices. Observable, most of the subjects interviewed were seated in open offices. Access to temperature control is regarded as one of the most important adaptation mechanism available to office occupants. Among all the offices, 72.1% subjects have access to temperature controls. Fig.1 shows the proportion of access to temperature control in various types of offices. Importantly, open offices have highest access (55.1%) while high partitioned offices have the least (3.5%).

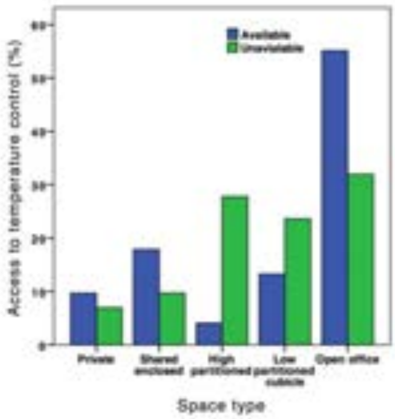

Figure 1: Availability of access to temperature control in various types of offices

The questionnaire included an enquiry into the set temperature in January (peak winter) and August (peak summer). Interestingly 47.2% voted the set temperature to be in the range of 22 – 24 °C in winter while 28.6% voted the same in summer. Also, 25.8% subjects voted the set temperature in summer to be 19 - 24°C, while less than 4% subjects voted the set temperature to be above 27°C. On the other hand, less than 1% subjects said the ACs would be turned off in winter as seen in Table 2.

Table 2 Range of air-conditioner set temperature ranges in peak winter (January) and peak summer (July) and the proportion of subjects preferring them

	Proportion voting in (%)	
AC Setting Range (°C)	January (N = 259)	August (N = 249)
off	0.6	
<=18	2.5	13
19 - 21	14.9	25.8
22 - 24	47.2	28.6
25 - 27	15.2	6.5
> 27	-	3.4

Researchers noted a significant impact on energy use, when it was tested with Energy Plus simulation software. For example, when compared to the base case of standard work-style, the austerity work-style expanded up to 50% less energy, while wasteful work-style consumed 90% more energy (Hong & Lin, 2012; Azar & Menassa, 2012).

On the other hand, Azar and Menassa (2012) used sensitivity analysis on the occupancy behavioral patterns in offices of various sizes in different weather conditions. They noted heating temperature set-point in small-size buildings being most sensitive in 'US weather zone 2 dry.' It appears that the majority of subjects in Doha are accustomed to the same set temperature (22 - 24°C) in both winter and summer. It is also important to note that about 26% subjects voted the set temperature to be 19 - 21°C in summer.

An operable window happens to be one of the important adaptive opportunities available to the users in naturally ventilated buildings mostly, and sometimes in air-conditioned buildings as well. We noted three types of windows in offices in Qatar: operable windows, operable curtain glazing and fixed curtain glazing. While 28.6% of the subjects reported to have an operable window, 13.4% and 20.8% have operable and fixed curtain glazing respectively. Interestingly 37.3% of subjects have no access to a window. Abbaszadeh et al. (2006) stressed the need for operable controls in work environments through the findings of a study in USA and Canada.

3.2 Energy use and occupants' attitude towards energy conservation

Occupants' energy use in offices is important as it affects the plug-loads, which are a major component of total energy used in buildings. In this study, we noted most subjects using personal computers (PC) with LCD monitors (84.2%). About 10% of subjects used laptops while 2% had PCs with CRT (cathode ray tube) monitors (Total N = 315). Most of the subjects (70%) worked with their computers for longer than 8 hours a day.

Energy Star promotes energy efficiency in buildings and appliances. Interestingly, only 55.6% had a star rated computer, reflecting poor proliferation of star-rated goods in Qatar. Recent research in the US noted higher satisfaction levels in Energy Star certified residential and office buildings than in non-star rated buildings (Amasyali & El-Gohary, 2016).

Turning off computers and monitors during their non-working time saves energy. In this study, we noted 87% and 85% respondents shutting-down their computers and monitors respectively. On the other hand, Sanchez et al. (2007) observed that when the building is unoccupied, the average turn-off rates for desktop computers, copiers, and scanner were 59%, 45%, and 41%, respectively.

Webber et al. (2006) reported that less than 50% of the equipment was turned-off after the office hours. For the equipment left switched on overnight, they noted less than 6% of the computers successfully migrating to the power saver mode. Masoso and Grobler (2010) also reported alarmingly high quantities of high energy being wasted during the non-working hours in South African offices. They found more than half the total energy being used during non-working hours. They attribute this to the occupant's behavior of leaving lights and equipment 'on' at the end of the day and in part due to poor zoning controls.

We observed more laser printers in use (64% cases) compared to inkjet printers (36% cases) in offices in Qatar. The majority of them are non-star rated (55%) and were not turned-off at the end of the day (57% cases). Conversely, 86% of the subjects expressed to have concern towards the energy use of printers.

Availability of scanners was limited to 11% of the occupants while 66% said to have non-star rated printers. Interestingly more than half of them do not switch these off at departure at the end of the day. Similarly, desk lamps were available only to 6% of the subjects and less than

2% of them are star-rated. About 67% of the subjects switch them off at the time of departure.

Most of the offices we surveyed have strict policies prohibiting the employees from using additional appliances such as desk lamps, heaters and fans. This is in part due to their restrictive policies aimed at containing the plug loads. While some of the private company's offices rigorously follow the dictum, the government offices are found to be lenient in its implementation.

Care and concern for the energy used in HVAC seem to be high among office occupants in Qatar. About 90% said they cared for HVAC energy. Similar concern was expressed for energy used for lighting. Moreover, 57% subjects mentioned that they switch off lights when leaving their offices by the end of the day. It is important to note that only 25% of the offices have motion sensor controlled lighting. Unlike the offices in the developed world, a majority of office occupants surveyed in Qatar do not have electric kettles, refrigerators, personal heaters and fans at their workspaces. Even when they have, they are non star- rated equipment.

User's ease of interaction with the building envelope/controls also affects the occupant behavior and energy expenditure eventually. Lindelof and Morel (2006) studied the probabilistic patterns light switching by building occupants in Switzerland. They noted the light switches were seldom operated when placed close to the office entrances (i.e., away from the desks). In another study, Mahdavi et al. (2006) investigated the behavior of occupants in 48 offices located in three buildings using digital cameras. They found that on average, occupants spend less than 50% of their time at work while they do not turn off the lights and other office equipment during non-working hours.

3.3 Occupant perception of indoor environmental quality

During the survey, we collected information on occupant satisfaction on a number of environmental parameters such as: thermal comfort, air movement, indoor air quality (IAQ), noise and satisfaction on a three-point scale (-1: Unsatisfied, 0: Neutral, 1: Satisfied). Distribution of occupant' satisfaction on these parameters is shown in Fig.2.

As can be observed, thermal satisfaction was very high with 67% subjects being satisfied. Similar was IAQ satisfaction (25% unsatisfied). On the other hand, acoustical satisfaction was rather low, with 48% subjects feeling unsatisfied with the noise levels.

Noise level satisfaction was lowest in high partitioned cubicle offices, with 60.7% subjects expressing dissatisfaction. On the other hand, dissatisfaction was lowest in low-portioned cubicles. At the same time, proportion of subjects dissatisfied in open offices is significantly higher than those satisfied with the acoustical environment in open offices at 95% confidence interval (CI).

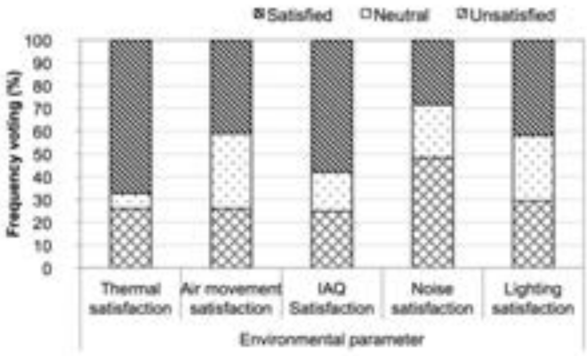

Figure 2: Distribution of occupant satisfaction on various environmental parameters (N = 322).

The distribution of noise level satisfaction in various types of offices is shown in Fig. 3. Jensen et al. (2005) noted similar pattern of noise level satisfaction in subjects from office buildings in USA and Canada. They noted open office subjects being significantly more satisfied with noise level and speech privacy than occupants working in cubicles ($p<0.01$). They also suggested “People talking on the phone”, “People overhearing private conversations” and “People talking in surrounding offices,” as the major problems. Interestingly, Abbaszadeh et al. (2006) reported from a comparative study that a higher percentage of occupants were dissatisfied with light levels and sound privacy in green buildings, as compared to non-green buildings. This was partly due to the day lighting requirements of interior office spaces and aural privacy requirements clashing with one another.

Anecdotal responses of Qatar subjects revealed that subjects in low partitioned offices are generally more tolerant of the general noises originating from printers, co-workers, etc. While on the other hand, subjects in the private cubicles perceived the same noises annoying.

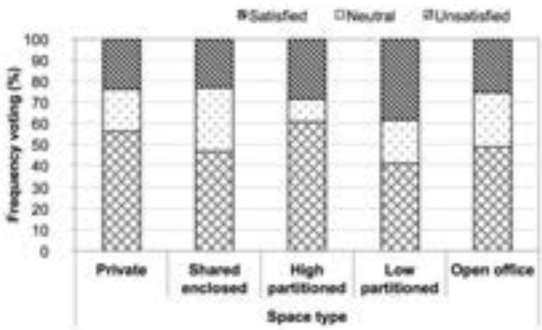

Figure 3: Percentage of occupants who voted the noise level was satisfactory, neutral and unsatisfactory in various workspaces (N = 273).

3.4 Building ownership and the effect of access to temperature control

Building operation, maintenance, space availability, and as a result occupant satisfaction were all noted to be influenced by building ownership in Qatar. The data were divided based on public and privately owned buildings (N = 58 and 264 respectively). Moreover, occupant’s access to temperature control was not the same. Only 70.5% subjects mentioned to have access to temperature control in their offices.

Subjects in buildings under private companies’ ownership recorded slightly higher satisfaction levels in all the five parameters considered as shown in Fig. 4. However, mean noise and lighting level satisfaction were -0.28 and -0.36 respectively in public buildings,

indicating a higher percentage of people being dissatisfied with these two environmental parameters. The difference in lighting level satisfaction in public and private buildings is statistically significant at 95% CI.

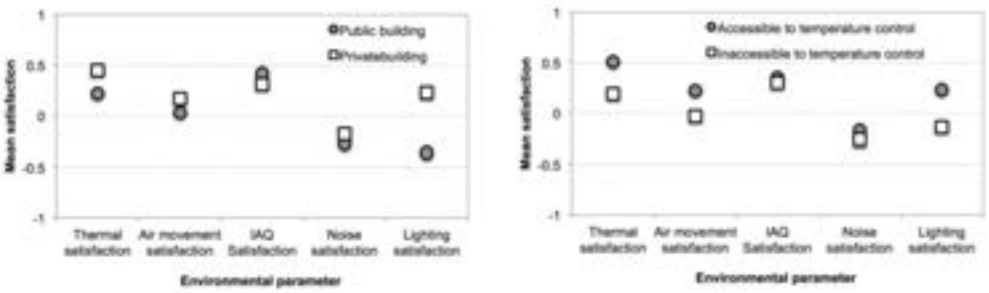

Figure 4: Mean satisfaction for various environmental parameters with respect to ownership and access to temperature control.

Access to environmental controls such as thermostats has a marked effect on indoor environmental satisfaction (Brager, Paliaga, & de Dear, 2004; Zagreus, Huizenga, Arens, & Lehrer, 2004). In this study, we noticed subjects with access to temperature control expressing higher satisfaction on all the parameters investigated as shown in Fig. 5. For example, thermal and air movement satisfaction are however much higher when a temperature control is provided to the subjects and the mean differences are statistically significant at 95% CI. Similarly, lighting level satisfaction was also noted to be higher when temperature controls are provided to the respondents.

Also, Amasyali and El-Gohary (2016) identified higher satisfaction levels in occupants who displayed adaptive behavioral control actions: operating humidifiers, thermostats, windows, air-conditioners, etc. On the other hand, from a large-scale occupant satisfaction survey in offices in USA, Canada and Finland, Huizenga et al. (2006a) found 80% or more of the occupants expressing satisfaction with their thermal comfort, only in 11% of the surveyed buildings and with air quality in 26% of the surveyed buildings.

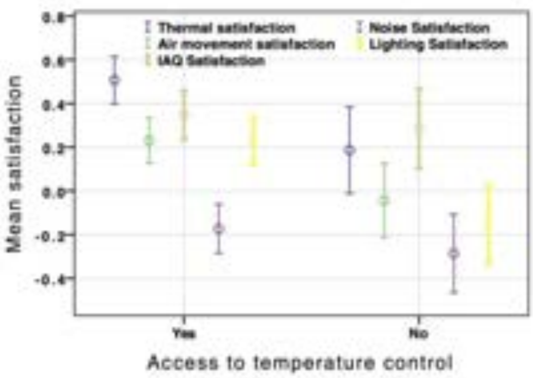

Figure 5: Mean satisfaction under various environmental parameters. Error bars indicate 95% CI.

3.5 Overall environmental satisfaction (OES)

We measured the overall environmental satisfaction in the field survey on a six-point continuous scale (1: very satisfied, 2: Moderately satisfied, 3 Slightly satisfied, 4: Slightly unsatisfied, 5: Moderately unsatisfied, 6: Very unsatisfied). Mean OES was noted to be 2.53 (standard deviation = 1.07, N = 318).

Proportion of subjects voting at each scale point on OES scale is shown in Figure 6. On the whole, subjects in offices in Qatar are generally satisfied with their environments. For example, 38.2% and 32.4% subjects were moderately and slightly satisfied respectively. Only 14.5% subjects voted on the dissatisfaction side of the scale. Although not statistically significant, we noted slight variations in satisfaction in both the genders. Men expressed slightly higher overall environmental satisfaction.

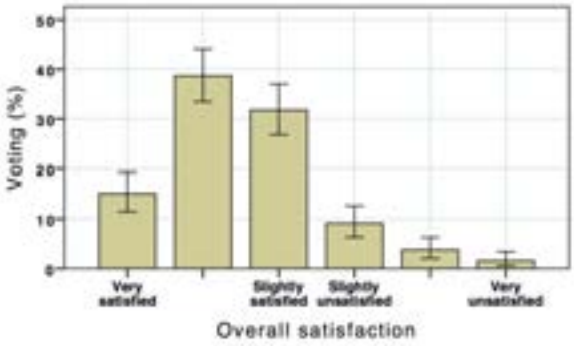

Figure 6: Distribution of overall environmental satisfaction vote. Error bars indicate 95% CI.

Similarly, overall satisfaction of the subjects with operable windows were higher than those with fixed glazing and those without any windows. On the other hand, occupants in government offices were less satisfied as shown in Table 3 and Fig. 7. Although these variations in satisfaction are not of great engineering significance, they however provide deep insights into the occupant choices and behavior in offices and provide vital design inputs.

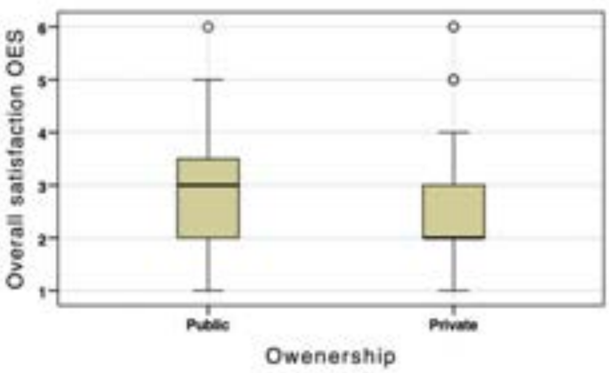

Figure 7: Box plot of overall environmental satisfaction.

Table 3. Distribution of overall environmental satisfaction

Overall environmental satisfaction scale	Voting (%)			
	Ownership	Window Operability	Ownership	Window Operability
	Public	Private	Public	Private
Sample Size (N)	55	263	134	184
Very satisfied	7.3	16.7	14.2	15.8
Moderately satisfied	34.5	39.5	41.8	36.4
Slightly satisfied	32.7	31.6	32.1	31.5
Slightly unsatisfied	12.7	8.4	8.2	9.8
Moderately unsatisfied	10.9	2.3	2.2	4.9
Very unsatisfied	1.8	1.5	1.5	1.6

Similarly, subjects in US offices reported slightly higher levels of satisfaction in green buildings compared to non-LEED buildings, as investigated by Abbaszadeh et al. (Abbaszadeh, Zagreus, Lehrer, & Huizenga, 2006). They attribute this variation to certain design decisions and operational practices generally adopted in green buildings, such as: improving ventilation, removing indoor pollutants, task air-conditioning, or under-floor air-distribution systems, using green materials, providing occupants with better environmental control, use of daylight, reducing ambient light levels by giving task lighting, etc.

On the other hand, Wu et al. (Wu, Ng, & Skitmore, 2016) found direct positive correlation between indoor environmental quality (IEQ) comfort level demands and energy consumption through a simulation study in Hong Kong. They determined IEQ by aggregating the effects of thermal comfort, indoor air quality, acoustic comfort and visual comfort. They estimated occupants' comfort levels through the building operational settings, such as lighting power density, relative humidity, indoor temperature, air speed and ventilation rate.

3.6 Self-declared productivity as affected by the environmental parameters (SP)

We measured occupant's self-declared productivity (SP) on a five-point continuous scale measuring from -2 to +2 (-2: much lower than normal, -1 lower than normal, 0: normal, 1: higher than normal, +2: much higher than normal). Distribution of SP is shown in Figure 8. It can be noted that most of the subjects voted toward the center and in right hand side of the scale, indicating increased or normal productivity. About 16.4 % of the subjects voted to have increased productivity as an effect of the environment.

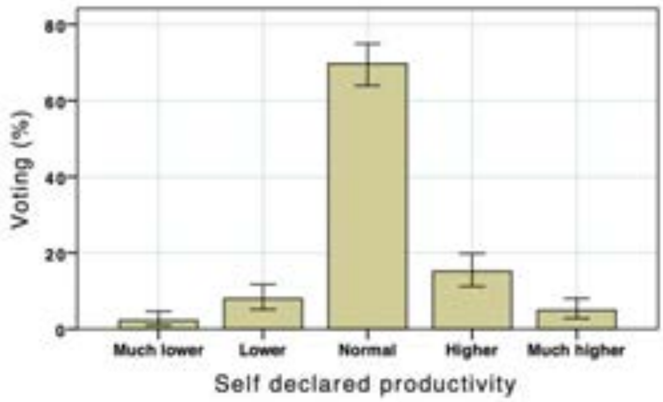

Figure 8: Distribution of self declared productivity vote. Error bars indicate 95% CI.

4 Conclusions

We conducted an energy use and environmental satisfaction survey in office buildings in Qatar. This is a first of its kind study in this country. It involved over 300 subjects in seven buildings, both public and private companies' offices. Through a paper based and an online survey, it collected 322 datasets from a variety of space types ranging from private offices to open plan offices. The following are the conclusions:

1. Awareness and availability of star rated systems are very limited, while most subjects use computers and other electrical gadgets at work.
2. Most of the occupants (85 – 87%) habitually turn off the computers and monitors while leaving the offices. However, IT policies prevent some of the occupants from turning off their systems.
3. Care and concern for the energy used in heating and air-conditioning (HVAC) seems to be high among office occupants in Qatar. About 90% said they cared for HVAC energy. Paradoxically, the set temperature range most of the occupants chose was 22 - 24 °C in peak winter (47.2% cases) and summer (28.6% cases).
4. We measured the indoor environmental satisfaction of occupants under five parameters: thermal, air-movement, indoor air-quality, noise and lighting levels.
5. Mean environmental satisfaction was found to be generally higher in all the parameters excepting for noise level. It was higher in privately owned buildings and in offices with occupant accessible temperature controls and operable windows.
6. Overall environmental satisfaction was also very high. Majority of the subjects (85.5%) voted in the upper three categories (most satisfied, moderately satisfied, satisfied).
7. Subjects in the low-partitioned cubicle offices expressed highest levels of satisfaction with the noise levels while those in high partitioned cubicles have greatest dissatisfaction with their acoustical environments. These findings have important design implications.

Acknowledgements

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UNDERSTANDING HOUSEHOLD SOLAR ADOPTION IN AUSTRALIA

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Abstract: *The energy system of the future will require customer engagement. However, there is little understanding of how the energy system will incorporate this engagement. Many electricity-planning models make unreasonable assumptions of the willingness of customers to make changes that will optimise the electricity system. This policy analysis on a robust set of Australian household solar adoption data, seeks a statistical measure of policy and price effects on solar adoption. This offers an insightful window into new methods of electricity planning through an improved understanding of household electricity customers. The Australian Government has tracked monthly household solar adoption since 2001. Solar is on 16% of all dwellings in Australia and this creates an opportunity to test the relationship between policy, price, household characteristics, and household solar adoption. Analysis of this data offers an understanding of the key drivers of household solar adoption. This paper reviews our statistical analysis to select variables. The next stage planned for this research is spatial-temporal statistics and system modelling of the Australian energy system.*

Keywords: *Solar, Photovoltaics, Domestic Housing, Policy, Australia*

1 Why understand Australian household photovoltaic solar (PV) adoption?

There is a looming crisis in the electricity sector and some of the challenges include grid defection, home storage, and electric vehicle charging. These three relate to household energy decisions. Ways in which they may be integrated in energy planning are:

- Customers may agree to avoid grid defection, and instead trade their electricity and electricity services peer-to-peer. Gassmann, Frankenberger *et al.* (2013) explore new peer-to-peer business models.
- Customers may accept controls on their household batteries, if the energy plan rewards them for this imposition.(Ochoa, Pilo *et al.*, 2016).
- Electric Vehicle charging is set to double household electricity charging according to Morgan Stanley (2017). To avoid huge costs of grid augmentation from the charging of EV, these customers could agree to optimise their charging time on a network level, not on an individual level (Hoog, Alpcan *et al.*, 2015).

The participation of customers is a common issue in each of these prospective solutions. Technical and infrastructure challenges are surmountable, but customers may prove a key to these solutions. Optimal design is in fact only possible with the participation of customers. Energy planning and regulation have struggled to integrate customers into their modelling due to poor understanding of the factors driving customer behaviour.

Some regulatory change is starting. The Australian Energy Market Commission “Power of Choice” review reported 30th November 2012 was the first major Australian Government report to recognise the role of customers in energy planning. It covered energy efficiency, peak demand shifting, changing consumption patterns, and customers generating their own electricity. Chapter 5 of this “Power of Choice” report referred to the opening up of non-energy services such as ancillary services (AEMO, 2015). Although the AEMC was seeking to open up choice, their report was still a top-down view. Their paradigm was that customers are recipients of energy services, and not active participants in the energy system. We see this changing in recent press from AEMO and the Finkel (2017) Report.

2 Australian Energy Market

Few saw the coming shortfalls in supply in the Australian Energy system. In fact Infrastructure Australia ran an audit on Australia in 2015 (Infrastructure Australia, 2015) and their view was that the electricity system was robust. The only warnings come in audit findings 63 and 66 of their report, which warned that climate policies were interfering with investment, and that regulatory changes were needed (including “tariff reform to reduce peak period demand.”) This was an early warning of the South Australian blackouts the following year.

Blackouts stuck South Australia on the 28th September 2016, then again on the 8th February 2017. There are 19 recommendations made in the AEMO Final Report on the South Australian blackouts (AEMO, 2017a) and it is notable that no recommendations refer to managing customer load. A further shortage of energy in NSW on 10th February 2017, prompted an AEMO Incident Report (AEMO, 2017b).

As shown by these supply problems there has been a lack of forward planning to handle the changes in Australia’s electricity system (AEMO, 2017a). These changes include the addition of distributed generation, the outbidding of fossil generators by renewables, peak loads driven by air-conditioning, and the lack of investment due to policy uncertainty. Electricity regulation thus far has focussed on central generation and market

forces. This paper explores how policy could engage customers as an input to the energy system.

3 Research on Australia's household PV market

There has been high interest in the Australian household PV uptake. This is due to the world leading rates of adoption of over 15% (Catchpole, 2016). Socio-economic characterisation of NSW PV households by Higgins, McNamara *et al.* (2014) concluded that drivers of PV adoption in Australia are;

- Annual savings in energy costs
- Upfront cost
- Household income
- Familiarity
- Socio-economic advantage and disadvantage
- Dwelling density
- % of Greens Votes

Bruce, Watt *et al.* (2009) concluded age (older people were more likely to buy), and environmental concerns were key drivers of PV adoption. They found a high adoption by couples over 40 years of age, and particularly professionals and retirees.

Figure 1 taken from APVI (2017) shows the percentage of households with PV in each postcode/district PV in Melbourne, Victoria. The darker colours show higher concentrations of PV, with the purple showing 40%. The outer fringe of Melbourne has higher concentrations of PV. This effect also appears around the other capital cities of Australia.

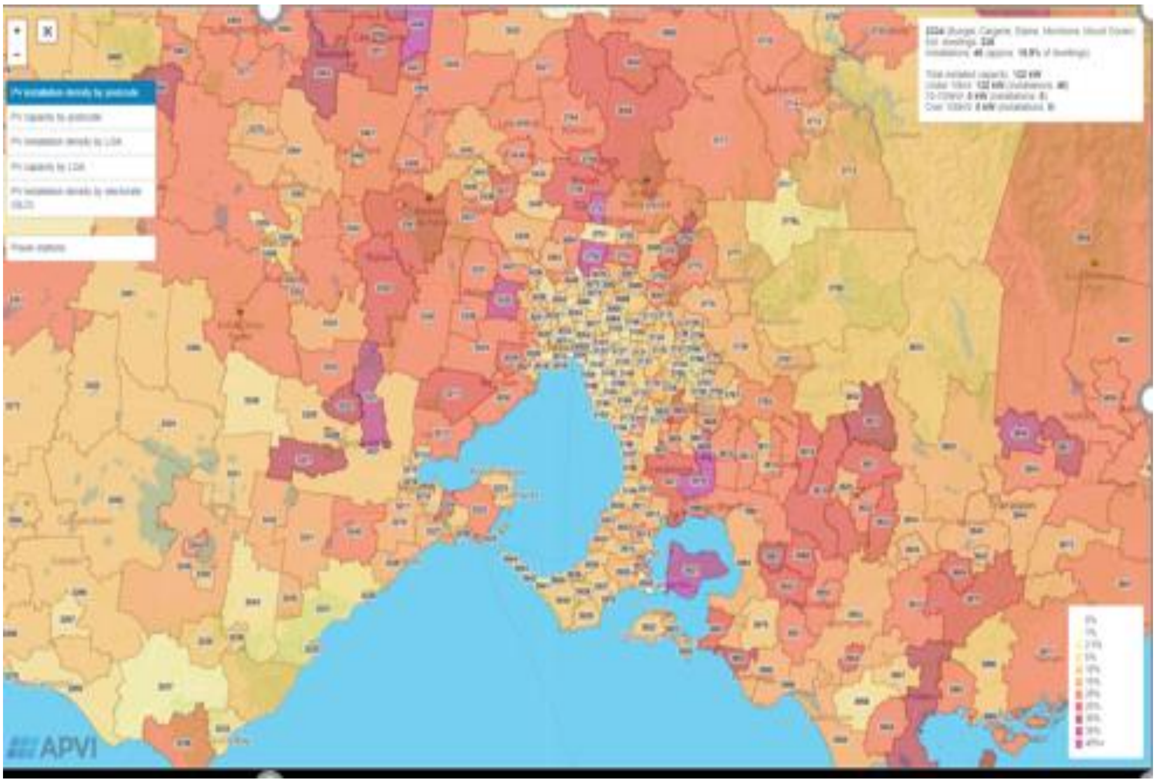

Figure 1: Melbourne household solar density by postcode (APVI, 2017)

Rapid uptake of solar in Australia has occurred at the same time as rapid reductions in price as shown in Figure 2.

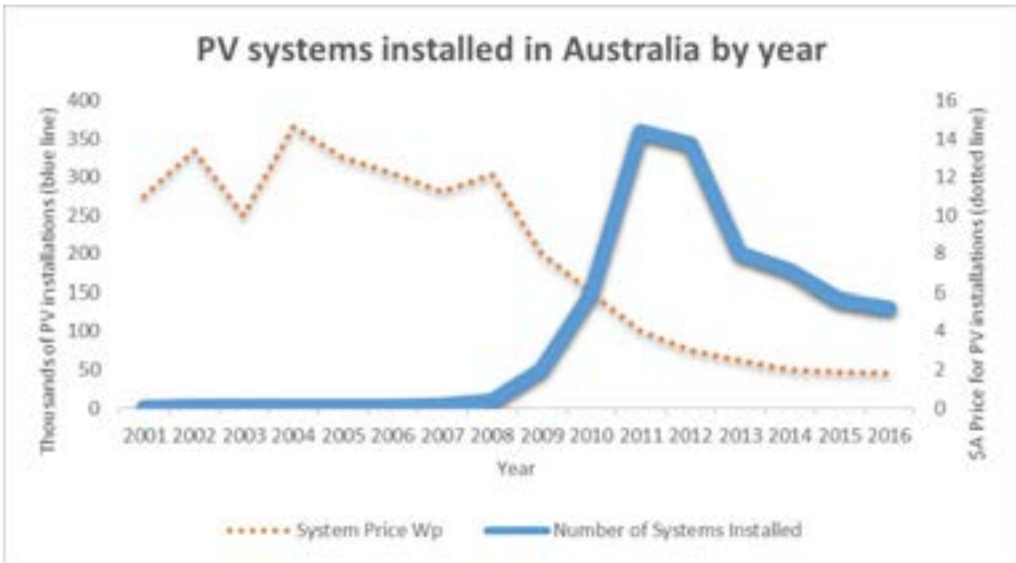

Figure 2: Price of solar and rate of installation in the period 2001-2016

The above graph (Fig. 2) shows there is a correlation between the PV price decrease and the consequential huge increase in installation. Subsidies through the carbon price, feed-in tariffs and increases in electricity prices were important drivers of the increase in PV sales. Key PV policy milestones are shown in Figure 3.

Year	2001-2007	2008	2009	2010	2011	2012	2013	2014-2017
Carbon Certificates	MRET system				RET system			
Certificate Multiplier for PV			X5 to Jun'11		X3 to Jun'	X2		
Feed-in Tariffs		Start, SA,Tas & Qld	Start, Vic & ACT	Start NSW & WA	Stop NSW, ACT & WA	Reduced in Vic, Qld & SA		

Figure 3: Key dates of PV subsidy changes in Australia

Of particular note is the Certificate multiplier for PV systems up to 1.5kW, which ran from 2009-2012.

3.1 Carbon certificates for domestic PV

The PV installation count started as a consequence of the Renewable Energy (Electricity) Act 2001. This Act led to the creation of the Mandatory Renewable Energy Target (MRET) and certificate administration by the Office of the Renewable Energy Regulator (later changed to the Clean Energy Regulator.) From 1 January 2011 the MRET was renamed the Renewable Energy Target (RET) and this then had a separate system for Small Scale Renewables including small scale PV, solar hot water and heat pumps. Customers received the value of the carbon certificates at the time of installation.

3.2 Feed-in tariffs (FIT's)

The NSW Government reviewed solar feed-in tariffs (FIT's) in 2012 (IPART, 2012). Their report noted that 1 kW of solar PV would generate 2 kWh per day in winter and 4.6 kWh

per day in summer with an annual average of 3.5 kWh per day. The average size was 1.6 kW and average exports were 35% of total household PV generation.

State feed-in tariffs had a more significant impact on PV adoption than carbon certificates. The evidence for this is the huge spike in PV installations in NSW from 2008 when the NSW government introduced a feed-in tariff and the subsequent drop when the NSW feed-in tariffs were removed in 2012.

The subsidy levels became very high relative to the prices of systems, and drove a huge spike in solar installations in 2011-2012 as shown by the thick blue line in Figure 4.

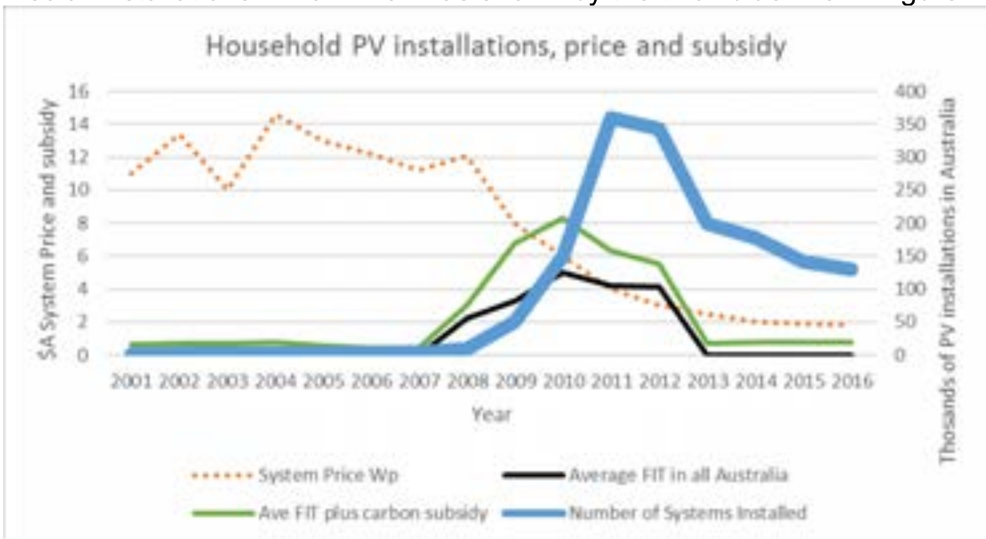

Figure 4: $A FIT plus carbon subsidy, FIT average, system price and PV installation total by year

Note: This analysis reflects the first year of FIT income (a weighted average of the state FIT rates)

The other lines on the graph related to the price and subsidy for PV are:

- The total PV system cost (orange dotted line) drops as the PV installation rate soars
- The FIT normally falls into the pocket of the consumer over time through their electricity bills, but is represented here as a single value for one year of FIT (black line); and
- The sum of the average FIT and the carbon subsidy (green line).

During 2010-2012, the green line is above the orange dotted line, which means the total subsidy exceeded system cost. The main spike in installations occurred 2011-2012, so the consumers responded strongly to this policy lever.

4 International research on household PV

Household PV is an active area of research. Research on the neighbourhood effect on solar adoption by Graziano and Gillingham (2014) has been widely quoted in advertising for the new Google Sunroof application. Other examples of international research on household PV:

- Lund (2015) raises some interesting diffusion work.
- Palm (2017) published recent work on peer effects of PV adoption in Sweden.
- Sardianou and Genoudi (2013) published a review of a survey of 200 homes in Greece. They came to the interesting conclusion that middle-aged and highly

educated people were more willing to adopt renewable energy and concluded that marital status and gender were not statistically significant. They argued that the most effective policy intervention was a tax subsidy (as compared with an energy subsidy or the doubling of the energy price).

- Strupeit and Palm (2016) used policy and business models to study household PV customers in Japan, Germany, and the United States. They conform to our view that market and policy structures may encourage consumers to take a larger role in the future energy system. The most important will be the trading of energy and energy services by households. This view is supported by Wolske, Stern *et al.* (2017) who have integrated behavioural theories on their study of US PV customers.
- Schelly (2014) studied homeowners in Wisconsin and identified an interesting motivating characteristic of "enjoyment of technical innovation and enjoyment of the technical aspects of energy systems". This may be important in early adopters, but we do not think it will be important later in the diffusion cycle.

Based on the above research it is clear that agent-based-modelling (ABM) is popular for solar adoption work. Also from the above research, the neighbourhood effect (Graziano & Gillingham, 2014) is important.
This research does not use ABM. An alternate approach of statistical analysis seems reasonable, as follows.

5 Statistical analysis of district data

There are two particularly relevant papers for our research. These focus on the socio-economic aspects of solar PV uptake. Higgins, McNamara *et al.* (2014) studied PV uptake in NSW, and Adil and Ko (2016) explored policy issues related to decentralised energy. Both these papers have informed the following statistical analysis.

Postcode district data for the volume of solar panel sales up to 2017 was matched with corresponding census data. This data is robust due to the high quality and broad reach of data collection by the Australian Government. Table 1 shows the number of PV installations for all the Australian states/territories.

Table 1: The number of domestic PV installation by state/territory in the period 2001-2016

YEAR	ACT	NSW	NT	QLD	SA	TAS	VIC	WA	NATIONAL
2001-2007	102	779	26	475	1037	26	828	262	3535
2008	278	2890	88	3087	3456	161	2036	2068	14,064
2009	803	14,008	215	18,283	8569	1452	11,847	11,157	66,334
2010	2323	69,988	637	48,697	16,705	1889	35,676	22,293	198,208
2011	6860	80,272	401	95,303	63,553	2475	60,214	51,667	360,745
2012	1522	53,961	513	130,252	41,851	6364	66,204	42,653	343,320
2013	2411	33,998	1024	71,197	29,187	7658	33,332	21,600	200,407
2014	1225	37,210	1026	57,748	15,166	4207	40,061	23,496	180,139
2015	1066	33,484	1197	39,510	12,084	2020	31,360	20,799	141,520
2016	999	29,796	1793	35,717	12,682	2580	26,506	25,302	135,374

TOTAL	17,619	357,438	7024	501,387	205,946	28,882	308,977	221,533	1,648,805

5.1 Data sourcing

The PV data is from 2001 to mid-2017. The 2011 census was used for socio-economic data in this paper. The census dates of 2001, 2006, and 2016 will be added to the next stage of research.
This research uses Australia wide data (all postcodes).

5.2 Choosing the initial set of socio-economic variables

This research tested for drivers of Australia wide solar PV purchases. Therefore thirty five different socio-economic variables was tested using Principal Component Analysis (PCA). The selection of variables was influenced by the work of Islam and Meade (2013) and Higgins, McNamara *et al.* (2014) as detailed in Table 2.

Table 2: Hypotheses and Variable selection to measure household adoption of PV in Australia

Drivers	Hypothesis and comment	Variables tested and Data sources
Cost related	Adoption more likely if electricity is a higher percent of income.	Initial investment and payback period (from industry). Average income, average number of cars, average income below $2000/week, and income over $2000/week (from the ABS). Subsidy from government.
House roof is suitable and house is owned or under mortgage	Adoption will be higher if there is lower urban density to shade or cause aesthetic concern. This may be indicated by the need to drive to work, the number of bedrooms, and the number of people in the house.	Average number of bedrooms, separate house, percent of dwellings owned, percent rented, percent under mortgage, average number of people in the house, car driven to work and density of dwellings (from the ABS)
Previously bought energy technology	People who have bought energy technology previously are more likely to buy again.	Heat pumps (for hot water), and solar hot water (from the CER.)
Environmental concern	Voting, transport mode to work and # children are possible indicators of the level of environmental concern.	Voted for Greens (AEC) Bike to work, average number of children, and walked to work (from the ABS).
Awareness of PV technology	High-speed broadband adoption will assist Awareness of PV technology is expected to be higher with high-speed internet and the frequency of mentions of solar on Twitter and media mentions.	Twitter mentions of solar. No internet, broadband internet, and dial up internet (from the ABS).
Socio-demographics	The retired community is expected to adopt more PV due to relative wealth, their need to save money and having the time to explore PV. There may be patterns in other socio-economic variables.	Unemployed/retired, SEIFA Income, mortgage payments, %rent, %rent over $650,family moved in the past 5 years, ratios of homosexual couples, any couples, work at home and the number of cars (from the ABS.)

Note: AEC, ABS, and CER are all departments of the Australian Government. The AEC is the Australian Electoral Commission, the ABS is the Australian Bureau of Statistics, and the CER is the Clean Energy Regulator. SEIFA measures of social and economic status are from the ABS.

5.3 Principal Component Analysis

Our PCA approach was influenced by two previous papers on Australian solar drivers, (Higgins, McNamara *et al.* (2014) and Bruce, Watt *et al.* (2009)). Higgins *et al* nominate the following drivers:

- Annual savings in energy costs;
- Upfront cost;
- Household income;
- Familiarity;
- ABS SEIFA index of relative socio-economic advantage and disadvantage;
- Dwelling density; and
- Percent of Votes for the Greens Political Party (Greens Votes).

Our research consequently tested these drivers, but with the following exceptions;

- Familiarity: No data was available for this paper, but a measure of Familiarity using Twitter is planned in future research.
- Savings in energy costs, and upfront costs were not included in this initial stage as they are temporal, and this initial research is not temporal. However, they will be used in later research using temporal-spatial statistics. A preliminary test on the percentage of income spent on electricity did show a correlation between the percent of income spent on electricity and PV adoption.

5.4 Linear Regression uncovered patterns in PV adoption in Australia.

Regression testing on the district household PV adoption rates found the following patterns:

- Green voting made little impact on the correlation and was therefore excluded.
- The indicator for bedrooms was originally included for the a priori reason that more bedrooms should mean more suitable roof area for solar, but it did not contribute much to the correlation.
- The "percentage of homes owned and homes with mortgages" gave strong correlations to PV adoption. This was previously found by Higgins, McNamara *et al.* (2014). Our research found that the variable "percentage of mortgages" was more effective than "level of home ownership", so this was used in further testing.
- A consistent negative correlation between PV adoption and "urban density" was found. This corresponds to the outer suburbs having a higher rate of solar installations. The negative correlation to "urban density" may be explained by known factors such as low-density areas having higher rates of separate homes, fewer trees and bigger roof areas (all a priori drivers of solar adoption).
- Negative correlation to income was found. Negative correlation with income levels has been noted previously in work of Green Energy Trading (2014). Their paper stated that solar adoption drivers were:
    - Level of home ownership;
    - Suitability of buildings (number of detached and semi-detached dwellings);
    - Relative importance of energy bills (families that spend a higher % of their incomes on energy); and
    - The level of new home and renovation activity (many builders offer solar in new home packages).

The negative correlation between PV adoption and income may be caused by the higher rates of PV adoption in outer suburbs (where average incomes are lower), and mask the true effect of income on PV purchase decisions. Therefore, "income" was not included in further tests and the model retained high results. Other testing results showed that a measure of "Relative Importance of Energy Bills" improved the model. We plan to test the variable "Relative Importance of Energy Bills" further.

5.5 Results

The variables chosen after the Principal Component Analysis and further regression testing were:

- Percent of Separate housing;
- Percent of homes with Solar hot water; and
- Percent of homes with that are owned or under mortgage.

Testing was then carried out on subgroups. The subgroups tested were:

- The Australian states except NT;
- The wealthiest 20% of Australian postcodes;
- The wealthiest 75% of Australian postcodes; and
- The highest density communities (inner suburban), mid density communities (outer suburban) and country areas.

The three variables (percentage of mortgages, percentage of separate homes and percentage of solar hot water) gave correlations between the predictor and actual PV adoption of up to 80% as shown in Table 3.

Table 3: Correlation between actual PV installations and three chosen variables. By state, and by state for the wealthiest 50% of suburbs

State	Correlation 50% wealthiest suburbs	Correlation all suburbs
NSW	74%	60%
Vic	74%	61%
Qld	76%	63%
SA	51%	53%
WA	80%	74%
Tas	76%	67%
ACT	73%	73%

This analysis shows the correlation between PV purchase and previous purchases of solar hot water. This is one of the key foci of the research as the ability to introduce new technology and market options such as demand management, P2P electricity sales and home storage (batteries.)

In summary, the results to date show there is a strong correlation between PV adoption and the three variables, of solar hot water purchases, separate dwellings and ownership of those dwellings. The percentage of mortgages was the proxy for ownership percentage. Of particular interest is the correlation between PV and solar hot water, which is shown in Figure 5.

Correlation between PV and solar hot water in Australia			
		PvPerHouse	HotWaterPerHouse
PvPerHouse	Pearson Correlation	1	.571**
	Sig. (2-tailed)		.000
	N	1098	1098

Figure 5: Correlation between PV and solar hot water installations by postcode/district

6 Applications for this research in Industry

Household engagement in the energy system is likely to involve some form of trading or financial rewards. This would optimise the last "mile" of the distribution grid. In fact, the most direct benefit sits below the level 1 transformer. If the local community can move electricity and balance the grid on a local level, below the level 1 transformer, there is a reduction in the remaining grid infrastructure.

We will illustrate this reduction in grid infrastructure using a simple example. A new house with 3kW of general load and 16 kW of air-conditioning that replaces an old house with 3 kW peak load (kettle, stove, and fridge). The new house turns on the 16kW air-conditioned only at times when the grid is at its peak (during hot weather.) The grid infrastructure in a business as usual system will require 16kW of additional network assets from the house back to the main central power station (often 100km + away.) By balancing the power locally, there is the potential to avoid delivering that additional 16kW from a far distant power station (which would therefore reduce network costs).

There are businesses springing up that are working to tap into the interest of customers selling electricity. In Australia, for example, L03 Energy, and Power Ledger use peer-to-peer trading of electricity and high existing adoption of PV is a key element in their business models. This research could help them plan their business.

7 Applications for this research in Government policy

States have tended to leave energy system planning to private operators especially in Victoria. AEMO (and its predecessor NEMMCO) has been a market operator since 1996, but since the establishment of the Australian Energy Regulator (AER) in 2005, active energy planning has seen a resurgence in Australia. This research aims to contribute in this energy planning space. The AER 2017 report states:

"Price pressures are also motivating consumers to take greater control of their energy consumption, including by installing rooftop solar photovoltaic (PV) and battery storage systems."

The trend to batteries, electric vehicles, and fuel switching found a voice recently in Australian energy planning. This is seen in the report Emerging Technologies Information Paper (AEMO, 2015) and the Finkel Report (2017), where the domestic customer has now emerged with a clear voice in Australian energy planning.

PV adoption has a proven neighbourhood effect (Graziano & Gillingham, 2014). This research could be used in government policy to develop communities that would share energy resources and reduce the peak load on the electricity network (hence reducing infrastructure costs.)

Policy and social dynamics of renewable energy to build resilience into Australian cities was researched by Newman, Beatley *et al.* (2010). Peter Newman is a specialist in socio-ecology systems, but in our view missed the need for the consumer to engage in trading and sharing of energy resources before the economics of renewable energy can be acceptable to the broader society. His view is that integration of more renewables is possible ipso facto. We argue that to do this, policy development must include customers as active participants.

8 Conclusions

There is currently a lack of understanding of how Australian customers (and groups of customers) might play a role in the future energy system. This role may be through adoption of energy devices, such as PV and batteries. This research aims to develop a model of electricity customers in relation to the energy system. This model will include policy levers that effect consumer action. The outcome of this first stage of our research program is that just three variables predict high correlations (Table 3). They are powerful predictors but are not useful as levers. They are:

- Separate houses as a percent of total housing stock.
- Percent of homes with solar hot water systems.
- Percent of homes that are under mortgage or fully owned.

Subsidy is a policy lever. Figure 4 shows the surge in PV installations in 2010-2011 was driven by a subsidy policy lever that effectively offered free installations. This policy lever caused a boom in solar was followed by a bust in 2012. Many PV businesses went out of business during that decline. The PV subsidy policy lever could have been more effective.

Improved forecasting and control of the consumer side of the energy system may enable more effective policy levers. This research offers a method to understand which Australian postcodes have seen high adoption of PV. Further research aims to identify effective policy levers and a policy control system.

9 Future Research

The next stage of this research is spatial-temporal modelling to understand more about the dynamics of domestic PV adoption in Australia. Then a control system will be developed to allow policy to be dynamically controlled. Adil and Ko (2016) suggest ways system modelling of the energy system could be used in urban planning and policy. Adil and Ko make a call for changes in local energy infrastructure to accommodate domestic energy systems. They argue that urban planning has missed the dynamic system effects of these decentralized energy systems.
The spatial-temporal model in the next stage of this research will test:

- Relative importance of energy bills (families that spend a higher % of their incomes on energy);
- Familiarity in terms of solar references in Twitter; and
- Level of new home and renovation activity (many builders offer solar in new home packages).

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LOW ENERGY BUILDING RETROFIT: A REVIEW OF OBJECTIVES AND SOLUTIONS

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Abstract: *Worldwide, the building sector is accountable for one-third of final energy consumption. This is expected to increase in the future. It is due to the continuing growth in demand for new buildings and the poor energy efficiency of the existing building stock. In developed countries, the ratio of new to old buildings is around 1% per year. According to the European Energy Performance of Buildings Directive Recast (Directive 2010/31/EU), optimal solutions towards low and near-Zero Energy Building (near ZEB) retrofit is of critical importance in order to achieve European Union (EU) climate and energy objectives. This has led to a large number of projects on deep building retrofit during the last 20 years. Each project has specific objective functions, depending on the adopted stakeholder's perspective and the selected retrofit strategies are dictated by the objective functions set. This study investigates stakeholders (legislators, investors, owners and users), objectives and optimal retrofit strategies and their interrelationships. The focus is on residential buildings due to the significant opportunity for reducing their Greenhouse Gas (GHG) emissions. A matrix has been developed to classify information in order to facilitate comparison and apparent correlations to be identified. The expected outcome is the better understanding of stakeholders' perspectives on financial, energy, GHG emissions, thermal comfort and the resulted optimal strategies.*

Keywords: *Residential Buildings, Building Stock, Deep Retrofit, Energy Efficiency, Europe*

Abbreviations and acronyms

CHP	combined heat and power	LCEIs	life cycle environmental impacts
DH	district heating	LCPEn	life cycle primary energy
DHW	domestic hot water	low-e	low emissivity
EEn	embodied energy	MFH	multi-family house
EPBD	energy performance of buildings directive	near ZEB	near-zero energy building
EPS	expanded polystyrene	net ZEB	net-zero energy building
ESMs	energy saving measures	NPV	net present value
EU	European Union	OC	operational cost
GHG	greenhouse gas	OEm	operational emissions
GSHP	ground source heat pump	OEn	operational energy
GWP	global warming potential	PBP	payback period
HP	heat pump	PEn	primary energy
HVAC	heating, ventilation and air conditioning	PV	photovoltaic
IC	initial cost	RES	renewable energy systems
IR	inconvenience rate	SFH	single-family house
LCA	life cycle assessment	TC	thermal comfort
LCC	life cycle cost	VoM	visibility of measures

1 Introduction

Among all building types, residential buildings hold great potential to reduce Greenhouse Gas (GHG) emissions, as they account for one-quarter of global final energy demand and 73% of the total energy demand of the building sector (IEA 2013). Buildings are the largest energy consumers in Europe. They are responsible for the 40% of the total final energy consumption, two-thirds of which is for residential buildings (Gynther et al. 2015). At the same time, the annual growth rate of the residential sector across Europe is low, around 1%, while the average annual refurbishment rate is between 0.5% and 2.5% (BPIE 2011).

Building retrofit has been seen as a key way to reduce buildings' energy consumption and related emissions of the existing building stock. Despite the fact that the large variety of residential buildings across Europe does not facilitate a consistent retrofitting approach (BPIE 2011), the EU, trying to address this issue, launched the Performance of Buildings Directive (EPBD) Recast (EU 2010). It provides member states with a methodological framework for the calculation of the energy performance, both for new buildings and existing buildings that undergo a major retrofit. However, the details are defined by the individual member states, in a national, regional or local level. Local characteristics, such as the climate conditions or the available solar radiation, can play a critical role in setting the legislative framework in each country (Cansino et al. 2011). The maturity of each member in implementing the energy efficiency measures depends on the established practice of the country in adopting building energy regulations and on the established commitment in achieving EU targets (Annunziata et al. 2013).

In accordance with national and EU energy performance legislation or through the setting of higher energy efficiency goals, various residential building retrofit projects have been carried out. Holding different perspectives, projects employ methods to explore a number of retrofit strategies against one or more assessment criteria. Some also consider possible uncertainties and risks involved in the retrofit process, including, financial limitations, governmental policy change, energy prices and climate change.

An early systematic review on building retrofit was conducted by Ma et al. (2012). Their work analysed a number of projects around the world, focusing on the retrofit interventions proposed, the assessment method used and their major results. After that, De Boeck et al. (2015) conducted an extended literature review of residential building

retrofit projects, classifying the information accordingly to identify trends. The classification categories were: the building type and location, the design variables, the objective functions, the type of analysis performed, the methodology and software used.

Other researchers, investigated building retrofit projects from different perspectives. Moran et al. (2015) limited the reviewed studies to those located in Europe and target a near ZEB retrofit outcome and Vilches et al. (2017) focused on Life Cycle Assessment (LCA) retrofit studies. Pombo et al. (2016) assessed the sustainability level of residential retrofit projects. They reported that the environmental and the economic dimension of sustainability had been addressed but the social was absent from the assessment criteria.

The findings of the aforementioned reviews show that while passive renovation strategies are widely introduced, Heating, Ventilation and Air Conditioning (HVAC) systems and Renewable Energy Systems (RES) are less often considered among the retrofit strategies. Retrofit strategies are similar throughout the works analysed, however, assessment criteria differ. Location is also a key factor, since local databases are used for cost, energy and GHG emissions estimations, and issues differ depending on climate conditions.

The decision support tools used for the residential building retrofit were addressed by Ferreira et al. (2013). It was pointed out that the selection of the assessment criteria is the most important step of the retrofit process; if they are being modified, final results differ. They also noted that financial analyses are conducted from the specific decision maker's perspective, while environmental impacts are mainly assessed by the LCA method.

A deeper investigation of the relationship between the decision maker and the objective functions used was conducted by Lizana et al. (2016), in order to support the decision management of residential retrofit projects. They claimed that the assessment method is determined by the combination of the objective functions used and can be either a cost-benefit analysis, a multi-criteria analysis, a multi-objective optimisation analysis or an energy rating system. It is mentioned that most of the studies, aiming at reducing the problem complexity, use only two objective functions, which are: financial and energy or financial and GHG emissions. However, there are not many studies that employ three or more objective functions. Three major stakeholders were defined in Lizana et al. (2016): the 'private owner/user', the administrator as the 'public promoter' and the 'private promoter'. The private owner is mainly interested in the initial cost and the possible operational energy savings. The public promoter focuses on GHG emissions reduction and meeting the environmental targets. Whereas, the private promoter focuses on the financial benefits of the investment.

Based on the existing literature, the aim of this review is to further explore and analyse the inter-relationships between the stakeholders' perspectives and the objective functions used by the residential building retrofit projects, as well as to compare and discuss results. More specifically, the intention is to identify which objective functions are related to which specific stakeholders and how outcomes vary among the conducted optimisations. Local characteristics, such as climate conditions, are considered, however, other economic, environmental or political aspects of each case study are outside the scope of this research. Section 2 describes the review method and Section 3 discusses the identified objective functions sets in association with the stakeholder's perspective and major results. Findings are highlighted in Section 4.

2 Method

The selected documents are those that use a single-criteria or a multi-criteria assessment method to evaluate retrofit strategies, or retrofit packages, for residential buildings, aiming to reduce the energy used or their GHG emissions. The selected information is classified and summarised in Table 1 and Table 2, in order to facilitate correlation analysis.

The reviewed studies are limited to buildings located in Europe. Case study location and the corresponding climate zone play a significant role in heating and cooling loads and the available energy sources and technologies utilised. A proposed retrofit approach could be unsuitable if applied in different climate or urban characteristics (Li et al. 2017). Thus, the case studies considered are further classified according to the climate zone they belong.

Building type is also a critical parameter for the determination of energy consumptions. Multi-storey buildings consume less energy for heating and cooling compared with detached low-rise buildings. Three building types have been defined to facilitate case studies' classification: 'single-family houses' (SFH), 'medium-rise multi-family houses' (MFH) and 'high-rise multi-family houses'. Construction period for each building is also noted down, as older buildings tend to have higher energy consumptions. The overall target of each retrofit project is also taken into consideration. Projects that set high energy or GHG emissions reduction targets require not only high-efficiency levels of a proposed retrofit strategy but also an increased number of retrofit actions.

The selected stakeholder categories broadly follow the classification previously introduced by Lizana et al. (2016). These are: the 'owner/user', the 'public promoter/legislator' and the 'private investor/developer'. It should be noted that a considerable number of projects analysed do not declare the adopted stakeholder's perspective and thus this field has been left empty. On the other hand, there are studies declaring that they respond to all stakeholders' requirements.

Case studies are also classified according to the so-called assessment criteria or objective functions they consider. The major categories are the 'environmental', the 'financial' and the 'social' objective functions, while further categorisation is based, among others, on the life cycle stage considered in calculations. Finally, the retrofit strategies are assigned into three categories, based on Pombo et al. (2016) classification: 'building envelope', 'HVAC systems' and 'RES'. The strategies are further sub-classified, as shown in Table 2. It is apparent that the residential building retrofit is a multifactorial task and there is no straight comparison of the selected case studies, as results may vary not only depending on the selected objective functions, but also on the climate conditions, the target setting and the retrofit strategies under consideration.

Table 1: Literature review case studies classified according to climate zone, construction period, house type, target, stakeholder's perspective and assessment objective functions.

				House Type				Stakeholders			Assessment Objective functions												
											Environmental						Financial				Social		
No	Reference	Climate Zone	Construction Period	SFH	Medium-rise MFH	High-rise MFH	Target	O/U	PP/L	PI/D	OEn	PEn	EEn	LCPEn	OEm	LCEIs	IC	PBP	OC	LCC	IR	VoM	TC
1	Penna et al. (2015)	Continental & Mediterranean	a) before 1976, b) after 1976	×	×	×	near ZEB	×			×									×			×
2	Risholt et al. (2013)	Boreal	1980-1989	×			near ZEB	×			×									×		×	×
3	Hasan et al. (2008)	Boreal		×			low energy				×									×			
4	Amstalden et al. (2007)	Continental	1948-1975	×			low energy	×			×									×			
5	Brown et al. (2013)	Boreal	a) 1963, b) 1973		×	×	low energy	×			×									×			
6	Kuusk and Kalamees (2015)	Boreal	1986			×	near ZEB	×				×						×		×			
7	Ferreira et al. (2014)	Mediterranean	1990			×	net ZEB	×				×								×			
8	Hamdy et al. (2013)	Boreal		×			near ZEB		×			×								×			(1)
9	Ballarini et al. (2017)	Mediterranean	a) before 1920, b) 1921-1945, c) 1946-1960, d) 1961-1975, f) 1991-2005, g) after 2005	×	×	×	low energy	×	×	×		×								×			
10	Lizana et al. (2016)	Mediterranean	1955			×	low energy		×			×								×		×	×
11	De Angelis et al. (2013)	Continental	1960-1979			×	low energy									×				×			
12	Cetiner and Edis (2014)	Mediterranean	1992			×	low energy	×								×				×			
13	Pombo et al. (2016)	Mediterranean	1960-1969			×	passive house		×							×				×			
14	Antipova et al. (2014)	Mediterranean					low environ. impact									×				×			
15	Ostermeyer et al. (2013)	Atlantic	1950-1960			×	75% primary energy reduction									×				×			
16	Verbeeck and Hens (2005)	Atlantic	1970-1979	×	×		low energy							×						×			
17	Ascione et al. (2015)	Mediterranean				×	low energy		×			×					×						×
18	Huws and Jankovic (2014)	Atlantic		×			zero carbon								×		×						×
19	Lizana et al. (2016)	Mediterranean	1955			×	low energy			×		×			×		×						
20	Assiego De Larriva et al. (2014)	Mediterranean	1983			×	low energy and carbon	×	×	×		×				×							
21	Wang et al. (2015)	Boreal	a) before 1945, b) 1946-1960, c) 1961-1975	×	×	×	low energy	×	×	×		×	×					(2)					
22	Dodoo et al. (2010)	Boreal	1995			×	passive house							×									
23	Desogus et al. (2013)	Mediterranean	1950-1959	×	×	×	low energy	×	×									×		×			
24	Salata et al. (2017)	Mediterranean	2000			×	class improvem.	×									×	×	×				
25	Lizana et al. (2016)	Mediterranean	1955			×	low energy	×									×		×		×		

SFH: Single-Family House, MFH: Multi-family House, O/U: Owner/User, PP/L: Public Promoter/Legislator, PI/D: Private Investor/Developer, OEn: Operational Energy, EEn: Embodied Energy, LCPEn: Life Cycle Primary Energy, OEm: Operational Emissions, LCEIs: Life Cycle Environmental Impacts, IC: Initial Cost, PBP: Payback Period, OC: Operational Cost, LCC: Life Cycle Cost, IR: Inconvenience Rate, VoM: Visibility of Measures, TC: Thermal Comfort, (1) restriction, (2) considered in a secondary assessment process.

Table 2: Literature review case studies classified according to the retrofit strategies under consideration.

		Retrofit Strategies																
		Building Envelope						HVAC Systems									RES	
No	Reference	Wall Insulation	Roof Insulation	Ground Floor Insulation	Infiltration	Window Replacement	Shadings	Mechanical Ventilation	Control Systems	Existing System Retrofit	Electric Heater	Boiler	HP	CHP	DH	Cooling	Solar Thermal	PV
1	Penna et al. (2015)	×	×	×		×						×						
2	Risholt et al. (2013)	×	×	×	×	×					×		×				×	
3	Hasan et al. (2008)	×	×	×		×		×										
4	Amstalden et al. (2007)	×	×	×		×												
5	Brown et al. (2013)	×	×			×			×		×							
6	Kuusk and Kalamees (2015)	×	×	×		×				×							×	×
7	Ferreira et al. (2014)	×	×	×		×						×	×			×	×	×
8	Hamdy et al. (2013)	×	×	×		×		×			×	×	×		×	×	×	×
9	Ballarini et al. (2017)	×				×											×	
10	Lizana et al. (2016)	×	×		×	×	×	×				×	×	×			×	×
11	De Angelis et al. (2013)	×	×	×		×												
12	Cetiner and Edis (2014)	×	×	×	×													
13	Pombo et al. (2016)	×	×	×		×												×
14	Antipova et al. (2014)	×	×			×											×	
15	Ostermeyer et al. (2013)	×	×	×		×					×	×					×	
16	Verbeeck and Hens (2005)	×	×	×		×					×	×	×				×	×
17	Ascione et al. (2015)	×	×			×			×			×				×		
18	Huws and Jankovic (2014)	×	×	×	×	×	×		×			×	×				×	×
19	Lizana et al. (2016)	×	×		×	×	×	×				×	×	×			×	×
20	Assiego De Larriva et al. (2014)	×	×	×		×	×											
21	Wang et al. (2015)	×	×	×	×	×			×	×			×		×			
22	Dodoo et al. (2010)	×	×			×					×		×	×	×			
23	Desogus et al. (2013)	×	×			×												
24	Salata et al. (2017)	×				×			×			×	×	×	×		×	×
25	Lizana et al. (2016)	×	×		×	×	×	×				×	×	×			×	×

HVAC: Heating, Ventilation and Air Conditioning, RES: Renewable Energy Systems, HP: Heat Pump, CHP: Combined Heat and Power, DH: District Heating, PV: Photovoltaic

3 Analysis

There are three major types of objective functions identified: a) the financial, b) the environmental and c) the combination of financial and environmental. Social objective functions are rarely used as assessment criteria. In general, they are combined with environmental and/or financial objective functions, either as a third objective function or as a constraint.

According to Table 1, environmental objective functions are further sub-divided based on the energy consumption or GHG emissions consideration and the building life cycle stages included into analyses. The categories are: the 'Operational Energy' (OEn), the 'Primary Energy' (PEn), the 'Embodied Energy' (EEn), the 'Operational Emissions' (OEm), the 'Life Cycle Primary Energy' (LCPEn) and the 'Life Cycle Environmental Impacts' (LCEIs). The financial objective functions commonly employed are: the 'Initial Cost' (IC), the 'Operational Cost' (OC), the 'Life Cycle Cost' (LCC) and the 'Payback Period' (PBP). The Social objective functions are the 'Inconvenience Rate' (IR), the 'Visibility of Measures' (VoM) and 'Thermal Comfort' (TC).

3.1. Financial Objective Functions

Projects that employ financial objective functions only, are not commonly met at building retrofit studies for the improvement of energy performance. If they are, they include financial terms of energy consumption or GHG emissions mitigation criteria such as the return of investment. Purely financial criteria could be employed by the investor, who is, in most of building retrofit cases, the owner of the house. All three studies under this category adopt the owner/user's perspective.

Desogus et al. (2013) investigated the financial feasibility of the envelope retrofit, in terms of LCC and PBP, for three different building types in Italy. The aim of their investigation is to challenge national legislation, claiming that it is too strict and not cost-effective for homeowners. According to the study's results, the combination of all proposed interventions, wall and roof insulation and window substitution, has the lowest Net Present Value (NPV) and is cost-ineffective. When subsidies are introduced, complete retrofit works are preferred to partial, despite the high IC.

Salata et al. (2017) conducted a research, focusing on financial objective functions, for a high-rise MFH retrofit case, located in Rome. A large spectrum of retrofit interventions was considered: external wall insulation, window replacement, control units installation, such as sensors and thermostat settings, boiler substitution alternatives, including Combined Heat and Power (CHP) technologies and Solar thermal and Photovoltaic (PV) panels. The performance of all potential retrofit strategies and their combinations was assessed using three financial criteria: the IC, the annual economic return and the return of investments. Calculations showed that the envelope's thermal performance improvement does not have a considerable impact on energy demand reduction, while it has high installation cost and a payback period of more than 30 years. PV panels are more effective when combined with a Heat Pump (HP) instead of a Condensing Boiler, because HP uses electricity. However, the choice between a Condensing Boiler and a HP is also determined by the local electricity and gas prices. The installation of smart control systems is a high-scored strategy on all assessment objective functions, as it leads to satisfactory annual energy savings and their amortisation period is less than 20 years. The combination of CHP and a HP, despite the high IC, has a PBP of 15 years and allows the building to reach an 'A' energy class, according to national regulations for energy certification which are based on the EPBD.

Finally, Lizana et al. (2016), employed financial assessment criteria in combination with social criteria, for a case study located in Southern Spain. They look at IC, the annual economic return, the TC and the IR caused to occupants. Low investment retrofit interventions have been identified as optimal, among them water flow reducers in taps installation and the sealing of frames for the improvement of air-tightness. Other proposed interventions are the installation of retractable window awnings, roof insulation, the replacement of HPs with more efficient ones and the insulation of exterior walls.

3.2. Environmental Objective Functions

LCA is among the most popular decision-making support methods used for the selection of the optimal alternatives among the retrofit strategies available. A number of LCA studies explore alternative solutions for Energy Saving Measures (ESMs), looking at their embodied energy and the influence they have on primary energy consumption of the building during its operational phase. The interest is focused on the environmental impact of different envelope insulation materials and window frames. High performance targets, such as Passive House standard or near ZEB, aim for optimal solutions at all available intervention categories: ESMs, HVAC systems and RES. Table 1 shows that the majority of projects employing environmental objective functions claim that they meet the requirements for all involved stakeholders (Wang et al. 2015; Assiego De Larriva et al. 2014).

Assiego De Larriva et al. (2014) compared insulation and ventilation strategies to achieve Global Warming Potential (GWP) reduction for the retrofit of a high-rise residential building in South Spain. Ventilation strategies are proved to have a lower GWP and thus are preferred. They generalised results saying that for buildings located in temperate climates, the design that enables better ventilation leads to less GHG emissions.

Wang et al. (2015) investigated the trade-off between PEn savings and EEn for the retrofit interventions of three different building types in Sweden. The options considered are ESMs addressing the thermal insulation and air-tightness of the envelope, efficient ventilation and the introduction of a low temperature heating system with connection to a District Heating (DH) network when available. Results vary, depending on the building type. For the SFH and the low-rise MFH, the most effective retrofit strategy is the combination of small-scale retrofit of the building envelope, such as air-tightness improvement and window replacement, with a low-temperature heating system. For the high-rise MFH, additional envelope retrofit options should be implemented. The installation of a heat recovery system leads to PEn savings and embodied GHG emission levels.

Dodoo et al. (2010) estimated the LCPEn consumption of a wood-frame apartment building in south Sweden, after being refurbished to Passive House standard. A number of ESMs, the installation of efficient water taps and mechanical ventilation systems with heat recovery were investigated under three different end-use heating systems, which are resistance heating, HP and DH. As expected, the heating system that shows the biggest PEn usage decrease is resistance heating, because of its low energy efficiency. The installation of ventilation systems with heat recovery, followed by the replacement of windows, the use of efficient hot water taps and the insulation of external walls lead to higher energy savings. It was also found that the EEn of materials has increased 17% when the building is retrofitted to Passive House standard. However, the operational phase is still responsible for the largest PEn consumption share.

3.3. Environmental and Financial Objective Functions

The identified trends of the studies that uses multi-criteria assessment methods to evaluate retrofit alternatives are the combination of the LCC objective function with OEn, PEn and LCEIs. The driving force behind these trends is the EPBD Recast methodology, considering the determination of the cost-optimal solutions for a near zero energy or zero carbon emissions building retrofit.

3.3.1. Life Cycle Cost and Operational Energy

Four out of five studies reviewed that choose to minimise LCC and OEn are employed by researchers who look the building retrofit problem from the owners' perspective. This can be justified by the fact that energy bills are among the highest household expenses and energy savings can be used as an incentive for homeowners in order to initiate retrofitting their houses.

Amstalden et al. (2007) considered envelope insulation and window replacement as potential energy efficiency improvement strategies for a SFH in Switzerland. They argued that the wall and roof insulation are the better strategies, since both floor insulation and window replacement have negative NPV. Hasan et al. (2008), also investigated a SFH in Finland, considering passive energy efficiency strategies and mechanical ventilation. Their findings agree with that of Amstalden et al. (2007) on the insulation of walls and floor and the replacement of windows, but not with the insulation of the roof. Mechanical ventilation systems with heat recovery were also found to be cost-effective. Brown et al. (2013) compared three alternative packages for two different house types in Sweden, including passive measures, mechanical ventilation and additional system controls. They concluded that the balanced mechanical ventilation with heat recovery and the addition of thermostat settings to radiators, followed by high-efficiency window replacement, are the optimal retrofit interventions.

Different owner types, the 'aesthetic homeowner', the 'well-kept homeowner' and the 'do it yourself homeowner', were defined by Risholt et al. (2013) in order to indirectly introduce social criteria. Adding TC as the third objective function, Penna et al. (2015) provided three optimal retrofit solutions for each residential building type studied in two different climate zones in Italy. They mentioned the importance of window type selection and the installation of a mechanical ventilation system to improve TC. They also pointed out that the overuse of conventional ESMs, such as the addition of extended insulation of the building envelope, is responsible of summer overheating.

3.3.2. Life Cycle Cost and Primary Energy

The objective functions set of LCC and PEn are not correlated with any specific stakeholder's perspectives. From the owners' perspective, Kuusk and Kalamees (2015) in Estonia, targeting a net-Zero Energy Building (net ZEB) and exploring both ESMs and the installation of RES, found that the indoor climate requirements can be fulfilled using thermostats and mechanical exhaust ventilation system without heat recovery. The major energy saving requirement is fulfilled with additional envelope insulation, window replacement and the installation of a two-pipe radiator heating system to replace the existing one-pipe system. Moving to the energy efficiency requirements for new buildings, additional ventilation units with heat recovery is the optimal retrofit intervention. A near ZEB is achieved with the installation of additional solar thermal collectors, while a net ZEB with additional PV panels.

In Portugal, Ferreira et al. (2014) looked for the cost-optimal retrofit strategies to achieve a near ZEB MFH. They found that the cost-optimal option is the combination of low

thickness envelope Expanded Polystyrene (EPS) insulation for the external walls and low thickness Extruded Polystyrene insulation for the roof and floor, with a high-efficiency gas boiler for heating and Domestic Hot Water (DHW). A net ZEB target is achieved with the addition of PV panels. They also pointed out that the introduction of high-level envelope performance requirements in the national building code can lead to retrofit strategies that deviate from the cost-optimal options. Retrofit interventions should improve the performance of all envelope elements, while ensuring thermal comfort levels and cost-optimality. In addition, renewable energy technologies play a critical role when a net-zero level is required.

From the public promoter's perspective, the investigations that uses LCC and PEn as assessment objective functions, take also TC into consideration, either as a constraint (Hamdy et al. 2013) or as a third objective function (Lizana et al. 2016). Hamdy et al. (2013), explored the near ZEB retrofit options for a SFH in Finland. A large number of variables were considered in a matrix, which eliminates mutually exclusive interventions. The included variables are ESMs, such as envelope insulation, air-tightness, window replacement and heat recovery options, heating, cooling and DHW technologies, as well as RES, such as solar thermal and PV systems. The LCC-PEn consumption chart shows that clusters are formed based on the heating and cooling technologies used. The highest cost-operating system requires high-level ESMs interventions and vice versa. It was noted that investing in heating systems is more viable than high cost ESMs investment. The optimal cost-efficient heating system is the Ground Source Heat Pump (GSHP) and can be combined with RES, which does not improve the financial performance of the GSHP strategy, but leads to near ZEB building performance. In addition, retrofit strategies that do not consider cooling systems are more preferable than those that do consider; the latter can improve the energy performance of the building and the financial feasibility of the strategy when RES are installed. Both solar thermal and PV panel systems are selected, but PVs are more economically viable than solar thermal.

Lizana et al. (2016), from the public promoter's perspective, applied the weighted multi-criteria assessment method, employing a large number of assessment criteria. Among them LCC, PEn consumption and TC were highly weighted. The considered retrofit strategies are ESMs, HVAC systems and RES. The cost-optimal and energy-efficient retrofit strategy is the combination of the placement of retractable awnings, window replacement with aluminium frames and low emissivity (low-e) double glazing, external wall and roof insulation and the application of solar thermal collectors to cover energy for DHW.

Ballarini et al. (2017), using IEE-TABULA project's (Anon n.d.) building typology, developed a multi-criteria assessment method for the evaluation of retrofit strategies, applicable to all building types of the Italian residential building stock. The strategies include envelope insulation, window replacement, heat generator replacement, thermal solar system installation and their combinations. Heating system replacement is the most cost-effective intervention, especially for warm climates (less than 1400 heating degree days), due to low initial cost and short payback period. The retrofit package that combines envelope insulation, window replacement and heating system replacement is the most cost-effective and cost-optimal for medium and large size buildings that have been constructed before 1975. The initial cost is high but the payback period does not exceed 19 years.

3.3.3. Life Cycle Environmental Impacts and Life Cycle Cost

Life Cycle studies often combine LCEIs with LCC assessment criteria under a multi-criteria decision making process, in order to look both at the environmental and financial point of view. Once more, there is no obvious correlation of this objective functions set with any stakeholder's perspective. De Angelis et al. (2013) and Cetiner and Edis (2014) both studied envelope insulation alternatives, in terms of materials and thickness, for the optimal retrofit of high-rise MFH in Italy and Turkey, respectively. An interesting study of Pombo et al. (2016) investigated several retrofit scenarios of a high-rise residential building in Spain, from the 'business as usual' to Passive House standard, using ESMs. Environmental indicators were interpreted to monetary values to estimate the cost of the damage to the environment and humans. The best practice among the ESMs suggests high thickness roof (24 cm) and wall insulation (16 cm), or a slightly thinner insulation and the addition of a second PVC frame, low-e, double glazing window. The Passive House standard scenario was rejected as it involves high initial costs.

Antipova et al. (2014) evaluated a number of retrofit strategies for a residential building in central Portugal, under two objective functions: the LCC and the LCEIs, based on the LCA method. The major finding of the study is the high correlation among the different environmental impacts employed and their inversely proportional relation with the LCC objective function. Verbeeck and Hens (2005) assess a large variety of all intervention categories (ESMs, HVAC systems and RES), under the same objective functions, LCEIs and LCC, using typical Belgium detached and terraced houses as case studies. Their findings prioritise ESMs, with the insulation of the roof to be the most effective measure. Better performing glazing is also suggested, but the wall insulation is too expensive to be among the optimum strategies. In terms of LCEIs, gas boilers are preferred over electrical heating systems. It is also worth noting that RES are not part of the optimal solution set for any of the reference buildings.

Ostermeyer et al. (2013) introduced the concept of Life Cycle Sustainability Assessment, using LCC, LCEIs and social acceptance criteria. However, the last criteria was limited in identifying the driving retrofit technologies and taking into account their implementation consequences on residents. A multi-storey residential building in France was used as a case study and a number of ESMs, HVAC systems and RES were considered as potential retrofit interventions. A high thermal resistance envelope insulation, triple glazing windows and mechanical ventilation was proposed under the high-score LCEIs scenario. Whereas, lower thermal resistance insulation, double glazing window replacement and natural ventilation under the LCC-LCEIs balanced scenario. A high-efficient condensing boiler is the optimal choice of heating system for both scenarios.

3.3.4. Investment Cost and Primary Energy/Operational Emissions

From the private investor's perspective, Lizana et al. (2016) studied the same retrofit strategies under PEn consumption and IC. They found that the optimal strategy is the installation of an air-source HP for heating, cooling and DHW, that compliments the substitution of existing windows with aluminium framed, low-e double glazing windows.

Adding TC as a third assessment objective function, Ascione et al. (2015) and Huws and Jankovic (2014) made retrofit proposals in order to achieve a low energy consumption and a Zero Carbon Building level, respectively. Their case study in Italy, assessed selected budget based retrofit scenarios, that consist of EMSs and heating and cooling systems. The optimum strategy combines low-thickness EPS wall insulation with high thermal resistance rockwool roof insulation, a mechanical exhaust ventilation system without heat recovery, the replacement of the existing boiler with a condensing one and

the replacement of air-cooled chiller with a higher coefficient of performance water-cooled one.

In the United Kingdom, Huws and Jankovic (2014) assessed numerous variables of all three retrofit intervention categories, under the same criteria. According to them, a high-level external wall insulation stabilises the internal temperature and increases TC. Triple glazing windows provide the minimum GHG emissions, while quadruple glazing windows provide the maximum TC conditions.

4 Results and Discussion

When financial objective functions are considered, the improvement of the envelope thermal properties is not a cost-effective retrofit strategy, especially for buildings located in temperate climates, because the energy demand reduction is not enough to pay off the initial cost. On the other hand, low initial cost interventions, such as frame sealing, retractable awnings and the installation of sensors are among the global optimal solutions.

When environmental objective functions optimisation is the desired outcome, the envelope insulation and air-tightness and the replacement of existing windows with more efficient ones are among the optimal strategies, especially for cold climates. The embodied energy of these components increases, however, the life time operational energy reduces more which makes the net energy saving. Natural ventilation saves cooling energy in temperate climates while heat recovery saves heating energy in cold climates. Having low embodied energy, natural and mechanical ventilation are considered among the optimal retrofit solutions. The installation of high-efficiency heating systems, such as HPs, are also appropriate.

The majority of investigations that consider LCC and LCEIs objective functions introduce balanced solutions, combining medium thermal resistance insulation for the retrofitted envelope parts with efficient heating systems. It should be noted that RES are not part of the optimal retrofit strategies, despite the fact that they are necessary in order to achieve a low energy/carbon target.

Similar balanced strategies are proposed by investigations that employ LCC and OEn or PEn objective functions, prioritising efficient HVAC systems over high cost ESMs. The combination of medium envelope insulation levels with efficient HVAC systems form the optimal solution. Among them, mechanical exhaust ventilation system with and without heat recovery and window replacement are the selected strategies. In general, heating systems are more cost-effective than high-cost ESMs. RES are introduced for near and net ZEB retrofit targets but without improving the LCC objective function.

Considering TC as the third objective function, there is not a clear consensus in the literature over the role of the level of envelope insulation. Case studies located in temperate climate zones (Penna et al. 2015; Ascione et al. 2015) argue that lower level of insulation, combined with mechanical exhaust ventilation system, increase thermal comfort, however, case studies located in colder climates (Hamdy et al. 2011; Huws & Jankovic 2014) call for higher thermal insulation levels of the envelope and higher R-value windows. Finally, at those studies, shading systems are also considered as ESMs and selected among the optimal retrofit strategies.

5 Conclusions

This paper presents a literature review related to retrofit investigations on residential buildings, located in European countries. It is to address the issue of high contribution of the residential building stock to the GHG emissions. The aim is to identify the sets of objective functions employed in various projects, associate them with the adopted stakeholder's perspective and compare the resulted retrofit strategies.

It is acknowledged that the residential building retrofit process is a complex multifactorial task and the selection of the optimal strategies does not solely depend on the objective functions employed but on a large number of parameters, such as the climate conditions, the building type and the target or the constraint settings.

A strong correlation was observed among owners, as research stakeholders, and the objective functions set of LCC and OEn. Owners, being the retrofit investors, also employ purely financial objective functions to assess the financial viability of the venture.

The major finding is that, when ESMs are assessed under financial objective functions they are not among the cost-effective options. Under both financial and environmental objective functions, energy efficient heating systems are preferred from costly ESMs. Investigations employing the LCC objective function do not favour RES. Finally, natural and mechanical ventilation, heat recovery and smart control systems are among the optimal strategies under all various sets of objective functions discussed.

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OPEN DESIGN: SHARED AUTHORSHIP IN MASS CUSTOMIZED DESIGN

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Abstract: *Open-source design is predicated on a collaborative process which builds on existing information, organizations, or base files. Most often associated with software development, groups including Google, Facebook, and Tesla have adopted the mindset as a way to encourage the rapid, comprehensive development of their products. A genotype base file (or source code) is offered for development and in turn sees a series of phenotypes which are either accepted or rejected based on fit and performance. The ability for rapid development and iterative option testing was seen as having high potential in the design professions of the built environment, and the resultant work is the subject of this paper. The University of Nebraska collaborative design studio used an iterative process of design research to guide interdisciplinary teams through proposing solutions for conditions where a traditional practice scenario has failed due to timeframe, or availability of resources such as professional consultation, skilled workers, contemporary construction technology, or materials. The results of this studio demonstrate an user-centric approach to contexts which are challenging to comprehend and propose impactful design ideas through a low and high tech positions on mass customization in architecture.*

Keywords: *Mass Customization, Open-source Design, Prefabrication, Design for Refugees, User Interface Design (UI)*

1 Introduction

"Software is just the beginning … open-source is doing for mass innovation what the assembly line did for mass production. Get ready for the era when collaboration replaces the corporation." Wired Magazine (Goetz 2003)

Post-Renaissance design disciplines of the built environment are predicated on the Albertian model where conception and representation of built form occur initially, followed separately by construction of the edifice as represented without alteration. Referred to in print media as bon à tirer (ready for press), this relationship seeks to assure control of the content by the author; it is copyrighted. This model is being challenged in the 21st century as the line between designing and constructing becomes increasingly blurred. Enabled partly by a democratization of fabrication, the maker and end user are now authors in the process.

Open-source design, a term first coined late 20th century in the context of software engineering and computer science, embraces the concept of a sharing community where the development of results outweighed the authorship of artifacts. Recently, the idea of open-source and what it stands for has become even more popular as groups including Google, Facebook, and Tesla have adopted the mindset as a way to encourage the rapid, comprehensive development of their products. Open-source design, at its core, endeavors to fuel collaborative innovation through the principles of "Share the Goal, Share the Work, Share the Result." (Goetz 2003) It has been translated in various scales from furniture (OpenDesk) to architecture addressing social issues such as a global housing crisis (Wikihouse and, more recently, free, downloadable housing designs by Pritzker Prize laureate Alejandro Aravena.) Oftentimes this content is shared through copyleft venues such as Creative Commons that offer protection and licensing encouraging sharing on the grounds that the first-generation author deems appropriate.

Open-source design seeks to offer authorship to a larger audience than traditional processes which only engage design professionals in a top-down strategy. Open-access materials often exemplify traits of embedded knowledge where intelligence is intrinsic to their use (ie. organizational frameworks, assembly, etc.) and can be activated without specific training or experience. The designer is able to establish smart design parameters anticipating a range of acceptable options desirable to the user all while not allowing variations that could 'break' or sacrifice the integrity of the system. With embedded knowledge, the guidance of an experienced designer is with the user or novice designer as they work within the immediate context searching for the most appropriate solution. Smart parameters offer the ability to generate variations which meet the specific needs of various user groups. These variations on a base framework are the beginning to approaching a condition of mass customization.

Mass customization is often associated with solutions engaging the latest software and CNC technology within a modulated construction system. While this is certainly pushing the agenda forward, there is also a place for mass customized solutions which apply a low-tech approach. Student work presented in this paper employed both low and high-tech approaches to mass customization responding to the diversity of people involved in the design and construction/assembly process. Initial design investigations employed parametric modeling software and digital fabrication. Design parameters offered projective decision making prior to fabrication with digitally-generated phenotypes. Additionally, the design framework predicted user interaction in its field assembly and produced a kit of parts which made available several custom variations. This approach saw students proposing user interface (UI) and user experience (UX) proposals which

could respond much quicker to field and program adjustments while considering the users and their context (skills and tools).

This paper will unpack built environment design research into open-source, shared authorship and mass customized fabrication and assembly by means of collaborative design thinking teamwork. The research question set forth as a catalyst for the design studio was whether open-source design, in the context of the design disciplines of the built environment, could offer quicker and more empathetic solutions to situations where traditional practice has failed to make significant impact. Interdisciplinary team proposals addressed construction in the context of limited time, resources, and/or professional availability. Resultant work proposes user interface (UI) and user experience (UX) design empowering people in these contexts to embrace authorship within a controlled set of parameters allowing for democratic access to design and disciplinary knowledge.

2 Why open-source and for whom?

During the 2016 AIA national convention in Philadelphia, Rem Koolhaas gave an interview in which he cautioned the profession of architecture about an uncertain future. Several topics were covered but two significant quotes served as catalysts to the work of this design studio. Regarding to the pace of the profession, he stated, "Architecture is a profession that takes an enormous amount of time. The least architectural effort takes at least four or five or six years, and that speed is really too slow for the revolutions that are taking place." (Budd 2016) Open-source design is not for all projects and all situations. Since it builds from existing knowledge sets and models, it can often decrease design and response time, and potentially demonstrate larger efficacy through its adaptability to various situations which are anticipated through adaptation over stasis, in other words through mass customization. The wicked problems (Rittel 1973:155-169) that are paramount in the global condition are transdisciplinary, and need architecture to respond much quicker with competent and timely design solutions. To address these problems, the user is not looking for a design that is qualified based on its perceived novelty, but rather on its ability to enact change and empower the users to act within their own context.

Regarding the referenced revolutions, Koolhaas stated, "In Europe, we're facing an influx of 2 million refugees, mostly from Syria, which poses interesting possibilities. In eastern Germany, there is an area where cities are almost completely abandoned and, partly with the help of architects, there's an experiment of seeing if Syrian refugees who are highly educated, motivated, and committed can re-inhabit those territories. Refugees could reenergize sections of the cities. They offer to architecture an interesting provocation or invitation to do good work and collaborate in interesting ways." (Budd 2016) Open-source architecture is inherently team-oriented and often transdisciplinary with design teams demonstrating the mantra of sharing the goal, work, and results. Carlo Ratti refers to the open-source architect as the choral architect suggesting that their role will be to "determine a set of parameters that direct a potential architecture. Architects [will] design the questions, not the response." Ratti expands on this mindset shift stating "Its proponents see it as distinguished by code over mass, relationships over compositions, networks over structures, adaptation over stasis. Its purpose is to transform architecture from a top-down immutable delivery mechanism into a transparent, inclusive and bottom-up ecological system - even if it still includes top-down mechanisms." (Ratti 2015:103) Koolhaas went as far as saying that architecture's future might not even be architecture itself but possibly organizational systems and the like. (Budd 2016)

3 User Empowerment

The user of architecture in the 21st century desires, and even expects, to be engaged in the design process. The trust in design from the outside has seen its challenges as the public is no longer able to 'pay no attention to that man behind the curtain.' Many have felt encouraged, even empowered to take on the design of their own space, and engage a self-generated design process. This process all too often involves copying and sampling without knowledge of the intent, compositional logic, or disciplinary knowledge essential to the execution of a successful or impactful design thus creating a project lacking depth and sophistication. These novice designers are often able to determine what the user wants/needs but are ill equipped with the resources to manifest something as complex as the average architectural edifice. In turn, the results of this design process see users employing a cut and paste approach with focus on stylistic mimicry rather than performative potential.

The success of open-source design in the field of computer science is due to a careful management of base code that is competently shared, developed, and vetted through a team of experts able to both identify and correct deficiencies. This is then offered at large to allow for phenotypes that are built on a solid base. Open-source architecture proposes a condition in which the development of base systems encourage authorship of various decisions points, and do so with accurate vision of how those decisions affect the overall systemic logic. Users are empowered to be active in the design process, but are not abandoned without appropriate resources to make informed decisions regarding discipline specific conditions requiring specialized knowledge. The user interface becomes a guide in the process offering professional advice at a distance.

In the book *Languages of Art* (Goodman 1976) Nelson Goodman discusses the ways in which artistic authors communicate with their works, and in so addresses a comparison between several formats including art, literary works, dance and architecture and a relationship between autographic and allographic systems of communication. Simply stated, the autographic system works with direct adjacency to the material in which it is affecting without a system of communication or notation; for example a sculptor working with the final piece. Comparatively, the allographic system contains notational systems and allows for the work to happen with distance from the author, and for duplication to exist based in either time or distance. Music and architecture both work within an allographic system where an instructional set, referred to as a 'score' by Goodman, is a prime source of communication. This allographic system allows for replication and guidance from afar, and potentially more impact as the design can reach a much larger audience.

The rise of maker cultures and digital fabrication have allowed the architect to come closer to bridging the gap between maker and made, but the tools enabling this proximity still require the designer to manipulate form and material through a digital interface at least one degree of separation from the final artifact. An open-source system which engages controlled options in the field offers sophistication from the design professional simultaneous to contextual and empathetic variations for assembly desired by the user group in the factory or field. In other words, it is both autographic and allographic.

4 Design Research Methodology in the Academic Studio

The final year of the undergraduate design curriculum at University of Nebraska brings together the disciplines of architecture, interior design, and landscape architecture for a

studio titled “Collaborate.” Capitalizing on previous years built on a base of design thinking which then moves into disciplinary specificity in year 2-3, this studio seeks to provide students an opportunity to be part of a team-based, collaborative design challenge. The work discussed through this paper represents a group of architecture and an interior design students who were asked to consider the potential of open-source design in the context of the built environment. Student teams of 4-5 members engaged design research which was outlined such that it oscillated between research FOR design and research THROUGH design. Research and low resolution prototypes ultimately coalesced into hypotheses which lead to more focused design investigations with the aim of proving the hypothesis. Although certainly not linear in its deployment, the diagram below was given to the student teams to assist in guiding them through the project development. (Fig. 1)

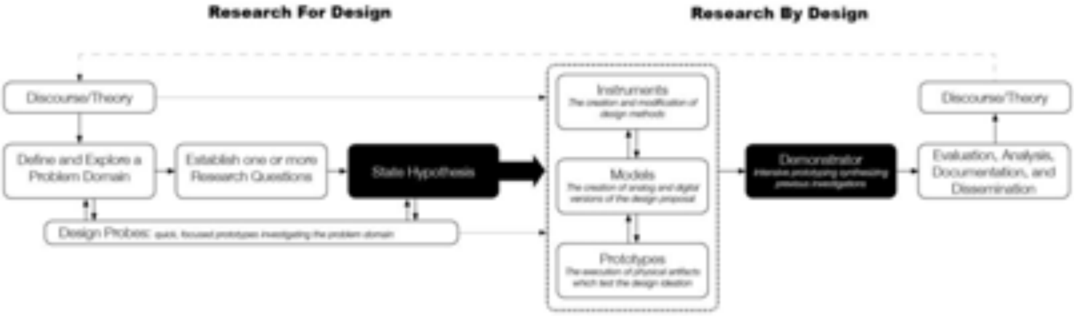

Figure 1: Design process diagram (Image by author)

The work for the semester was separated into 2 projects; Blasphemy lasting 4 weeks and Quick Response System (QRS) lasting 9 weeks. Blasphemy was a shorter project aiming to begin conversations and develop sophistication in the students’ vocabulary, digital proficiency, collaborative skills, and overall position on the studio topic. QRS allowed more refined investigations with higher levels of resolution to the proposed construction system and resultant edifice. The following text briefly summarizes the studio process.

4.1 Research FOR Design: Blasphemy

Blasphemy sought to interrogate open-source design in the context of historical precedent. The role of history, and more specifically precedent, in the design disciplines of the built environment is significant as a way to learn from, and guide future steps. The strategic use of precedent is also not limited to our disciplines. Legal, medical, and scientific practitioners also integrate the lessons of the past into setting courses of action for future. The connecting trait between those who use precedent is that they are engaged in practice; practice of law, practice of medicine, etc. Practice implies a posture which is continually searching for a better answer, knowing that there is not a single right answer. This seems to be the case with the history of the roof as well. Rem Koolhaas states that “Because of its primitive origin, the roof is seemingly our most local element. The roof in fact originates from a condition of continuous exchange - never a single source but a process of constant change and updating… the roof was used by the powers that be to express social status and political stability (while remaining flexible for regime changes)...” (Koolhaas 2015:403) This quote charged the studio to document a portion of the history of the dome and oculus with particular focus on the Pantheon and Palazatto dello Sport, both sited in Rome. Within a scaffold pedagogic approach, research topics were seeded in the groups (precedents throughout history, performance, ritual, historical context, construction process and materials, and mathematics, geometry and proportion) and literature was distributed for review. This information was a starting

point for teams to build upon as they sought to parametrically define the precedent through objectively understanding the conditions which helped to develop the formal and constructional condition. (Fig. 2)

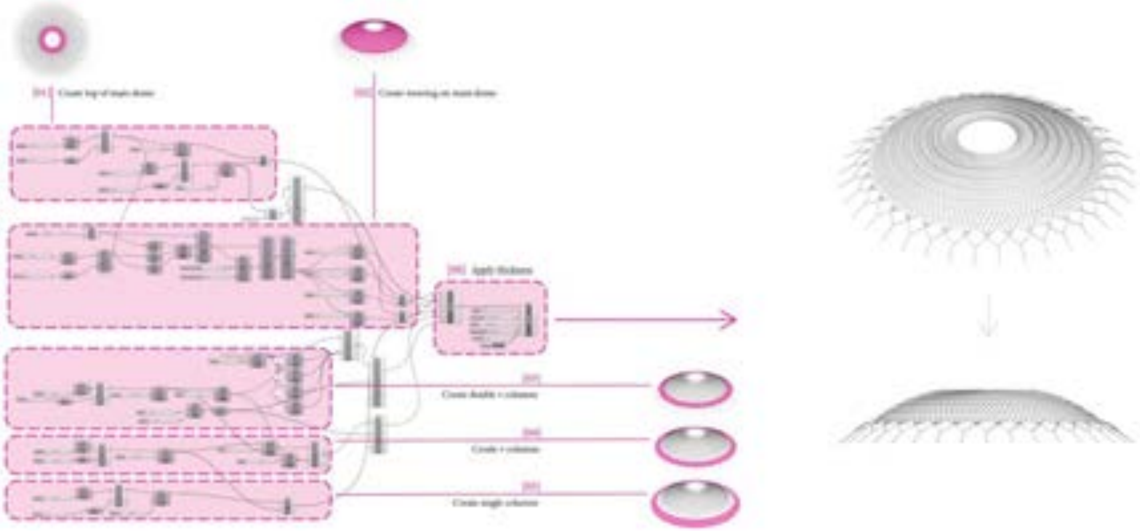

Figure 2: Nervi's Palazzetto dello Sport – Genotype Parametric Definition (Image by permission of author)

4.2 Research THROUGH Design: Blasphemy

Open-source design is predicated on the creation of a base file condition, or genotype, in raw form with specific performance criteria flexible enough to allow for variation. The determination of the parameters that are adjustable also requires disciplinary proficiency to know how those adjustments work when deployed within the larger system. Limits built into that system contain knowledge sets maintaining the relationships, networks, and adaptability relating to empirical data of user and/or environment, and based on disciplinary knowledge of construction techniques, materials, and building codes. Parametric software allows for the design of an instruction set (genotype) which has the opportunity to generate nearly infinite options (phenotypes) based on the depth and sophistication of the data and parametric definition. The flexibility of the various components within the definition contains necessary limits while allowing for intervention at strategic touch points. (Fig. 3)

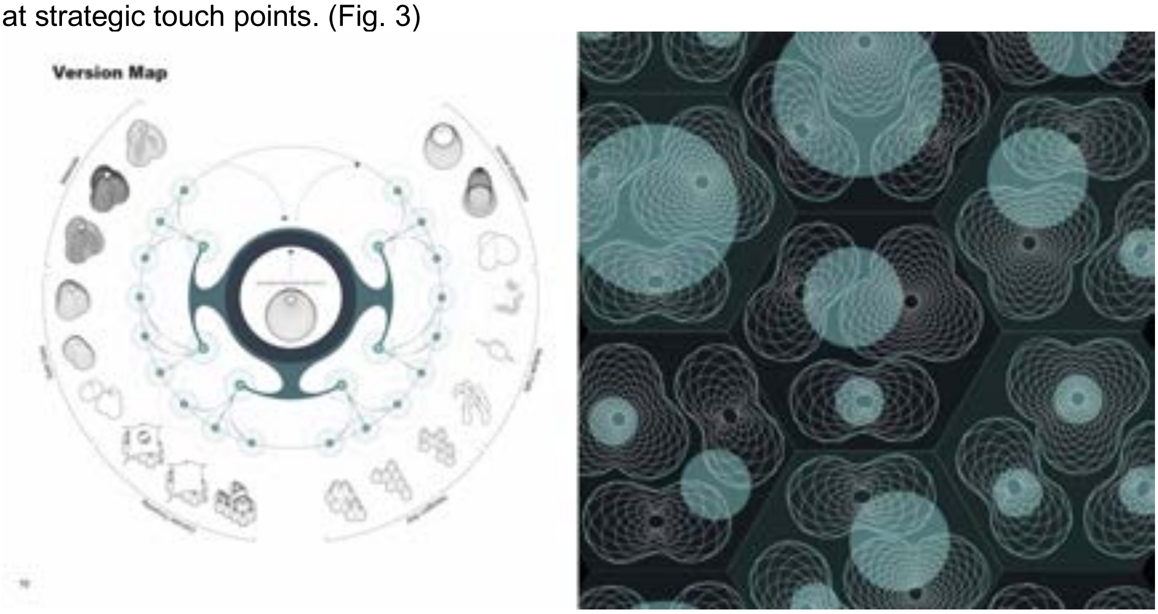

Figure 3: Palazzetto dello Sport Phenotype Version Mapping (image by permission of author)

Student design work in this phase continued to refine student positions on the topics through intensive analog and digital form-finding strategies. Focus was not on the delivery of one proposal, but rather to test the development of the genotype and its ability to generate several phenotypes representing varying levels of fit. The phenotypes' fit was evaluated based on their ability to address the core needs of the program and user, and to do so within a constructional logic which built upon the dissection of precedent. Design process culminated with the development of large-scale physical models which demonstrated the ability of the parametric definition to delivery customized artifacts. Interaction with the physical models made the adjustability of the parameters in the digital environment physically manifest. Domes were adjustable, construction systems were fabricated and assembled, and students were able to discuss both the object made as well as projective ideas of where it might go in future studies. The stage was set for a more in-depth investigation. (Fig. 4-5)

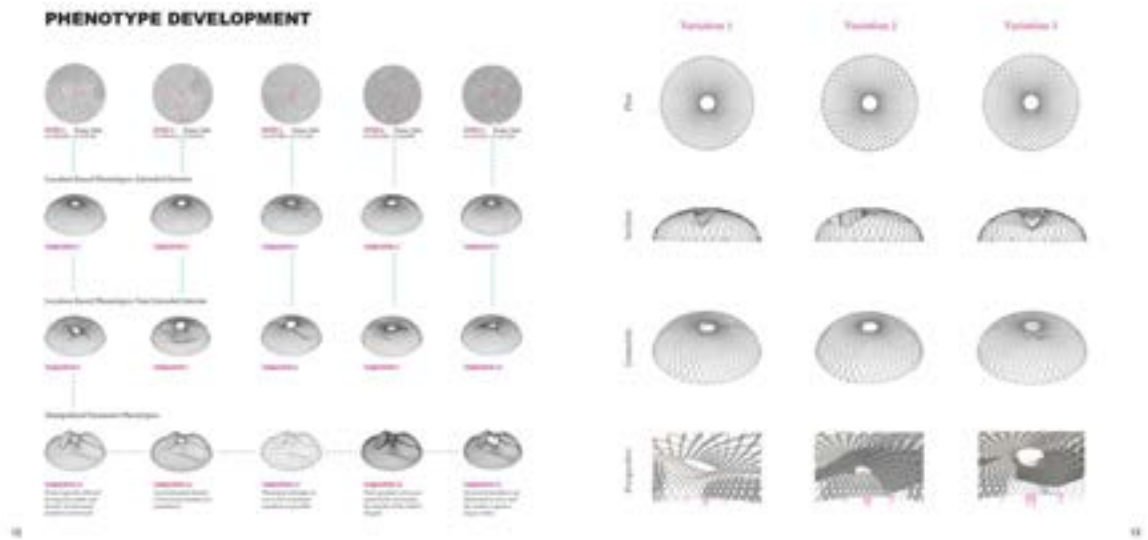

Figure 4: Blasphemy Phenotype Development (Image by permission of author)

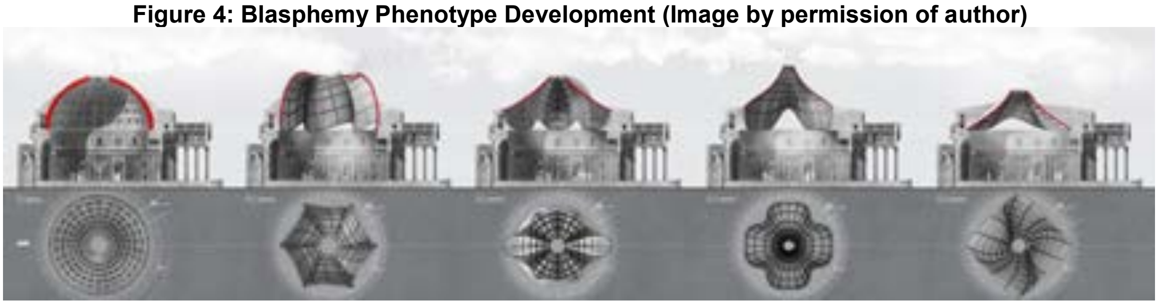

Figure 5: Pantheon Genotype with Various Phenotypes (Image by author)

4.3: Research FOR Design: QRS

Building on Blasphemy, QRS asked teams to propose an open-source system to addresses a condition where traditional practice has failed to deliver thoughtful solutions due to timeframe, expertise, materiality, etc. Examples of these conditions typically were situated in the areas of refugee housing and disaster relief where there is a significant lack of resources available, and where one discipline alone cannot solve the issues. Students teams were asked at the beginning of the project to consider the following questions with regard to their Blasphemy deliverables:

- Is it open-source and if so how is this demonstrated? If not, what are the conditions which are limiting it being so?
- Can it be built and if so, how?

- Are the materials and assembly closely linked to the design intent?
- What are the computational traits which are integral, and do these traits link meaningfully to a material, formal, spatial, or organizational logic?
- Did the analog model extend the investigation and add more clarity? Were the materials supportive of the project hypothesis?

Initial research topics were in the areas of construction innovation, open source design, social design, materiality, and research development skills. A series of “What if…” questions in conjunction with a several small design probes testing various aspects of the research through quick, low-resolution, and focused investigations students would eventually lead to the development of a hypothesis to guide the design work. “What if…” questions were to individually address the topics Program/Context, Materials(s), and Assembly.

Phase 1 of this work ended asking teams to posit a hypothesis distinguishing the could from the should. “What if…” questions considered what could happen in general terms, and empathetic research into the topics specific to the immediate context explored through several design probes helped each team to determine what they believed should happen. The remainder of this academic term was focused on the development of deployable open-source systems of design and construction based on their hypothesis.

4.3 Research THROUGH Design: QRS

To this point, teams had been heavily engaged in *‘research for design’* probing the context considering the factors which were essential to its comprehension and ultimate intervention. This phase asked students to build on the proposed hypothesis and, as a team, to develop design materials which address the charge. Teams were able to internally self-organize their tasks based on the emergence of skillsets in the previous project, and deploy them in ways which would represent a high performing team, one where parallel work is continually feeding into the project narrative creating a condition of perpetual motion oscillating between refection and projection.

Phase 2 of QRS shifted to a more projective mindset of *‘research through design’* where prototyping was foregrounded. It was considered unfruitful to simply talk about the potential of the problem space, rather the dialog revolved around instruments (analog and digital jigs, rigs, and tools) and prototypes (models testing portions of the design proposal). In turn, each team engaged making as a core activity. Ultimately, each team was required to comprehensively demonstrate the open-source condition of their project through the high-resolution, large-scale prototype called a “Demonstrator” coupled with user experience (UX) and user interface (UI) designs. (Fig. 6)

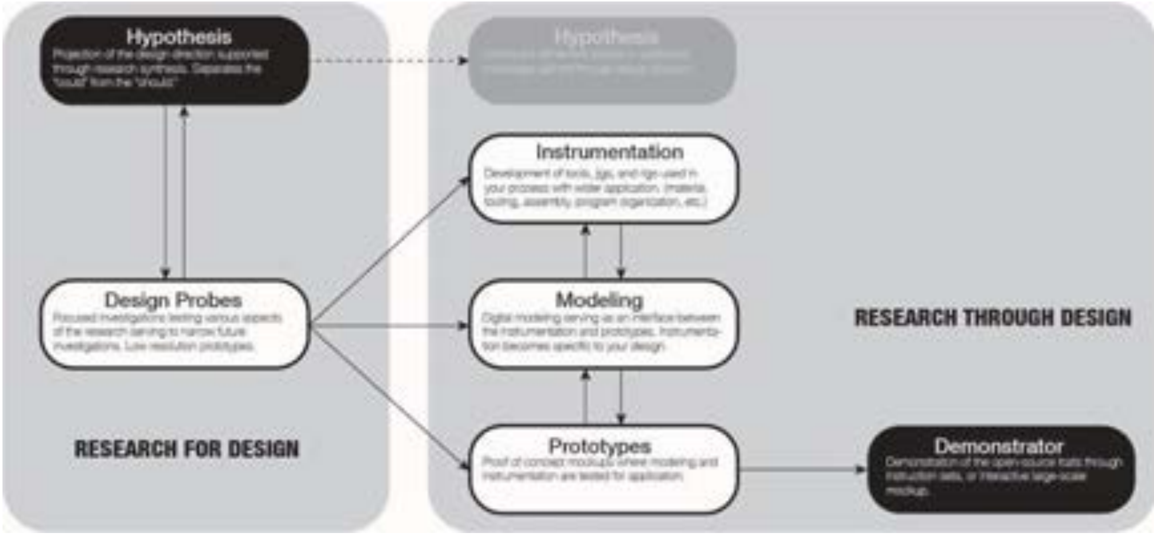

Figure 6: Research Through Design Methodology Diagram (Image by author)

5 Results

This paper shares the results of one of the four teams as representative of the process and product which was achieved throughout. The work of this team represented the full spectrum of team dynamics, moving through significant conflict and ultimately emerging as a high performing team fully utilizing their skillsets. This team developed a highly empathetic design proposal for a construction system which could be used in refugee camps specifically, in this case, the Zaatari refugee camp. The results of this team and the entire studio take an open-source approach to pedagogy and knowledge sharing as students in the subsequent Collaborate studio have access to all information and files, and are building on that knowledge to generate new work.

5.1 QRS: Beyond Survival

“Beyond Survival deals with the psyche of people, to recognize that they need to regain everything they have lost and this is not material, this is about their dignity.” Kilian Kleinschmidt (Radford 2015)

Beyond Survival, a phrase borrowed from humanitarian aid expert Kilian Klenschmidt, was the name given to the work from one team from the Collaborate studio. The makeup of this team was very diverse including first-generation citizens representing families immigrating from Mexico and Syria. Over the course of 10 weeks, this team worked rigorously to understand the context of the refugee camps and their inhabitants, digging deep into topics including the schedule of daily life, cultural traditions, existing skillsets, and underutilized resources existing within the camps.

The Zaatari refugee camp, which was founded in July of 2008, now hosts nearly 83,000 refugees. (Carissimo 2016) By the end of 2015, 63.91 million people have been displaced as a result of conflict, war, persecution and human rights violations and 33,972 people are forced to flee their homes daily. (UNHCR) The average amount of time a person spends in a refugee camp is 17 years (UNHCR) and 56% of Zaatari’s population is under the age of 17. (Muheisen 2016) Due to lack of jobs, the daily schedule of the camp inhabitant is often not utilized to its capacity leaving many skilled workers. (Nelson 2014). These facts were critical in the development of a design which represented empathetic intervention aimed to create impact.

The research lead this team to investigate constructional systems which were flexible and could facilitate several programs. While the programmatic options were wide open, they decided to focus in education delivery as it offered the most potential for enacting change in the camp inhabitants. “What if…” questions proposed by this team included the following:

- “What if we go beyond basic survival needs for refugees and start providing them with accessible education in order to elevate their quality of life?”
- “What if we use an open-source, mass-customized kit of parts assembled by community members in refugee camps to create place for several programs including education?”
- “What if the construction, beyond the basic framework, varied depending upon location, so that different locations could design their own chassis based upon the cultural and sustainable needs of the area?”

These “what if…” questions, in conjunction with several design probes, lead the team to propose a hypothesis of “If we provide refugees with an open-source system to create a built environment conducive to educating refugee children, then we will elevate their quality of life and allow them to become empowered and productive global citizens.” Discussions throughout the process asked design teams to consider the placement of mass customization and whether the context would better utilize a system which allowed for variation prior to fabrication and in the virtual environment (factory), or if the system allowed for variation by the end user in the field through a flexible kit of parts approach. It was determined that this context would be better served by allowing variation based on immediate need, as well as variation over time through intervention into the systems. This team’s proposal considers the skills and needs of the people group, offering a construction system which is semi-permanent and highly efficient in it material deployment.

The Beyond Survival design proposal calls for an open-source kit of parts which is comprised of varying diameters and lengths of cardboard tubes with a digitally fabricated joint system capable of adapting to several module configurations (Fig. 7-8). This team worked through spatial morphologies which would allow for both 6 and 8-sided configurations. (Fig 7) The joint system is able to be flat packed and shipped, and user interface graphics are included as etched graphics on the surfaces of the material components. (Fig. 8) The most efficient configuration for the educational program determined to be the octagon, but hexagonal configurations were also highly efficient due to their nesting potential. Final deliverables for this academic term show the system and its deployment as an octagonal pattern. (Fig. 9)

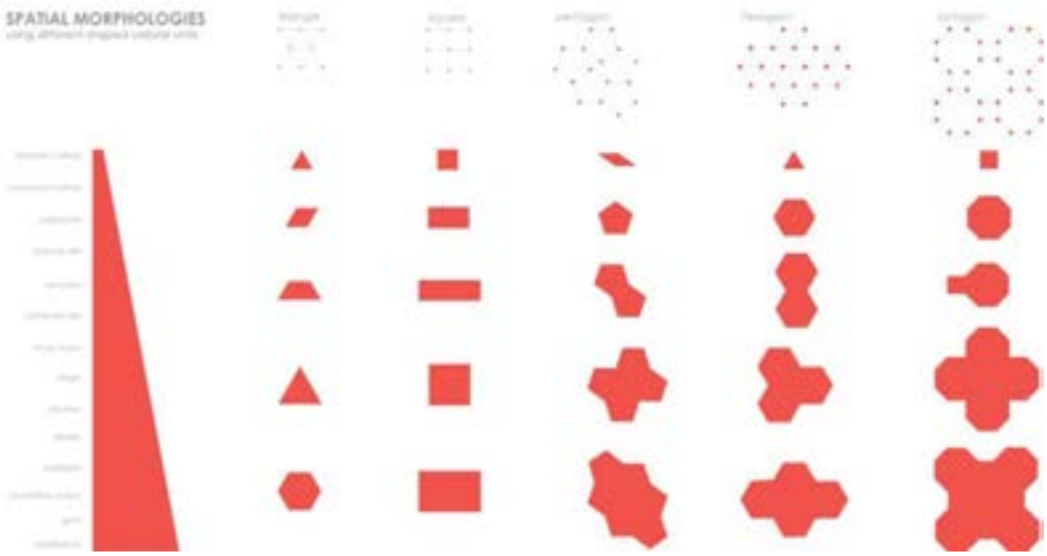

Figure 7: Open-source system layout options based on ornamental patterns and geometrical nesting (Image by permission of author)

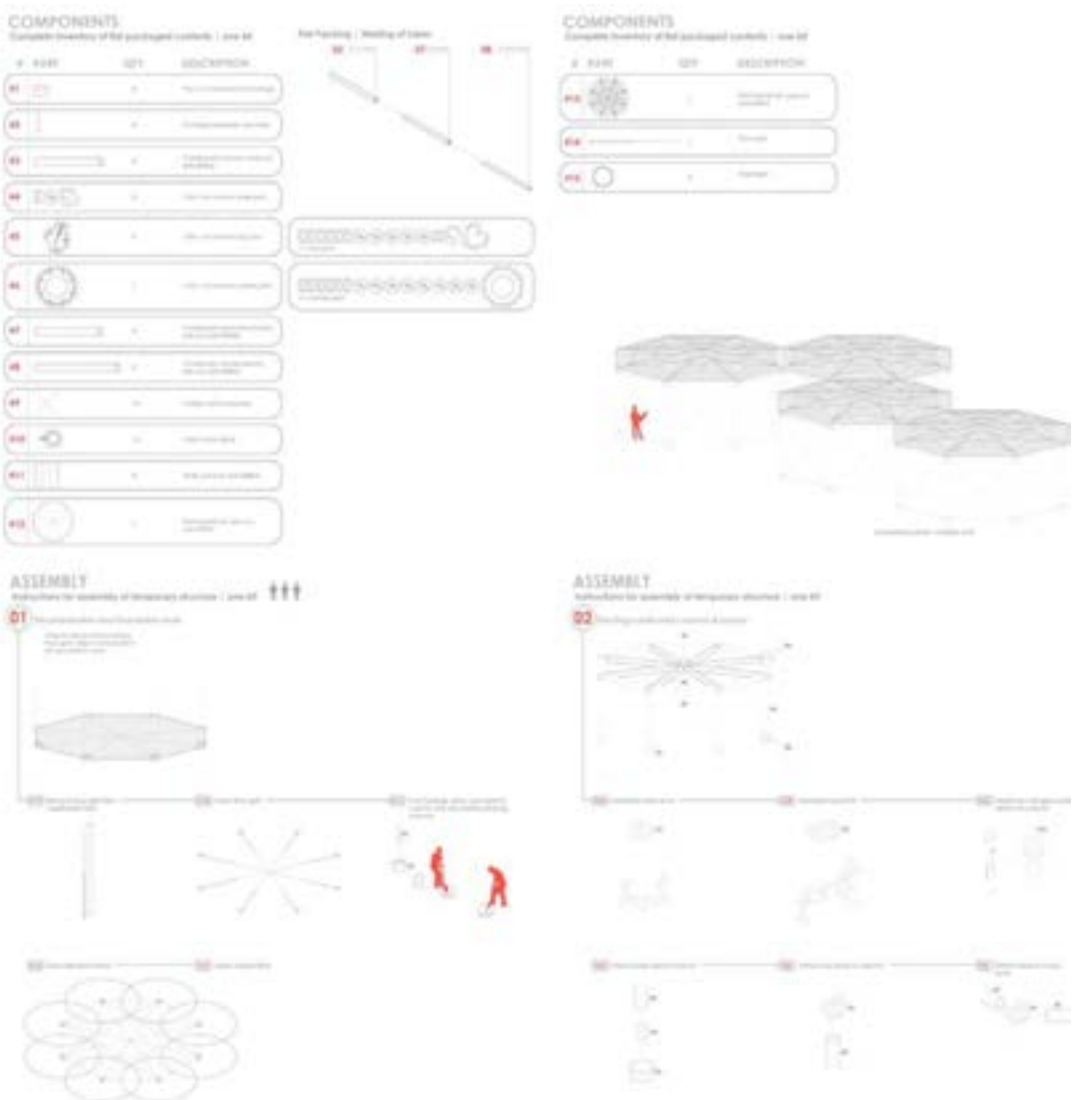

Figure 8: "Beyond Survival" Parts List and Assembly Diagram (Image by permission of author)

Figure 9: Interior render with construction system including mass-customizable joint, floor patterns guiding layout and pivoting partitions for adjustable social programs (Image by permission of author)

6 Discussion and Future Investigations

Work completed through the inaugural Collaborate design studio sought to explore the potential of open-source design in the context of the built environment design. More specifically, could precedent analysis and its subsequent use allow design iterations and their developmental to be primarily based on a performative agenda as opposed to visual? In this case, students were required to comprehend precedent on a level of organizational and systemic relations. Conversations on the visual always attempted to relate a visual condition to a performative outcome (ex. relationship of visual hierarchy to structural arrangement). These discussions always returned to what their impact was on the versioning of the design proposal and how it might be defined in a virtual environment or assembled in the factory/field.

Future work will focus in two areas that offer the most potential for refinement and development; toolsets and genotype base files. Each team will be coached more specifically on the role of collaboration in the conception of open-source design proposals. This requires the development of interpersonal skills as well as the purposeful and appropriate use of software packages which can both aid in the most efficient and timely communication and hold each of the team members accountable for tasks in the project development. High performing teams do not duplicate tasks and simultaneous work is supportive moving design ideation much quicker. Version 2 of the Collaborate design studio will partner with industry experts on the deployment and subsequent development of toolsets assisting in the communication and streamlining of information. Base files which are shared efficiently and developed collaboratively will help to vet solution sets and offer more potential for testing scenarios which might prove certain areas of the design to be less than feasible or viable. The studio-wide development of a parametrically-defined mass customizable, digitally fabricated, factory assembled chassis will serve as a vehicle to tighten up the process. This chassis will then allow individual teams in the studio to develop sub-systems (building skin, facades, interior partitions, program adaptability, etc.) which integrate into the framework and demonstrate the potential for customization.

In the end, refinement of the design proposal is only one of the core objectives. Focus also remains on the life of the genotype outside the bounds of the academic term as it generates phenotypes in future Collaborate studios as well as future studies of these emerging design professionals. The studio, titled Collaborate, is strategically positioned in the curriculum and is seen as a place to foster essential skills in the design professionals. These skills of teamwork and collaboration become very important as they move into graduate programs or the profession and are required to be a high-performing team member addressing challenging issues which face future generations.

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ZEMCH NETWORK

ANALYSIS AND VISUALIZATION OF THE NEW ARCHITECTURAL SPATIALITY: LIGHT AND SOUND TOPOLOGIES IN MUSEUMS

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Abstract: *This work aims at demonstrating that like geometry or anthropology, topology can offer the architectural space a new form of dimensioning and spatiality, this would amount to a participation of daylight and sound ambiences. We will explore this new spatiality in the architectural space and especially the museum space. The definitions of topology helped us to build a new analysis model based on the notions of 'route' and 'sequence'. To do this, a corpus of thirty international museums was submitted to analysis according to the model. Subsequently support by statistical analysis of the data collected for this corpus. It must be admitted that for the seen ambience, sequential analysis can alone define the luminous topologies and the use of the software will confirm them. However, for unseen ambiences, such as sound, the software is more than necessary to visualize and define sound topologies. This new way of interpreting the space and visualizing it topologically, by taking into account the sensory aspects, can allow us to reach an optimal conceptual model. One can also through these results develop software that can judge the architectural space designed topologically.*

Keywords: *Daylight, Sound, Topology, Discontinuities, Sequences, Route.*

1 Introduction

Architectural space has always been the center of the most relevant problems in architecture, its importance depends on the role that it plays in the comfort of the human being, by the success of its appropriation.

The definitions of architectural space refer to two main classical aspects, the first is the dimensional and formal aspect which depends on the geometry and the measurements, or to the form of space itself, which is solely geometric. The second refers to space as an anthropological entity as pointed out by Cousin (1980) where the human body defines the specialty through the relations maintained between the human body and space.

The drawing is the most replied geometric representation of space, especially if it is on a scale, and it obeys the Euclidean geometry. Drawing tools have expanded considerably, from hand-drawn to the computer-assisted drawing, or the computer assisted design.

Based very recently on the development of the theories of architectural ambiences, space has become subject of the relations between its qualitative and quantitative aspects, and it will be defined according to that (Lam 1986).

The objective of this new definition is to reconcile objectivity (physical element) and subjectivity (sensory element linked to the feeling of man). At present there is a tendency to present space with all its architectural-temporal references, thanks to software development. This representation of space is called visualization.

If we admit that the visualization allows the presentation of space, are there any other concepts that can link the geometry of space and its sensory component? The answer seems evident in recent geometry, more precisely the non-Euclidean .The topology that supports this new nascent reflection is by definition the continuous transformation within the same space.

Our work aims to use the notion of topology as a tool for defining and presenting architectural space, just like geometry. The topology may possibly offer a new spatiality based on discontinuities obtained by "sequential analysis". We will see later to what degree the visualization by software will participate in highlighting these luminous and sound topologies

1.1 The visualization of seen and unseen in the field of ambiences:

The visualization is widely used in the field of ambiences; it offers a representation of the architectural space very close and in line with reality, with an interest in the physical characteristics of space and the ambience as soon as it appears. It places the user of space always in the centre of all questions related to space (Siret and Wolonszyn 1998).

It should be noted that the ambiences differ; the seen (visual) ambiences (Millet 1996), in particular the luminous, are easier to detect and to evaluate than the invisible or unseen ambiences such as sound, olfactory or thermal. They provide information related to the existence of the physical signal, and the evaluation criteria depend on the user and his / her way of qualifying the space. However, all these unseen ambiences are simulated; this will confirm or affirm the comments of the users.

We will take in these paper two scenarios, the luminous and sonorous ambiences which, according to Bonnet (2005), are similar natures. However, the behaviour of the objects

that exist in the architectural space is not the same as the two waves? We note that the light reflection is made just by the effect of mirrors. While the sound wave is reflected by all objects in space.

Bonnet (2005) argues that our perceptions of sound and light are different: hearing and visual organs handle information differently. In particular, the eye comprises the crystalline lens, which enables it to form an image on the retina, while the ear does not have this organ. Moreover, when the information coming from our sight and that from our hearing are in conflict, those from our sight tend to dominate. For the analysis of daylight or sound ambiences, many tools are used. Simulation will remain the most practiced method for its effectiveness in evaluating and visualizing the ambience (Herde and Reiter 2004).

In front of this very varied palette of visualization types, we note that the latter is only the result of an analysis chosen by the researcher, and defines in advance in the methodology. In our case, we must explore the notion of topology so that we can define the new method of analysis to be adopted.

1.2 Topology as tools of spatiality:

The topology is ancient in architecture, its appearance dates back to the last century as a response to the urban problem of the seven Königsberg bridges (Sossinsky 1999). It should be noted that no topological theory specific to architecture had been formulated until then. The essays of definitions that exist are expressed by architects from two angles; the first is that of theorists, and the second is adapted by the practitioners who in both cases revert to mathematics. Topology in this case is a simple solution to the architectural problems (Guiseppa 2001).

After seeing through the various definitions of the topology, it has been concluded that it is defined as the act of displacement over a period of time. The dynamic movement of the body crosses the duration, creating points, successively, All along the route. This point once created constitutes an event (Fig. 1).

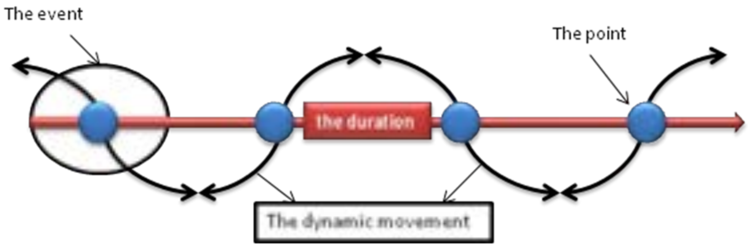


Figure 1: Synthesis of the topology definition

In order to verify this definition in architectural space, It will be necessary that there is a route, So that the duration of the walk can be determined, to arrive at the series of events which are in our case events seen (luminous) and unseen (sound), these events will highlight the primordial element of the Visualization that is the sequence.

1.3 The museum route a sensory composition:

The choice had been made on the museum, the concept of route and promenade are highlighted at the design stage of the project. The visitor of the museum contemplated the beauty of the places and the exhibited works, guided by the daylight of the interior

spaces and by the sound composition of the visit. This complementarity is important for the success of the exhibition.
The route varies according to the architect's primary intention, and can also be a result or a constraint that is imposed from the beginning of the design. For this reason we find different types of routes in architectural works all classified according to several criteria. The important aspect in this study is the morphological elements of space, and according to the form we note three types of route (Mariani, R, 2000). : The "linear", the "labyrinth", the "centered".
There are also three types of routes linked to the three levels of exposure according to Jean Davallon:
• The route planned before the exhibition is mounted.
• The proposed route (s): the possible route (s) actually offered to the visitors.
• The lived route: the route chosen by the visitors. (Thibaud 2001)
In the case of our research, we focused on the route lived.

2 Methodology and case studies:

2.1 Sequential analysis:

If we refer to the definition of the topology already mentioned in the topology part as a tool of spatiality, comparing it with the characteristic of the museum route, we can admit that the duration is no more than the visiting time of the whole route; the momentary encounter between the visitor and the ambience constitutes an event (Fig. 2) that can be luminous or sonorous.

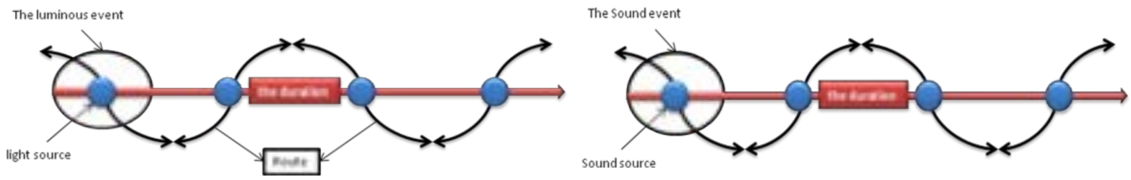


Figure 2: Definition of the sequential analysis for the daylight and sound ambience following the museum route

2.1.1 The construction of the analysis model to be simulated:

For each case study, you must have in addition to the graphic folder all the textual references, photos, analyzes or criticisms already made

2.1.1.1 The The 3D modelling:

It is about reproducing the model of the museum in drawing software, in the details in 3D with the same characteristics of the materials.
We also opted for the use of the technique of the layers to reproduce the following elements:
• The museum route
• The source: in the case of the luminous ambience, the axes of the bays are determined by the red color, in the case of the ambient sound, the location of the sound source which will represent the position of the visiting guide.
• The sequences: for the luminous sequence it is defined by the portion that is marked by the axis of a bay in the wall and whose boundaries are in the vicinity of the axes, of the same route, located halfway between the bays of the sequence in question. And for sound, the portion of the architectural space that is part of a route, identified by the existence of a sound source that is situated at a human height.
Modeling will allow us to describe the sequences for the luminous ambience well before the simulation, for the sound ambience we must first simulate to obtain the

characteristics of each sequences, it should be noted that the criteria of the sequences are distributed as follows in Table 1:

Table 1: Description criteria used to analyze sequences

daylight Ambience		Sound Ambience	
Conformation	**Bay**	**Conformation**	**Sound**
Materials, morphology	The type of lighting The orientation, the position, the tilt, the form, the size, The glazing, the percentage, The additional glazing.	The geometry of the shape, The materials.	The sound source The intensity, The Frequency, The direction, The orientation,
			The characteristics of the diffusion sound wave
			The reflection , The refraction, The Absorption, The diffraction,
			The characteristics of the transmission sound wave
			The Direct transmission, The lateral transmission, The Spurious transmission.
			The characteristics of the sounds according to the surfaces of incidences
			The direct sound The useful sound: reflected, The sound borders, The echo, The reverberation The masked sound

It was noted that each type of ambiences had been analyzed separately.

2.1.1.2 The simulation:

The role of simulation for this work is to be able to visualize the topologies so that they can be qualified. We can for the luminous the ambience stop at the phase of the description of the sequence; the simulation of the luminous topologies will be done by exporting the model of Ecotect v5 to radiance and are role is optional, it will be used just to confirm Discontinuities.

The role of simulation for this work is to be able to visualize the topologies so that they can be qualified. We can for the luminous ambience stop at the phase of the description of the sequence; the simulation of the luminous topologies will be done by exporting the model of Ecotect v5 to radiance and its role is optional, it will only be used to confirm discontinuities.

In the case of the sound ambience Ecotect v5 software will be used, which will allow us to visualize the sound sequences by simulating them. This phase is more than necessary to be able to describe the sequence.

2.1.1.3 Application example:

The Museum Beyler Riehen (Renzo Piano between 1994 and 1997)

2.1.1.4 For the luminous ambience:

a) Step of the sequential analysis:

We took the plans of each level of the museum separately. A layer is superimposed on each plane, and the lived route is drawn with a blue line (Fig. 3).

On another layer and with the color red (Fig. 3), we place and draw the axes of the zenith and lateral bays. We refer to the various graphic parts illustrating the project, including cuts.
We then determine the axes midway between the axes of the bays, the new axes determine the sequences (Fig. 4), which will be named by the letter S and the number that locates the sequence in the route.
For each of the sequences, the descriptor criteria are introduced into a table which serves as a database, including all the variables relating to the route, the space and the bay, which will be called a descriptor of the luminous sequences, By a statistical analysis.

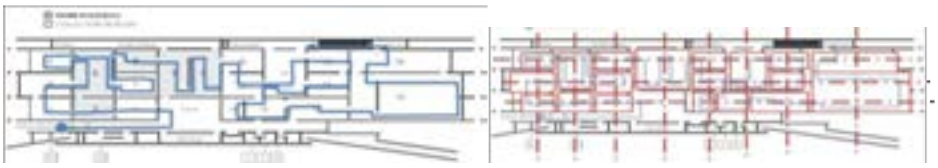


Figure 3: Illustration of the trajectory of the route and the positioning of the axes of the bays

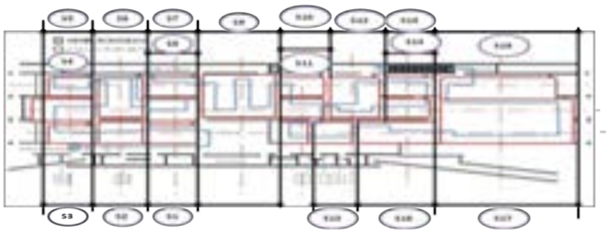
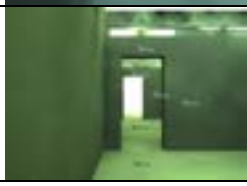


Figure 4: Illustration of the sequence drawing.

b) Steps of confirmation of the topologies by simulation:
Once the 3D model is ready (Fig. 5), we make the necessary settings on Ecotect v5, we define the cameras and export under radiance. To get the visualization. We take the hour of visiting the highest visit and we simulated to check the luminous topologies through the seasons. The most critical parts of the route are subsequently taken (Table 2), 05 sequences are defined with their three points of luminance measurement, in this order: the floor, the wall and the ceiling, the curves for the variation of the amounts of light in the sequences are then drawn.

Figure 5: The 3D model of the Beyler Rhein under ecotect v5

Table 2: Simulation of the discontinuities in the luminous sequences case of Beyler Rhein Museum.

Time of attendance 13H	Discontinuities of Space	Continuities of the conformation and the bay	Discontinuities of the shape of the bay	Discontinuities of the shape and type of the bay
Mi saison				
winter				
summer				

2.1.1.3.2. For the sound ambience:

Step of the sequential analysis and simulation:

The plans of each level of the museum were taken separately. A layer is superimposed on each plane, and the route is drawn with a blue line. The modeling is carried out on Ecotect v5 with the different settings. And the sound sources are assigned their positions and heights (Fig. 6).

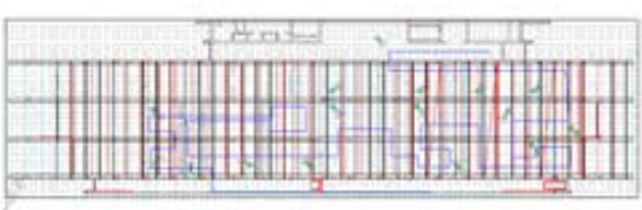
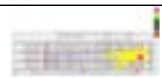


Figure 6: Illustration of the sequential analysis of the sound ambience

The sound sequences are then simulated as a function of the sources in order to obtain the sound discontinuities. For each of the sequences, the descriptor criteria are introduced into a table which serves as a database as Table 3, including all the variables. Called a descriptor of sound sequences

Table 3: simulated sound sequences

Sequence	S01	S02	S03	S04	S05
Result					
Sequence	S06	S07	S08	S09	S10
Result					
Sequence	S011	S12	S13	S14	S15
Result					

The methodological principle of all the work is summarized in this diagram (Fig 07).

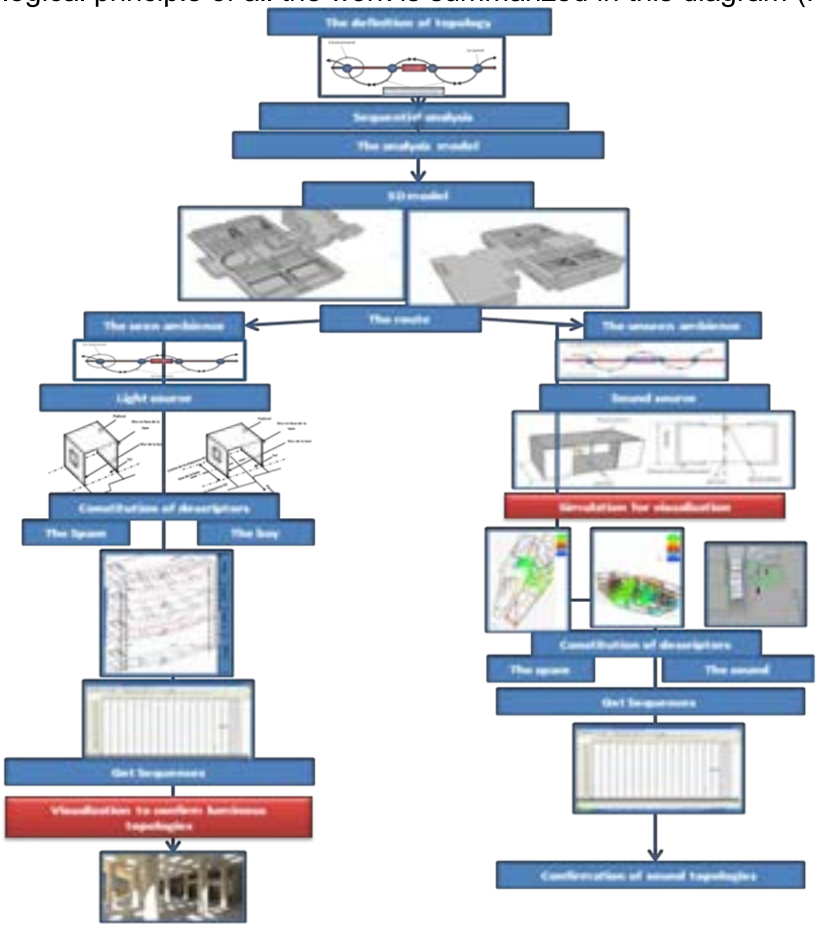


Figure 7: The methodological principle

2.2 The study corpus

There is therefore a multiplicity of museums, of our era that fulfils this function. The designs are varied, shapes, colors, functions, adding to it the type of exposure.

Our study will select museums that meet a number of criteria: (i) the historical period, (ii) the intention to design the architectural work with the daylight we call "luminous intent", (iii) the Quantity of information available to us (speech, textual, graphics, images ...). And the study corpus will include thirty European museums (Table 4).

The justification for this choice in relation to the sound ambience is at the level of the first criterion of selection, the museums that were chosen were all designed between 1980 and 2008, and this period is characterized by the influence of Museography based on sound, on the design and realization of museums (Meyer, 2013). In this research we will only take, the sound sources called human in the natural state.

Table 4: Museums in the study corpus

N°	Museums	Architect	Year
	France		
01	Departmental Museum of Prehistory	Roland Simounet	1981
02	Museum of Fine Arts of Grenoble	Olivier Félix-Faure, Antoine Félix-Faure et Philippe Macary Lorenzo Piqueras	1990-1994
03	National Museum of Tayac	Jean-Pierre Buffi	1994-2004
04	Museum of the quay of Branly	Jean Nouvel	2006
05	Museum of Natural History	Paul Chemetov et Borja huidobro	1991-1994
06	Museum of the quay of Branly (competition)	Rudy Ricciotti	1994
	Germany		
07	Museum of SAMMLUNG GOETZ Munich	Jacques Herzog et Pierre de Meuron	1989-1992
08	Humbuguer Bahenhof museum ,fur Gegenwart	Josef Paul Kleihues	1988
09	Vitra design museum	Frank Gehry	1988-1989
10	Berlin Jewish Museum	Daniel Libeskind	1999
	Spain		
11	Guggenheim Museum Bilbao	Frank Gehry	1993
12	Centro Gallego de Arte contemporaneo	Alvaro Siza	1994
13	Hydraulic museum	Juan Navarro Baldeweg	1989- 1992
14	Museum of Maritime Archeology CARTAGENA	Alberto campo baeza	1998
	Switzerland		
15	Jean Tinguely Museum	Mario Botta	1993-1996
16	Museum of Swiss Ethnography	Hanger, Monnerat, Petitpierre	1995
17	Beyeler Riehen Museum	Renzo Piano	1998
	Austria		
18	Historical Museum of Salzburg	Hans Hollein	1989-1990
19	KUNSTHAUS BREGENZ museum	Peter Zumthor	1990-1997
	Great Britain		
20	American air museum Duxford	Foster partners	1993-1997
	Italy		
21	Museum DE MAXXI	Zaha Hadid	2007
22	Ara Pacis museum	Richard Meier & Partners	1995-2006
	Netherlands		
23	Bonnefanten museum,Maastricht	Aldo Rossi	1990-1994
24	KUNSTHAL museum, Rotterdam	Rem Koolhaas	1987-1992
	Belgium		
25	The Hergé Museum	Portzamparc Christian	2006
	Finland		
26	Museum Nykytaiteen Kiasma, Helsinki.	Steven Holl	1993-1998

Sweden			
27	The Museum of Modern Art and Architecture Stockholm	Rafael Moneo	1990-1997
Denmark			
28	North Jutland Art museum, Alborg	Elissa and Alvar Aalto	1998
Greece			
29	Museum of the Acropolis Athens	Bernard Tschumi	2007
Norway			
30	Aukrustsentret museum, Alvdal	Sverre Fehn	1993-1996

3 Results and discussion

3.1 Results of the sequential analysis for the discontinuities of the luminous ambience

The notion of discontinuity, as defined above, is directly related to the continuous transformations that affect the characteristics of the luminous ambience along a route. The sequential analysis made it possible to highlight the discontinuities that exist in our corpus of study (Saraoui and Belakehal 2011). The term "major discontinuities" refers to those that are encountered in a percentage greater than or equal to 50% within the corpus.

There are also a number of existing discontinuities (Table 5), or small discontinuities, that are referred to as minor discontinuities. This is the set of discontinuities that characterize space, namely conformation, in our study corpus.

We observed a single discontinuity of wall morphology with a frequency rate of 17%. The rest of the discontinuities in the characteristics of the wall are absent. In what follows we will highlight only the major and average discontinuities.

Table 5: Summary of light discontinuities

Light topology	major		average		Minor	
	The orientation discontinuity	85%	The discontinuity of the position of the bay	40%	The discontinuity of the shape of the bay	20%
	The discontinuity of the lighting type	80%	The discontinuity of the proportion of the bay	43%	The discontinuity of the inclination of the wall	17%
	The discontinuity of the size of the bay	63%				

3.1.1 The discontinuity of orientation

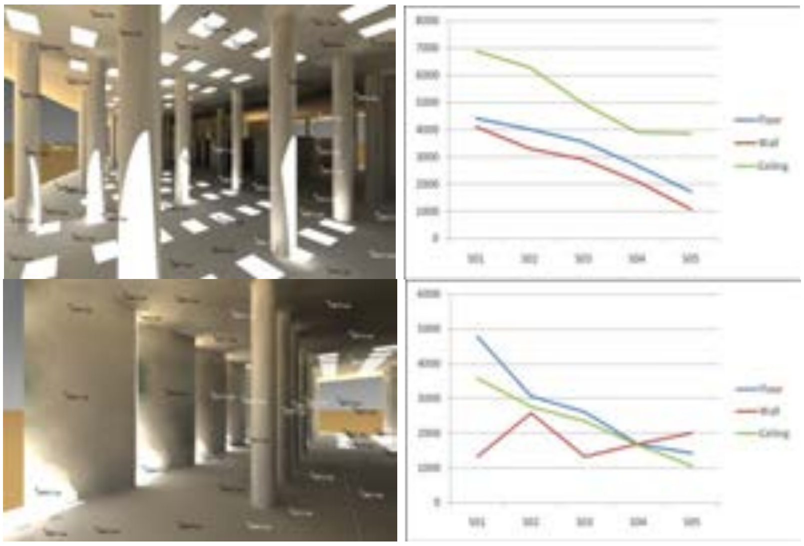


Figure 8: Visualization of the discontinuities of orientation cases of the Museum of Athens

The orientation discontinuity corresponds to the set of orientation variation of the bay along the existing route.
In the museum of Athens (Fig. 8), for example, the route is of a linear type. This makes it stable. If we take the first graph we see that the curves are perfectly parallel and decreasing varies between 7000 and 2000lux for the west orientation, this revises to a stability of the sequences with a distance of the bay.

For the second graph the curves are between 1000 and 5000 lux, they tend to part, then approach and finally intersect. For the first three sequences we have just the west orientation, the variation of the illuminance is due to the spatial component, When approaching sequence 04 the influence of the north orientation begins that justifies the darkening of the floor and the ceiling.

3.1.2 the discontinuity of lighting type

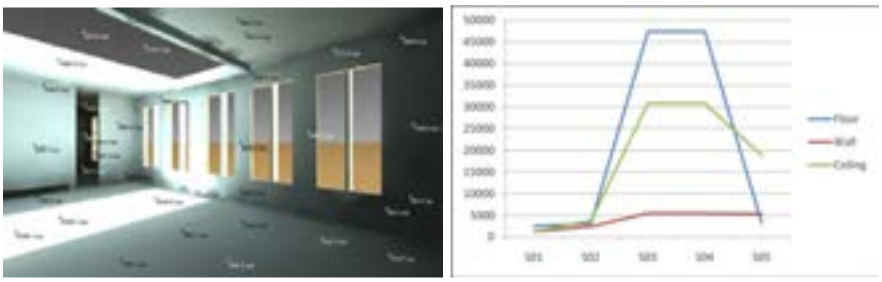


Figure 9: Visualization of discontinuities of illumination type case of the Spain Hydraulic Museum

The second discontinuity observed is that of the type of lighting. In the same route a bay can be in a horizontal or vertical position.

The example of the hydraulic museum in Spain confirms this, we note in the graph that for a stable lateral illumination (Fig. 9), the sequences 01 and 02 have the same interval 0 to 5000lux, As soon as there is influence of the zenithal lighting; the interval becomes wider, only the wall will retain these characteristics.

3.1.3 The discontinuity of the shape of the bay

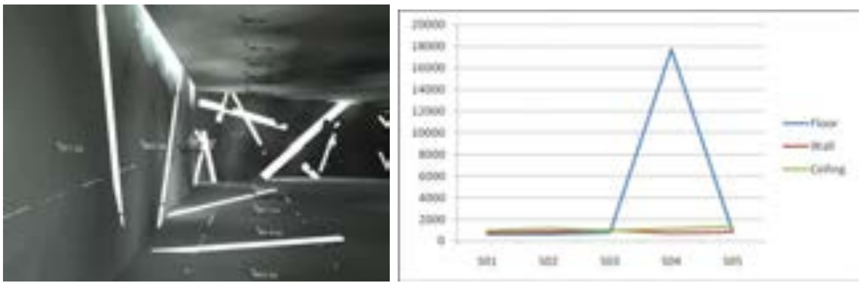


Figure 10: Visualization of discontinuities of type of illumination case of the Jewish Museum in Berlin

The shape of the bay can cause a number of sequential variations in the route. This variation in form appears through a partial or complete change of form. This is confirmed in the Jewish Museum in Berlin (Fig. 10), on the same route, sequences 01 02 03 have practically the same illuminance distributions from 0 to 2000 lux, and the shape of the bay is stable. From the sequence 03 the curve of the ground increases this is due to the change of the shape of the bay.

3.1.4 The discontinuity of the proportion of the bay

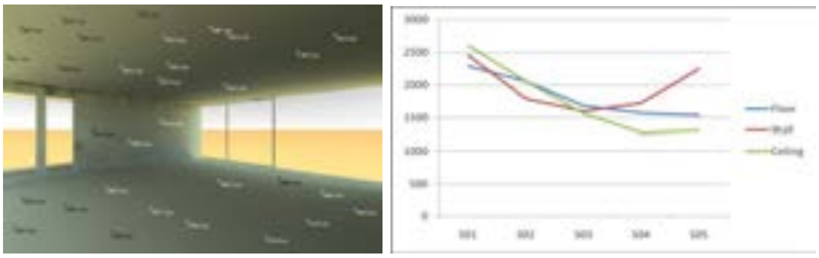
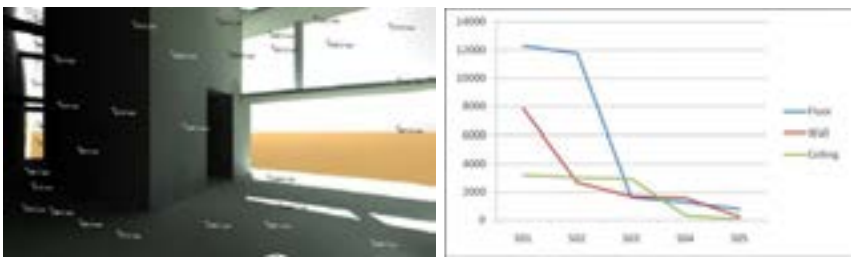


Figure 11: Visualization of discontinuities of the proportion case of the SAMMLUNG GOETZ Munich

A bay can occupy a large or a small area of the wall. Transformation in the dimensions of the bay can also be varied in the route.
This is confirmed in the SAMMLUNG GOETZ, or on one part of the route the bay occupies the whole wall, and in the other one third, if we observe the curves, we observe an interval of 1000 to 2500 lux (Fig. 11), no sequence resembles the other.

3.1.5 The discontinuity of the size of the bay



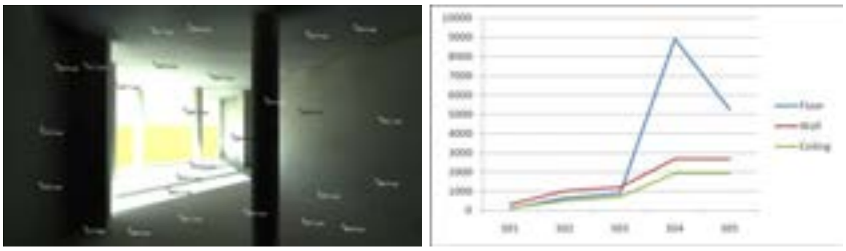


Figure 12: Visualization of the discontinuities of the size of the bay case in Museum Hergé

The size of the bay can also vary in a large number of sequences. In the case of the Hergé museum, at the level of the ground floor there are discontinuities of the size of the bay, which generates a graph with varied sequences (Fig. 12). On the other hand, it is noted in the graph that the sequences 01, 02, 03 are stable, and this is due to the absence of bay, for the change of the quantities of light afterwards.

3.1.6 The discontinuity of the position of the bay:

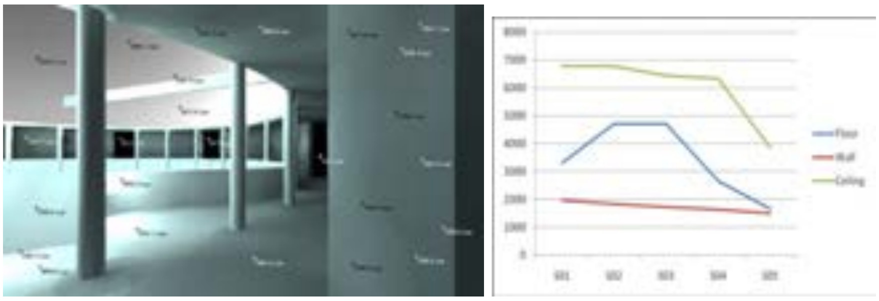


Figure 13: Visualization of the discontinuities of the bay position case of the Historical Museum of Salzburg

The position of the bay in the wall can also vary, because in the same route, one passes from one low window, to another high.

In the Historical Museum of Salzburg (Fig. 13) for side-skylight lighting the curves are stable in the same interval, and the ceiling is the most illuminated element. The stability between the sequence 2 and 3 is due to the existence of a zenith opening.

3.2 Sound topologies and their visualizations

Concerning sound, continuous transformations characterize very essentially the variations of the characteristics of the sound ambience throughout the museum route. A total of 506 sound sequences were obtained and the discontinuity rates are shown in the table 06 as follows:

Table 06: Summary of sound discontinuities

Sound topology	Major		Average		Minor	
	The orientation discontinuity	43%	The Discontinuity of Refraction	43%	The discontinuity of Diffraction	13%
	The Discontinuity of Direction	73%	The Discontinuity of Direct Sound	53%	The discontinuity of Parasitic Transmission	27%
	The Reverberation discontinuity	77%	The Discontinuity of sound borders	43%	The discontinuity of Echo	20%
	The useful Sound Discontinuity	57%			The discontinuity of Masked Sound	30%

3.3 Results of the sequential analysis for the discontinuities of the sonorous ambience

3.3.1 The discontinuities of orientation

The orientation discontinuities are linked to the change in orientation of the sound source along the entire museum route. The sound source will therefore retain the same characteristics, but the sound ambience will vary according to the physical characteristics of the museum space. We can cite the Hergé Museum (Fig. 14), or the sound sources do not follow the same direction. This generates sound topologies of orientation.

Figure 14: Sound discontinuities in orientation Hergé Museum

3.3.2 The discontinuities of direction:

The sound discontinuities of direction are much related to the route, it is observed if the direction of the sound source does not follow that of the route.
The directional discontinuities vary throughout the route, in some cases the direction of the sources follows that of the route as in the case of the SAMMLUNG Museum GOETZ Munich, and in others it is not that of the route as the case of the Nykytaiteen Kiasma Museum, Helsinki (Fig. 15).

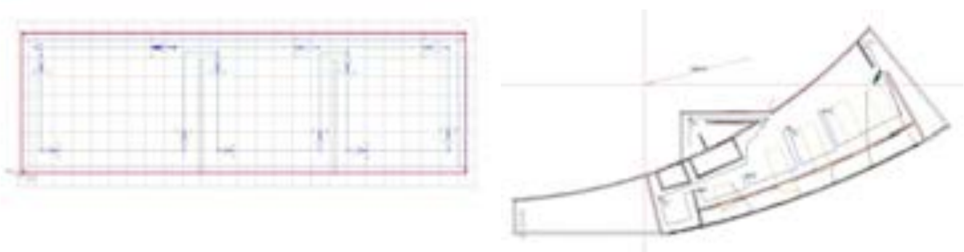


Figure 15: the discontinuities of the direction

3.3.3 The discontinuities of the reverberation:

Reverberation discontinuities are related to the existence of several sound reflections within the same sequence, which are variable from one sequence to another.

For example the North Jutland Art Museum, where reverberation is presents in some sequences, absent in others, and even when it is present it is variable, it is average in sequence 02, and is Low in sequence 08 (Fig. 16).

Sequence 02 **Sequence 08**

Figures 16: Sound discontinuities of the reverberation of the North Jutland Art museum Alborg

3.3.4 The discontinuities of its useful (reflected):

The sound reflected is the sound useful in the study of the sound wave, its visualization by the software makes it possible to detect the impact of the sound wave and the limits of the sound wave in space. The discontinuities of the useful sound make it possible to bring out the limits of sound reflection.

In some cases the wave of the useful sound respects the geometrical form of space, which was found at the Nykytaiteen Kiasma Museum, Helsinki (Fig. 17). In other cases, such as the Jewish Museum in Berlin, it goes beyond the boundary of the simulated sequence to the outside or the neighboring sequence (Fig. 17).

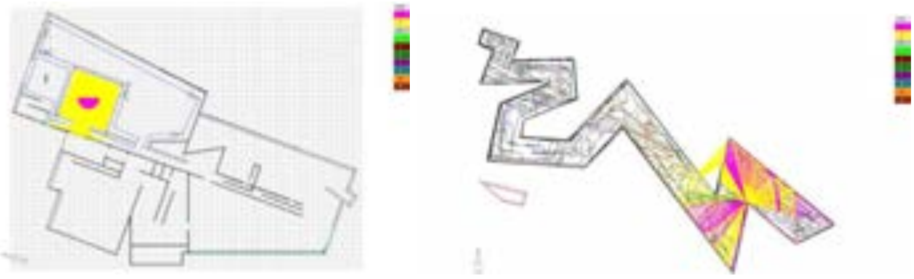


Figure 17: Useful sound discontinuities, Nykytaiteen Kiasma Museum, Helsinki and Jewish Museum

3.3.5 The discontinuities of refraction

The discontinuity of refraction characterizes the composition of the walls of the sequence; it appears when the sound waves which characterize the sequence undergo a change of angle as they pass through the walls thus changing direction.
This break can be at the level of the outer walls as in the case of the Guggenheim Museum Bilbao, or at the level of the inner walls as in the Ara Pacis museum (Fig. 18).

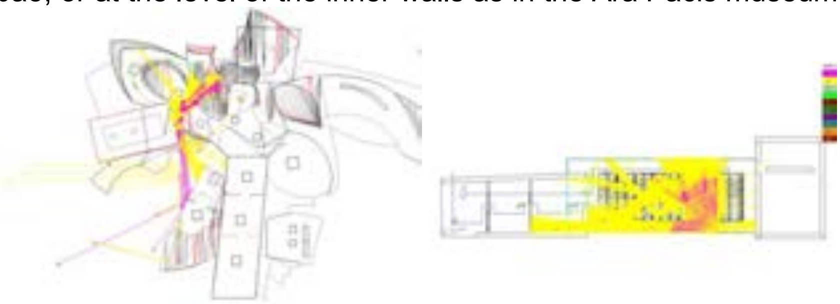


Figure 18: the external and internal refraction discontinuities

3.3.6 The discontinuities of the direct sound

Direct sound discontinuities are linked to the existence of an obstacle or sound modifying element that prevents the direct wave from passing from the transmitter (guide) to the receiver (visitor). The sound discontinuities related to the direct sound vary according to its intensity each sequence and another; we can cite the case of the historical museum of Salzburg, where the direct sound is strong in most sequences. Museum of Acropolis Athens, where it is medium. and the Museum of Modern Art and Architecture Stokholm, where it is very weak (Fig. 19).

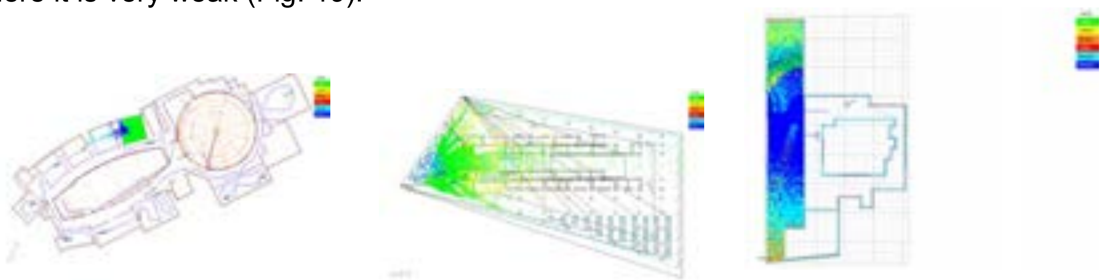


Figure 19: Direct sound discontinuities

3.3.7 The discontinuities of the sound frontier

The discontinuities of sound borders are linked to the existence of the limits of the audibility zone. It is the places in the conformation or the sound is above or below the audible limits. We will cite the Museum of the quay of Branly (Fig. 20) where there are no sound borders and the hydraulic museum where it is present in Sequence 11.

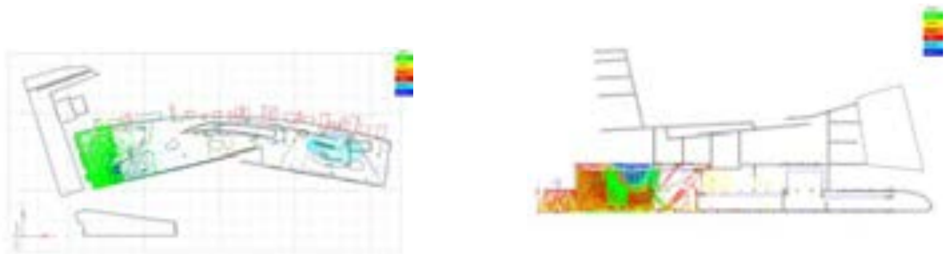


Figure 20: The discontinuities of the sound borders

4. Conclusion

The visualization in architecture remains one of the tools that allow the representation of architectural space. The development of technology has accelerated the use of visualization especially if it is consistent with reality.

The architectural space will remain a very ambiguous element for all those who have tried to define it, At present, defining tests all tend to be based on the axis of the ambiences, where the subjective and the objective are reconciled.

We have observed from the beginning of our research that topology is a notion very much related to space and used by architects. And that despite the existence of this notion in architectural thought, its definition still remains non-existent, and always refers to mathematics.

We then compared the existing definitions of topology given by architects, to be able to give it our own definition. Our definition concluded that it had connected between the act of displacement on a route and the creation of the sequence.

Based on the concept of the route, the choice was made on museums, where this concept is the key element in the success of design and exhibition after. To do this, thirty international museums chosen according to selection criteria were analyzed by the technique of sequential analysis.

This allowed us to detect a great difference between the analysis of the perceived ambiences such as the luminous ambience and the unseen ambiences such as the sonorous ambience, despite the similarities that can qualify the physical characteristics of the two types of wave ,Visualization is more than necessary in the analysis phase for unseen ambiences, whereas for the viewing ambiences it complements and supports the results obtained by the analysis which is in our case a sequential analysis based on sequence.

The visualization makes it possible in both cases to materialize the sequences of the ambient topology. This implies that the topology can generate new spatiality within the architectural space.

The field of the research will remain open, since the results obtained concerning the sequences can be exported in the field of computer programming in order to create an interface which makes it possible to evaluate the topological sequences of the ambiences while visualizing them.

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ZEMCH NETWORK

BEHAVIOUR CHANGE VIA SOCIAL SANCTIONS AND SHARED ELECTRICITY

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Abstract: *Applying behaviour change methods to reduce home energy consumption has resulted in varying outcomes and also conservation effects that were short-lived. Some of the more promising treatments included In Home Energy Displays (IHDs) and home energy bills with comparisons to unknown others (Schultz, Nolan, Cialdini, Goldstein, & Griskevicius, 2007) - for individual homes. In contrast, so-called collective "energy communities" reduce individual energy consumption (Bauwens & Eyre, 2017) and report other benefits such as group cohesion and community building. A question arises as to whether conservation norms would emerge in ad-hoc urban groups if they we able to co-own and operate a Distributed Renewable Energy (DRE) asset. Secondly, can an economical DRE size for a small group be arrived at via demand aggregation and conservation together? The aim of this paper is to propose a methodology that will test this hypothesis. The approach is to deploy an IHD to display home energy consumption against the fictitious electricity available from a shared solar and battery system, as if it were installed. The IHD will also prompt group members among 6 neighbours to sanction or reward specific (but not identified) group members based on how they use the "shared energy". A multiple baseline approach will be used and correlation of time series (energy consumption against user actions on the IHD) will be performed in R. We expect to observe a sustainable reduction in overall energy due to the effect of an IHD on occupant behaviour. The outcome of the study will help the community to scale the solar and battery storage combination that works best for them based on their usage and their willingness to invest and participate. The proposed system could provide an optimum net zero energy district tailored for the community based on the local parameters and their behaviour.*

Keywords: *Electricity conservation, Applied Behaviour Analysis, Home Energy Display, Group Dynamics, Net Zero Energy Community*

1 Introduction

Tackling the problem of greenhouse gas emissions in Australia should require concerted effort to curb electricity demand since electricity generation is a very large emitter. However, energy efficiency measures which save consumers money may result in savings being spent on energy-derived goods and services in the greater economy. Approaches to this complex problem require more than single interventions. The current study proposes testing a both a technical means to make home solar and battery systems more efficient and cost-effective along with a behaviour change mechanism to suppress demand.

Home solar electricity generation, particularly with energy storage batteries is expected to be a large contributor to Australia's energy system - up to 50% of all electricity (Brinsmead, Graham, & Qiu, 2017). At present the average home solar system supplies about 30% of electricity for the home. A correctly sized battery could double this rate of self-consumption. At present, battery cost and lifespan are serious constraints to broad residential adoption and it has previously been stated that battery cost would have to fall to about a tenth of the current value for there to be widespread domestic adoption as there has been for solar panels (Palmer, 2014). Since 2014, retail electricity prices have nearly doubled and battery costs have almost halved but this does not yet meet Palmer's criteria. Even when they are met, it will take more time again for the formation of a critical mass of home storage large enough to significantly offset centralised generation at any time of day or night.

There are possibly many ways to increase battery uptake, and subsequent grid independence and emissions reductions. For a single home, simply reducing demand would mean that a smaller (cheaper) battery could provide acceptable energy independence to the household. Home energy batteries are typically used to charge from solar energy and discharge to reduce the evening peak demand (which is aligned with peak tariffs in many Australian states). Moving loads (such as clothes drying or ironing) to draw on the system during the day when available solar energy is at its peak will thus reduce the evening energy demand and the battery capacity needed. This is called "load shifting" and is already an anticipated behaviour change to accompany new demand-based tariffs being deployed in Australia to reduce stress on the electricity system. With renewable generation this is even more desirable because peak supply also varies (see for example peak consumption controls on the Isle of Eigg in Scotland (Gardiner, 2017).

Behaviour change is considered a fast and inexpensive means to reduce emissions, potentially more economical than any new technology (Kelly, 2010). Load shifting will join a long list of government stimulated consumption behaviours including energy efficient purchasing, use of devices that sleep, turning off lights, turning down thermostats and many building insulation and envelope changes. However, despite many campaigns for energy efficiency to reduce energy demand, along with a carbon price, closures of large industry consumers in Australia, and a very high electricity price, demand has grown with population and is predicted to keep growing to 2050 (Brinsmead et al., 2017; BREE, 2014).

Home electricity demand accounts for more than 28% of national electricity consumption (BREE, 2012) and households consume more secondary energy (via the products and services consumed) than any other sector (ABS, 2011). However, home occupants tend to consistently underestimate the consumption of devices (Attari, DeKay, Davidson, & Bruine de Bruin, 2010) and indeed consumption itself is felt to be price inelastic (Hobman, Frederiks, Stenner, & Meikle, 2015). It seems that consumers are unable to reduce their demand, even when residential electricity in Australia is the most expensive in the world.

However, the UNDP (2004) identifies examples of other countries which have high living standards (via its Human Development Index) that consume less than half of the energy of Australian households. In addition, a number of organisations promoting "zero carbon" rely on reducing electricity demand, usually by at least 50% (Ison & Lyons, 2013; Wright & Hearps, 2011). Finally, due to the use of brown coal in electricity generation, most Victorians (home to a quarter of Australia's population) are not aware that they are the worst per-capita emitters of CO2 in the world. Home energy consumption in Australia is thus an important and a potentially fruitful target for redoubled conservation efforts.

To this end, there is a broad literature base around feedback to home occupants on their energy use. The details of this inform our experimental design below but it is sobering to consider that in reviews of up to 194 studies (Abrahamse, Steg, Vlek, & Rothengatter, 2005; Delmas, Fischlein, & Asensio, 2013) many have reported highly varying results, with methodological problems or observed short lived outcomes and even increased consumption during conservation programmes. It is likely that home energy conservation is difficult and that changed behaviours are hard to validate.

Setting up potential strangers to share electricity of course raises many questions concerning technical design, privacy, governance and many others which we attempt to address but the benefits may be substantial for consumers, the environment and also the utilities. The next section expands on our literature findings. This is followed by a methodology section explaining the experimental design. A conclusions section discusses implications and provides suggestions for future research.

2 Energy use, feedback and social mechanisms

Successful behaviour change in home electricity consumption has taken two main forms. Since electricity is measured in at least two units (confusingly kWh and kW or "energy" and "power") it can be difficult to quantify consumption for specific appliances (rated in Watts or Amps). A home display than can report electricity consumption along with actual costs makes it easier for consumers to understand the final bill and also to isolate devices consuming large amounts of electricity. Studies of these devices began around 1980. With each solar panel installation in Australia, an IHD showing solar productivity has also been installed and so the homeowner has information to hand concerning both their consumption and the availability of solar energy they can consume for free. These devices have been typically information-only with no normative cues such as an assessment of how well the household has performed.

2.1 Feedback and norms

A friendly assessment of household conservation (or high consumption) was first reported as beneficial for conservation by (Schultz et al., 2007) when home energy bills were accompanied by a hand-written comment and an "emoticon" to clearly indicate

good, bad or average performance relative to other houses in the study. Relative reporting, as it is called, has resulted in sustained electricity conservation of 2.5-7% (Allcott, 2011) and has been a legal requirement for home energy bills in Australia since 2013 (AER, 2017). In this form of customisation the comparisons to others include examples like “average of 100 homes near you”, “similar others”, “conserving others” but the others are not known or identified in any way. It has also been reported that when a low-consuming home is shown to be below “others”, their consumption is likely to increase. Comparison to others establishes a norm, which the consumer then moves to conform to.

Social norms are even more effective when energy consumption is compared among known others, for example a small study in Sydney installed energy reporting placards on the facades of 6 houses in a busy street (Moere et al., 2011) which was reported to cause a competitive game to emerge as to who could consume less. This went further to a form of cheating where loads were shifted to known consumption reporting gaps. In a related study at the University of California Los Angeles, residential students were given energy saving advice but also had their consumption reported against their names on a bulletin board (Delmas & Lessem, 2014). The energy advice led to reduced consumption but the public reporting had a much greater effect which persisted. A preliminary study combining real-time consumption (a phone-based IHD) with comparative information about one’s consenting social network connections finally connects IHD information with relative reporting (Petkov, Medland, & Krcmar, 2011) like the Sydney study, finding people fell into competition to conserve but preferred only to compete with people they knew.

These effects are due to social norms but the interventions are aimed at the individual or individual home with normative effects only as the antecedent. Treating the group as the consumer (the utility framing the challenge as a “community challenge”) was found to be effective in home water conservation in the face of the Victorian drought of 2001-09 (Liubinas & Harrison, 2012) but this was not compared to historic water conservation programmes. A tendency for people to group together in times of civil or environmental stresses is well documented in history (for example, see Victory gardens for food (USDA, 2015) as well as post-soviet Cuba’s response to supply crises (Quinn, 2006)). Appealing further to group effects in energy consumption, particularly groups of people who know each other, should lead to greater conservation. However, without a WWII or other crisis, what can bind the group together has not been explored.

2.2 Conservation and community

Self-selecting groups already form large “energy communities” which may share a common Distributed Renewable Energy system (DRE) such as windmills, or an entire off-grid energy system, but such groups may also be concerned with lobbying, supply-side changes and energy efficiency (Ison, 2017). Energy collectives are more common in Europe where not-for-profit retailers have been established for distributing renewable energy - but such communities have been found to attract more large consumers who have the most to gain from conservation campaigns within the collective (Bauwens & Eyre, 2017). Nonetheless such groups in Victoria have reported social benefits of community cohesion and self-direction (Dumais, 2016), social cohesion of community cooperation (Essential Services Commission, 2016, p. 65), and that they “stimulate community relations” (Smith, 2016, p. 2). The social value of energy for these groups is encouraging.

Whether climate change is perceived as a sufficient emergency to stimulate arbitrary groups of neighbours to cooperate is debatable and a recent study for Melbourne found only 41% of neighbours report they would pull together in an emergency and only 39% trust each other (City of Melbourne, 2016, p. 40). This suggests there is not likely an automatic transfer of energy community cohesion to arbitrary sets of neighbours. However, this has not been tested and so it is not clear whether the community precedes the shared energy system or vice versa. It may well be the case that if neighbours co-owned a renewable energy system, they may cooperate to conserve energy from that system at least because this saves them more money (than owning separate systems, or not conserving).

2.3 Conservation and common resources

A binding force between energy communities and their renewable energy assets is probably related to sharing benefits. In Daylesford Victoria, a large commercial wind-farm development was challenged as it was forced on the community with no direct benefit to them. Once the community gained some ownership of the windmills, and accessed shared benefits, the project was accepted (Hepburnwind, 2011). With a large system like Hepburn Wind, energy sharing can only take the form of profit sharing from the windmill energy sales to the greater market. So the conservation effects would not be a direct result of sharing a limited resource, which is quite a different form of community.

In contrast, historic village commons with real resource limits required active governance - committees to distribute benefits and resolve conflicts. This governance successfully managed (among other things) deviant behaviours like free riding (taking too much) and shirking (not working enough) by enacting sanctions, usually fines (McKean, 1986). A desire for fairness and for appropriate consequences for deviant behaviour are reliable findings in group studies and sanctions have been found to reinforce group cohesion (Dentler & Erikson, 1959). This in turn is beneficial for normative behaviour. It is thus desirable for the group to enforce limits - in return there may be even tighter group binding:

> “The deviant supplies a group with a problem that the group needs to solve. The members can unite against this problem as they try to do something about it. They will attempt to bring about conformity in the deviant. Their attempt can serve as a "rallying point" for coordinated group activity. Thus, the presence of a dissenter allows the members to express and nurture group cohesion” (Pavitt, 1998:202).

Of course there are limits to how complex sharing rules can be and how punitive or encouraging reinforcement can be. The field of APEX games has explored how limited resources are shared under varying rules and constraints, but also that there can be retribution (Oliver, 1984, p. 124). In an environment where conflict between neighbours may be possible, it is desirable to design group governance so that sanctions do not escalate or that subjects quit the study. One way to do this is to anonymise both the giver and receiver of sanctions. Although this would seem to diminish group bindings based on identity, in a small group it is still clear that it is the group that is acting on the group deviant. This of course is not certain and our final question asks to what extent this simplified social reinforcement will actually be effective.

This diverse literature provides some emergent themes:

1. Feeding back more and more regular information about electricity consumption to home occupants results in significant conservation outcomes (for example Gans et al 2013)

2. Comparison of home electricity consumption to the consumption of unknown others results in moderate reductions in consumption (for example oPower.com 2015)
3. Comparison to the consumption of *known* others leads to additional conservation outcomes (Moere et al 2011)
4. Treating consumers as a group (a community) and framing conservation problems as a community concern has resulted in improved conservation efforts (for example in water conservation (Liubinas & Harrison 2012). More generally in the environmental movement, individuals who assemble in groups report much greater collective agency against larger challenges (drought, climate change).

To which we add

5. Sharing renewable energy goals in a group ("energy community") reinforces group cohesion and leads to energy conservation (Bauwens & Eyre 2017)
6. Sharing a renewable energy asset or generator purportedly reinforces group cohesion, identity and community (Essential Services Commission 2016, p.65)
7. Sharing from a limited commons (a "limited pool resource") brings about consumption awareness in individuals (for example Gardiner 2017)
8. Social sanctions (positive and negative reinforcement, as a form of governance) are part of many historical shared common resources and this reinforces group cohesion and effective sharing while preventing conflict (for example Ostom 1990)

Taken together, these findings suggest potential for a socio-technical intervention for energy conservation to be effective at the group level, but also a potential for collective behaviours over isolated behaviour change within the home. To what extent any group can be artificially assembled and then cooperate around a conservation goal will be tested.

3 Method

It is difficult to align cause and effect in home energy consumption because it occurs in a non-experimental environment and energy consumers have complex motivations, varying understanding of their consumption and experience varying costs and benefits of energy use. Households interact with the economy to the extent that savings from curtailing energy consumption are often spent on either more energy (direct rebound) or on more devices that consume energy (indirect rebound).

Conventionally, behaviour change in energy consumption is measured by establishing treatment households and control households. Because households differ greatly in their composition, many studies have attempted to pair controls with treatment homes on a range of characteristics. Because energy use for the household is effectively an aggregate of all demands from all devices, it is impossible to control for many confounding effects (Delmas et al., 2013) and likewise to pair for all possible categories (for example: issues with Propensity Score Matching (King & Nielsen, 2016)). This problem is likely present in many of the studies with methodological problems and invalid outcomes. For example, one pledge-based conservation study even paired households on the independent variable (Hannah & Murphy, 2013). Because this study will measure consumption of a collective of energy users (aggregating proximate causes even

further), it seems appropriate to consider another approach than separate controls and matching.

Fortunately, the problem of so many unknown variables in a naturalistic setting has been tackled in medical science using multiple baseline intervention - advised for complex, confounding or small treatment groups (Sanson-Fisher, D'Este, Carey, Noble, & Paul, 2014). This approach is used to stabilise a patient with a high blood temperature due to an undiagnosed affliction based only on frequent temperature measurements and a set of treatments applied iteratively. That is, there is one reliable measurement, and total control over how the treatments are tried. A certain medicine is then given in a certain concentration and the patient's temperature before and after is compared for a set period. If the temperature remains high, another treatment is attempted. If the patient's temperature drops, the treatment can be halted to see if the temperature has stabilised, or whether in the absence of the medicine, the temperature then rises. It should be noted that this last condition provides the strongest evidence of the causal relationship between the intervention and the effect.

This has strong parallels to home energy use. For one, the data are the kilowatt-hour consumption values which can be obtained continuously and which are accurate to the watt-hour. Second, we have the house group's historic consumption for any arbitrary period, establishing the house group as its own control. We can then apply a range of treatments, even different treatments with different parameters to different house groups and use home energy consumption measurements to find significant effects, or not, as the case may be. This can form a cycle: in the case of the medical patient it ends when the treatment that stabilises temperature is found (or temperature stabilises itself). In our case, it can continue until a repeatable intervention suppresses demand. Ideally, our treatments cause demand to remain low, so it may not be possible to rely on the above observation of the negative effect of removing the medicine. Instead, the validity of the energy consumption finding has to be determined by running "successful" interventions over multiple groups and measuring regression.

3.1 Participants

The experimental design and recruiting approach is presently under consideration for approval by the University of Melbourne Central Human Research Ethics Committee.

Participants are being recruited via Moreland, Port Phillip and Melbourne City councils which are partners on the broader research project. To counter self-selection effects somewhat, the participants will consist of 5 groups of 6 adjacent inner urban homes. Adjacency also would be a requirement of a shared energy system installation. One set of homes will be made up of apartments (all within one apartment block) which would interconnect via the shared wiring of the site.

Figure 1. A modified image showing a group owned solar system at left, and potential local network with central battery storage to distribute and share generated electricity at right.

Participants that already have home solar installed will have their solar generation measurements obtained from their solar MODBUS meter. Self-consumed solar will be added to imported electricity as if the existing solar system was not present.

3.2 Apparatus

An in-home display (IHD) has been designed and created and occupants are instructed to refer to it at least twice a day (Figure 2). The IHD remains on and continuously lit and will be put in a high traffic area such as a kitchen bench. The study will run for six months over the Australian summer, a peak demand period. Nonetheless occupants are told not to forgo basic electricity needs such as air conditioning on a hot day for the sake of energy conservation the study asks for. Occupants will be instructed not to interact with their neighbours on what their IHD conveyed to them.

Occupants are instructed to read and understand any of five treatment features of the IHD which are introduced at certain times. They are

1. Home energy use and home energy use goal - this is a graph showing home energy use against shared system generation. A gap indicates grid import, which should be minimised.
2. Group energy use and group energy use goal - this is the same for the whole group with the home shown relative to it.
3. System pay down graph - shows how the group as a whole adhere to the goal of "fitting" within the capability of the shared system and so can realise positive net present value (NPV) in the predicted time period
4. Deviant reporting and social sanctions - occasional prompts about over- and under- achievers in the group (de-identified) and the option to increment or decrement that group member with a fiat currency called Sparks. Sparks are used as an alternative to both money and kWh for simplicity (Anderson & White, 2009).
5. A passive mode of the social sanctions feature merely displays deviant consumption (again anonymously) but occupants cannot interact (this is similar to

the Petkov et al (2011) study where the performance of known others cues conservation).
6. Informational pop ups - energy saving tips that are weather-aware such as closing blinds on a hot day or wearing a jumper on a cold day. These are taken from a state government energy saving guide (DELWP, 2014)

These treatments are turned off and on via a central server accessed over the Internet by each IHD.

Social sanctions are provided using the following algorithm

1. The consumption trends of each household against their historic consumption will be calculated regularly and adjusted for temperature and precipitation. A household trend will be weighted against the performance of the other households.
2. The system will determine if the occupants are home by the presence of demand aligned with daytime and night-time.
3. A sustained 5-day rising trend is detected as an overconsumption event. Likewise, a conservation event is detected for the converse of this except if the occupants are determined to be not home. This home will be called the deviant group member.
4. A selection of 3 other group members will be made at random by the IHDs.
5. Each of the 3 group members will be solicited with a statement to the effect that a certain group member (who was not identified) can have their energy savings incremented or decremented. The solicitation could be refused.
6. The total of accepted solicitations then resulted in a deviant home being informed its savings due to conservation had increased or dropped due to the collective action of the group.
7. The system introduced delays to make it difficult to align the arrival of a sanction with other group members being home, for example.

As above, study households will be informed not to share the details of their IHD displays. Any occupant asked if they had caused or received a sanction will be advised to respond that they did not know. The social sanctions are thus a minimal, semi-transparent reinforcing system with the usual risks of retribution seen in APEX games (Oliver, 1984) diminished due to de-identification and plausible deniability. Nonetheless, the presence of social sanctions is expected to reinforce group norms for both the giver and the receiver (Caldwell, 1976).

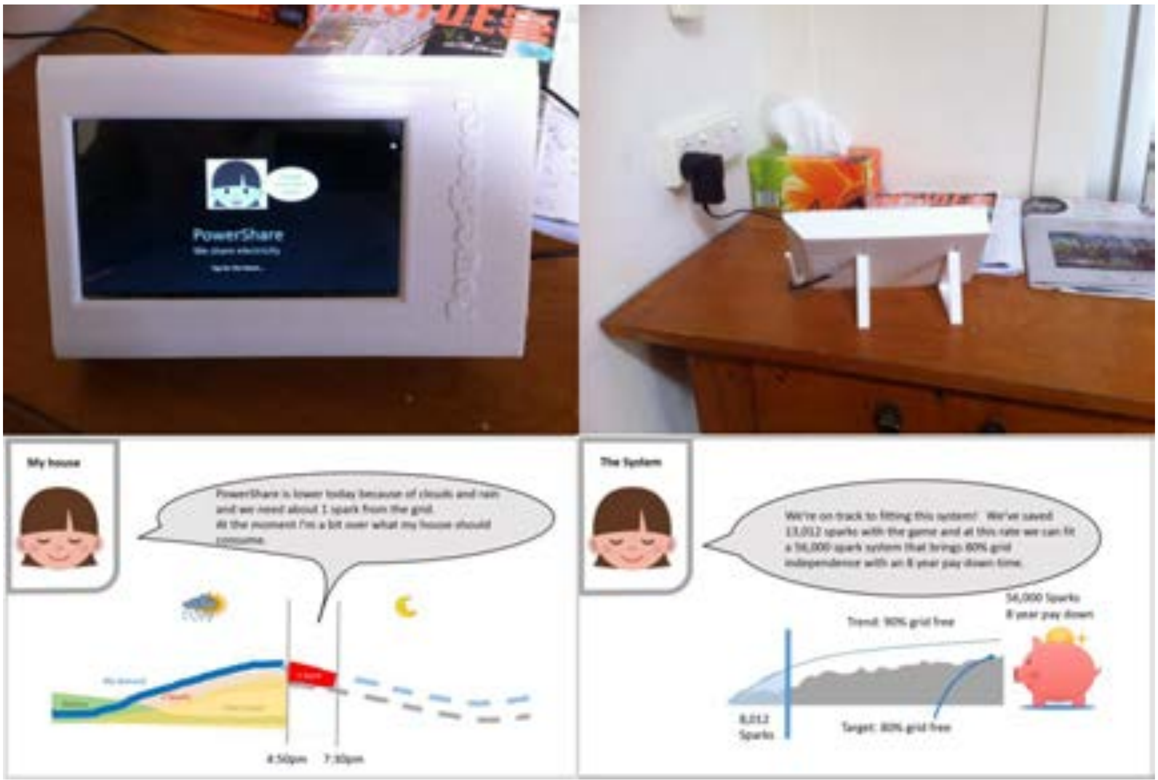

Figure 2. Top left: experiment in-home energy display. Top right: in-home energy display rear view with LoRA radio antenna visible. Bottom left: Performance, generation and goal for participant home. Bottom right: final goal for the group. The display communicates with the home smart meter and with a central server via an internal 3G dongle. The IHD does not interact with conventional electricity billing at all.

The IHD produces a number of prompts which require the occupants to touch the screen. This in turn results in time series of events being recorded (Figure 3). This time series is aggregated centrally at the server. If the IHD goes offline or occupants cannot or are not using the IHD this can be detected centrally and the affected home can be contacted.

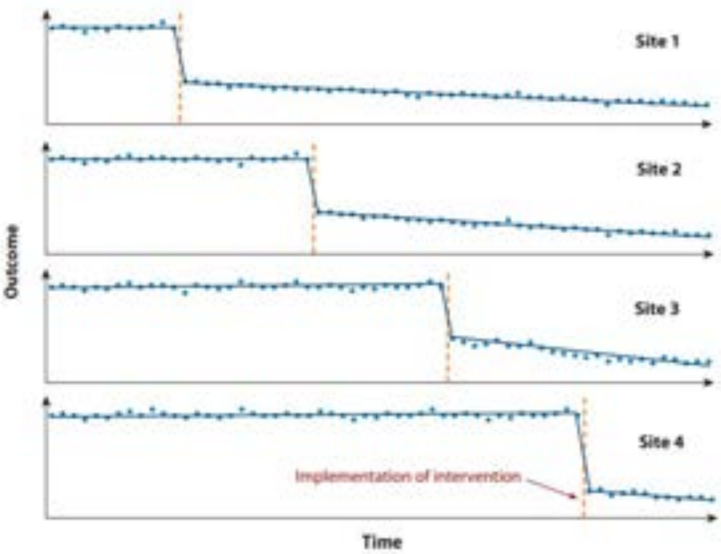

Figure 3. The interventions will be deployed per group and group energy consumption recorded as above. The correlation strength and significance of consumption and timed interventions will be determined. If the intervention is significant it will then be tried on another group remotely via the IHD. Taken with permission from (Sanson-Fisher et al., 2014:20).

The time periods over which to run a treatment and then observe for effects have not been determined at this stage. When the experiment runs, it will first be deployed to only one house group for a month in order to calibrate the system. This includes establishing the reinforcement schedule. Once the multiple baseline process emits significant data, then the remaining four groups will be set up.

3.3 Risks

The study requires that occupants can provide reinforcement to other (anonymous) group members who are adjacent homeowners, via the IHD. A group member who uses a lot of energy may receive negative reinforcement from the others causing annoyance. This may cause the participant to quit the study, to complain to the University, and/or to fall out with one- or all- of the other neighbours. To address this participants are told that if they are a habitual large energy consumer that they will not be unfairly treated and that all standing energy profiles are simply based on the participant's 2016 energy consumption as a starting point. The system does not identify reinforcement opportunities from one-off events and instead identifies over- or under- consumption as the 5-day trend (adjusted for weather) of the household over- or under- their 2016 energy use records (respectively). This means that a household having guests, or trades work done, or using an energy intensive device for a day will not receive negative reinforcement. Likewise, a household that goes away for a few days will not receive positive reinforcement for low energy consumption (in fact the system detects when no one is home and such periods are discounted from the analysis). Reinforcement events impose a cost on the issuer. This cost has been observed to reduce the risk of retribution in other social games.

4 Conclusion

The study will attempt to determine if ad-hoc groups of urban neighbours can be coordinated to share a co-owned solar and battery system. An In Home Display will be deployed to both display home energy use as well as the fictitious production of the shared system, and to solicit group sanctions to head off common limited pool resource conflicts.

The outcomes of this study, if found to be valid and consistent may be important for new efforts in the Australian energy transition. If groups of neighbours can share such systems then the technology will be far more affordable than if neighbours had to all buy separate systems. Such collective groups could enjoy high levels of energy independence and consume less large scale generated energy through more efficient self-consumption of generated solar power. In turn, less solar power exported to the utility would reduce stress on the grid.

A group that can share may also enjoy the additional benefits reported by energy communities more widely, namely group cohesion, and community forming. Perhaps more importantly, emergent energy groups that learn to conserve may be more open to the concept of final energy consumption, lifetime carbon cost and even sharing other utilities such as water, waste and transport.

If a group can share a renewable energy generator on a supplementary (that is, a private) network, then the group has a redundant supply and so can enjoy more reliable power, islanding power, or poor quality grid power, (reducing the imperative, cross-subsidies and overall great cost of 99.998% power for all domestic consumers).

In future, it would be desirable to run this study at a greater scale. This could allow varying the neighbour group sizes, or adding and removing group members to determine shared system designs that are robust to change. In the current study, renters are not catered for and they may not benefit from the projected long term savings once a system is collectively paid down. Instead, future studies might consider how owners enjoy improved property values with DRE systems and could be incentivised to subsidise their tenants or even join a sharing scheme as a virtual member contributing directly to the pay down curve of the system (which may also be tax-deductible).

In future it would be valuable to follow up on the groups tested in this study and to this end, participants' permission is being requested for future recruitments and data access. It would be desirable that a sharing group can continue to conserve without the requirement of social sanctioning features since these are intended to change behaviours. Of perhaps greatest interest in future is the potential for neighbours to cooperate to shift or aggregate demand through personal interactions (such as to spread solar day loads). In this study interaction was limited to only those social cues served via the IHD.

Acknowledgements

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EFFECTS OF CHANGING CHILLED WATER SUPPLY TEMPERATURE OF DHC SYSTEM

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Abstract: *District heating and cooling (DHC) system has been promoted energy savings in various ways, for example, using of unutilized energy, introduction of CGS, and the like. However, researches which consider energy saving by improving operation of existing DHC system are very few. General existing district DHC systems are operated at a constant chilled water supply temperature capable of handling peak load during the year. However, the peak period of the demand is very short in midsummer, and the demand for most periods is not so much. Therefore,The purpose of this research is clarify energy conservation in the whole area by comparing energy saving amount of plant side by change of water supply temperature during winter season and interim term, and energy increase amount of customer. The subject of trial calculation is Nishi-Shinjuku DHC area where our university is located. As a result of trial calculation, energy consumption of 0.34% (10.9 MWh) as assumed on the customer side due to power increase of the air conditioner fan / Chilled water supply pump. Meanwhile, DHC plant side energy reduction of 10.8%(115.5 MWh) was expected due to high efficiency of heat source equipment. In the whole DHC area, the energy consumption was expected a 2.5%(104.6MWh) reduction. It was confirmed that raising the chilled water supply temperature at the time of low load in district heating and cooling could lead to energy saving as a whole region.*

Keywords: *DHC, Area-wide Energy Usage, Reduction of Energy Use, Change Chilled Water Supply Temperature*

1 Introduction

One of the causes of global warming and heat island phenomena is an increase in energy demand of buildings. Energy demand is especially high in urban areas where high-rise utilization of land is progressing, and thus it is necessary to promote energy conservation in urban areas. District heating and cooling (DHC) can be cited as a method of saving energy in urban areas. DHC is a system that consolidates the heat source equipment ordinarily possessed by each building at a DHC plant and supplies chilled water and steam for air-conditioning from there to each building. The advantages of introducing district heating and cooling are that it enables easier utilization of unused energy and eliminates the need for space to house heat source equipment and cooling towers on the customer side. It is known from the reference that district heating and cooling can be more effective in areas with higher thermal load density.(Sadohara, 1998), (Takada,2007), (Suda,2007), (Lee,2012),As an example, I will explain the Nishi-Shinjuku district heating and cooling (Nishi-Shinjuku DHC) where our university is located. Figure 1 shows the supply area overview, Figure 2 shows the bird's eye view, and Figure 3 shows the system profile. The Nishi-Shinjuku DHC supplies heat from two DHC plants indicated with red shading to each customer via piping buried underground.

Existing DHC systems are operated at a constant chilled water supply temperature capable of handling peak load throughout the year. The water supply temperature of many DHC is set between 7.0 ° C and 4.0 ° C. In a refrigerator, the COP tends to improve as the temperature of the produced chilled water supply rises. (Ichikawa,2008) Therefore, there is potential for energy saving on the DHC plant side by changing the chilled water supply temperature during the period of low demand. Tamura, Orima and others showed that raising the water supply temperature in the office building contributes to the reduction of power consumption.(Tamura,2014) However, only the examination in the office building has been reported, and there is no example which the change of the water supply temperature was examined in district heating and cooling.

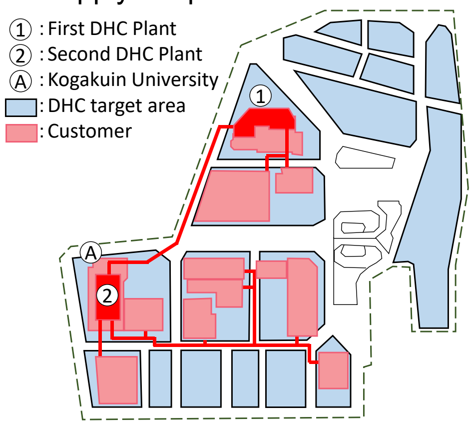

Figure1: Supply area overview

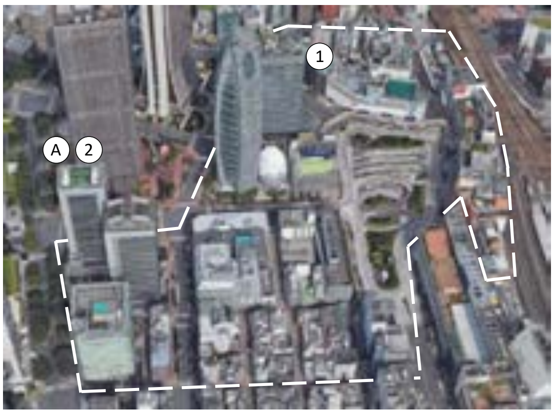

Figure2: Bird's eye view

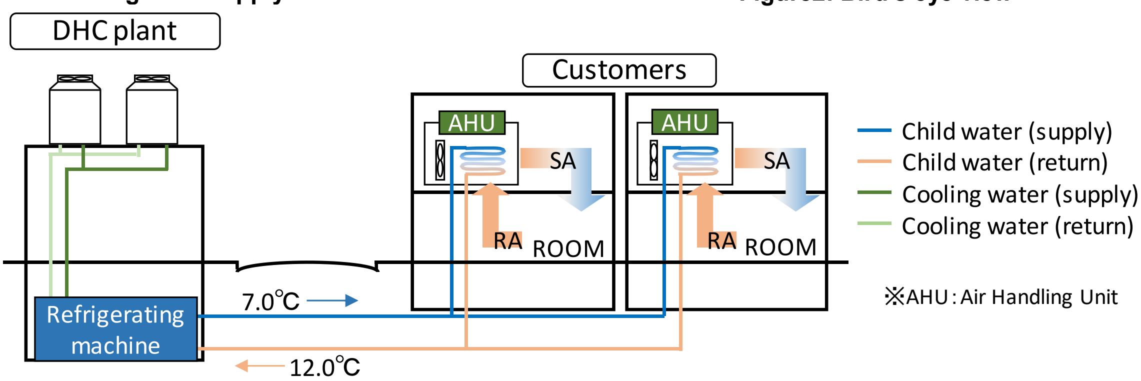

Figure3: The system profile

Figure 4 shows the peak usage rate in the third week of each month (calculated by dividing cold demand of each building at a certain time by the maximum cold demand) in the Nishi-Shinjuku DHC in 2015. It is evident from this figure that there is demand near the peak only in the summer season, and demand is low in many other periods.

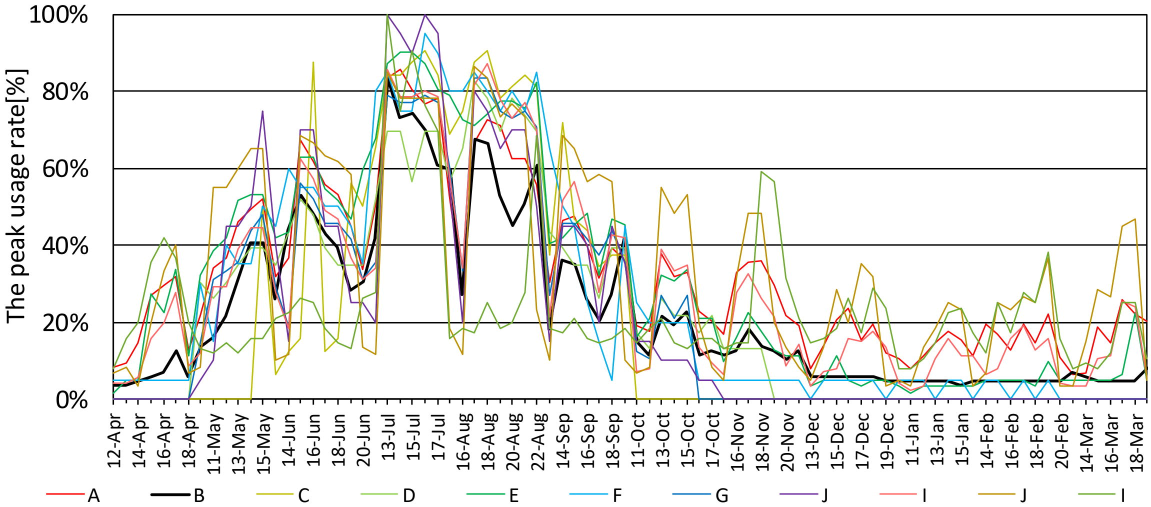

Figure4: The peak usage rate in the third week of each month of the Nishi-Shinjuku DHC in 2015

However, if the chilled water supply temperature is increased, then on the customer side, the temperature difference between the chilled water supply temperature and the supply air temperature decreases, and the heat exchange efficiency of the air handling unit coil decreases. In order to compensate for the reduced amount of heat, the chilled water flow rate and the fan air volume increase, and it is expected that power consumption of pumps and air handling unit fans will rise. Already Iwai and kitta show that when changing the water supply temperature, the energy saving amount of the refrigerator from a certain temperature exceeds the energy increase amount of the pump / fan.(Iwai,2010)

Based on the above, the purpose of this study is to clarify the effect by using a simulation to calculate the energy savings on the DHC plant side and the energy increase on the customer side when the chilled water supply temperature is changed in the winter / intermediate season in an existing DHC.

2 Improvement of efficiency of heat source equipment by changing chilled water supply temperature

2.1 District heating and cooling area overview

In this study, energy savings were calculated for the heat source equipment of the Nishi-Shinjuku DHC. In order to simplify the calculation, there were assumed to be nine customer buildings with the same demand intensity as Kogakuin University

2.2 Trial calculation conditions

The estimate in this case was made based on the following assumptions.

1. Electric turbo refrigerators will be introduced in a future facility renewal
2. The number of electric turbo refrigerators is taken to be nine, the same as the number of customer buildings, and the capacity is set to 300 RT which can handle the maximum cold demand of Kogakuin University from October to the following April. Figure 5 shows the relationship between COP and the load factor at the chilled water production temperature of a turbo refrigerator (300 RT) at the cooling water temperature of 32°C.

For the performance of these turbo refrigerators, we used the inverter turbo refrigerator model[8)] created by Togash.

3. As a method of controlling the number of refrigerators, the system is set so the number of units necessary for the load operate with a uniform load factor.

4. Customer data is that for Kogakuin University from October 1, 2015 to April 30, 2016.For the performance of these turbo refrigerators, we used the inverter turbo refrigerator model(Togashi,2010) created by Togash.

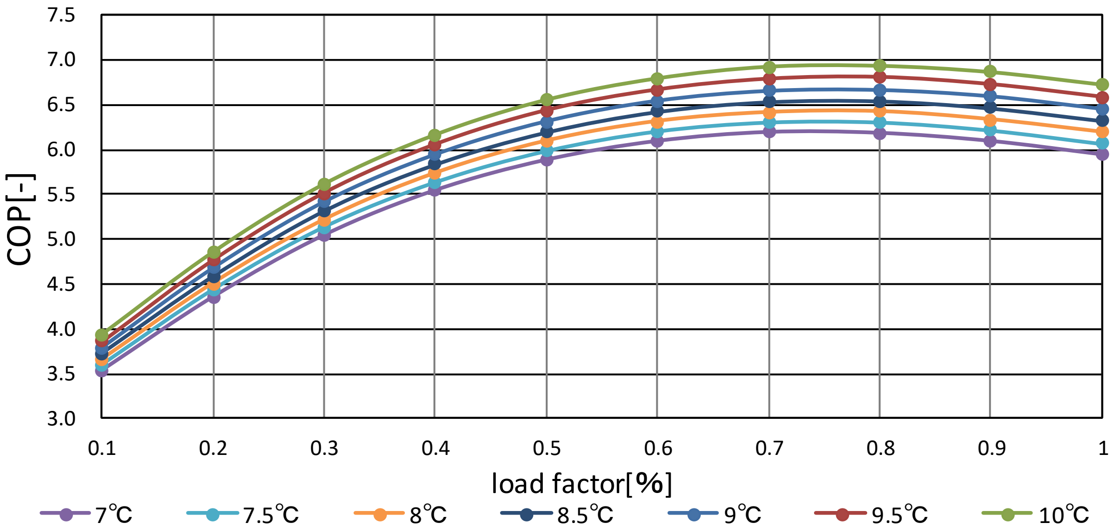

Figure5: The relationship between COP and the load factor at the chilled water production temperature of a turbo refrigerator (300 RT) at the cooling water temperature of 32°C

2.3 Results and discussion

Table 1 summarizes the calculation results, and Figure 6 shows the power consumption reduction rate for 7.0°C. Due to the rise of chilled water production temperature of the electric turbo refrigerating machine, power consumption was reduced by a maximum of 10.8% and 115.5 MWh.

Table1: Summarizes the calculation results

		7.0℃	7.5℃	8.0℃	8.5℃	9.0℃	9.5℃	10.0℃
The power consumption	[MWh]	1066.1	1046.4	1027.0	1007.9	989.2	969.8	950.7
The power consumption reduction value for 7.0℃	[MWh]	-	19.7	39.1	58.2	76.9	96.3	115.5
The power consumption reduction rate for 7.0℃	[%]	-	1.8%	3.7%	5.5%	7.2%	9.0%	10.8%

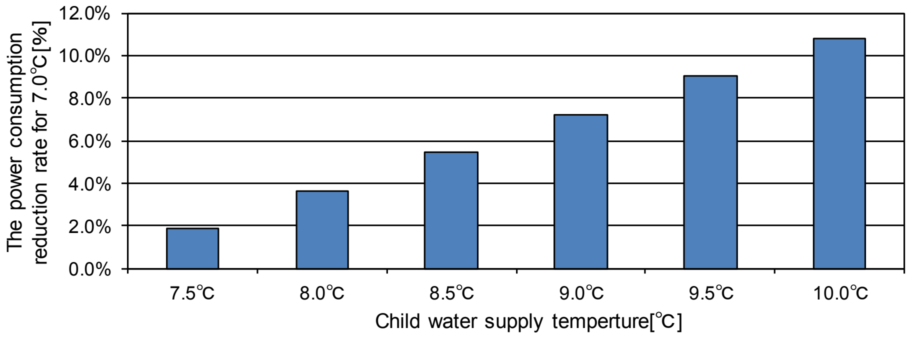

Figure6: The power consumption reduction rate for 7.0°C.

3 Estimation of pump and fan power consumption when changing chilled water supply temperature

3.1 Equipment performance survey

In this study, the increase in the pump/fan power consumption when changing the water supply temperature was estimated using Kogakuin University (located in the Nishi-Shinjuku DHC) as a model.

In order to create a relational expression between the flow rate (air volume) of the pump/air handling unit fan and the power consumption, a performance test table of pumps and air handling unit fans was obtained from the facility section of Kogakuin University. In order to simplify the calculation, the air handling units investigated were the standard floor type of a high-rise system. An expression was approximated by comparing the results test table and actual measurement values and making corrections. Figure 7 shows the performance of the high-rise/low-rise pump, and Figure 8 shows the SA/RA fan performance. In addition, it was necessary to ascertain trends in the flow rate and the air volume when the chilled water inlet temperature changed in the same air handling unit. To do this, trial data such as flow rate and the chilled water temperature difference when the chilled water supply temperature was changed between 7.0 and 10.0°C were obtained by fixing the air volume and the cooling capacity from the air handling unit manufacturing company. Based on the results, a relational expression between flow rate and cooling capacity, and a relational expression between flow rate and air volume, were created for 7.0°C–10.0°C. In this trial data, if the air volume is lower than 6400 m^3/h, the error will be large, so we set the minimum air volume of the air handling unit to 15.8 kW corresponding to 6400 m^3/h.

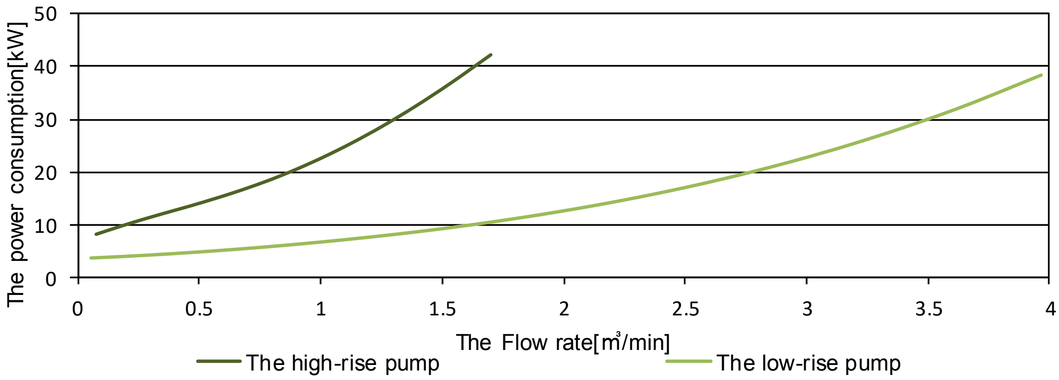

Figure7: The performance of the high-rise/low-rise pump

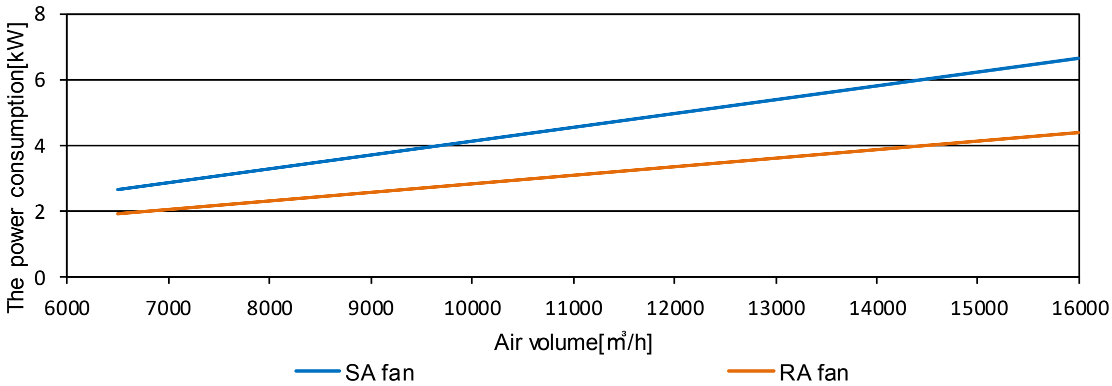

Figure8: The SA/RA fan performance

3.2 *Trial calculation conditions*

Calculation was done using the integrating flow rate (time product) of high-rise/low-rise chilled water in BEMS data from October 1, 2015 to April 30, 2015.
Table 2 shows calculation conditions of the air handling unit, and Table 3 shows calculation conditions of the high-rise/low-rise system. The minimum circulating flow rate in Table 3 represents the flow rate required to fill the main pipe of the chilled water pipe. The air volume of the air handling unit at the time of trial calculation is assumed to be unchanged even if the chilled water supply temperature changes because the trial data obtained in 3.1 is obtained with fixed air volume.

Table2: Calculation conditions of the air handling unit

Calculation conditions of the air handling unit			
Maximum cooling capacity		125.8	[kW]
Maximum flow rate		18.0	[m³/h]
Maximum air volume		16000	[m³/h]
Minimum cooling capacity		15.8	[kW]
Minimum flow rate	7.0℃	0.95	[m³/h]
	7.5℃	0.98	[m³/h]
	8.0℃	1.01	[m³/h]
	8.5℃	1.04	[m³/h]
	9.0℃	1.07	[m³/h]
	9.5℃	1.10	[m³/h]
	10.0℃	1.13	[m³/h]
OA rate		0.5	[-]

Table3: Calculation conditions of the high-rise/low-rise system

		The high-rise pump system		The low-rise pump system	
Number of air handling units		16.0	Number	46.0	Number
Minimum circulating flow rate		17.0	m³/h	27.0	m³/h
Pump	Numner	2.0	Number	2.0	Number
	Maximum flow rate	78.6	m³/h	190.8	m³/h
	Operation period	Oct.1～Nov.27、Apr.17～Apr.30		Oct.1～Apr.30	

The following shows the trial calculation method for pump and air handling unit fan power consumption when changing the chilled water supply temperature.

$$N_{AHU} = (V_{int} - V_{Cmin}) \div V_{AHUmin}$$

$$V_{AHU} = (V_{int} - V_{Cmin}) \div N_{AHU} \quad \cdot\cdot\cdot \quad (1)$$

N_{AHU}: Number of operating air handling units [Number]
V_{int}: Integrating flow rate [m³/h]
V_{Cmin}: Minimum circulating flow rate [m³/h]
V_{AHUmin}: Air handling unit minimum flow rate [m³/h]
V_{AHU}: Air handling unit chilled water rate[m³/h]

- Air handling unit SA/RA Fan Power Consumption
  Air volume was obtained from the relational expression of air volume and flow rate obtained in 3.1 and Equation (1). Power consumption was obtained by substituting the air volume into the relational expression of Figure 7. When assigning the RA air volume, the OA ratio is multiplied by the RA air volume

- High-rise/low-rise pump power consumption
  In the case of 7.0°C, the same as in the present situation, each integrating flow rate in the BEMS data is substituted into the relational expression of Figure 6 to obtain the power consumption.
  In the case of 7.5 to 10°C, where the water supply temperature is changed, it is necessary to obtain the required flow rate from the relational expression of the cooling capacity and the flow rate created in 3.1, and substitute the flow rate into the relational expression in Figure 6 to obtain the power consumption.

3.3 Results and discussion

Table 4 shows summarizes the calculation results, and Figure 9 shows the power consumption increase rate for 7.0°C, Figure 10 shows the power consumption of pumps and fans on the representative day (Tuesday of the second week of each month).
In the results of this calculation, the power consumption increased by 0.34% (1.21 MWh) at the chilled water temperature of 10°C at which the increase in flow rate was maximal.

Table4: Summarizes the calculation results

		7.0℃	7.5℃	8.0℃	8.5℃	9.0℃	9.5℃	10.0 ℃
The power consumption	[MWh]	353.0	353.2	353.4	353.6	353.8	354.0	354.2
The power consumption increase value	[MWh]	-	0.22	0.43	0.61	0.82	1.00	1.21
The power consumption increase rate	[%]	-	0.06%	0.12%	0.17%	0.23%	0.28%	0.34%

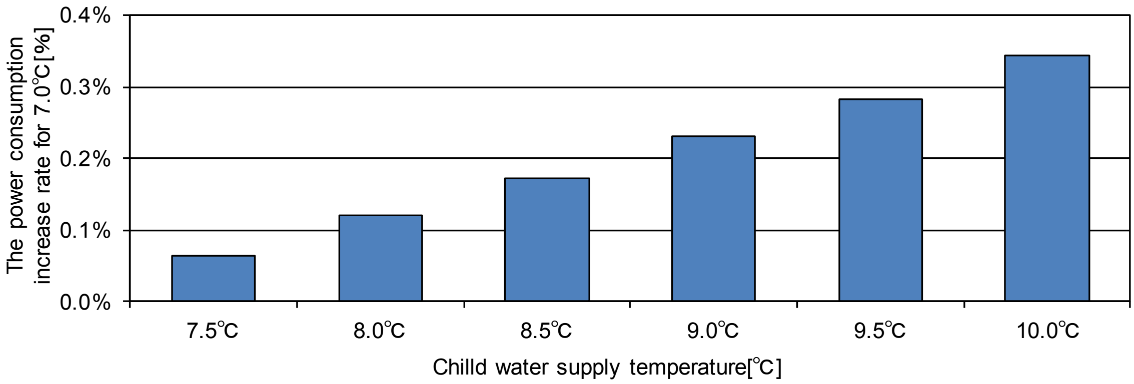

Figure9: The power consumption increase rate for 7.0°C

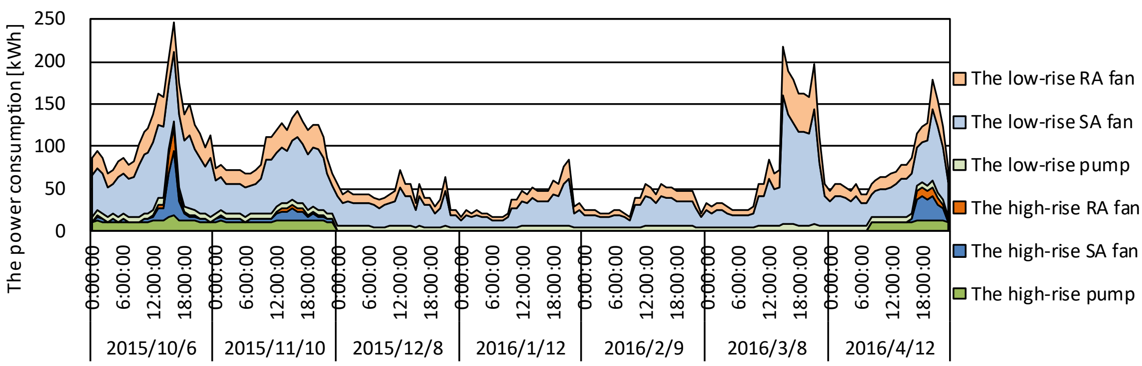

Figure10: The power consumption of pumps and fans on the representative day (Tuesday of the second week of each month)

4 Consideration of the energy conservation effect for the whole district heating and cooling area

Based on the results in 2.3 and 3.3, we compared the power consumption increase on the customer side and the power consumption reduction amount on the DHC plant side at each chilled water temperature. Calculation was done by using the DHC plant side results in 2.3 as is, and multiplying the customer side results in 3.3 by the number of customer buildings (nine). Table 5 shows a comparison of the power consumption of the entire district when the chilled water supply temperature is changed. Figure 11 shows the power consumption reduction rate for 7.0°C for the entire district.
In this trial calculation, it was possible to reduce the power consumption as the chilled water supply temperature was raised, and the maximum power consumption reduction amount was 2.5% (104.6 MWh) at 10°C

Table5: A comparison of the power consumption of the entire district when the chilled water supply temperature is changed

Chilled water supply temperature		[℃]	7.0℃	7.5℃	8.0℃	8.5℃	9.0℃	9.5℃	10.0℃
The power consumption reduction amount on the DHC plant side		[MWh]	1066.1	1046.4	1027.0	1007.9	989.2	969.8	950.7
The power consumption increase on the customer side		[MWh]	3177.2	3179.2	3181.0	3182.6	3184.5	3186.2	3188.1
The entire district	Reduction	[MWh]	-	17.7	35.3	52.7	69.6	87.3	104.6
	The power consumption reduction rate for 7.0°C	[%]	-	0.4%	0.8%	1.2%	1.6%	2.1%	2.5%

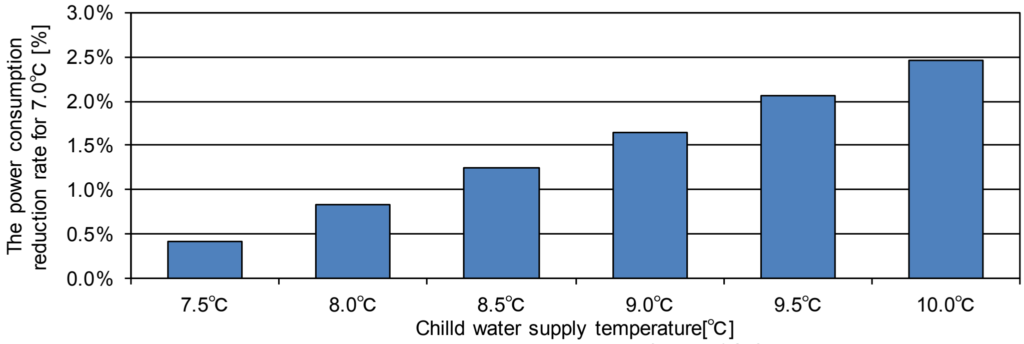

Figure11: The power consumption reduction rate for 7.0°C for the entire district

5 Conclusion

The results of this trial calculation showed that energy savings can be achieved by changing the chilled water supply temperature during the winter/intermediate season when the load is low. On the customer side, an overall increase in energy of 0.34% or 10.9 MWh is expected. On the plant side, energy savings of up to 10.8% or 115.5 MWh are expected. Based on the above results, energy savings of up to 2.5% or 104.6 MWh can be expected in Nishi-Shinjuku DHC as a whole. Since reduction of power consumption can be expected with almost no cost for implementation, it will be necessary to further improve accuracy and continue further studies to achieve realization.

Acknowledgements

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INVESTIGATION OF HIGH HUMIDITY ENVIRONMENT IN THE UNDER FLOOR SPACE

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Abstract: *In the summer, past studies have found that the floor insulated houses tends to have a high humidity environment in the under floor space in detached houses in Japan. In the high humidity environment in the under floor space, there is a high risk of condensation and fungal contamination, so it is important to improve the under floor environment of the floor insulated houses. In this research, we propose a humidity control method for the under floor space in floor insulated houses. The proposed method is to supply indoor air to the under floor space. The effect of that proposal for the under floor were clarified by actual measurement and simulation. In the actual measurement, high humidity in the under floor space was reduced by about 10 points compared to the humidity of last year in a detached house where high humidity in the under floor was confirmed. In the simulation, the influences of the outdoor air conditions and life style of residents for high humidity environment were clarified. It was confirmed that if one of the most humidity conditions were improved by the proposed method. In this study, it was shown that supplying indoor air to the under floor space is effective for reduction of high humidity in the under floor space.*

Keywords: *Crawl Space, Actual Measurement, Floor Insulated House, Detached House, Humidity, Condensation*

1 Introduction

The durability of structural members of wooden houses is impaired in most cases by biological degradation such as rot fungi and ants. Kawada et al. conducted a deterioration survey of structural members of wooden houses with a building age of about 30 years. It was confirmed that many houses, including detached houses that have been subjected to antiseptic and ant-proof treatments, have experienced deterioration of major structural parts. In particular, it was reported that there is marked deterioration of floor system members, and that deterioration due to moisture is one factor. Recent years have seen the wide adoption of floor insulated houses in which ground damp proofing is used as a measure to prevent deterioration of floor members. However, many studies in the past have reported the high humidity of crawl spaces in the summer season. Because there is a high risk of condensation and fugal contamination, there is concern about deterioration of floor members in crawl spaces in a high humidity environment. Therefore, it is important improve the crawl space environment of floor insulated houses.

Matsumoto and Iwasa et al. carried out a survey of crawl space temperature and humidity in floor insulated houses in various parts of Japan. Even in the case of crawl spaces with ventilation holes defined by the Japanese Building Standards Law, it was reported that in the summer season, the crawl space has high humidity in many detached houses and condensation also occurs. Kanayama et al. conducted a survey of the temperature and humidity behavior in a crawl space. They reported that water vapor pressure is generally uniform throughout the crawl space, but the central part is lower in temperature than the outer part, and the probability of increased humidity in the central part of a crawl space is high. Fukuda et al. conducted a survey on the effects of differences in the insulation performance of floor insulation material on the crawl space temperature/humidity environment. They reported that in houses with high thermal insulation performance, temperature in the crawl tends to be lower, and humidity higher, than in houses with lower insulation performance.

As described above, many aspects of the temperature and humidity behavior of crawl spaces have been clarified by past research. However, although many studies are being conducted via simulation about humidity control methods for crawl spaces, there are not many studies that have been verified by actual measurement surveys on real houses.
In this research, we propose a humidity control method for crawl spaces in floor insulated houses based on actual measurement data. The effects of that proposal on crawl spaces were clarified through actual measurement and simulation.

2 Summary of crawl space temperature/humidity environment survey

2.1 Summary of target house

In this study, actual measurement was conducted at a house in Tokorozawa city, Saitama Prefecture. The target housing was completed in 2013, and is a floor insulated, wooden, two-story detached house. Table 1 shows a summary of the house.

Figure 1: Target house

Table 1: Summary of the house

Location	Tokorozawa city, Saitama Prefecture
Construction	Wooden, two-story detached house
Final complation year	2013
Groundwork	A floor insulated

2.2 Proposal for humidity control method and actual measurement summary

It was confirmed from actual measurement data up to last year that at most times the indoor space had a high temperature and low humidity environment compared to the crawl space. It was conjectured that high humidity of crawl spaces, associated with lower temperature and higher absolute humidity, can be suppressed by supplying indoor air to crawl space. We made a proposal to fabricate and install an air supply fan unit at the crawl space inspection hole in one corner of the kitchen, and then actually carried out the installation experiment. For the measurement, a temperature/humidity logger and a surface thermometer were installed in the center of the crawl space, and the measurement was performed at intervals of 10 minutes. Figure 2 shows the floor plan view and measurement points of the crawl space. Figure 3 shows the air supply fan installation, and Table 2 shows the air supply fan summary. The measured air flow from the air inlet was 21.1 m^3/h. In the actual measurement, the current situation in the first week after the rainy season was ascertained. Then the air supply fan was operated in the daytime of the second week, and at night in the third week. Table 3 shows the actual measurement schedule.

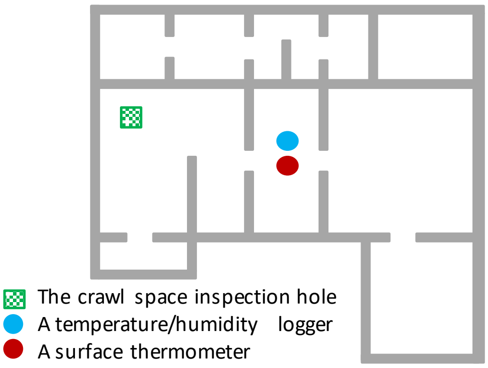

Figure 2: Floor plan view and measurement points

Figure 3: Air supply fan installation

Table 2: Air supply fan summary

One air volume	14[㎥/h]
Number of air suppuly fans	4 [units]

Table 3: Actual measurement schedule

7/28～8/4	The current situation
8/4～8/11	The air supply fan was operated in the daytime(7:00～19:00)
8/11～8/18	The air supply fan was operated in the night(19:00～7:00)

3 Actual measurement results

3.1 Change over time

Figure 4 shows the relative humidity change over time outside, indoors and in the crawl space for 4 weeks after the rainy season. Crawl space relative humidity outside the air supply fan operating period is a high humidity environment exceeding 80% at many times. On the other hand, there are an increased number of times when the crawl space relative humidity from August 4 to August 18 during the operation period of the air supply fan decreased to 80% or less. However, effects due to decreasing humidity of outside air are conceivable, and thus it cannot be said, based on this graph, that effects of air supply from indoors to the crawl space have appeared.

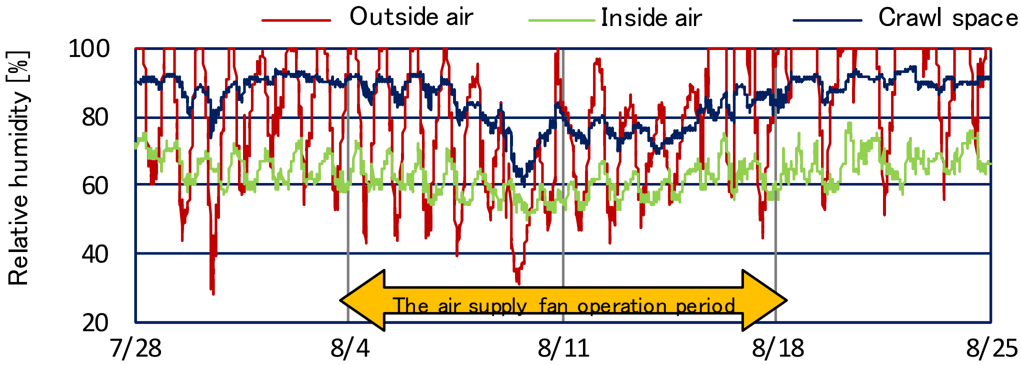

Figure 4: Relative humidity change over time

3.2 Detailed analysis

In order to clarify the effect of air supply from indoors to the crawl space, we compared the actual measurement data of 2014 and 2015 for 3 weeks after the rainy season. Also, to take into account the effects of outside air, for the following comparison condition we referred to actual measurement data when outside air absolute humidity was greater than 16 g/kg' and less than 21 g/kg'.

3.2.1 Cumulative percentage of time

Figure 5 shows the cumulative percentage of time of crawl space relative humidity. In 2015, the cumulative percentage of 90% or more relative humidity was 90% or higher. On the other hand, in the air supply fan operation data, the cumulative percentage of 90% or more relative humidity decreased to 50% of less for both daytime and nighttime operation data.

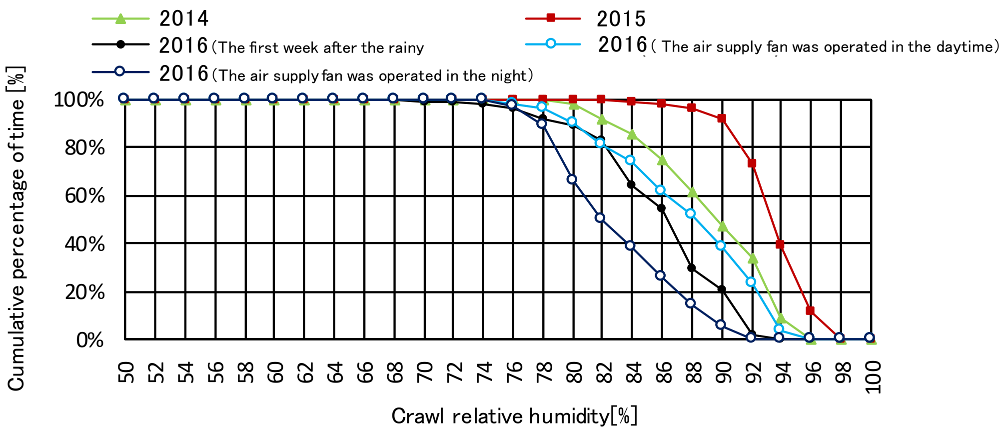

Figure 5: Cumulative percentage of time of crawl space relative humidity

3.2.2 Crawl space – outside air correlation diagram

Figure 6 shows the correlation between the relative humidity, temperature, and absolute humidity of the crawl space and the outside air. The data for 2016 is a combination of data for daytime and nighttime operation of the air supply fan. For each data set up to the previous year, the crawl space relative humidity is always high humidity. When the outside temperature is low, the temperature of the crawl space is low. The absolute humidity shows that absolute humidity of the crawl space rises with increasing absolute humidity of outside air. However, in air supply fan operation data, relative humidity decreases overall and even in the state of high humidity with outside air at 80% humidity or more the crawl space relative humidity has decreased to 80% or less. Although the absolute humidity does not change and correlation is evident, it can be confirmed that there has been an increase in plots below 16 g/kg'. If the absolute humidity is 16 g/kg' or more, the risk of dew condensation tends to increase.

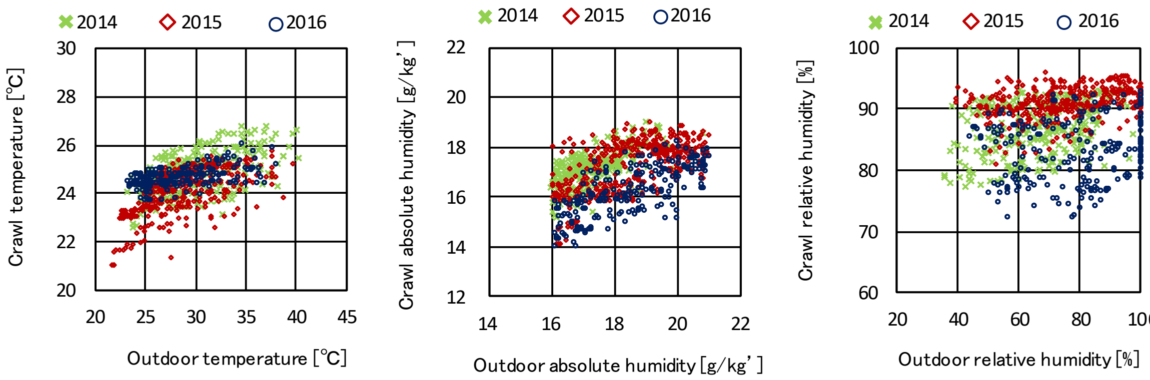

Figure 6: Correlation between the relative humidity, temperature, and absolute humidity of the crawl space and the outside air

3.2.3 Cumulative percentage of time of relative humidity

Figure 7 shows changes by the hour in relative humidity in the crawl space during, respectively, daytime and nighttime operation of the air supply fan. Focusing on the operation time in the daytime (7 o'clock – 19 o'clock) and the nighttime (19 o'clock – 7 o'clock), the cumulative time with relative humidity less than 80% is higher compared to times other than operation hours of air supply fan. This indicates that an effect of suppressing high humidity in the crawl space appears during the time when the air supply fan is operating.

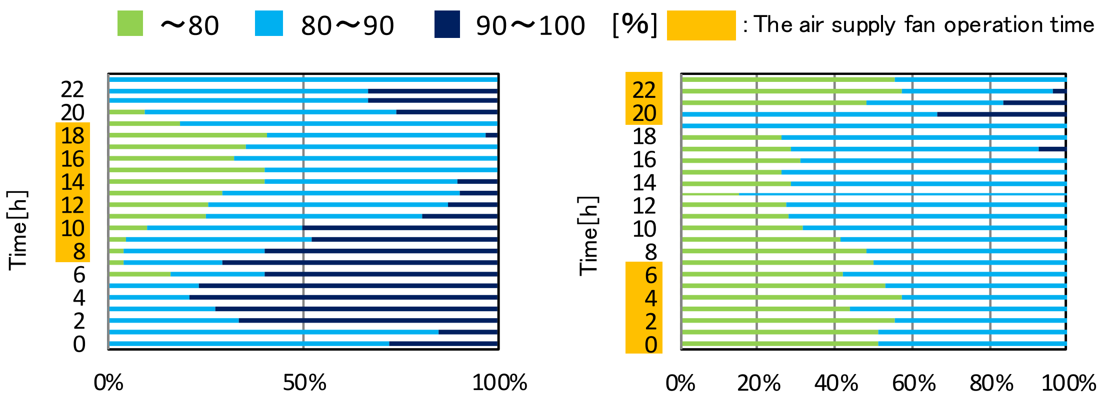

Figure 7: Changes by the hour in relative humidity in the crawl space

3.3 Prediction of fungal contamination by the fungal index (FI)

3.3.1 Summary of the fungal index (FI)

In this study, the fungal index, a parameter expressing the mold growth environment, was calculated to confirm the possibility of fungal contamination in the crawl space. Table 4 shows the relationship between the fungal index and the mold growth rate and calculation method.

Table 4: Relationship between the fungal index and the mold growth rate and calculation method

FI	The relationship between the fungal index and the mold growth rate
7 and more	Spores of Eurotium herbariorum germinate in one week
20 and more	Spores of mesic fungal germinate in one week
35 and more	The asexual lifecycle of Eurotium herbariorum proceeds: (Spore germination→Hyphal elongation→Spore scattering→Curing of new spores)

$$FI(h,T) = 187.25exp\{(x^2 - 2axy + y^2)^b/(2a^2 - 2)\} - 8.25$$

$$x = \frac{(h-c_1)}{c_2},\quad y = \frac{(T-c_3)}{c_4}, a = -0.3, b = 0.685, c_1 = 0.95, c_2 = 0.7,\ c_3 = 25, c_4 = 7.2$$

3.3.2 Change over time in the fungal index (FI)

Figure 8 shows the change over time in the fungus index for the 4 weeks at the end of the rainy season each year. Outside the period when the air supply fan is operating, the proportion exceeding FI = 7 continues to be high, indicating risk in the mold growth environment. However, from the 8th day to the 22nd day of the air supply fan operation period, the ratio of FI = 7 or more is continuously decreasing. From this, it can be confirmed that the risk of mold contamination is reduced when the air supply fan is operating.

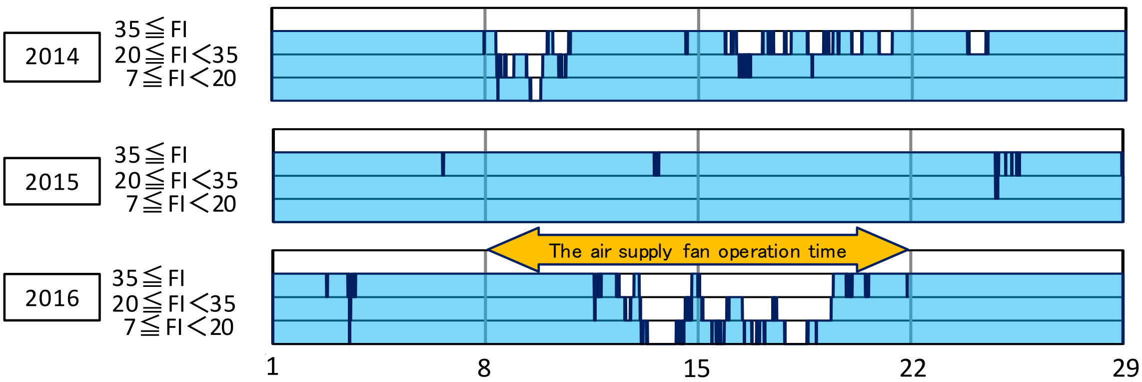

Figure 8: Change over time in the fungus index

4 Crawl space temperature/humidity simulation

4.1 Simulation summary

In the actual measurement survey, it was inferred that increased humidity in the crawl space from the rainy season to the summer season can be suppressed by the supply of indoor air to the crawl space. However, this method does not necessarily have the same effect as the actual survey in all houses. This is because the lifestyle of residents, outside air conditions, insulation specifications and other factors differ depending on the

housing. Therefore, the crawl space temperature/humidity environment was calculated using the simulation software "THERB" based on three lifestyles of residents in Sapporo, Sendai, Tokorozawa, Tokyo, Fukuoka and Naha. The three lifestyles of residents were as follows: (1) with cooling, with night purge, (2) with cooling, without night purge, (3) no cooling, constant ventilation. Based on the calculation results of the simulation, we selected regions likely to need improvement in the crawl space temperature/humidity environment. After that, calculations were performed to supply indoor air to the crawl space as in the actual measurement. Finally, effects on the crawl space temperature/humidity environment were clarified.

Table 5 shows the simulation summary, Figure 9 shows the building model floor plan, and Table 6 shows the lifestyles of residents. For ambient air conditions in each region we used the standard year data for the 20 years from 1981 to 2000 in expanded AMEDAS weather data. For the end of the rainy season we referenced the year of the average month used in July. Also, as with actual measurements, air supply was set to come from the kitchen. Air supply was set for 24 hours, and the amount was calculated by setting the hourly rate to, respectively, 0.5, 1.0, 2.0, and 4.0 times the crawl space volume.

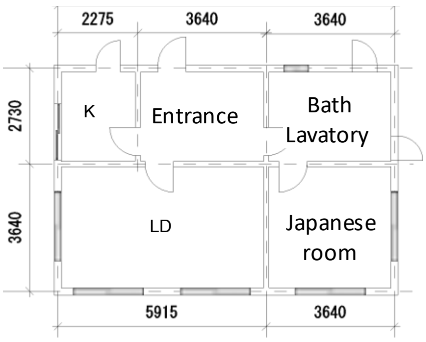

Figure 9: Building model floor plan

Table 5: Simulation summary

Used software	THERB
The building model	Model of IBEC
Heat insulatation performance	The Energy Conservation Act
Calculation interval	10min
Calculation period	4 weeks after the rainy season
Target area	Sapporo, Sendai, Tokorozawa Tokyo, Fukuoka and Naha

Table 6: Lifestyles of residents

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
①	Open Windows											Cooling						Cooling						
②												Cooling						Cooling						
③	Open Windows																							

4.2 *Simulation results*

4.2.1 Prediction of crawl space environment using expanded AMEDAS weather data

Figure 10 shows the cumulative percentage of time of crawl space relative humidity. Focusing on Sendai, Tokorozawa, Tokyo, and Fukuoka, regions where the outside air is not at high temperature even with extremely low humidity, the cumulative time with relative humidity of 80% or higher is high, and thus the environment has high humidity. Tokorozawa and Tokyo are in the same climate category, but Tokorozawa is a humidity environment compared to Tokyo. It is presumed that crawl space temperature and

humidity environments differ greatly not only due to the lifestyle of residents and the climate, but also due to the location conditions of the housing. In terms of the difference in lifestyles of residents, in regions outside of Tohoku (northern Honshu), the cumulative time with relative humidity of 80% or more was higher for lifestyles using air conditioning than for those not using air conditioning, and a high-humidity environment can be confirmed. This is thought to be due to the lowering of temperature in the crawl space due to lowering of the indoor temperature based on air conditioner use, and this results in high humidity.

Figure 11 shows the time course of the fungal index for 3 weeks after the rainy season for lifestyle pattern ②. It can be confirmed that Sendai, Tokorozawa, Tokyo, and Fukuoka continuously exceeded FI = 7 for one week. The cumulative time of 80% or more relative humidity exceeds 50% in these four regions. Sendai and Tokorozawa in particular have figures of FI = 35 which continue over most periods. On the other hand, in Sapporo and Okinawa, where the cumulative time with relative humidity of 80% or more is relatively low, a value exceeding FI = 7 has not been confirmed during the 3 weeks after the rainy season.

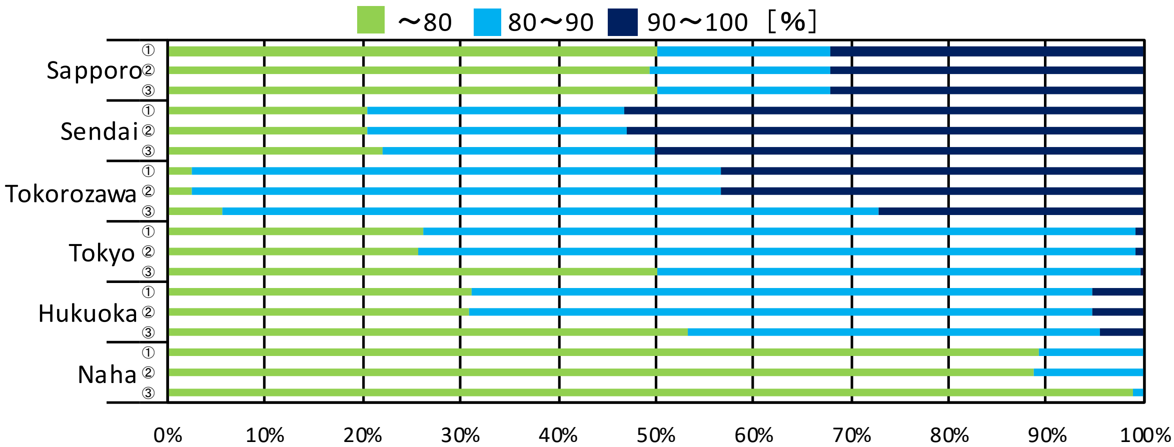

Figure 10: Cumulative percentage of time of crawl space relative humidity

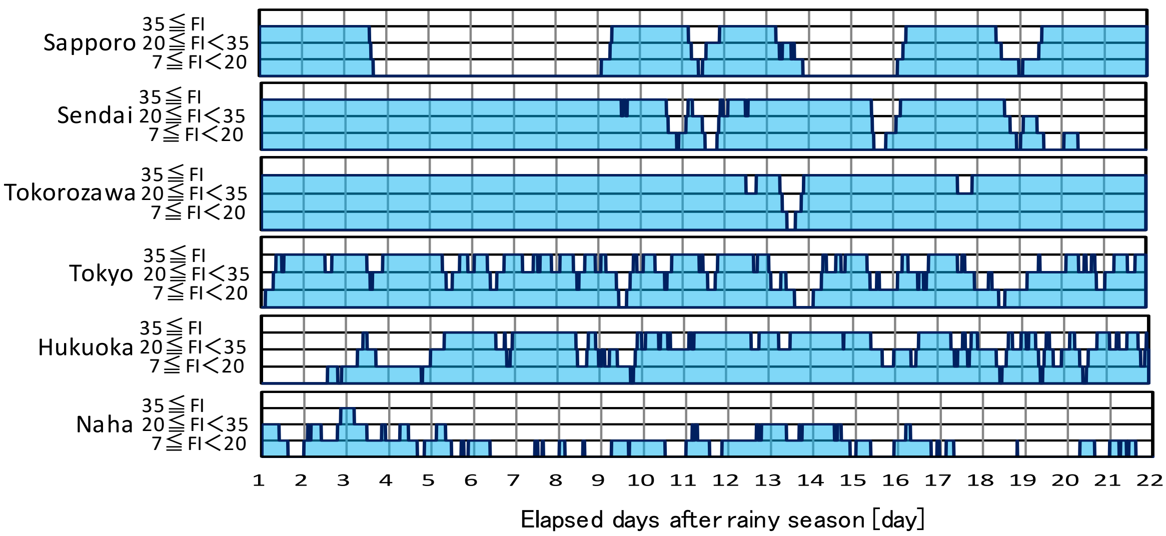

Figure 11: Time course of the fungal index

4.2.2 Prediction of the crawlspace environment using the humidity control method

Based on the results in the previous section, we focused on the three regions of Sendai, Tokorozawa and Fukuoka where it is easy for a high fungus index to continue, and performed a prediction simulation of the humidity control method in which indoor air is supplied to the crawl space. Figure 12 shows the change over time in the fungal index, and Figure 13 shows cumulative time of crawl space relative humidity. Values of FI = 7 or more continue for one week when Sendai and Tokorozawa air supply volume is 4.0 times/h and Fukuoka air supply volume is 1.0 times/h, and it can be confirmed that the risk of fungal contamination in each region decreases. Also, with regard to the air supply amount, when attention is paid to the crawl space relative humidity in each region, it is evident that the occurrence frequency of 80% or more relative humidity is about 50% in all regions. It is estimated that the risk of fungal contamination is relatively low in an environment where the occurrence frequency of relative humidity of 80% or more is 50% or less.

Although there is considerable variation depending on factors such as the frequency of air conditioning use and outside air conditions, it is presumed that supplying indoor air to the crawl space will be effective in all regions for suppressing crawl space high humidity. However, since these are simulation results, it will likely be necessary verify these results by conducting an actual survey at houses throughout the country, and comparing the results with the results of this simulation.

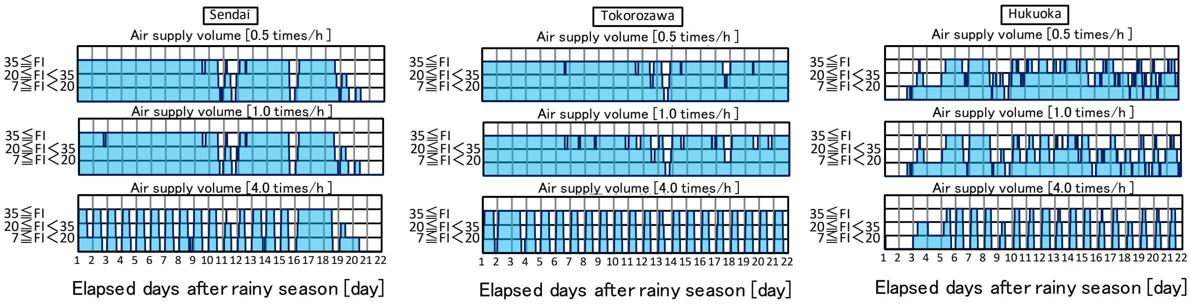

Figure 12: Change over time in the fungal index

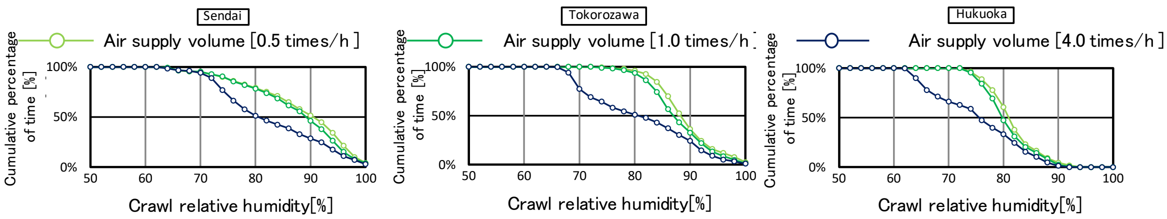

Figure 13: Cumulative time of crawl space relative humidity

5 Conclusion

The simulation clarified the effects of outside air conditions and the lifestyle of residents on the high humidity environment. It was confirmed that one of the conditions with the highest humidity was improved using the proposed method. In this study, it was shown that supplying indoor air to the crawl space is effective for reduction of high humidity in the crawl space.

Acknowledgements

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CONTEXT-RESPONSIVE MODULAR SYSTEM: A PRAGMATIC SOLUTION FOR SOCIALLY CONSCIOUS ARCHITECTURE

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Abstract: *This study focuses on finding an optimal solution for today's current economic, environmental and demographical issues by creating a modular system that is a pragmatic respond to the present-day issues in a holistic way. It provides a socially responsive architecture that can be modified and updated as the circumstance change in a future time. The main changing parameter that this study is concerned with is "the People". If there is ever any change in the way people's population or needs or expectations are, that means that a different solution needs to be proposed as the nature of the issue has changed. One of the main issues is the increasing rate of population and urbanization, particularly in Asia and Africa. There is a shortage of housing and this study aims to find a solution that allows Architectural Engineering to address the current issues like energy, economy, health and quality of life in a systematic way. The research was conducted through-out different applied research Quantitative methods including geometrical shape studies, Design data analysis for maximum utilization and parametric space efficiency simulations on different scales. Modularity allows us to simplify the issue and be able to find the correct response by breaking down the problems and solving them in a way that the final outcome is a solution in totality. As a result; this study outcome was a highly efficient-based design for all the living & functional spaces in the built system based on one uniform module that could be arranged in many different units and scales for living spaces. With high concentration on the level of innovation in pre-fab modular design. This study was able to achieve the smallest level of details starting from the manufacturing until delivery & on-site assembly and future modification scenarios; all in one fully designed innovative system.*

Keywords: *Modularity, Mass Customisation, Housing, Prefabrication, Parametric Design*

1. Introduction

One of the main problems that most of the world country face right now is the need for better housing solutions. Whether it is a social housing, refugee housing problems or affordable housing needs in general; it is considered one of the uprising architectural needs. Current population of earth is approximately 7.3 billion people and it is predicted to reach up to 9.7 billion by 2050, 66% of this population growth will be in urban areas and cities, which mean many more developments, need to be constructed to accommodate all this new growth in a way that is more efficient than current design techniques. (UN 2015)

Architectural sectors consume a huge sum of capital annually and by tailoring a more economical solution, the surplus can be invested in other issues of the time. Speaking from the population's point of view, a larger portion of people can afford these economical units and more people can be sheltered, which ultimately leads to a better prosperity of societies as the basic needs of life are taken care of. Earth is facing an energy crisis now; the crisis might not be evident since we are not facing major black outs or situations like the energy crisis in 1970s, but our consumption is at a higher rate that we can reproduce (Nace 2017).

Approach and Methodology
This research has a holistic approach that responds to existing issues, i.e. population growth, provision of adequate housing, provision of environmentally low impact structures, in our societies and tries to find a solution. This pragmatic approach sets different goals and objectives for various fields that contribute in shaping the outcome. The main goal is to breakdown the requirements and find a modular product that embodies the correct respond to the economic, environmental and user's needs in a way that can be adapted and modified in the future as the circumstances change. All the solutions together should accommodate a general set of features to follow the sufficient quality of living, sustainability, affordability, availability, customization levels, flexibility and a modern aesthetic design.

A practical objective of this research is to have a theoretical strategy using advanced computational design methods that facilitates the unlocking the potential of these modules and provides all the possibilities that can later be applied in practice once the project is built. This could be achieved by conducting design simulations for the proposed concepts after combining the learned architectural, modular or cross learning factors.

This research is carried out by mainly conducting a qualitative research method, and small parts of the research were using quantitative approaches to be able to fulfil all the possible research goals and objectives. In the study, qualitative approaches are used such as; theoretical and literature review analysis, election and discussion of theoretical material with descriptive material in context and detailed comparison of theories in terms of their applicability. On the other hand, quantitative approaches are used such as; collected data and verifying existing theories or hypotheses or questioning them while putting them to several applications and tests to be able to understand such theories and how beneficial it can be for conducting the research.

This is design-based research application; a summarised outcome of the modular system, Architectural Design, will be the following content of this paper. Representing the full courtesy of the authors' copyrights. This design is an ongoing research and development will include more phases and prototyping in the coming future.

2. Modular System Program Design

The proposed program for applying the modular system is represented by the following conceptual process diagram, consisting of four system subdivision stages (see Figure 1).

1-Basic Modular Elements.
2-System Modules.
3-System units and combinations.
4-Urban-scale and combinations.

The design process that will follow the mentioned stages is mainly controlled by the "variation levels" (The Modular Algorithms).

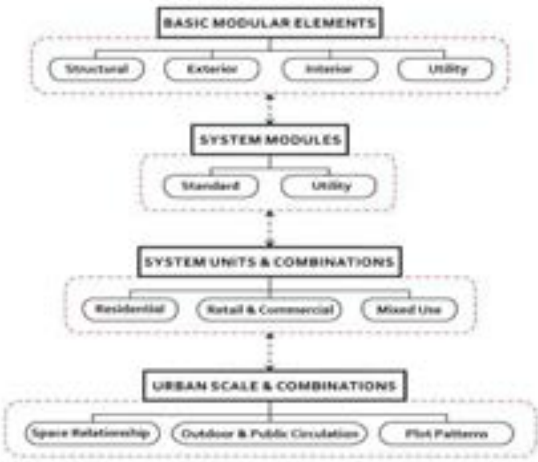


Figure 1: Modular system program diagram

3.1 Basic Modular Elements

Basic elements are the smallest form of the modular system; a defined set of different elements will create a basic module. There are four groups of elements based on their mutual function; each is considering a main aspect of the module design features and is closely related to the process of the selection, production, delivery and final installation of the designed module. Such element categories are based on the general data outcome from the first part of the research, and are further developed. In the design experimental process in the upcoming phases; which will be more effective as a pragmatic approach towards an ongoing research. The element categories are as shown below in Figure 2.

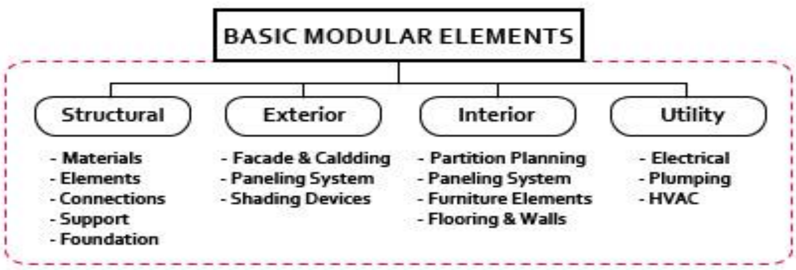


Figure 2: Basic modular elements diagram

<u>*Structural Modular Elements:*</u> This group includes all structural elements such as the basic elements of erecting, foundation systems, structural material selection, connections, joints and support systems.

Exterior Modular Elements: Exterior elements are all the modular construction treatment for the exterior of the built modules, such as façade and cladding, panelling systems and shading devices.

Interior Modular Elements: Interior elements are all the modular construction treatment for the interior of the built modules, such as panelling systems, flooring and wall treatments, interior partition planning and multi-purpose modular furniture.

Utility Modular Elements: Utility elements include all types of the service elements, such as electrical wiring, water connections and plumping, lighting fixtures and HVAC equipment and any other utility service that is required.

3.2 System Modules

Modules represent the smallest spatial unit; a final product of a set of basic elements grouped together serving a function and its variations through a defined interface. There are two general types of modules (see Figure 3): Standard and Utility, each with its own specific function combinations.

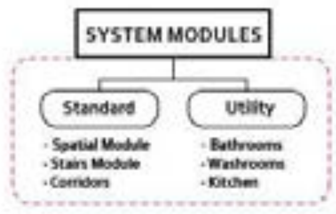


Figure 3; System module types diagram

Standard Modules: Standard modules are the basic forms of the multi-use units; it represents all kind of spaces that are used as rooms that doesn't require special equipment, connection, and utility. The space module can have any function based on the requirements, given that circulation modules are added for their connection if necessary. Variations in standard module are maximized to be able to produce the maximum modular customization options for the user.

Utility Modules: Utility modules are the complementary functional modules for the multi-use units; they represent all kind of general services as a complete stand-alone module. Bathrooms, washrooms and kitchens are the main utility modules; they work as service units for any type of the space combinations. The variation levels of such utility modules are almost minimized to be able to control its efficiency since it's strictly for services only.

System Units & Combinations: Units are the combinations of modules that will form the last stage of the actual design outcome of the modular system. The units represent the full functional architectural entity that could be the start of a community or a neighbourhood for instance; spaces such as: Apartments, housing units, compounds, retails stores, commercial spaces, exhibitions spaces, public buildings & spaces. Units combinations are fully integrated as the main practical outcome of the modular system. The units could be categorized into 3 different groups: Residential, Retail & Commercial, and Mixed Use (see Figure 4).

Figure 4: System units and combinations diagram

- Residential Unit Combinations
Residential category includes all types of housing units' variations and function, whether they are small housing units, multi-bedrooms' apartments, housing compounds or even normal homes (villas).

- Retail & Commercial Unit Combinations
Retail & Commercial category includes all types of multi-disciplinary buildings that serve different functions, which are not residential, or for housing purposes. Buildings such as: Hospitality & Retail, Offices & Administration, Public & Communal, Educational, Industrial & Energy Buildings.

- Mixed Use Unit Combinations
Mixed Use Unit category is a combination of a residential and retail & commercial into one built unit that serve different functions under the same roof of the built structure. Such category is mostly associated with a selection of cases that will require applying the modular system under special circumstances, cases that might be considered socially sensitive, for example, using the modular system approach to re-design an existing "shanty town" settlement in one of the developing countries; providing the people with better solution and a different way of living by having a relatively small mix-used structures like a housing compounds with its own retail shops and small workshops owned by the people who live in the same building.

Urban-Scale & Combinations: Urban-Scale Combinations are the final stage of applying the modular system, it is the level, which a group of units combine together with their different functions and scale and work as one community in the same urban fabric. This stage is not necessarily applied as a full product of this research, rather than it is carefully considered while designing and applying the system, so the system could be more pragmatic towards adapting to large future devolvement. The urban-scale and its combinations are mainly categorized in three aspects as the following diagram (see Figure 5).

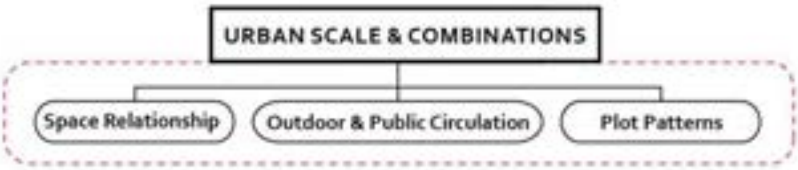


Figure 5: Urban scale combinations diagram

- *Space Relationships*

Space Relationships are the urban space treatment & constraint considerations, it controls the way that modular buildings are connected and the use of space between such buildings, space relationships mainly falls under the privacy & security concerns. Such relationships should be carefully addressed during the early design and planning stages of the modular system, so it can be easily applied in the future of modular buildings growth or functional changes later on. It helps in providing more quality of living for the users of the general urban fabric rather than a random urban settlement with no planned space relationships.

- *Street Layout & Outdoor Circulation*

Street Layout & Outdoor Circulation in urban fabric represent an important aspect of the urban-scale modular system. Street grid, road system and site access are the main parts of a well-designed urban fabric. Such circulations should be designed effectively and carefully, and to be able to easily adapt to the increase of the urban fabric forms without compromising the benefits that was already gained by using the modular system.

- *Plot Patterns*

Plot Patterns are the set of rules that control the overall urban grid layout and the distribution of building plots and site areas while trying to maximize the efficient use of land.

3.2 Variation Levels (The Modular Algorithms)

So far, the modularity concept in this research was introduced as a theoretical approach. Applying the concept of modularity in the built system as a pragmatic approach is defined under the “variation levels” of the system program. The “variation levels” controls the technical data input & output that would eventually lead to the product of this research as final architectural design application. Designated “variation levels” are applicable on all the modular system subdivisions (Elements, Modules, Units and Urban). It controls the selection of different element categories, module combinations, unit combinations and overall urban layout.

Modular “variation levels” depend on many factors and criteria, such as the site & location data, general economic state, selected users & clients and overall delivery of the process (construction & available materials). Those factors are essential for each site condition and individual case. Collecting such data will eventually help in creating the different algorithms & scales that will result in the “variation Levels” choices while using the design process side by side with the data analysis. Overall, to create the final modular design that would fit in almost all the similar site conditions with minimum changes between one site condition and another.

The outcome of the site factors & criteria analysis is the different “variant levels”, which will control the selection and design of the modular system consisting of the four main subdivision categories: Basic elements, system modules, modular unit combinations and urban scale combinations. Those two aspects of the modular systems are working simultaneously and will include a feedback looping system for better design results.

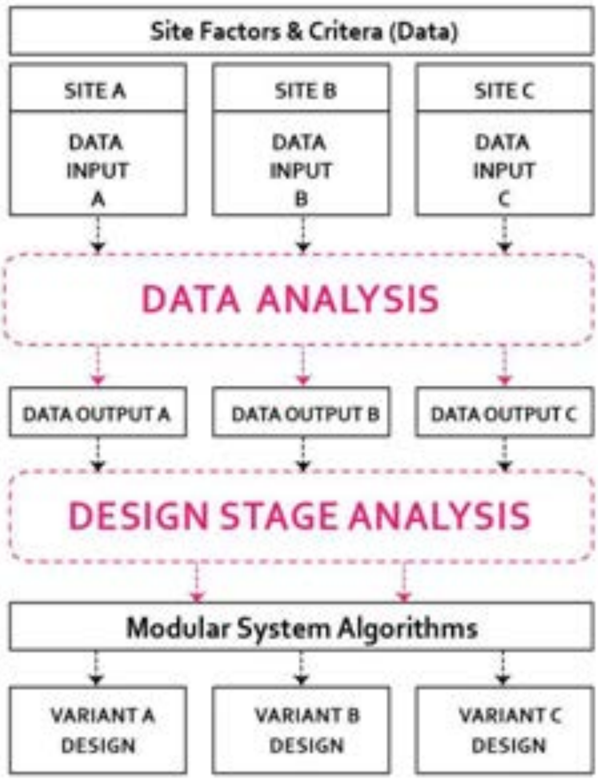


Figure 6: The approach to find the different variant levels

Benefits of Variation Levels: There are two groups of modular variation levels in the system based on the timeline. They are the result of the implementation of the modularity concepts & algorithms during all the stages of the design that will finally affect the modular built system even after it is built, which is one of the main goals for the modular system to have such modular development and flexible system.

Combinations Variation Levels: The basic set of variation levels that affects all the categories starting from the elements up to the unit combinations during the design stage. For instance, it is applied with the first level of elements variations, then the level of the modules variation with each other, then levels of units' variations and their combinations and ending with the urban scale level variations if applied. This will make sure to experience all the possible option throughout all the modular system stages.

Combinations Development Levels: These are the levels, which represent the future development of the already designed & built modular combinations. The scale of planned development which is an alteration of the original design could be as small as simple module's basic elements being upgraded or some modules being developed into a full urban scale project; in both case the construction and the process are happening after the structure has already been used and served its first user, as architects we need to plan for this further development considering the user's needs change over time.

4 Technical Design Approach

4.1 Modular Approach to Addressing the Issues

An important aspect or design approach in the project is that information needs to be broken down and organized modularity. Eventually the modular information turns into modular architecture after being processed by the designed "system" in order to reach the outcome.

4.2 Exploring Concept of Modularity and Its Application

Various scopes pertain to any architectural project. In the initial approach a study was conducted in order to find out how, could the concept of modularity be applied to any of these various scopes of the project. The concept of modularity was explored within the next scopes of the project:

- Modularity implemented in the structural system.
- Modularity implemented as building material.
- Modularity implemented as a living unit.
- Modularity implemented as a spatial division based on functionality.

4.3 The Experimental Design Process

It is quite critical to mention that all different design aspects of this project have been developed hand in hand since they all relate and affect one another strongly and their complete synergy is the only way that allows the functionality of the system.

<u>Comparing Performance of Basic Geometrical Volumes:</u> In the following segment (see Figure 7), the volumetric characteristics of major geometrical shapes have been explored including:

- Their surface to volume ratio, which pertains to energy efficiency.
- Possible clustering and arrangement of the modules next to one another
- Efficiency and geometry of the grid shaped by clustering of the modules.
- Early speculations regarding the interior space and furnisher placement in the module.

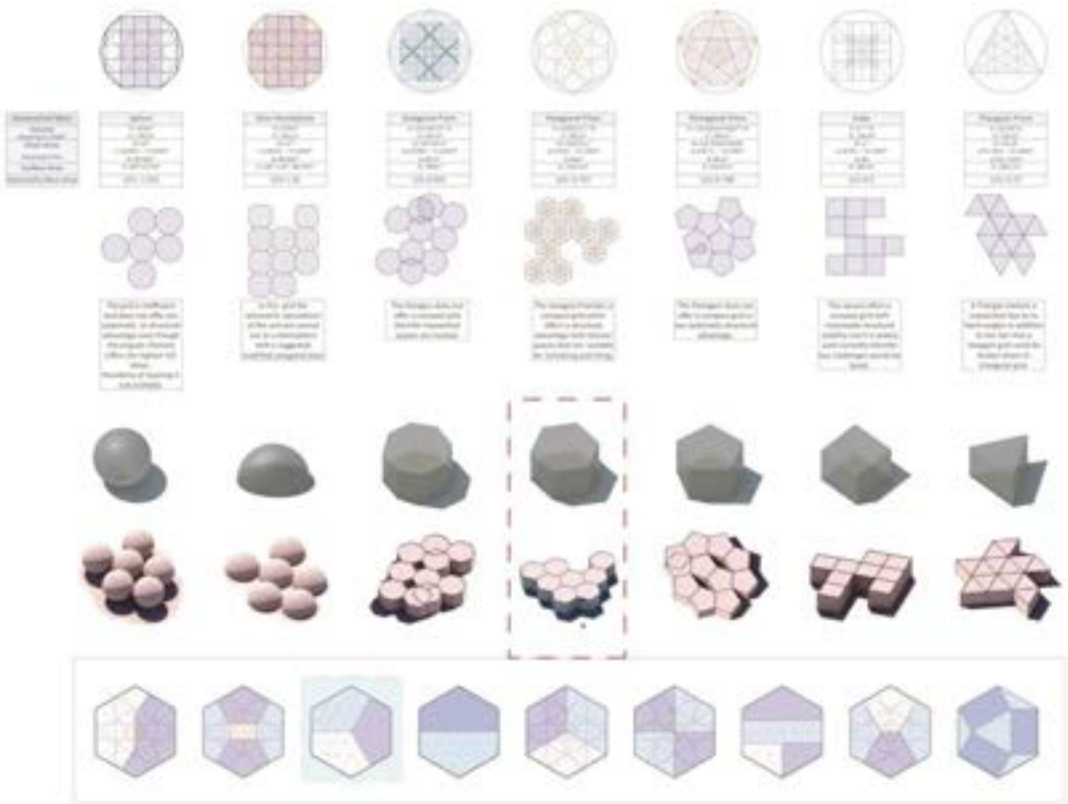


Figure 7: Diagram comparing the performance of basic geometrical volumes

Further Experimenting on the Hexagon: Based on the data provided by the previous segment, one of the two main geometries that were further developed was the hexagon. This volumetric entity was further explored in terms of modularity to create a cleared definition of the module and how the architectural functions and interior furniture are placed within the modules.

What is the Purpose of the "Parameterized Code"? The purpose of the design-parameterized algorithm is to confirm that all of the design aspects are fulfilled and this measure of quality control provides the correct infrastructure to make sure that all different aspects work in synergy with one another. The algorithm helps to create systematic design process, it does not design the modules, the modules are being designed by the architect, and meanwhile, the process is being quality controlled by the code.

4.4 The Module's Grid Parameter

The module's grid parameter is the first "Code Parameter" that is being discussed in this project. The factor distinguishing this grid from any other grid in a fundamental architecture project is that this grid corresponds to all different aspect of the project, it defines the interior spaces and furniture placement while it relates to the structural and clustering properties of the module. The parameterizing feature is the key element that allows further development and correction of the system later on in the project while controlling all the other factors and aspect to make sure all the aspect work in synergy with one another (see Figure 8).

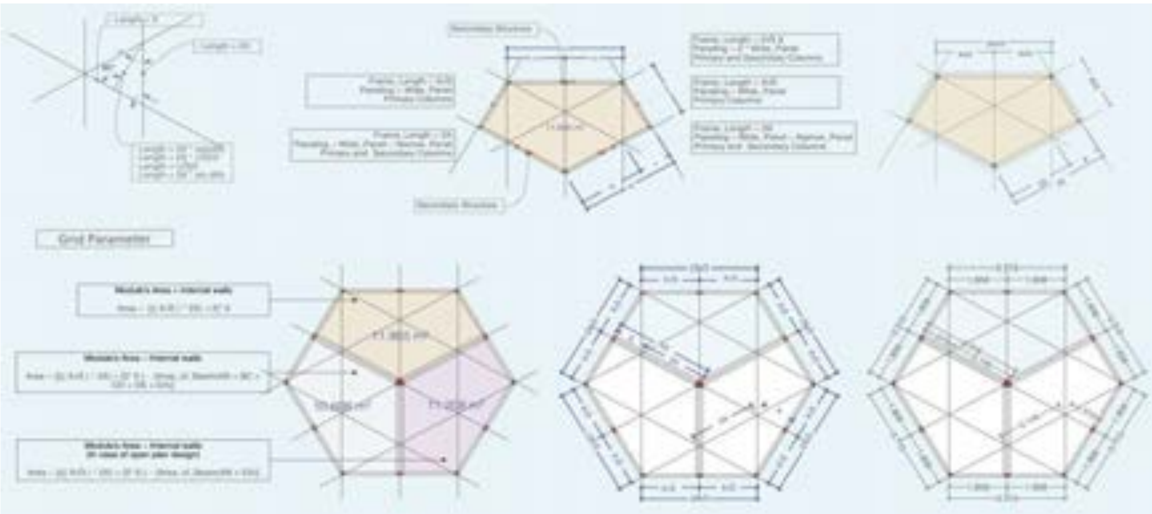


Figure 8: Basic module parameters

The Module's Combinational Parameters: These set of parameters control the probability of how the modules can be clustered and show cases different probabilities of how the modules can be multiplied and placed next to another one (see Figure 9).

Constructional Alternatives of the Module: The various construction alternatives of the module allow the interior division of the module to comply with all of all the required functions that are necessary to respond to different situations.

Functional Alternatives Generated by the Constructional Modules: Following the construction alternatives, various spatial functions and spaces are generated. It is worth mentioning that the construction variations were shaped based on the spatial requirements and their architectural attributes.

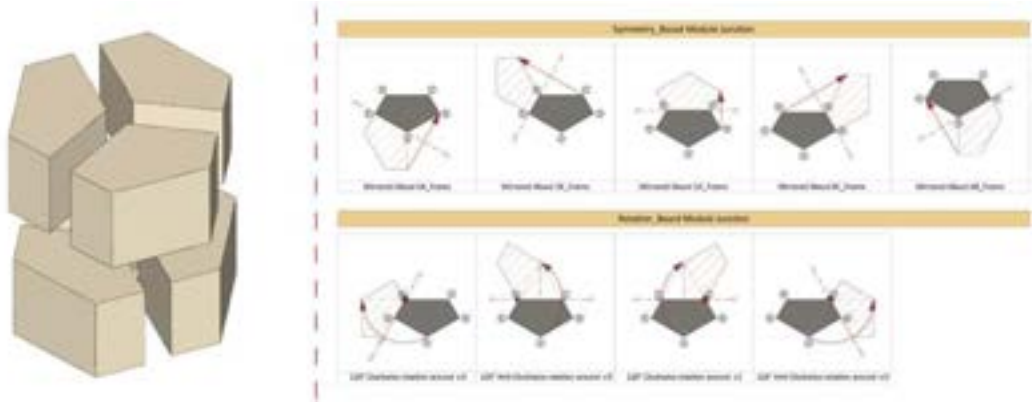


Figure 9: Combinations parameters diagrams

4.5 Module Development as a Unit

<u>*The Basic Units Planning:*</u> The smallest living unit consists of three modules are as follow:

1. Kitchen/bathroom
2. Bedroom
3. Living Room

In the following diagram (see Figure 10), the options and possibilities of the module development have been showcased beside how they can be converted to one another.

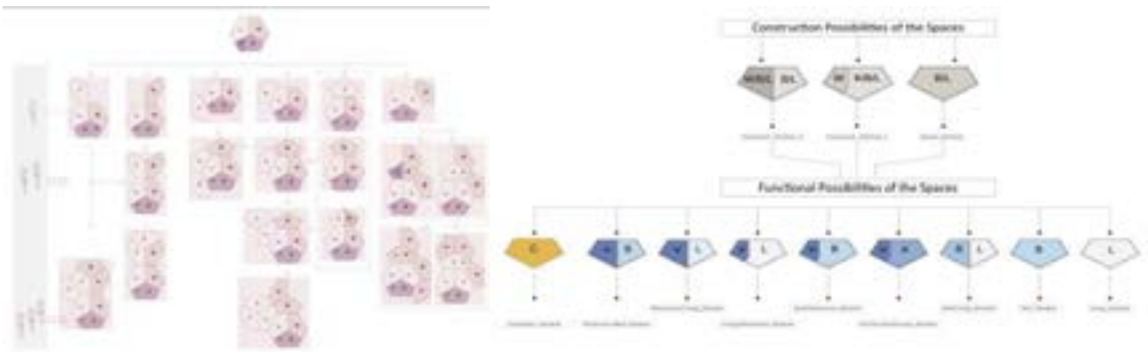


Figure 10: Typical unit expansion (left) and Module types diagram (right)

<u>*Combination Performance Graph:*</u> In the following graph (see Figure 11), a study was conducted to evaluate different modular combinations and compares them to one another in terms of Surface/Volume ratio, which pertains to energy efficiency. It is fair to mention that there are certain combinations that have a better energy performance and the selection of the correct unit should take into consideration many factors (Philip and Alan 2014)

Figure 11: Volume / surface area chart

Furniture Activity Space: Furniture placement was one of major deciding factors in grid and dimensional measurements that determined the size of the module, given that there are numerous possibilities on how the modules could be connected to one another, it would be impossible to design each furniture layout individually. The following segments account for all of the possible furniture layouts by breaking the modules apart and proof that there is sufficient furniture space regardless of the point of entrance (see Figure 12).

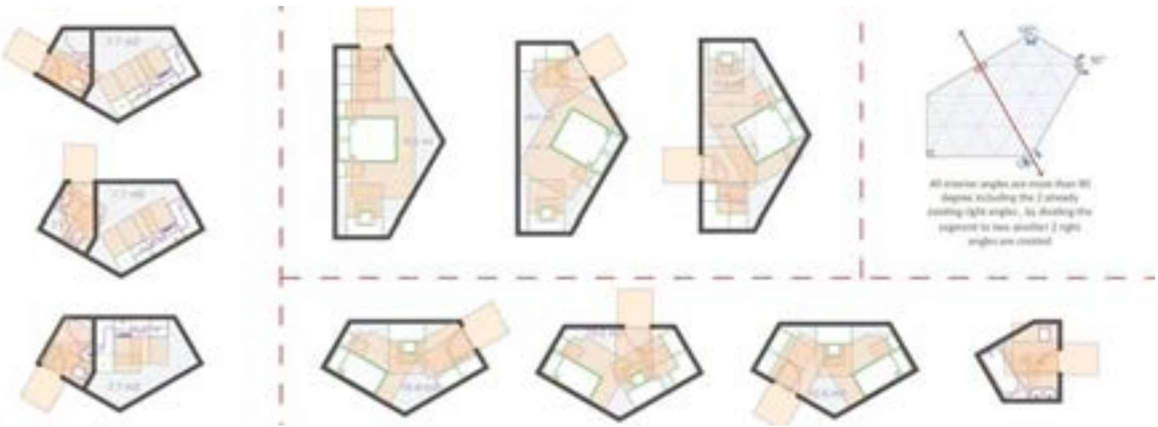


Figure 12: Furniture placement spaces

General Main Plan Samples:

6 Modules - Accommodating Three Occupants		
Type of Zone	Area (m^2)	Area percentage
Building Foot-Print	75.5	100 %
Internal Area+ Interior walls	71.7	94% [illegible]
Livin Space	22.7	31 % [illegible]
Kitchen	8	11%
Bedroom+Washroom	21.6	30 %
Bedroom	11.5	16 %
Bathroom	2.7	3.7 %
Surface Area	274 (m^2)	Area percentage
Volume	245.4 (m^3)	Area percentage
Volume - (surface/volume)	1.11 (m^{-1})	Area percentage

Minimal unit - 3 Modules - Accommodating One Occupant		
Type of Zone	Area (m^2)	Area percentage
Building Foot-Print	38.2	100 %
Internal Area+ Interior walls	37.2	97% [illegible]
Livin Space	11.4	30 % [illegible]
Kitchen+Dining	8.0	21%
Bedroom	11.05	29 %
Bathroom	2.72	7 %
Surface Area	151.15 (m^2)	Area percentage
Volume	124.15 (m^3)	Area percentage
surface/volume	1.217(m^{-1})	Area percentage

Figure 13: Sample plans with details

4.6 The Modular Structural System

Designing the structure and construction details for the modular system was one of the most critical stages throughout the design process, taking in consideration the level of details and considering the high need of design combinability between all the design aspects, such as architectural design quality, structure loads, construction process and material. The main building material of the structural elements is steel, including the 3 main structural elements: The cap, the frame and the joints (see Figure 14 and 15).

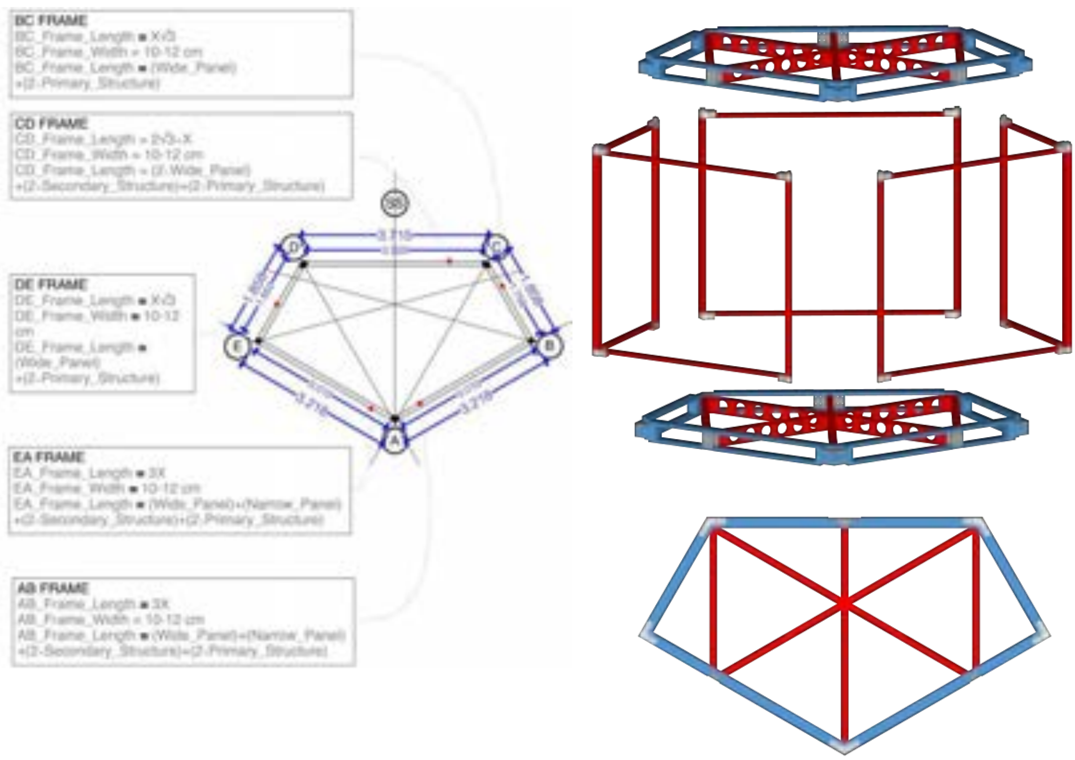


Figure 14: General structure design parameters (left) and Main steel frame and cap system (right)

Some structural system design elements were partially inspired by (Vector Praxis 2014).

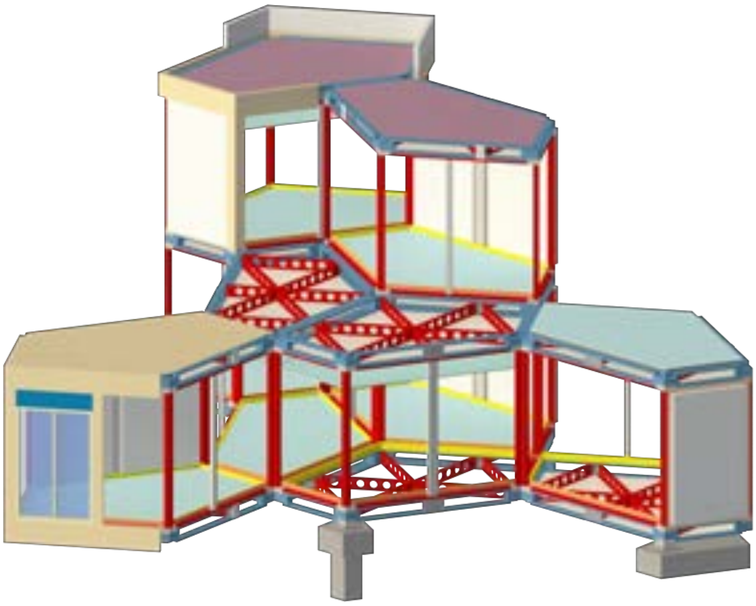


Figure 15: General model showing all structural elements

4.7 The Modular Panelling System

Wide / Narrow Panels Design Modular Calculations:

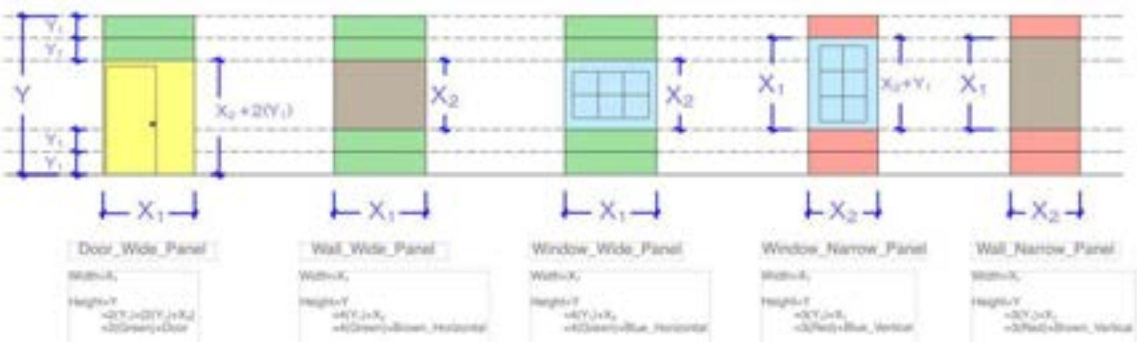
Frame_BC = Frame_DE = X√3
Frame_CD = 2(Frame_BC) or 2(Frame_DE) = 2*(X√3) = 2X√3
(Frame_AB) or (Frame_EA) > (Frame_BD) or (Frame_DE) = 3X > X√3

∵ BC :: CD :: DE

∴ They can all share the same panelling units, which is the Wide_Panel

Since the only Frames not directly proportional with the rest of the frames are the AB_Frame and EA_Frame there are two possibilities
If AB or EA < BC or DE → AB_Panel = AB's Length
If AB or EA > BC or DE → (Frame_AB) − (Frame_BC) = Narrow_Panel
Narrow_Panel = AB − BC = AB − $_{1/2}$CD

The width of the Narrow_Panel (Red_Panel) could be calculated as a result of difference in width of the AB frame verses BC or $_{1/2}$CD.



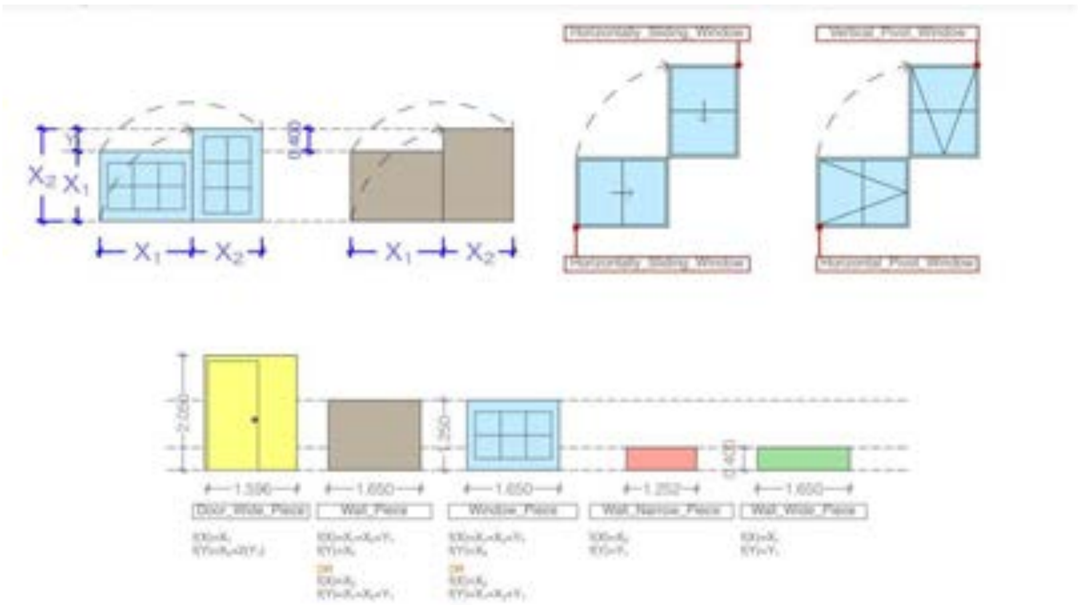


Figure 16: Window panel calculations

For the initial calculations the width of the joints have been disregarded since the width of the frames and panels are dependent on the grid dimensions and the calculations include first order mathematical operation (multiplication, division and square root), which cannot be mixed with the 2nd order operations (addition and subtraction) and they would bring many complications into the equation, once the general logic behind the overall frames and panels were decided the joint dimensions were integrated with the panels to design the precise construction pieces that would fit into the original planned spatial dimensions.

How was the Width and length of the Green/Red wall Piece Decided?;

The lengths of the wall segments were predetermined by the width of the panel size that they are installed upon. Length_Wall_segment = Width_Panel

The width of the wall pieces was critical since they determine the segmentation of the panels' pieces, which ultimately allow the placement of the window and door elements within the fixed height of the panel without a gap.

Y=Constant ∵ the constant distance between floor levels.

$$X_1 - X_2 = Y_1$$

Rotations of the elements do not create an issue since the difference in height between the vertical and horizontal alignment of the same element equals to the red/green wall segments.

- *Segmentation of the panels*

The segmentation of the panels is to create a more efficient production line by minimizing the number of pieces to be produced that is capable of satisfy all of the design requirements given by different projects. These segments are adjusted into the panel in the factory for quality controlling purposes but they would still offer some flexibility in the future in case further change or requirement is needed.

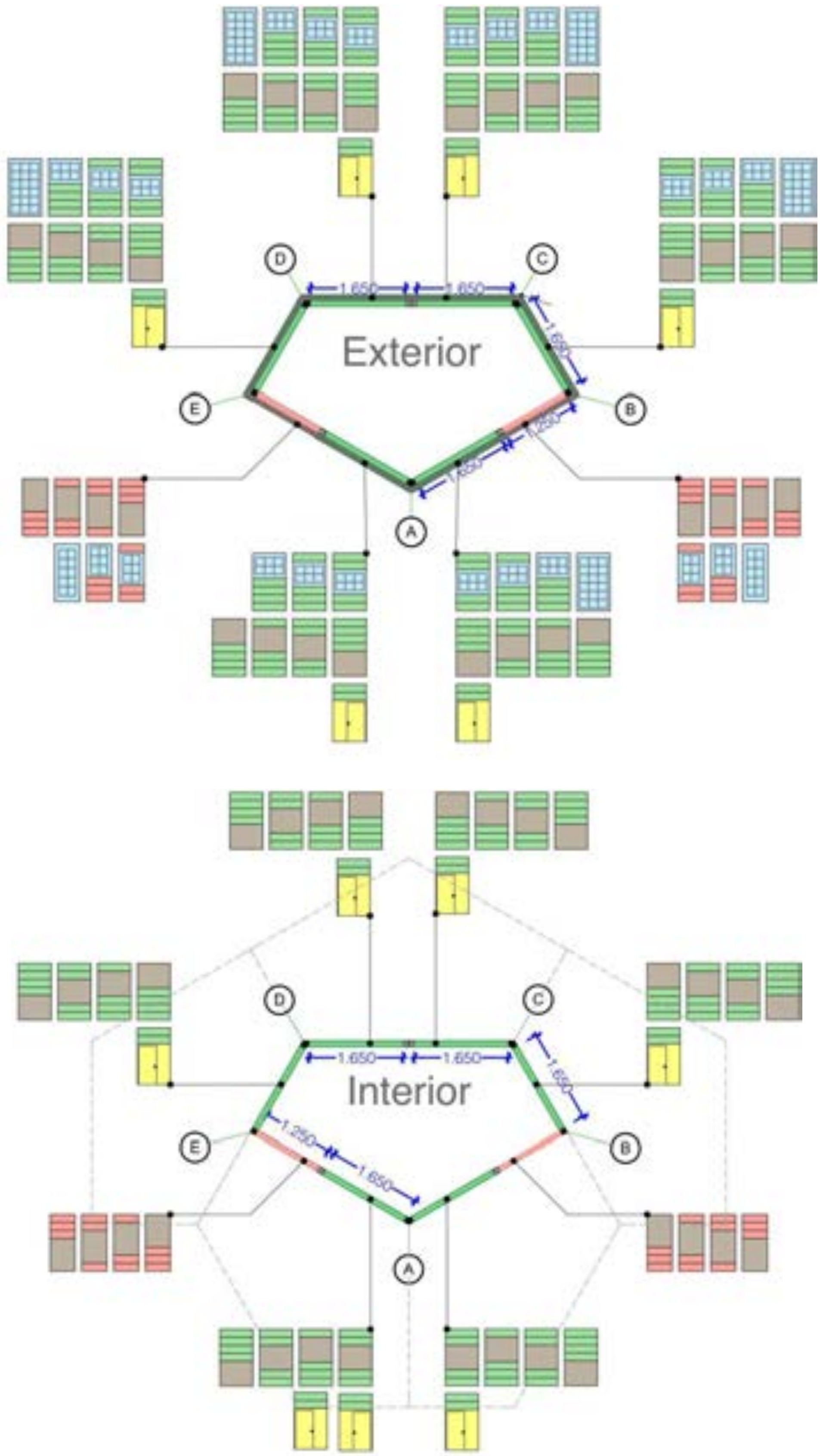


Figure 17: Windows and wall segmentation

3. The Modular Units Clustering

5.1 Units Combination Library

The most important factor affecting the design program of any residential unit is the number of occupants. The final living unit consists of modules that are combined based on the parameters that dictate the duplication and adjoining of the units, that being said not all of the created modules are suitable or at the have the highest living quality. In the following table (see Figure 18), different modules have been explored based on the number of occupants and the preferably factor that decides the living quality of the space.

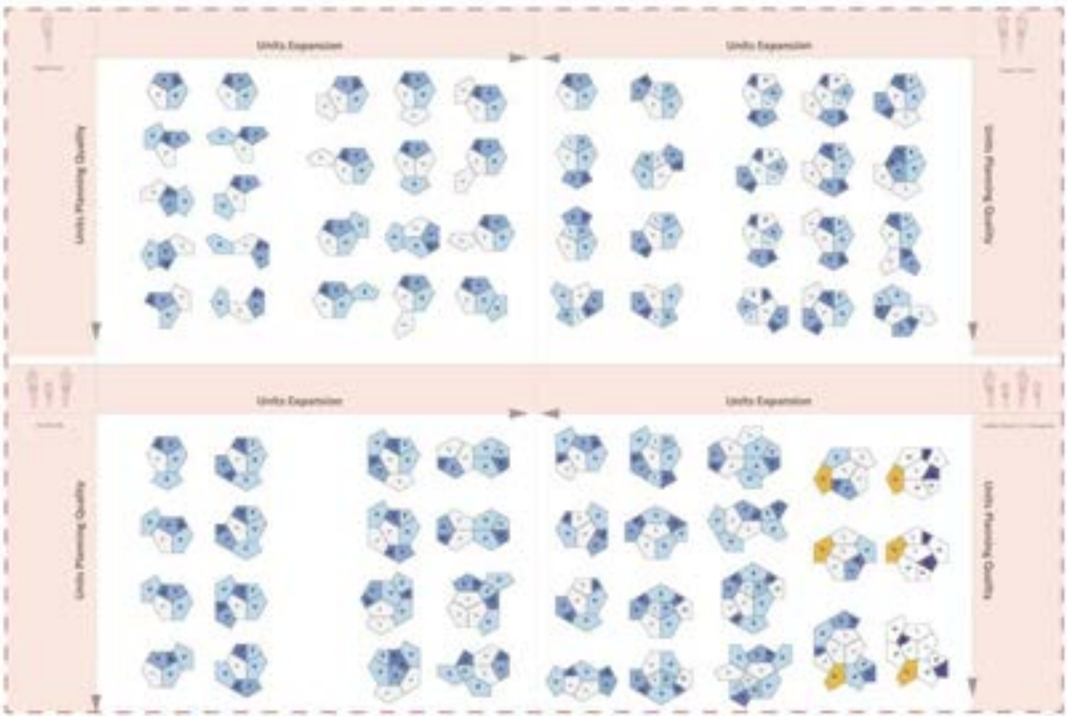


Figure 18: One person/ small family unit library

5.2 System Break Down (Urban design Strategy)

The system breakdown diagram illustrates the micro to macro transition of the modules and how the basic module is developed into the urban level. In addition, this diagram (see Figure 19) also illustrates the designing principles that the urban clusters are further developed in the later stage.

Figure 19: Modular system clustering diagram

5.3 Urban Clustering Combination

Similar to designing units, the design program depends on the requirements and different factors that shape the design decisions. In this segment of the research, there are various urban clusters and formation that are experimented upon based on different requirements and condition.

Unit Features:

- Number of bed space per unit.
- Number of living modules per occupant.
- Number of modules used in a living unit.
- Number of Washrooms per occupant.

Cluster Features:

- Number of occupants per primary cluster.
- Number of possible circulation accesses that can serve all of the units.
- Land efficiency of the cluster in terms of building foot print to total area used as the exterior space.
- Relative cost of the unit based on the theoretical pricing theory.

Figure 20: General clustering examples

4. Conclusions

The experimental modular design in geometry and structural systems opened the scope of the modular design represented in this paper, reaching a much wider scale of options for modular design and its applications. From a small module to a large scale urban context. One of the main goals in this paper was the design of the system and hierarchy itself, which is meant to be studied further maybe with other different shape of experimental modules. Parametric-based design was a successful approach for such a research, and allowed adding new elements and parameters or detailed level of system design based on different locations and circumstances.

Moreover, from the user perspective, the modular system design will bring new methods of building communities and owner-occupied houses for different types of users with lower costs and better options, covering the economic, environmental and occupant's needs, and overall conserved with the global rapid increase of population.

Overall, the outcome of the study was a highly efficient research-based design for all the living and functional spaces in the built system based on one uniform module that could be arranged in many different units and scales for living spaces. With high concentration on the level of innovation in pre-fab modular design.

Acknowledgements

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THERMO-ENERGETIC PERFORMANCE OF WOOD FRAME PANELS IN BRAZILIAN LOW-INCOME HOUSING

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Abstract: *The large amount of waste generated by the construction of new buildings has been damaging the environment. Due to an increasing number of housing developments delivered in conventional systems in Brazil, such as concrete and brick, natural resources are becoming scarce. As an alternative, the wood frame technology uses less water and energy in the construction process, allows prefabrication, reduces construction time and reduces waste. However, the energy efficiency performance of light construction systems has not been thoroughly investigated in the country. Thus, this study aims to analyses the energy performance of three wood frame panel compositions when applied to low-income houses, which accounts to a greater percentage of the typical housing demand in Brazil. For this, simulations were performed in a wood frame house and compared to the baseline study. Energy Plus software, the Technical Quality Regulation for the Energy Efficiency Level of Residential Buildings (RTQ-R) and ABNT NBR 15575, a Brazilian building code, were used for carrying out the simulations. Three Brazilian cities located in various bioclimatic zones were analysed: Curitiba (bioclimatic zone 1), São Paulo (bioclimatic zone 3) and Salvador (bioclimatic zone 8). The results show which panel composition guarantees better level of energy efficiency under the natural ventilation condition and when artificially conditioned. It demonstrated the need to adapt the composition of wood frame panels as well as interventions in the housing envelope to obtain better levels of efficiency, according to the index of degree hour for cooling and energy consumption.*

Keywords: *Low-income Housing, Thermal Performance Simulation, Energy Efficiency, Wood Frame Panels*

1 Introduction

In view of the high housing deficit in Brazil, about six million residences (Fundação João Pinheiro, 2016), the Brazilian federal government instituted the program "Minha Casa, Minha Vida" (MCMV). The program aims to stimulate the construction of new housing units and facilitate the low-income population access to financing the acquisition of residential properties (Amorin and Vieira, 2016, Chechinel et al., 2016 and Indiviata et al., 2016). In this program, the cost of producing real estate is extremely important, due to the limitation in the amount of financing by the bank responsible for the management of financial resources, Caixa Econômica Federal (CEF).

In this sense, several construction systems have been used to reduce costs and accelerate the production process, such as monolithic concrete walls, concrete blocks, steel frame and wood frame (Amorin and Vieira, 2016). The wood frame construction system is an advantageous option due to the abundant amount of wood in Brazil, where there is the second largest forest cover in the world (BNDES, 2002). In addition, the country has an enormous potential for the production of reforested wood, such as Eucalyptus and Pinus, which together with sustainable management contributes to reversing the degradation process of natural resources. Its use in civil construction was mainly in the South of Brazil as part of the cultural tradition of the region, influenced by English, Italian, German and Polish colonization (Laroca, 2007, Suzuki and Kruger, 2010, Amorin and Vieira, 2016).

According to Molina and Calil (2010), the wood frame construction system is convenient for: being industrialized; waste reduction, which cause major environmental impacts on traditional systems; increasing productivity, as the construction work is clean and dry and for its ease handling of structural elements and vertical sealing plates. However, the lack of knowledge about wood construction technology as well as the poor use of the technique has led to unsuccessful experiences in Brazil, including thermal performance. In addition, customers tend to have a certain bias regarding wood construction, being associated with poverty and poor quality (Laroca, 2007).

In Brazil, studies on thermal performance of housings are evaluated by the ABNT NBR 15575:2013 code and by the Quality Technical Regulation of Energy Efficiency Level for Residential Buildings-RTQ-R (BRAZIL, 2012). The NBR 15575 code (ABNT, 2013) presents requirements, criteria and methods for assessing the thermal performance of vertical sealing systems of buildings. The systems can be evaluated separately by the simplified (normative) method, calculated by thermal properties, thermal transmittance (U) and thermal capacity (CT), or by computational simulations, in this case, considering the overall response of the building. For the simplified method, the code permits maximum thermal transmittance values (U value) of 2.5 W/m².K or 3.7 W/m².K and minimum values of thermal capacity (CT) of 130 KJ/m².K, according to the region of Brazil.

Light construction systems, such as wood frame, are composed of elements with low density. They have low thermal mass and, consequently, low thermal capacity, below the minimum required value. In this case, the code recommends the analysis by

computational simulations. Thus, it is observed that the normalization existing in the country makes difficult the diffusion of the use of light construction technologies for external seal, so that more specific studies in thermal capacity parameter are necessary (Rocha et al., 2016).

On the other hand, the RTQ-R (BRAZIL, 2012), which regulates the Brazilian Program for Building Labeling, specifies criteria for classifying the energy efficiency level of autonomous housing. The housing envelope should be analysed from three criteria: efficiency in summer, when naturally ventilated; efficiency in winter, when heated artificially; and efficiency when artificially cooled, the latter being only informative. Figure 1 shows the National Energy Conservation Label (ENCE) of an autonomous housing unit, including evaluation of housing envelope systems for summer, housing envelope systems for winter, and water heating system.

Figure 1: National energy conservation label for autonomous housing
(Source: http://www.procelinfo.com.br)

Some studies have been carried out to evaluate the thermal energy performance of housings with light construction systems. Nevertheless, there is no clear understanding of what the composition of a light construction panel should be, so that it adequately meets the climatic requirements of each region. Rocha et al. (2016) carried out a simulation study in the city of São Paulo, demonstrating that a building with a lightweight facade composed of cement boards, a 90 mm fiber glass wool blanket, a 50 mm air chamber and two gypsum plasterboards showed performance similar to the masonry facade of ceramic blocks. Amorin and Vieira (2016), when comparing the energy efficiency levels of wood frame and masonry seals, found lower values of cooling degree-hour and relative annual consumption for wood panels, indicating the greater

thermal comfort provided by it. In both works, the light construction panel enveloping did not reach the minimum value of thermal capacity specified by the NBR 15575 code (ABNT, 2013).

On the other hand, in Donatello, Nico-Rodrigues and Alvarez (2013), when evaluating the thermal performance of a solid wood housing, obtained a level D of energy efficiency, demonstrating the lack of dominance of wood employment nowadays. Marcelino and Leite (2016) emphasize the benefit of thermal resistance property when comparing a traditional masonry housing with masonry carried out with the ETICS[1] system, evidencing the influence of using a thermal insulation, such as expanded polystyrene (EPS) in the thermal performance of the construction system.

In this sense, this work aims to analyse the thermo-energetic performance of different wood frame panel compositions for social housing by using the Brazilian Labeling Regulation for Residential Buildings, and considering three different Brazilian climatic conditions represented by the cities of Curitiba, São Paulo and Salvador.

2 Method

2.1 Object of the study

The building under analysis consists of a single-family residential house in the Housing Program “Minha Casa, Minha Vida", established by Caixa Econômica Federal. The house (Fig. 2), with an area of 41.3 m² and a height of 2.55 m, has two bedrooms and a combined living room / kitchen.

Figure 2: Ground floor and building section
(Source: authors)

[1] External Thermal Insulation Composite Systems

The building was developed by TecVerde company, and it is marketed throughout the country. The external vertical seals of the houses are usually constituted by cement boards, OSB board, pine wood structure, non-ventilated air chamber, OSB board and a gypsum plasterboard, from the outside to the inside part (Fig. 3). The internal seals are composed of a layer of gypsum plasterboard, followed by an OSB board, pine wood structure, air chamber, another OSB board and gypsum plasterboard. The floor is composed of slab foundation (radier) of 15 cm, which is in direct contact with the ground, laying mortar and ceramic tile flooring. The roof is composed of ceramic tile, wood structure, fiber glass wool of 10 cm and PVC lining. There are sliding windows with simple colorless single glazing of 3 mm, with no shading elements.

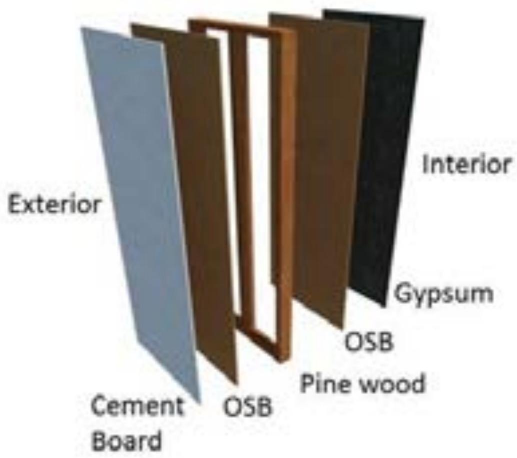

Figure 3: Light construction sealing system section
(Source: authors)

Three light construction panel compositions were elaborated for comparative analysis in order to evaluate the thermal performance of the housing envelope. The base case, named Case 1, represents the original panel delivered by the company (Fig. 3). The other three light construction panel compositions were named as Cases 2, 3 and 4. The performance of the building with light construction panels was compared to the performance of the same building when composed of masonry seals with ceramic blocks (Case 5), most commonly used in Brazil. The floor, ceiling, roof and internal walls were not altered, except in the analysis of masonry, which internal walls were also modified. Solar absorptance of 0.46 was adopted for the external seals, corresponding to the weighting of the white and dark green colors, according to Figure 2.

Figure 4 shows the graphical representation of the panels composed of homogeneous layers, perpendicular to the heat flow. This figure indicates the thermal properties of Thermal Transmittance (U) and Thermal Capacity (CT) according to the calculation method defined by the NBR 15220-2 code (ABNT, 2005). The materials used and their physical properties are shown in Table 1.

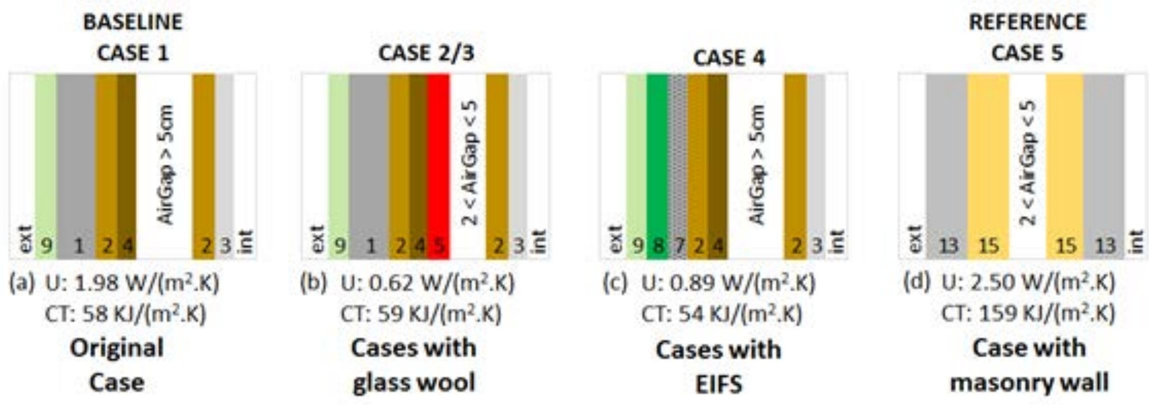

Figure 4: Composition of walls and their thermal properties
(Source: authors)

Table 1: Materials for internal and external seals
(Source: authors)

	Material	Tickness (m)	Thermal Property: Thermal conductivity (W/(m.K))	Thermal Property: Specific heat (kJ/(kg.K))	Thermal Property: Density (kg/m^3)
1	Cement Board	0,008	1,75	1	1700
2	Oriented Strand Board	0,0095	0,17	2,3	681
3	Gypsum wallboard	0,0125	0,35	0,84	750
4	Pine wood	0,0015	0,15	1,34	494
5	Glass wool (wall)	0,05	0,045	0,7	10,53
6	Glass wool (roof)	0,1	0,045	0,7	10,53
7	EPS - insulation board	0,025	0,04	1,42	16
8	Basecoat (EIFS)	0,005	1,15	1	1840
9	Acrylic finish	0,003	1,15	1	2000
10	Roof tile	0,02	1,05	0,92	2000
11	Ceiling PVC panels	0,01	0,20	0,96	1300
12	Radier - concrete	0,15	1,75	1	2200
13	Mortar	0,025	1,15	1	2000
14	Ceramic floor	0,01	0,90	0,92	1600
15	Clay Brick	0,014	1,05	0,92	2290

Case 1 represents the Base Case. Case 2 has an insulating material of 5 cm (fiber glass wool). Case 3 is composed of the same panel of Case 2, with a clear paint (α = 0.3) in the cover in order to reduce its solar absorptance. Case 4 has a clear paint in the cover and is composed of the Exterior Insulation and Finish Systems (EIFS), with the replacement of the cement board by expanded polystyrene. Finally, Case 5 (Reference case) represents the ceramic block masonry.

2.2 Climatic conditions analyzed
The NBR 15520-3:2005 code establishes the Brazilian bioclimatic zoning, subdividing the country into 8 Bioclimatic Zones according to the climatic conditions of each region. For the analysis of building, three Bioclimatic Zones with extreme characteristics were assessed. Thus, computational simulations were performed for Bioclimatic Zones 1, 3 and 8, represented by the cities of Curitiba (25° 25' 40” S, 49° 16' 13” W, 934 m), São Paulo (23° 32' 56” S, 46° 38' 20” W, 745 m) and Salvador (12° 58' 13” S, 38° 30' 45” W, 12 m) (Fig. 5). The Bioclimatic Zone 1 denotes a predominantly cold climate, with a cold winter and mild summer, in addition to high daily thermal amplitude. Rains are well distributed during the year, but more concentrated in the summer. The Bioclimatic Zone 3, on the other hand, is characterized by regions of milder climate, with dry and cold winters and humid and hot summers. The Bioclimatic Zone 8 is a region of hot and humid climate, with rains throughout the year (Ferreira, Souza and Assis, 2014).

The weather data are made available by the Laboratory of Energy Efficiency of Buildings (LabEEE) in the TRY format (Test reference year).

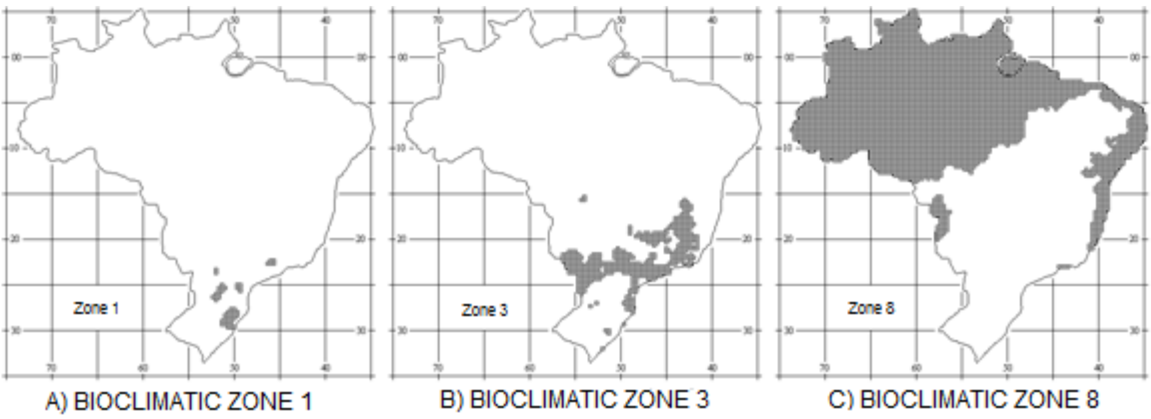

Figure 5: Brazilian Bioclimatic Mapping
(Source: adapted from ABNT NBR 15220-3:2005)

2.3 Thermo-energetic simulations
The housing performance was assessed by the computer simulation method of the Technical Regulation of Quality for the Energy Efficiency Level of Residential Buildings (RTQ-R), which classifies housing in levels of energy efficiency from "A" (more efficient) to "E" (less efficient).

The simulations were performed using the EnergyPlus software version 8.5. SketchUp software was adopted with the help of the Euclid plug-in to facilitate the geometry modeling process.

The RTQ-R establishes patterns of occupancy (Fig. 6) and lighting (Fig. 7) for weekdays and weekends, as well as the internal load of people and equipment to be considered in the simulations.

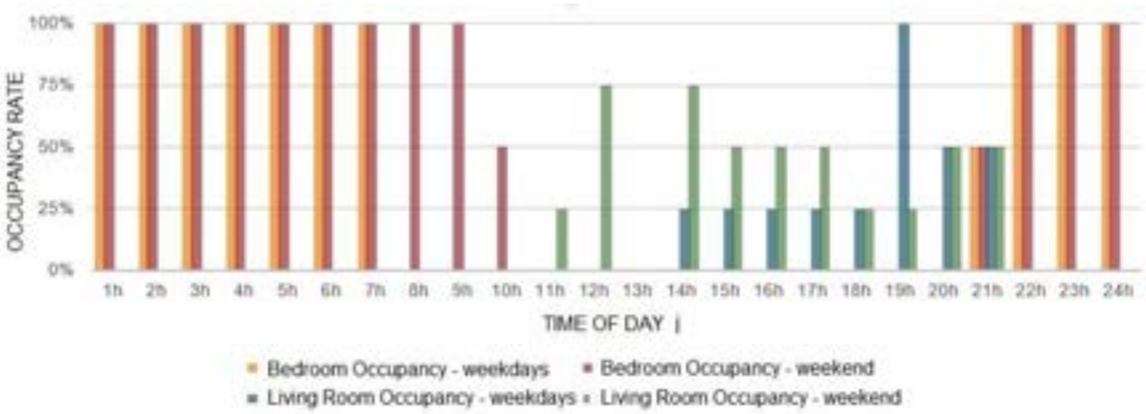

Figure 6: Occupancy pattern for weekdays and the weekend
(Source: adapted from Brasil, 2012)

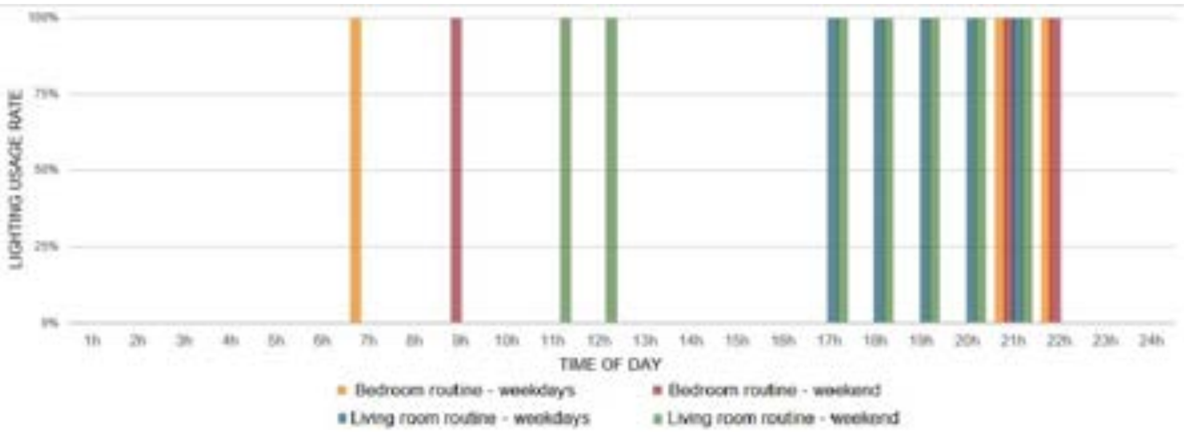

Figure 7: Lighting pattern for weekdays and the weekend
(Source: adapted from Brazil, 2012)

Four people were considered as the house occupants in the simulation. For the living room, occupants were considered sitting or watching television, producing 108 W for a standard skin area of 1.80 m². While for the bedroom it was considered that people were sleeping or resting, contributing with 81 W. Likewise, the internal load of equipment is standardized by the RTQ-R at 1.5 W / m², just for the living room.

The house envelope was analyzed in two stages: when naturally ventilated and when artificially conditioned. The natural ventilation was analyzed for the summer situation, where the performance indicator was cooling degree-hour (DH_C) of the extended housing environments. The indicator is calculated from the hourly operating temperature (T_0), i.e., an average value between the air temperature and the average radiant temperature. The DH_C consists of the annual sum of degree-hour above the reference temperature of 26 °C, given by the Equation 2.1.

$$DH_C = \sum_{n=1}^{\infty} (T_0 - 26°) \tag{2.1}$$

Where:
DH_C: cooling degree-hour indicator;
T_0: hourly operating temperature (°C).

For the building modeling, when naturally ventilated, an automatic control device for window openings whenever the internal temperature of the air was greater than or equal to 20 °C was adopted.

The artificially conditioned building was analyzed in the winter situation, by the relative energy consumption for heating (C_H) and, when cooling, by the relative energy consumption for cooling (C_C). These energy consumptions are calculated considering the use of Split type air conditioners from 09 pm to 8 am, being ventilated naturally the rest of the time. For heating, the thermostat temperature was 22 °C and for cooling 24 °C.

For the classification of the building energy efficiency level, the performance of the building in the summer (naturally ventilated) and in winter (artificial heating) was considered, where the performance for cooling (artificial) was informative only. For each case and environment, a numerical equivalent was determined, which consists of a representative value of the energy efficiency levels, ranging from 1 (level E) to 5 (level A). They were obtained by comparing the results obtained by simulation with reference tables according to each Brazilian Bioclimatic Zone. Each environment received a numerical equivalent of the environment envelope for cooling (EqNumEnvAmbResfr) and a numerical equivalent of the environment envelope for heating (EqNumEnvAmbA). These indexes are weighted according to the area of the environment, obtaining a final numerical equivalent, for cooling and heating. The numerical equivalent of the autonomous housing unit envelope is calculated by the Equations 2.2, 2.3 and 2.4, for the Bioclimatic Zones ZB1, ZB3 and ZB8, respectively. In the case of the ZB8, as it is a region with high temperatures throughout the year, it is not considered the thermal energy performance of the housing envelope for winter.

$$EqNumEnv = 0.08\ x\ EqNumEnv_{Resfr} + 0.92\ x\ EqNumEnv_A \tag{2.2}$$

$$EqNumEnv = 0.64\ x\ EqNumEnv_{Resfr} + 0.36\ x\ EqNumEnv_A \tag{2.3}$$

$$EqNumEnv = EqNumEnv_{Resfr} \tag{2.4}$$

3 Results

3.1 Bioclimatic Zone 1 – Curitiba

Figure 8 shows the performance results for summer, the Curitiba city´s climate, with the efficiency level limitations (from A to E) for the degree-hour (GHr) indicator. It is observed that the original case (Case 1) showed inferior performance than masonry (Case 5). Curitiba, due to its high daily temperature range (about 10 °C), requires thermal mass to dampen temperature variations, a characteristic that does not exist in light construction systems. Therefore, the use of insulating materials for Curitiba´s climate becomes

essential to increase the thermal resistance of wood frame systems.

In the simulation, even with the use of an insulating material such as fiber glass wool or the EIFS system associated with a clear cover of low solar absorptance, the wood frame system did not show a result as satisfactory as the ceramic block masonry. Thus, it would be necessary to further increase the panel insulation with greater thickness of fiber glass wool or EPS to obtain a higher thermal resistance, thus getting leveled with the masonry.

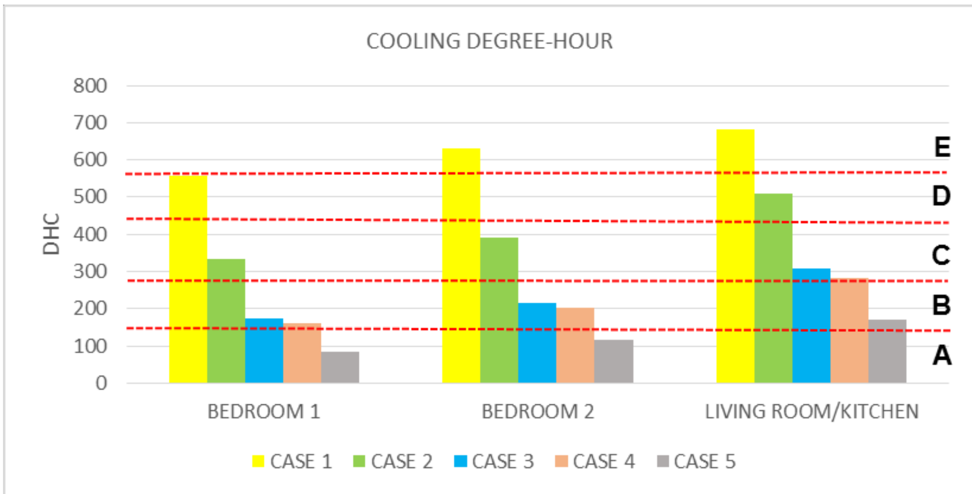

Figure 8: Degree-hour cooling indicator for each environment in Curitiba
(Source: authors)

Figure 9 indicates the performance results for winter, through the energy consumption, delimited by the level of energy efficiency. It can be observed that the low thermal transmittance of wood frame panels gave the housing better energy efficiency results than heavy seal, masonry, for the winter condition. The low thermal transmittance provides reduction of heat losses from the internal environment (warmer) to the external environment (colder). It is also observed that the living room/kitchen obtained inferior performance than the other extended housing environments because it has the wall with larger area facing to the South, side that does not receive solar incidence throughout the year. On the other hand, the bedrooms showed a good thermo-energetic performance, with the openings facing the North, which is favorable for the solar incidence in the coldest months. It is noteworthy that light construction systems have presented better performance in relation to masonry, where the cases with fiber glass wool have shown to be slightly more efficient in winter.

Figure 10 shows the performance results of the housing unit when artificially cooled, through the relative energy consumption indicator for cooling. It is observed that for night-time cooling, the bedrooms have shown worse performance in relation to the living room/kitchen due to the great incidence of solar radiation through the openings (without sun protection). In general, the results were similar for the different housing envelopes demonstrating the greater influence of the solar incidence on the energy consumption results for cooling. In relation to the light construction system, it can be observed that in

this case the EIFS system with the clear cover can better isolate the environment, obtaining results that are practically equal or better than the masonry in dorms.

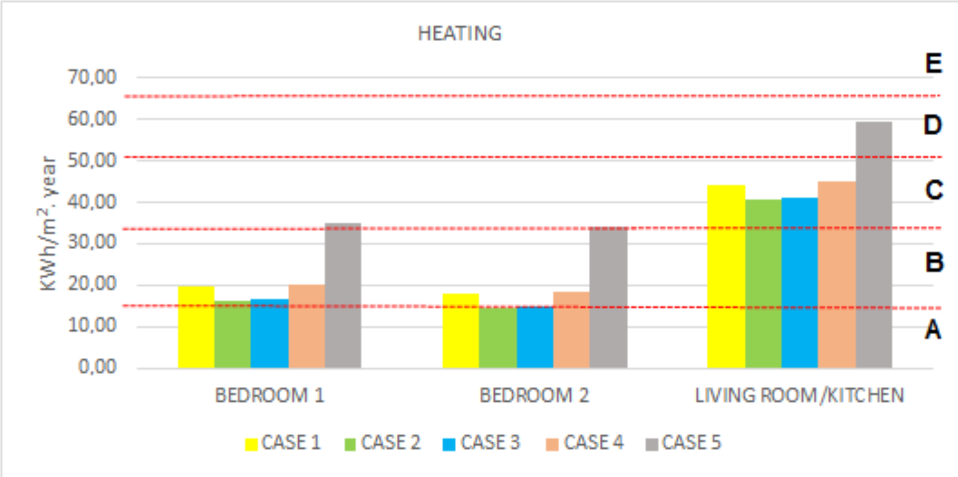

Figure 9: Energy consumption for heating each environment in Curitiba
(Source: authors)

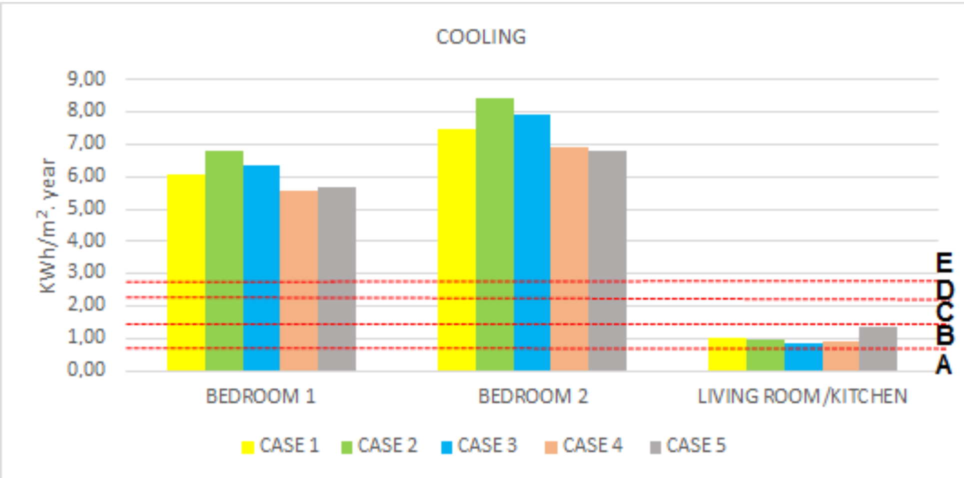

Figure 10: Energy consumption for cooling each environment in Curitiba
(Source: authors)

Table 2 shows the final energy efficiency levels for the housing unit located in Curitiba, obtaining level C for the cases 1 and 5, and level B for the cases 2, 3 and 4. It is observed that, although the light construction systems show lower performance when naturally ventilated (summer), they are more efficient for the winter condition, which shows greater weight in the final performance result (see equation 2.2). However, with simple strategies such as increasing the insulation of sealing panels it is possible to reach the level of energy efficiency of the masonry.

Table 2: Housing energy efficiency levels for each housing envelope in Curitiba
(Source: authors)

Envelope Efficiency - Curitiba					
	Case 1	Case 2	Case 3	Case 4	Case 5
Natural Ventilation	E	C	B	B	A
	1.2	2.5	3.5	4	4.5
Heating	B	B	B	B	C
	3.5	3.9	3.7	3.7	2.5
Cooling	C	C	C	C	C
	2.6	2.6	2.6	2.6	2.6
Final Efficiency	C	B	B	B	C
	3.3	3.8	3.7	3.7	2.7

3.2 Bioclimatic Zone 3 – São Paulo

Figure 11 shows the summer results for the city of São Paulo. As in Curitiba, the wood frame panel without the inclusion of thermal insulation (case 1) obtained the worst performance. The inclusion of rock wool and clear cover or to the EIFS system and clear cover provided very similar results to masonry, especially in dorms. It is observed that for a city with great thermal amplitude, like São Paulo, the thermal capacity is important to dampen the temperature variations. However, the adequacies proposed in Cases 3 and 4 conferred to the housing a performance similar to those obtained by masonry. Higher levels of efficiency could be obtained through opening shading strategies. However, the study focused to investigate only sealing systems, with the particularity of modifying the solar absorptance of tiles in the cases of panels with thermal insulation, due to the evidence observed in Galindo, Giglio and Hirota (2017).

Figure 12 shows the winter results for São Paulo. It is noteworthy, as in Curitiba, the living room/kitchen obtained a result much inferior to the dorms because it is facing predominantly towards south, facade by which the environment loses more heat. The wood frame panels of the living room/kitchen and the bedroom 2 provided better results with minor variation between these two cases. However, bedroom 1, which receives solar incidence in the late afternoon, ensured a higher retention of heat by ceramic masonry, reducing energy consumption for heating at night. It is important to consider that São Paulo has a less rigorous winter than Curitiba.

Figure 13 shows the energy consumption results for cooling. All cases with light construction systems obtained better results due to the low U value. It is observed that the dorms have shown lower performance in the living room/kitchen because they were facing north, whose facade receives higher solar incidence.

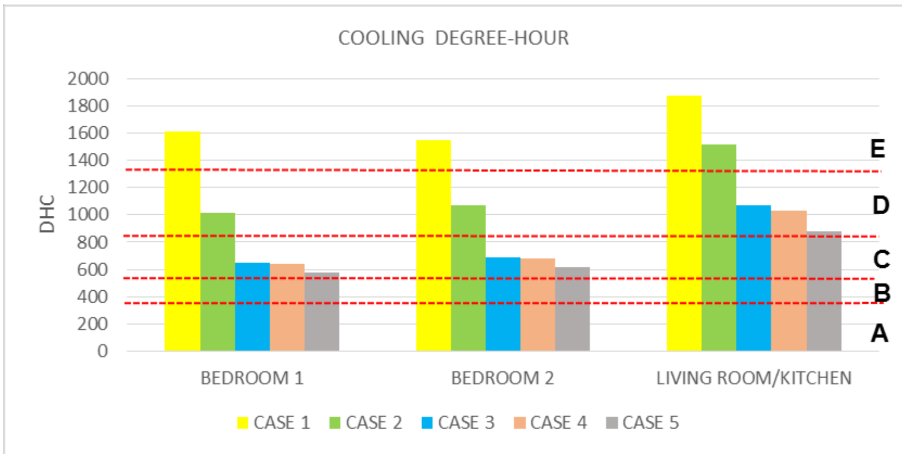

Figure 11: Degree-hour cooling indicator for each environment in São Paulo
(Source: authors)

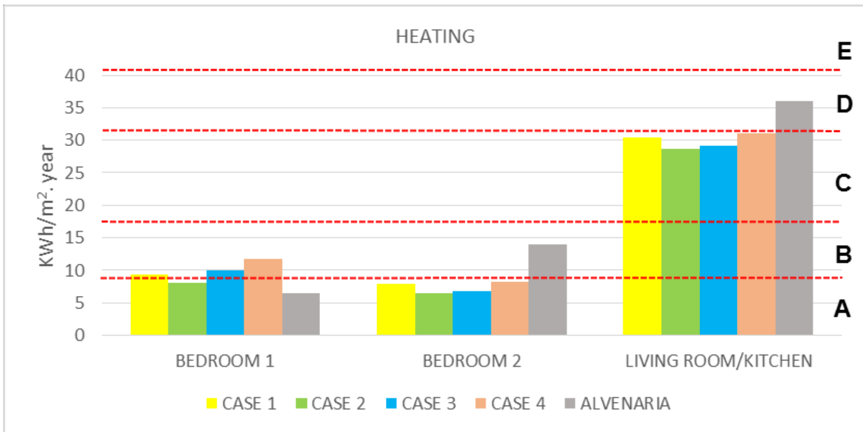

Figure 12: Energy consumption for heating each environment in São Paulo
(Source: authors)

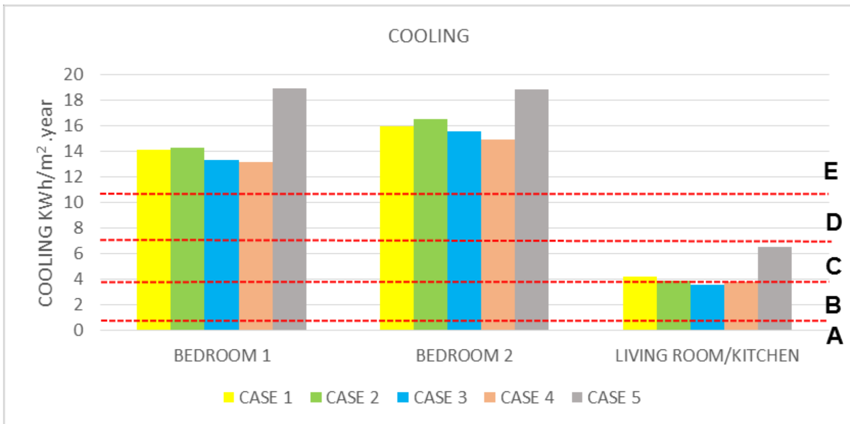

Figure 13: Energy consumption for cooling each environment in São Paulo
(Source: authors)

In general, for the naturally ventilated building, masonry showed higher performance. In contrast, for the artificially conditioned building, the light construction system with fiber glass wool and light cover (Case 3) and the EIFS system with clear cover (Case 4) have shown better results. Weighting the results for winter and summer (Table 3), it can be observed that both cases with insulating material and clear cover show energy-efficiency levels similar to masonry, where the three cases are level C. In order to obtain efficiency level A, the use of opening shading should be sought.

Table 3: Energy efficiency levels weighted for each housing envelope in São Paulo
(Source: authors)

Envelope Efficiency - São Paulo					
	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Natural Ventilation	E	D	C	C	C
	1	1.5	2.5	2.5	2.7
Heating	B	B	C	B	C
	3.7	3.9	3.1	3.7	2.9
Cooling	D	C	C	C	D
	2.1	2.6	3.1	2.6	2.1
Final Efficiency Level	D	D	C	C	C
	2.0	2.4	2.7	2.9	2.8

3.3 Bioclimatic Zone 8 – Salvador

Figure 14 shows the results of the different cases of housing envelopes when naturally ventilated for the city of Salvador. Unlike the previous cities, Salvador is a city with high temperatures year-round. Thus, there is no need of evaluating the housing envelope in winter. The efficiency levels of the housing envelopes with light construction systems are higher in this case compared to the other cities. It is observed that the light construction system with the incorporation of wool is already sufficient to get leveled with the masonry performance. In addition, the best results were obtained by the Cases 3 and 4, that is, the association of an insulating material, such as fiber glass wool or the EIFS system, with a clear cover, reaching level A in dorms and level B in the living room/kitchen. As in Salvador, the temperature variations are lower, the low thermal capacity does not affect the building performance since there is no need to maintain heat in the structure of seals.

Figure 15 shows the results of the energy consumption for cooling each housing envelope. It is observed that masonry has shown very unfavorable results in relation to light construction systems. This is because light construction systems have the capacity to keep air cooled. In this case, the four light housing envelopes that were analysed showed similar results.

Table 3 shows the levels of energy efficiency for the building when inserted in Salvador´s climate. The results have shown the efficiency level A was achieved for the housing envelopes of Cases 3 and 4, demonstrating light construction system’s efficiency for hot weather.

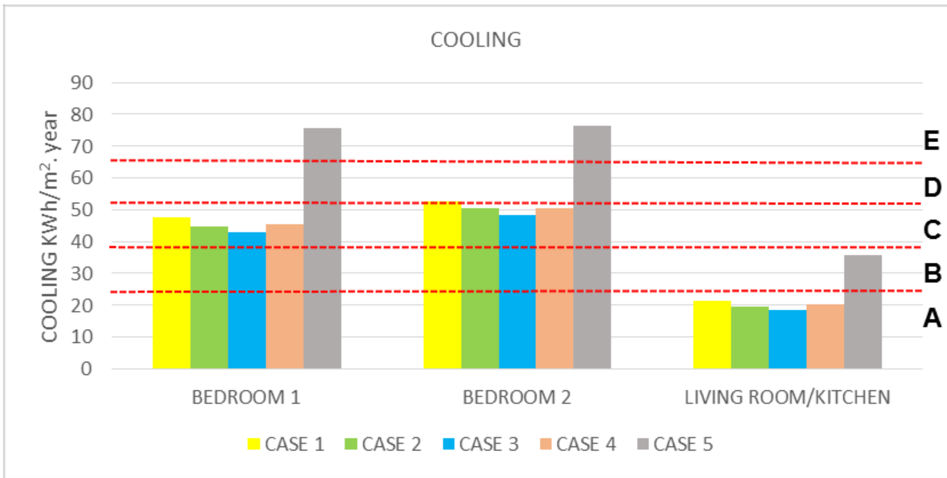

Figure 14: Degree-hour cooling indicator for each environment in Salvador
(Source: authors)

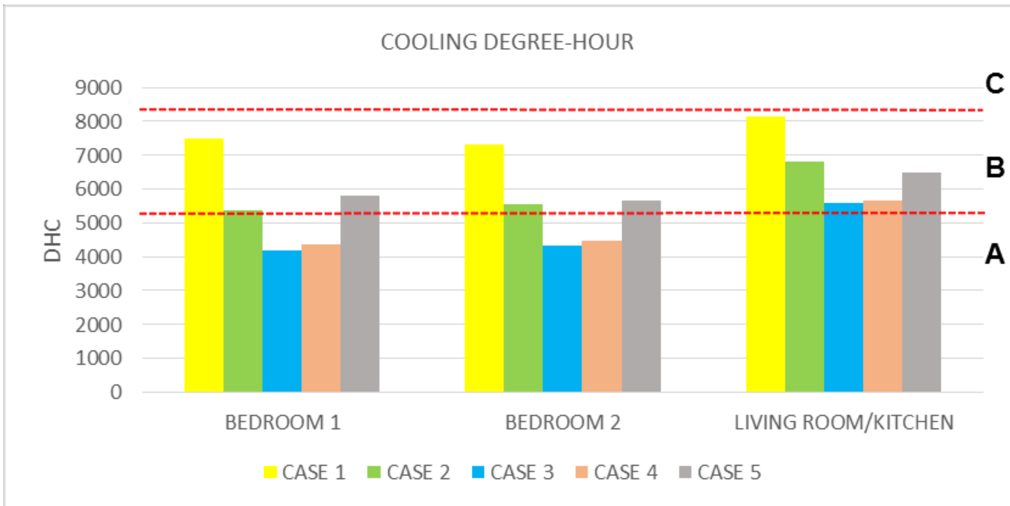

Figure 15: Energy consumption for cooling each environment in Salvador
(Source: authors)

Table 3: Energy efficiency levels weighted for each housing envelope in Salvador
(Source: authors)

Envelope Efficiency - Salvador					
	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Natural Ventilation	B	B	A	A	B
	4	4	4.5	4.5	4
Cooling	B	B	B	B	C
	3.9	4.1	4.1	4.1	2.6
Final Efficiency Level	B	B	A	A	B
	4	4	4.5	4.5	4

4 Conclusion

This study analysed the thermo-energetic performance of different wood frame panel compositions applied to a single-family social housing through the RTQ-R. Three panel compositions were compared to a base case in three different cities in Brazil: Curitiba, Sao Paulo and Salvador. The results show the need to adapt the panels to each Brazilian Bioclimatic Zone. For Bioclimatic Zones 1 and 3, represented by Curitiba and São Paulo, respectively, it was observed the need for lower values of thermal transmittance to compensate for the low thermal capacity. For regions with a high daily temperature range, such as both regions, thermal capacity influences damping of the thermal wave, reducing the temperature peaks by accumulating heat in the building structure during the day and releasing it at night when the climate is cooler. Thus, for Bioclimatic Zones 1 and 3 the original wood frame system is not sufficient to meet adequate levels of thermal performance. Thus, it is necessary to include insulation elements in the sealing panels to achieve higher levels of energy efficiency. The cover paint in light color was essential to ensure a good thermo-energetic performance in the houses with thermal insulation in seals. In summary, for Bioclimatic Zones 1 and 3, the best configurations were Cases 3 and 4, which consist of the inclusion of fiber glass wool or EPS (EIFS system) associated with clear cover, with results similar to masonry. The use of shading in windows through shutters or *brise-soleil* is also recommended, to reduce the solar incidence inside the environments.

The Bioclimatic Zone 8, represented by Salvador, was extremely favorable to the use of the wood frame construction system, reaching level B in the original case. With the inclusion of insulation materials and clear paint on cover, level A of energy efficiency can be reached, demonstrating the efficiency of the system for hot climates. Considering the large territorial extension of the Bioclimatic Zone 8, covering a considerable part of Brazil, a promising scenario for wood frame technology is observed.

The relevance of the use of the analysed system can be justified not only by the thermo-energetic performance provided in diverse conditions of the Brazilian climate but also because it allows accelerate the production process, and garantee quality of construction performed.

Thus, the technology has been shown to be feasible for the country. However, it should be emphasized that the great climatic diversity should be considered when making design decisions. Vertical sealing systems must be adapted to each region to achieve higher levels of energy efficiency, ensuring buildings with adequate thermal comfort and low energy consumption.

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EVACUATION VULNERABILITY ANALYSIS OF COLONIAL PERIOD BLOCKS IN NORTHEAST CHINA

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Abstract: *The urban fabric in Northeast China constructed by tsarist Russia and Japan in colonial period is formed with small scale grid blocks which are totally different with traditional Chinese city planning thoughts. After the colonial period, the historic area of these cities experienced intense land redevelopment only with block division remained. The sharp increase in population density and the occurrence of diverse types of block planning forms leave potential threaten to resident evacuation. In this study, safety risks of crowd evacuation in colonial period retaining blocks are discussed based on evacuation time and evacuee distribution characteristics. 6 typical planning patterns of blocks are obtained with an investigation of 30 communities with colonial period urban fabric. Moreover, evacuation simulations are performed to examine the influence of diverse planning forms of blocks on evacuation time and the change of crowd density. Vulnerable areas during evacuation are presented through the number, location, and duration time of the crowd congestion. Research results illustrate that design elements like block exits and building layouts can effectively impact on evacuation safety.*

Keywords: *Northeast China, Colonial Period Blocks, Planning Form, Evacuation Vulnerability*

1 Introduction

Northeast China is geographically located near the China-Russia border. Due to the severe cold climate, the urban development in Northeast China had been very slow until 1898. During the period of 1898-1945 this region was under colonial rule of Imperial Russia and Japan. Systematic urban planning had begun in most of the cities, with a focus on construction of the Chinese Eastern Railway. Influenced by western urban planning thought, city fabric at this time were built into small scale grids with block side lengths of 50 to 100 meters and radial network partly introduced, which is different from Chinese traditional urban form with large scale blocks (Zhao 2012). The streets and blocks constructed in the colonial period have been largely retained in the current urban fabric of northeastern cities, but the planning form within the blocks have been rebuilt to meet the increasing housing demand caused by population growth. As a result, the blocks from the colonial period now exhibit diverse building layouts.

Because of the complexity of city functions and high population densities, large scale evacuations of residents could occur in the event of a man-made or natural disaster. Studies have focused on the congestion phenomena and time consumption resulting from an evacuation of the overall urban form, with an aim to enhance security in cities from a macro perspective (Ye and Wang 2012; Péroche and Leone 2014). Nevertheless, little research has looked at safety risks associated with evacuation of people from blocks with varying internal layouts from a micro perspective. Moreover, due to the difference of disaster species and the ranges of impact, the possibility of evacuation happened in the partial section of city is much greater than that of the whole region. For instance, both the residential fire in Harbin in 2015 and the major explosion in Tianjin in 2016 have caused chaos in adjacent blocks while crowd fleeing (Xiao and Zhou 2015; Tianjin Emergency Management Office 2016). For the blocks in Northeast China retaining from colonial period, their internal re-planning has brought denser buildings and population, which increases the possibility of events such as stampede and congestion within blocks during evacuations. Therefore, it is necessary to consider the potential impact from these internal planning of blocks to the evacuation safety.

To fill this gap, this study focuses on the evacuation safety of blocks with diverse planning forms in Northeast China that are retained from the colonial period. The objectives of this research are to: (1) Extract the typical patterns of building layouts and planning characteristics of the historic blocks to provide spatial information of residential environment; (2) Propose method to simulate the evacuation process to obtain evacuation time and routes selection of evacuee of various block patterns; (3) Conduct a series of analyses towards evacuee distribution and crowd density changes with kinds of scenarios to evaluate safety risks. To achieve those goals, an investigation of the blocks is carried out to acquire the typical planning forms. Evacuation security evaluation of block patterns is realized by developing simulation models with the computer-aided platform.

2 Block Planning Form Investigation

The fabric of small scale grid blocks with side lengths of 50 to 100 meters represents a typical type of planning forms in Northeast China during the colonial period (Fig. 1) (Liu 2008). In this study, 30 communities with colonial period urban fabric are randomly sampled. In these samples, the buildings inside blocks were rebuilt from 1980s to the early 21st century which are far from the regulation of lifespan in China (50 years), and are still in a high residential occupancy rate. These blocks differed slightly in dimensions, with most of them measuring approximately 100 × 100 meters. Therefore, all the

samples are recorded as square blocks with dimension of 100 × 100 meters. The building layouts and road network inside the blocks are investigated to get the typical planning patterns (Table 1). The required information is obtained from visual documentation of urban territories (Rode and Keim 2014). As such, related geographic data is explored via Baidu Map satellite imagery and Open Street Map, and the spatial data of sites are acquired with the aid of measuring tool from Baidu Map.

Fig. 1 Urban Fabric of colonial period in Northeast China

Table 1 Indicators used in the investigation

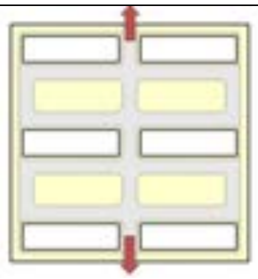
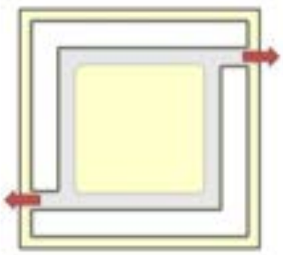
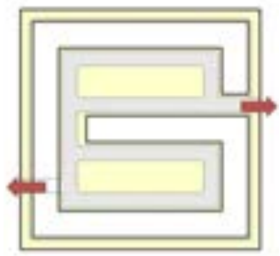
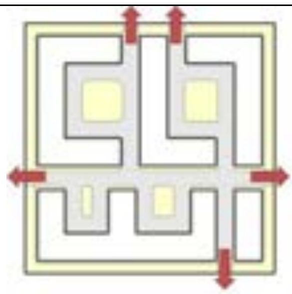
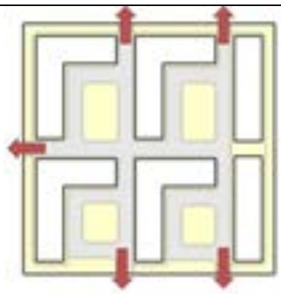
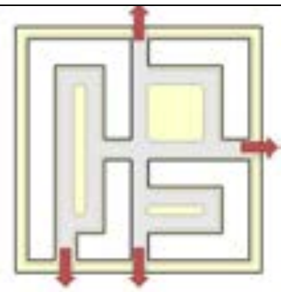
Indicator	***Data Source***
Layout of Buildings	*Open Street Map/Baidu Map*
Road network	*Open Street Map/Baidu Map*
Number and Location of Block Exits	*Baidu Map Street View*
Width of Residential Unit	*Baidu Map*

The investigation results reveal that these blocks have significantly different building layouts due to the influence of local geographical conditions and historical background. Six typical block planning patterns are found in these samples (Table 2). Among all these typical patterns, Pattern 1 is defined with buildings in parallel style; Pattern 2 and 3 are for buildings in enclosing style. These three layouts are the most common ones discovered during investigation. Other than these three patterns, the other planning forms are relatively flexible without regularity, among which three typical ones (Pattern 4, 5 and 6) have been chosen for analysis (Table 2).

All these 6 typical patterns share two common features. First, the residential buildings are mostly mid-rise ones with 6-8 floors. Moreover, there is no elevator in these building and staircases are the only vertical circulations. Second, each block provides a gated residential space surrounded by bounding wall or buildings and residents in the block can only access the city road network through limited exits. According to related Chinese community design codes, there is no specific regulation for evacuation routes or evacuation time. Therefore this research can provide evidence to figure out the deficiency of the block planning forms. The only limitation is that the distance of two pedestrian exits of blocks should be no longer than 80 meters (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2002). The residential spaces in Pattern 1, 2, and 3 are relatively enclosed and only accessible from two exits, which lead the distances not conformed to the requirement. In comparison, Patterns 4, 5, and 6, though with complex building layouts, have multiple exits, which ensure more

connections between the blocks and streets. But the exits are unevenly and randomly placed in which case some exits are more than 80m from each other in both pattern 5 and 6.

Table 2 Investigation Results

	Pattern 1	*Pattern 2*	*Pattern 3*
Block Planning Form			
Satellite Image			
Location	*Dalian·Zhongshanlu Community*	*Dalian·Pingdeng Community*	*Harbin·Yindu Community*
Number of Exits	*2*	*2*	*2*
	Pattern 4	*Pattern 5*	*Pattern 6*
Block Planning Form			
Satellite Image			
Location	*Dandong·Ersanling Community*	*Dandong·Beiqiao Community*	*Dandong·Beiqiao Community*
Number of Exits	*5*	*5*	*4*

3 Evacuation Simulation

3.1 Settings of related parameters

In the event of a hazard that could trigger evacuation in a city, residents are supposed to evacuate from their home to nearest shelter for safety security (Toyoda and Kanegae 2014). Since the blocks involved in this study are mostly gated, residents within these blocks should first move along the internal roads to the exits and then enter the external

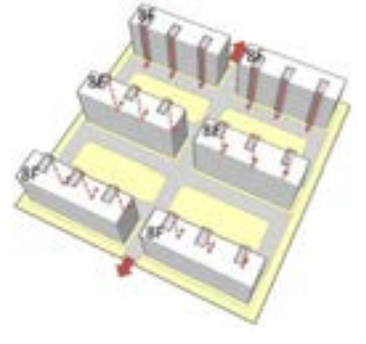
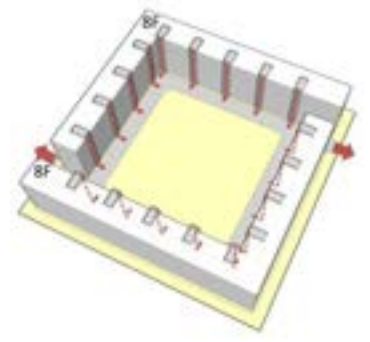
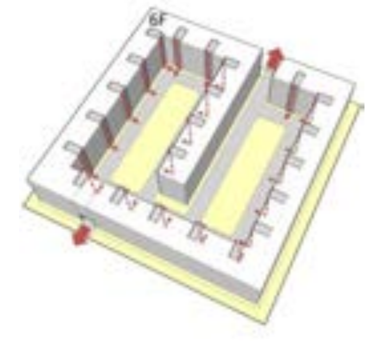
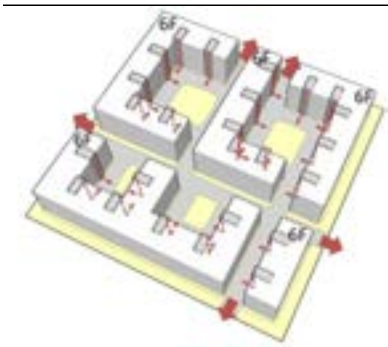
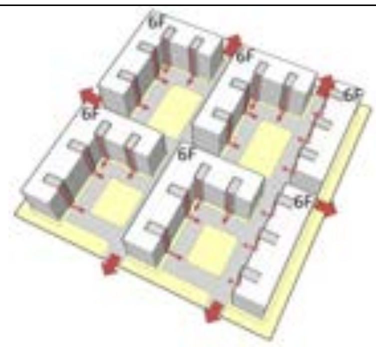
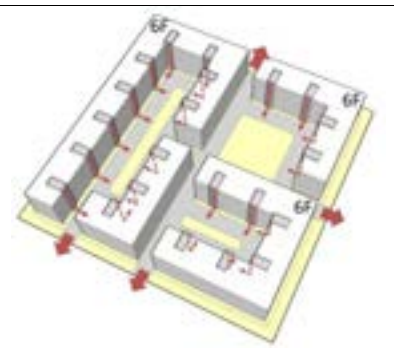
streets to seek shelter. However, rare studies have concentrated on evacuation safety of internal layouts of blocks. For this reason, this research build evacuation model through Pathfinder, an evacuation simulation platform developed based on the Agent-base model, to simulate the evacuation process of residents from apartments to downstairs through staircases and then along the internal road network to the block exits.

During simulation, evacuation paths that can guarantee shortest evacuation time are selected in order to avoid the problem of routes selection sameness in shortest distance algorithm. The maximum travel speed of people during evacuation was set at 1.4 m/s (Smith 1995). The behavioural difference of vertical movement through staircases and horizontal movement along ground are determined in accordance with SFPE Engineering Guide: Human Behaviour in Fire (Association, N. F. P. 2007) (Thunderhead Engineering 2017).

In research on urban morphology, creating a simplified model based on city fabric is an effective approach to removing unnecessary information that may affect the results of research (Yuan and Nordford 2014). Simplified models for the six typical patterns are generated based on the investigation results and related design codes. The width of road network in blocks is set at 6 meters (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2002). The width of block exits and residential unit are set at 3 meters and 15 meters respectively based on investigation results. Also, the distribution of staircases is inferred based on the width of residential units and planning forms (table 3). In addition, the population in simulation is calculated on the basis of land area per capita. According to the Code of Urban Residential Areas Planning & Design (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2002), the average land area per capita in block in Northeast China for mid-rise buildings is 14 m^2/capita. Therefore the number of residents in each 100 ×100 meters block is set at 715. In terms of residents distribution settings, one stair in each floor is assumed to provide service to two apartments, and each family has 2.5 people on average (Harbin Open Source Data Platform 2015). Hence there are five evacuees of one staircase in each floor (table 3). Comparing with the researches which focus on evacuation within specific blocks, this research although has not considered the fact that the changing number of households for one staircase may affect the analysis, the variables are set for the building layouts to avoid unnecessary effect of multivariable on simulation results and to explore safety risks that modern urbanization will bring to the conventional communities.

Evacuation simulation of 6 typical patterns are proceeded to get outcomes from two main aspects: 1) total evacuation time (fig. 2); 2) the location, quantity and duration time of congestion area in these patterns (table 4).

Table 3 Simplified Models of Blocks

Pattern 1	*Pattern 2*	*Pattern 3*
		
Pattern 4	*Pattern 5*	*Pattern 6*
		
	Legend	Staircases; Exits of Block

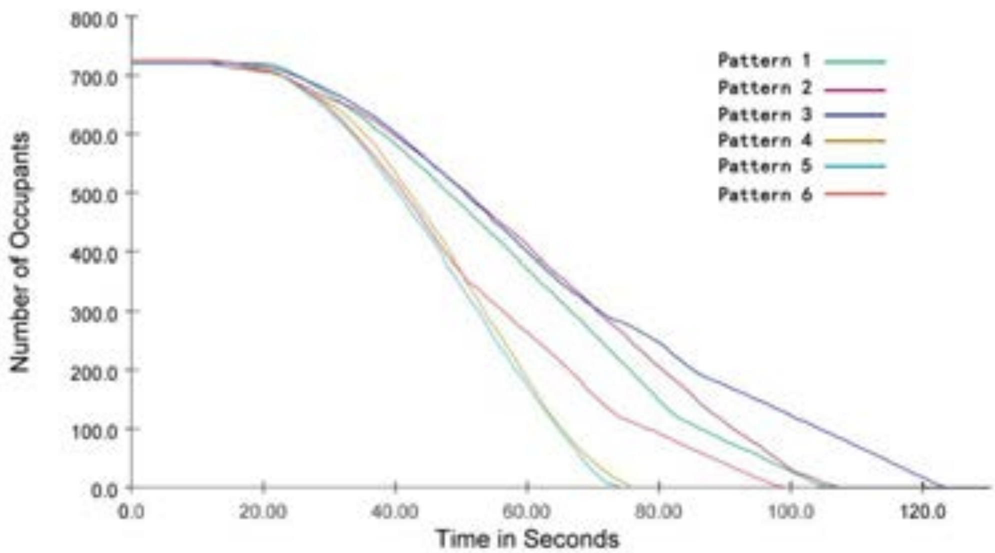
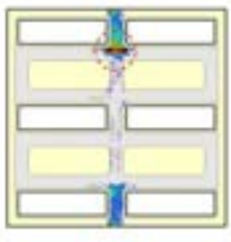
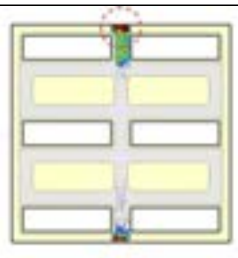
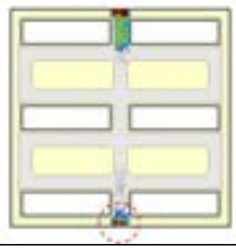
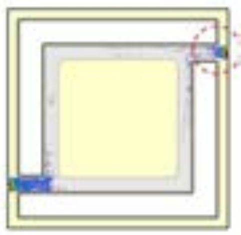
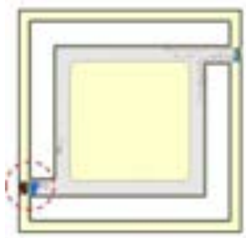
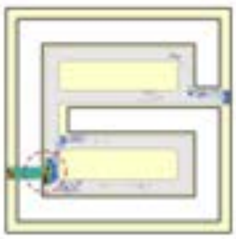
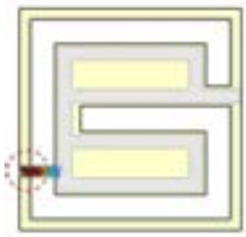
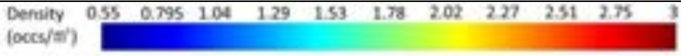


Fig. 2 Evacuation Time Comparison of Six Patterns

Table 4 Simulation Results

Pattern	*Evacuation Time (s)*	*Congestion Area 1*	*Congestion Area 2*	*Congestion Area 3*
		Duration Time (s)		
Pattern 1	*112s*	*27 s—60 s* 	*46 s—100 s* 	*46 s—87 s* 
Pattern 2	*108s*	*56 s—84 s* 	*56 s—98 s* 	
Pattern 3	*123s*	*43 s—84 s* 	*54 s—119 s* 	
Pattern 4	*76s*	*47 s—63 s* 		
Pattern 5	*64s*	*45 s—68 s* 		
Pattern 6	*69s*	*40 s—93 s* 	*52 s—69 s* 	

Legend	

4 Results and Discussion

4.1 Evacuation Time

It can be seen from the simulation results that the dissimilarity of planning patterns give rise to differences in evacuation time (Fig. 2). Among them, Pattern 3 with enclosed building layout gives the longest evacuation time --- 123 seconds; since there are more exits placed in Pattern 5, the evacuation time in this pattern is the shortest --- 74 seconds. For the impact of the number of exits on evacuation time, Pattern 4, 5 and 6 effectively disperse the evacuation flow benefiting from the added exits, with shorter evacuation time than the other three patterns. As to the influence of the building layouts on evacuation time, there are two exits in Pattern 1, 2 and 3 respectively though, Pattern 3 results in more evacuation time than the other two for the residents distribution disparity caused by the peculiar enclosed building layout, indicating that a reasonable building layout, with the same number of exits, can enhance evacuation efficiency by changing the crowd distribution. Therefore, the way of changing the layout of the buildings within the block and increasing the number of exits can effectively reduce the evacuation time.

4.2 Congestion Area

Crowd evacuation may trigger secondary disasters such as stampede for great population density and panic (Liu and Xing 2015), so the evacuation safety is not only reflected in the short evacuation time, but the safety of the entire evacuation process. The study assesses the safety of the block in the emergency state based on the total evacuation time and congestion cases. Congestion area are figured based on the various characteristics of crowd density among the six typical patterns of block planning, and the simulation results show that there are differences in the location, quantity and time of occurrence of the congestion area in various patterns of block planning (Table 3).

1) As for the number of the congestion area, the increase of evacuation time is not directly related to the number of the congestion area. Three areas easy for congestion appear in Pattern 1 while only two appear in Pattern 3 with longer evacuation time. So even in the case of a shorter total time, the potentiality of having multiple congestions also exists and may cause a high risk in safety.

2) Seen from the location of the congestion area, congestion may occur in the internal road network of the blocks and the exits; specifically, congestion in the road network occurs in Pattern 1 and 3, and that at the exits in all the six patterns. With the increase in the number of block exits, congestion appears in just one area in Pattern 4 and 5 and lasts only 20 seconds. A shorter congestion time can effectively reduce the likelihood of crowd anxiety, thereby improving the safety of the evacuation process. In the evacuation of Pattern 6, although there are a number exits, the flow is concentrated in the two southward exits which increases the evacuation time and shows that the effective road utilization is not balanced.

3) There is a difference in the occurrence time of the congestion areas. In Pattern 1, crowd stranding firstly occurs at the 27th second in the congestion area 1 and lasts for 25 seconds before easing. After that the crowd density begins to appear increasing at the second congestion point. It reveals the potential association between the occurrence

of congestion, serious degree and the evacuee moving direction, which can contribute to disaster management for emergency personnel in evacuation path arrangement.

5 Conclusion

This research explores the relationship between the evacuation safety and the planning patterns of small scale blocks retaining from the colonial period of the Northeast China.

Through sampling survey on the historic city fabric, six typical patterns of the block planning forms are obtained. The characteristics of these samples demonstrate the differences on building layouts and the numbers of block exits, which are vital spatial elements contribute to route selection and passing capacity.

Furthermore, combined with relevant design codes requirements and crowd behaviour theory as well as the computer simulation platform, the evacuation simulation experiment is performed to give data support to changes of velocity, density and congestion, which provides reliable information for evacuation safety evaluation.

From the analyses of evacuation time in block patterns, along with the congestion area generated in the evacuation process, the block with reasonable number of exits ensures a shorter time in the escape process; meanwhile, the differences in initial distributions of the crowd caused by the building layout have the potential to result in an imbalanced route selection that will reduce the utilization efficiency of the evacuation paths and thereby increase the evacuation time. On the other hand, with the analyses of congestion phenomena arisen during evacuation, the exits are the most vulnerable area lead to crowd congestion with high possibility of secondary disasters; the internal network of the block which occur intersection of pedestrian flows from various directions also have probability of crowd stranding; moreover, for hazards preparedness, the data related to occurrence time and duration of congestion can provide evidence to disaster management.

In order to improve the safety of the evacuation process, some targeted optimization measures can be taken in block planning and disaster management based on the location, quantity and duration of crowd stranding phenomena. As for the specific design and management measures for the congestion area, it is an urgent task to be tackled in the further studies.

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PORCHES, GARAGES AND YARDS: “THIRD PLACES” FOR AGEING SOCIALLY

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Abstract: *Ageing in the first world is not going to be what it was. For the first time in contemporary history, a massive wave of Baby Boomers is retiring. They are without a secured financial future and most new retirees will be obliged to age in place with very scarce assistance and resources. In parallel, longevity is increasing, offering elderly people a long new life as retirees. In this situation, social relationships are key for guaranteeing a more resilient community. Latest research shows that being social has a strong influence on people’s health, equivalent to giving up smoking, and nearly twice as beneficial as physical activity. Increased social interaction will promote mutual care and will support informal economies that will help retirees’ finances. Architecture, in this new social landscape, has an important responsibility. The suburban context that could respond to isolated-family-with-children way of living, is a hostile environment for an ageing couple or a single retiree. This paper explores the possibilities that architecture can find for retrofitting suburban fabrics in order to encourage social interaction. Traditional elements of suburban architecture, such as porches, yards and garages, could be transformed to aid the situation. The porch could adapt a more communal condition, through extensions and connections that can transform it into a casual clubhouse for a new community. The yard can be evolved as a commons for gathering or supporting suburban farming for subsistence or for the promotion of informal economies. The activity provoked by the communal gardens will provide physical and social benefits to the retirees. Lastly, the garage is a flexible piece that can be reinvented in retirees’ homes. The use of the car will be spaced out progressively and shared vehicles will start to be more usual with new retirees, which is also more economical. The garage would offer a place for gathering and for hosting common hobbies or for teaching retirees’ expertise to other people. These kinds of activities would socially and financially aid elder people.*
This paper proposes these ‘third places’, with graphic examples where these new ideas have been applied to different suburban fabrics in the United States and also proposes how these could be adopted in the Australian suburban landscape.

Keywords: *American Urbanism, Elderly Community, Social Bonding, Public Health, Retrofitting Fabrics*

1 Introduction

It is not new at all that in the history of American urbanism, a warning about the importance of community engagement related to the welfare of human beings, has been regularly dismissed. From Jane Jacobs (Jacobs 1961) to Colin Ellard (Ellard 2015), from journalistic to neuroscientific points of view, theoreticians have been insisting that space, and more specifically public space, is a key ingredient for wrapping the community life with a sense of belonging, that is, at the same time, welcoming and protective. Planning for public spaces in USA, with the main target of providing social welfare has been historically hitting an insurmountable wall made by bricks, so to speak, from very different origins—ranging from the independent idiosyncrasy of the settler mentality to the misunderstood identification between interventions for the sake of community welfare and those of a communist nature (Conn 2014). The stubbornness of constructing this wall is comparable with the persistence of trying to advocate for a more socially sensible planning of public space—from the Jane Adams Hull House's studies in the beginning of the Twentieth Century to the hippy communes of the 1960s, and to the artificiality of the elitist communities proposed more recently by the proponents of 'New Urbanism.' Architecture, in this social landscape where aging is becoming an important factor with 79 million retired Americans by 2030 (Cohn and Taylor 2010), has an important responsibility, given the challenge any socially driven agenda has to face. The suburban context, which responded to isolated-family-with-children way of living in the post-war era, has become a trap and is a hostile environment for an ageing couple or a single retiree. In such a scenario. This paper explores the possibilities that architecture can find for retrofitting suburban fabrics in order to encourage social interaction which benefit ageing and present results from an investigation that was done by design as a research method, taking three characteristic suburbs from the endless sprawl in the US.

2 Literature Review

Upon an examination of the existing literature and looking at the history of planning, it is important to point here that strangely only a few of these American attempts for a caring and socially enabling community planning were truly connected to the city, which is the most historically tested and spontaneous formula of planning for community welfare. The same people that have worked hard against applying the city formula to the American context have cynically recognized the wonderfulness of life in the European cities. Density, informality, mixed-use, open boundaries, uncertainty, undefined spaces… are all concepts that have been mentioned tirelessly as part of this efficient formula by various sociologists and anthropologists, under various names such as *Open City* (Sennet 2013) or *Third Spaces* (Oldenburg 1989). All of them failed, most without even being tested, basically because, as Oldenburg pointed out prudently, the lack of city experience in collective psyche and the necessarily associated informality, makes the American citizenry "literally forget how to create one" (Oldenburg 1989:11).

For the purpose of our research, we took the concept of Third Spaces and used as a design operational tool. So, it is important that we look at the definition of what a *Third Place* is? Ray Oldenburg referred to "third places" as the ones after home (first places),

and workplaces (second ones), and he explained them as “great good places” for informal public gathering. He mentioned that the most important function of this spaces is “that of uniting the neighborhood”, referring also to their importance for creating a convivial atmosphere where people getting to know each other then take care for one another, fact that, he remarked, is extremely significant for the elderly people. Third places are also fun and serve significantly as political and intellectual fora (Oldenburg 1989: xvii-xxv).

Someone would say that American way of living is different and that American society found other ways of feeling the community embrace, a basic human necessity, and they would be right, but we should mention some important counterparts to this assertion. One is that community gathering in America, based in places socially segregated and politically deactivated (such as the Church of the Mall), has nothing to do with a happening or *buzz* (Storper and Venables 2004) in the city, because the latter is always based on social mixture and intense negotiation, therefore always politically charged. Paraphrasing Oldenburg, we could say that the lack of quotidian political experience made Americans also forget about what real politics is, and the 2016 Presidential elections’ output was a very clear evidence of this dismissal. On the other hand, accepting the *status* of the American way of living is also an inconsiderate sacking of a public health problem denounced at least from the early 1980s (Wallis 1983), when it was noticed that “our mode of life… is emerging as today’s principal cause of illness”. In more pragmatic terms, as Oldenburg quoted, two-thirds of the $50 to $75 billion economic loss due to absenteeism (billions from 1989, which taking inflation into consideration is twice the amount today—as shown at *Dollar Times* Web page) are related to stress, something that is undeniably connected to a way of living (Oldenburg 1989:10). The balance—that Oldenburg required for a fulfilling daily life—between the domestic, the productive and the social (Oldenburg 1989:14), has been clearly denied in the American way of living. The domestic is based on a self-sufficiency where each room replicates the whole house (skipping most of the family interaction), the production aspect is placed in a way where each one needs to spend time and energy as forced commuters, and the social, as we explained, is framed in very specific places based on homogeneity where negotiation has been deactivated. The responsibility that architects have to all these facts, as the professional of the built environment, is undeniable and can no longer be ignored.

A survey of the facts regarding aging and mental health reveals that although almost half of the American population suffer from some kind of mental instability in their lifetime (the U.S.A. is the country with the highest prevalence of reported mental health problems as showed report from Centers for Disease Control and Prevention—CDC 2011)—a fact that can no longer ignore the way people live. This paper is focused on a specific sector of the community that is going to be even more defenseless in the next coming years: the elderly people. One must keep in mind the growing dynamic of this population sector in the United States (it will increase at a rate of around 10,000 new retirees per day for the next 19 years), that will result in 79 million retired Americans by 2030 (Cohn and Taylor 2010). This social sector is retreating, for the first time in American history, with quite a long life expectancy (an average around 80 years old—Geoba.se 2017), and with

shortages in social services and health care seriously threatening on the close horizon. The caring cost of this retirement rhythm is estimated at $3 trillion per year (Durett 2009), a cost which has to be in some way paid privately or publicly spent. Moreover, some of the retirement funds available for this purpose were drained by the 2008 crisis, and the baby-boomers are now facing their retreat immersed in an atmosphere of financial uncertainty for the first time in America contemporary history (Khanna 2016:111). In a very alarming way, more than half of the households where the head is over 55 has to rely almost entirely on Social Security income (Saad-Lessler *et al.* 2015), a program that is extraordinarily stressed in a nation with very urgent necessities, between them, 44 million people fed by public funds through the Supplemental Nutrition Assistance Program (USDA 2016). The situation looks like the clear announcement of a social collapse. Before asking about the way in which architects can contribute to relieving the situation we need to assume our responsibility given the facts portrayed above. We know that isolation is a fundamental base of the weakness suffered by a population in many senses (mental, social, economic, and political), and in this isolation urban planning has been the merciless executive hand. Many architects and urban planners have been underestimating the way in which their decisions would affect people's lives, pushed by neoliberal economic forces or focused on their own disciplinary experimentation. This can't be go any longer—an ethical imperative must become the norm.

We need to use our imagination, reinventing architectural fabrics in a way that is able to reshape social relationships, aiming for a more resilient community to front this unclear future. As American activist and Director of the National Domestic Workers Alliance, Ai-Jen Poo pointed, the situation is such that it will require the reinvention of an infrastructural solution, similarly to the interstate highway system of the 60s or the transcontinental railroad (Poo 2015). The resiliency that would result from the fortification of the social bonding provoked by a reshaped fabric will be reflected in a community that will be politically stronger, economically more independent, and physically healthier. A united community would be able to better fight for their rights, and it would develop alternatives to the capitalist economy for relieving their finances more readily. We also know nowadays that people with strong social relationships increase their survival odds by 50 percent (benefit equivalent to giving up smoking and nearly twice as beneficial as physical activity—Harmon 2010). We have been traditionally focusing on retirement as something associated with medical assistance and we only recently realized that it is much more a social issue. If all the mentioned benefits are important at any age, then they are critical for elderly communities as a way to build self-defense mechanisms for advancing when society will no longer be able to take care of them.

3 Research Methodology: research-by-design

For knowing how to act as architects, we need to start defining the architectural framework where these communities are aging. In a different way than it was at other times--when retirement was associated with a family move to a more relaxed place--nowadays 85 percent of the elderly community will be forced by their situations to age in place (D'Vera and Taylor 2010). *Natural Occurring Retirement Communities* (or NORCs)

are happening spontaneously all over America, and these places are not prepared for a necessary new way of living and the desired increase in social activity. We need to add to this that, although official government data is very vague in the quantification of how suburban America really is, 53 percent of American citizens described their life routine as suburban and 21 percent as rural (Kolko 2015). As a result of both of these facts, much more than two-thirds of Americans will be condemned in the actual situation of ageing in an isolated way.

We have used the research-by-design method as a way to explore what are the alternatives that architect can offer to this situation. This methodology is very specific of the discipline of Architecture for achieving cognition through ideas that are materialized with form and includes space (Hauberg 2011), with an output able to easily provide social feedback. With an architectural design as the response to a specific problem, we investigated typological solutions that are able to engage the imagination and concerns of the people and hence can be used as base for a public discussion and evaluation. The research-by-design exploration was elaborated to maximize the space of possibility (Delanda 2011) and research different alternatives for being comparatively analyzed by the different agents involved in the problem. With this methodology, we aimed to find out how the architecture of the fabric should be reacting to the local differences due to social, economic or environmental issues. A point that needs to be made here is the research process needs to be cognizant of the valuable input from various stakeholders– the owners, developers, construction companies, and public institutions, could be involved in different ways into this specific problem depending on their precise situation - from the owners economic possibilities to the different administrative levels or social policies that would be needed to enforce the change.

We researched here how to adapt three traditional elements of American suburban typologies (yards, porches and garages) for creating architectural fabrics that able to help to elderly communities. The typologies are set in three different American urban contexts that represents different socio-economic conditions. The first selected site is Levittown's suburbs in New York, a response that, as we shall explain below, investigated architectural interventions based on a spontaneous and modest private investment related to self-construction processes. The second site aimed for the upper classes living in gated communities in Miami sprawl, where the new necessities could promote neighborhood agreements for making possible the necessary restructuring of public and public spaces. The last selected context was Detroit, a context immersed in a climate of public and private investment for reclaiming the city's economic health, where the investigation led with the notion that architectural reformulations could result from private investors attending this new demand (houses for aging) and taking advantage of public initiatives and commodities.

4 Findings

The most basic architectural adaptations that was necessary to be thought of was due to the problem of mobility associated with age. However, the most challenging architectural task was to think how to reactivate *third places* for provoking social

interaction. The investigation of the three contexts of the suburban typology resulted in finding some common spaces (such as yards, porches, and garages) with flexible characters that was extrapolated in the design exercise to have the potential for transformation into *third places*. These spaces already offer us a kind of third-space condition in the sense that they are neither fully part of domestic intimacy nor properly public. Our initial context analysis showed great potential for easily adapting these spaces as community sharing and gathering spaces. Yards, porches, and garages contain opportunities for being redefined as part of an architectural strategy for triggering a new life routine associated with retirement.

Yards became the necessary contact with the outside (in a new retiree's life where there is time to spend just outside), offering the perfect frame for gardening as one of the most relaxing and popular retirees' activities.

Porches, especially in good weather condition, emerge as an outdoor living where the new retirees would stay long journeys, providing the idyllic space for social gathering.

Garages, the last component, would be able to provide a space that it can be reconfigured in a new retiree life more independent from the car, for instance, as a workspace—able to render extra income—, or as a hobby room for spending time in an active way.

In all cases, the design research guideline stipulated that the transformations must simultaneously bring changes in the family domestic life and provide provocation for community interaction. Keeping this in mind is a key factor for converting these single components of an architectural typology to a network of elements acting more as a communal infrastructure. In a sense, the design is an attempt to convert trees into rhizomes. The premise can be constructed thus–if one shares their garden as a community one, they benefit from other neighbors sharing theirs as a gardening school or an improvised farmer market. Opening their porches for a party or a political discussion would mean the imminence of another porch gathering happening in the following days. A garage could be someone else's appliance repair shop, and someone else's garage could be converted into your yoga classroom'.

The possibilities are endless and the ways of living that they draw are exciting. The sequence of all this social exchange would almost immediately produce economic alternatives based on the exchange of goods and services. This would encourage a passive member of the community towards integration and it would result in stability and resiliency for the whole community. As a result, each member will keep active as part of a social whole, with the undeniable psychological benefit of feeling their importance for the community with immediate repercussions in their physical health.

Even when the mentioned transformation is based more on programmatic changes than material ones, it is obvious that some architectural changes would be necessary and they will require some funding. We also acknowledged that despite of the socio-economic homogeneity that characterized suburban America, the economic stress could be happening in a specific community in different degrees, so we needed to think in

diverse funding sources. Some communities will become NORCs progressively, that means the impossibility of a coordinated effort for getting funding for the desired architectural transformations. In these cases the modifications would be based on very small economic efforts, privately based, made as a kind of business investment for farming your yard, renting your swimming pool or selling home-made cakes in your garage. Other communities will become NORCs more abruptly, so they will be able to coordinate in the community the required reforms for adapting the architectural framework to their new lives styles. In this last case, they could be able to arrange loans with the community endorsement or to manage the possibility of getting official support or donors for making their intentions became real. In some other cases, we could also imagine developers investing in these architectural transformations for getting back rent from the households, or even for taking advantage of some of the extra land in some of the houses for building services for the whole neighborhood as a business model.

It is important to point here that whatever way the project is to be managed, it would have an important relational role with the architectural solution, and this solution in turn would strongly affect the project management. The project of architecture becomes blurry and uncertain when it includes deep social implications, claiming with it a new definition for the architecture (far away from unpolluted modernist formalist paradigm), and a new role for the architect (who would act more as a community agent).

For displaying the way we envision the architectural retrofitting of the existing fabrics in their adaptation to their inhabitant's new situation, we present the following images of the mentioned real suburban fabrics as indicative of the different socio-economic contexts (Levittown, Miami, and Detroit), accompanying the representational results of this research-by-design exploration:

LEVITTOWN, New York

COMMUNITY: Multi-generational
TIMING: Progressive (15 to 20 years to completion)
FUNDING: Private with refund through barter or family business
CONSTRUCTION: Self-constructed

This is the first mass-produced suburb in the United States. Originally made with similar houses, the fabric has been customized by their inhabitants to the point that nowadays looks very diverse. With population from different generations, Levittown is already happening as a progressive NORC, hence we envision its transformation by casual aggregation in an informal and unpredictable way. The first household intervention would encourage others in a kind of chain effect. The drawn proposal has been done with mass-produced elements from a *Home-Depot* catalog as the cheapest and fastest way to accomplish the desired modifications. With respect to private property, each household would just release the necessary space at their back for opening a common alley as access to the different facilities that the owners would casually build in their backyards. Swimming pools, spaces for art, orchards, sports playgrounds, etc., all these are infrastructures provided by the different households as community contributions and potential value for being exchange by other goods or services. The new communal infrastructure also includes solar panels and domestic wind-power generators as a way to alleviate household future energy expenses.

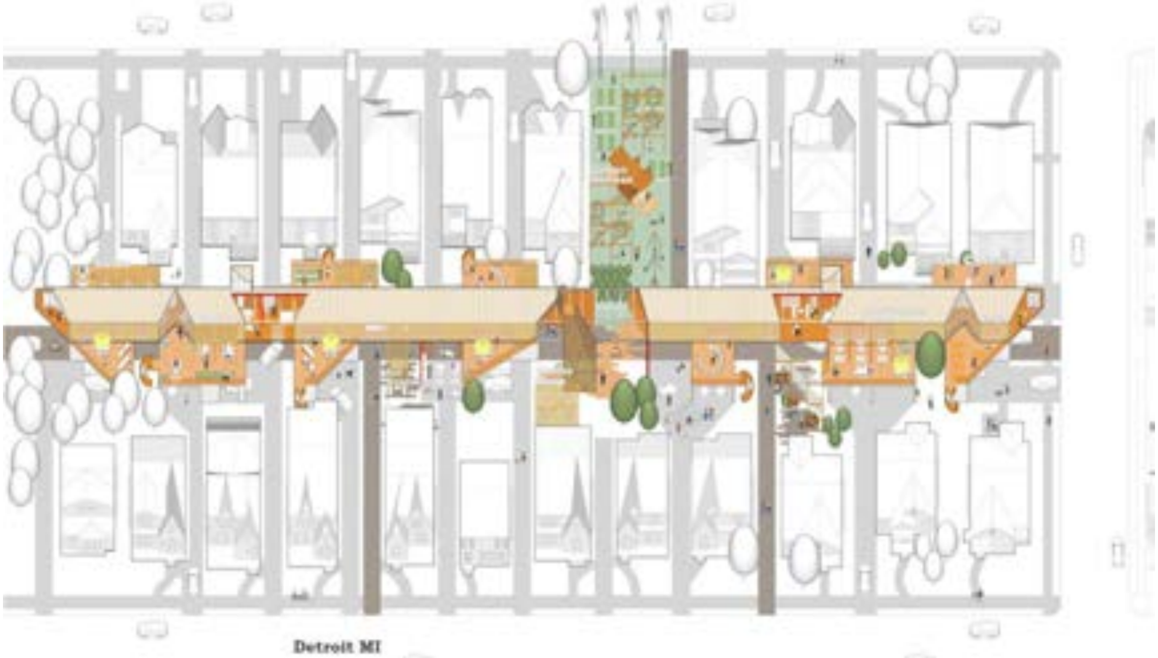
MIAMI, Florida

COMMUNITY: Single generation (mainly Baby-boomers)
TIMING: Instantly (1 to 2 years)
FUNDING: Private funds managed by community
CONSTRUCTION: Construction Company

Some of the Miami suburban agglomerations originally developed in the late 1940s and 1950s (as Bay Harbour area or Lauderdale-By-The-Sea), have been hosting newer developments done with more generous standards and oriented to the medium-high socio-economic class. Some of these communities were conceived as gated communities and are common to find a *cul de sac* urban structure where a few houses are totally segregated of the public roads. Mostly occupied by Baby-boomers with a comfortable financial situation most of them are obliged nowadays to age in place because, even selling their houses, they will not be able to find someplace to live with similar standards in the Miami metropolitan area. These neighborhoods, extraordinarily homogeneous, are becoming NORCs suddenly and their inhabitants have financial capacity for supporting the necessary architectural transformations. Organized as a community, they would fund the adaptations for their new life as retirees. The main reform is based on the idea of converting the *cul de sac* road in a new communal third-space, taking advantage of the expected decrease in the car use. Outside gardens and greenhouses, gathering places, sports playgrounds, walking paths, communal infrastructures (as small swimming pools and cafes), are some of the spaces built taking advantage of the road space that it will turn into a more pedestrian-oriented place.

DETROIT, Michigan

COMMUNITY: Mostly abandoned
TIMING: Midterm (3 to 5 years)
FUNDING: Private investment with the public support
CONSTRUCTION: Construction Company



It is well known the problem of Detroit City, affecting downtown and the closest suburbs to the city center. The White Flight phenomenon starting in the1950s progressively emptied the city in favor of an intense suburban growth. The most historic suburbs in areas as Midtown and New Center, built with fantastic Victorian homes from the beginning of the Twentieth Century, were gradually abandoned. The situation nowadays is that this extraordinary architecture must be demolished and the character of these places is disappearing. Local administration is making a huge effort trying to revitalize parts of the city. The necessity of fabrics with very specific demands (as the ones that we would be needing for aging socially) is a perfect excuse for the city's revitalization. In order to be able to bring as much life as possible with the smallest intervention in the street character, our proposal tries to incorporate a public building as a complementary infrastructure built on the internal alley road, encouraging mixed uses. Hosting the garages underneath this new building would be able to incorporate restaurants, coffee shops, co-working spaces and other facilities for the community. In this way, the new building becomes an activity seed encouraging the investment in its proximity. The covered alley road becomes also a pergola for social gathering and outdoor activities. Some of the existing vacant plots could be used as park gates for accessing the plot's social spine. The operation could be financially supported by a developer whose could own the houses, probably bought very inexpensively, as part of a business model. The development could be specifically oriented to elderly people and so too the services provided by the new

building (it could host day care centers, medical offices, and social clubs). The local administration would be very supportive of this idea as a way to help them to bring people back to Detroit city.

5 Conclusion

The first conclusion of this paper is the claim that a research-by-design methodology is self-evidently important for architecture and specifically for explorations related with social concerns such as this one. The resulting design is accessible by peers and other and it enables the collection of feedback from public discussion much easier, all the while stimulating one much more than policy documents and research reports. It is our responsibility as architects to produce images that are able to capture people's imagination offering solutions for fronting an existing challenge. Only through the design can we evaluate the possibilities that architecture has for involving all the agents and overcoming all the difficulties.

The second conclusion is related to the possibilities that some elements of the current American typologies have for being a seed of the necessary transformation that is able to build a more resilient elder communities in an uncertain future. Yards, porches, and garages have some of the social qualities that define third spaces and could be transformed in key components in this new social fabrics, as we can see in the developed examples.

The third conclusion is about the importance of contextual conditions for a research like this. The generic problem of ageing would always be embedded in socio-economic and spatial particulars and hence the end result would be substantially different depending on the socio-economic context and the specificity of the urban fabrics to work with. The application of this research to three different urban context is a way to make this explicit.

The last, but not the least, is the conclusion that as architects, we have the obligation, and the means to intervene in the social challenges that we need to overcome for a just, sustainable and equitable future. It is our specific agency by doing this in a proactive manner, which entails using our design capacities to explore spaces of possibility. By projecting imaginative design scenarios, while maintaining the rigor of research, we can offer what is most required by people facing an uncertain future–hope.

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For the drawings © Author as part of UACDC

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ENHANCING THE ENERGY PERFORMANCE OF SKYSCRAPERS

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Abstract: *As major energy consumers, skyscrapers do not usually conjure images of sustainable design. Nevertheless, this is changing rapidly and a new generation of skyscrapers is integrating new developments in technology and design to produce not only smarter, but also energy-efficient buildings. This paper discusses multiple modern techniques that can be used in -pre design stage- skyscraper projects to save energy. These techniques are; harvesting water from humidity, generating electricity using wind turbines and aiding ventilation using an atrium space. All of these techniques were logically proven by scientific facts, calculations and simulations. The previously mentioned techniques were generated based on the location, climate conditions and the surroundings of a senior design architectural engineering project, "The Iconic Tower". The proposed Iconic Tower is a 280-metre landmark that is located in Al Khan Island, Sharjah, United Arab Emirates. The hot-humid climate of Sharjah emirate/city is the main factor of harvesting water from humidity by steel mesh coating that can be placed within the skyscraper's exoskeleton. This technique works as a shading device and at the same time produces reasonable amount of water, which saves resources and energy. The second technique is using wind turbines that are placed at the highest part of the skyscraper to maximize energy efficiency, which leads to minimizing air-conditioning cooling loads. The third technique is the atrium space created, which saves energy by utilizing passive ventilation that is also aided by an active system. The atrium provides natural light and ventilation to the interiors. By using Autodesk Revit energy simulation and daylight analysis, benefits of enhancing energy efficiency through an atrium space within a proposed skyscraper has been demonstrated. Moreover, dealing with the surrounding climatic conditions created value towards a sustainable future for Sharjah city.*

Keywords: *Skyscrapers, Energy Performance, Building Simulations, Atrium Space, Sustainable Design*

1 Introduction

The direction of the world nowadays is toward green and sustainability. Designing and building sustainable buildings all around the world will minimize the pollution percentage. It is well known that pollution is the main reason of climate change. The basic factor of pollution is burning up our planet's coal, oil and gas. People tend to behave in this way to obtain their needs of energy without expecting the bad impact of it. The construction industry worldwide uses 60 % of the world's energy to ventilate, heat and light buildings (Data.World 2011). Sustainable design of the built environment can improve the quality of life within the local culture, tradition, climate and the environment in the region. Green buildings are designed in a way to increase the efficiency of using resources, such as energy, water and materials. Throughout the whole building life cycle, sustainable buildings can minimize the hazardous materials amount, which can harm all organisms including humans by better sitting, design, construction, operation, maintenance and elimination. Sustainable buildings should be designed specially to reduce the overall impact of the built environment on human health and the natural environment by considering three methods, (1) including efficient ways of using resources, such as water and energy, (2) improving productivity and protecting the health of all occupants, and (3) reducing waste and pollution. Moreover, sustainable towers are high-rise buildings that emit zero pollution to the air, water and land. As well, it contributes to the local community in a positive way and is also economically occupied throughout its design life. To achieve the goal of sustainable towers, designers should consider the site, location, transportation, indoor environment, water, active and passive energy sources, building orientation, wind direction, sun path analysis, materials, waste and pollution.

To state some environmental facts about UAE, recent studies showed that the total GHG emissions have increased from 74 million ton of CO_2 in 1994 to 173 million ton of CO_2 in 2012. This is related to the electricity consumption that has increased by more than 8 % per annum since 2007, exceeding 100 TWH in 2012 (MOCCAE 2014). Figure 1 shows the percentage of each sector of electricity consumption in the UAE. Moreover, the water usage has been among the world's highest as the daily consumption of water for household and commercial purposes, it was recorded as 353 L per capita in 2013. On the other hand, the daily municipal waste that was generated by the country was 1.82 kg per capita in 2014. As a result, to these facts, it is a must to think of multiple solutions to eliminate the different causes of pollution.

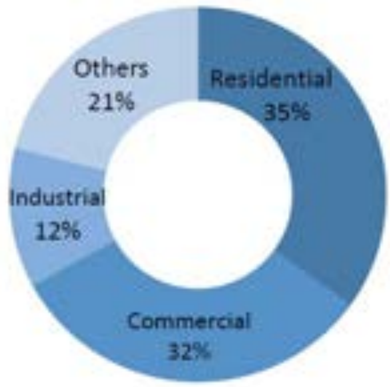


Figure 1: Sources of electricity consumption in the UAE, 2012 (FEWA 2014)

2 Case Study - The Iconic Tower Project

2.1 Location

The site is located in Al-Khan Lagoon Island, which is between Sharjah and Dubai, near the Cornish Road and Al Khan Street as shown in Figure 2. Al Khan Lagoon is geographically located at latitude (25.3219 degrees) 25° 19’ 18" North of the Equator and longitude (55.3694 degrees) 55° 22’ 9" East of the Prime Meridian on the Map of Dubai.

Figure 2: Al Khan Lagoon since 2016

2.2 Climatic Data

Figure 3 shows the site plan of the Iconic Tower project. It shows how the sun path and wind direction affects the site. Hot/humid wind which comes from the sea in summer is directed north-west towards the island, while in winter, cold/dry wind from the desert is directed south-east to the island. Sharjah has a typical climate like the rest of the Middle East, which means there is barely any change, so instead of four major seasons, there are two seasons. In summer, normal hot sunny day with high humidity. In winter, it is slightly colder, which contains rain and cool weather.

During the summer, which occur during the months April till October, Sharjah’s average temperature rises up till 40 °C combined with high humidity, also the temperature hardly drops below the thirties from how hot it is. All that shows the main reason why people try their best to stay in the shade. On the other hand, during winter, which occurs during the months November till March, the temperature is reduced below 30 °C. This leads tourists to come and enjoy Sharjah’s weather. During the first couple month’s Sharjah receives a little amount of rain, which makes night-times cool and enjoyable for everyone. This location has variable possibilities of precipitation. It is more likely to precipitate around February, where the percentage of the occurrence is 19 % of days; meanwhile, it is less likely to precipitate in June, where the percentage of the occurrence is 1 % of days.

Over the course of the year, the relative humidity usually ranges from 22 % (where it is dry), to 93 % (where it is very humid). Relative humidity is rare to drop below 10 % or reach as high as 100%. In May, the air is the driest. Thus in May, relative humidity drops below 28 %. On the other hand, December has the most humid weather surpassing 87 %. However, dew point usually differs from 8 °C to 26 °C, and it is very rare to be below 1 °C or above 29 °C. There are two periods that appear to be most comfortable. The first period is from January 1st till April 17th. Meanwhile, the second period is between November 16th and December 3rd.

Figure 3: The Iconic Tower' site plan

2.3 Wind Simulation

The wind simulation was carried out based on the consideration of the daily maximum speed of Sharjah's wind. The highest wind speed was indicated during March, which is almost 9 m/s as shown in Figure 4. Based on this wind speed, which is the worst scenario, the simulation was carried out in four cases as shown in Figure 5. The first case is about designing the tower based on a cuboid shape. This case is the worst case scenario, because the sharp edges do not allow the flow of the wind to act smoothly around the building. The second case is designing the shape of the tower as a cylinder. Table 1 measurements shows that the wind load will affect the cylinder tower badly. The

third case is about designing the tower based on an ellipse shape. Figure 5 shows how the wind acts when it hits the tower. Since the ellipse has the smooth curved edges characteristic, the load of the wind will be distributed wisely. After studying the previous cases, and analyzing them well, the shape of the iconic tower was generated. Many trials have been undertaken and tested by Design-Flow-Revit (Autodesk 2017) to come up with the iconic tower shape. As shown in Figure 5 and Table 1, the wind analysis assures that this shape is the best-case scenario.

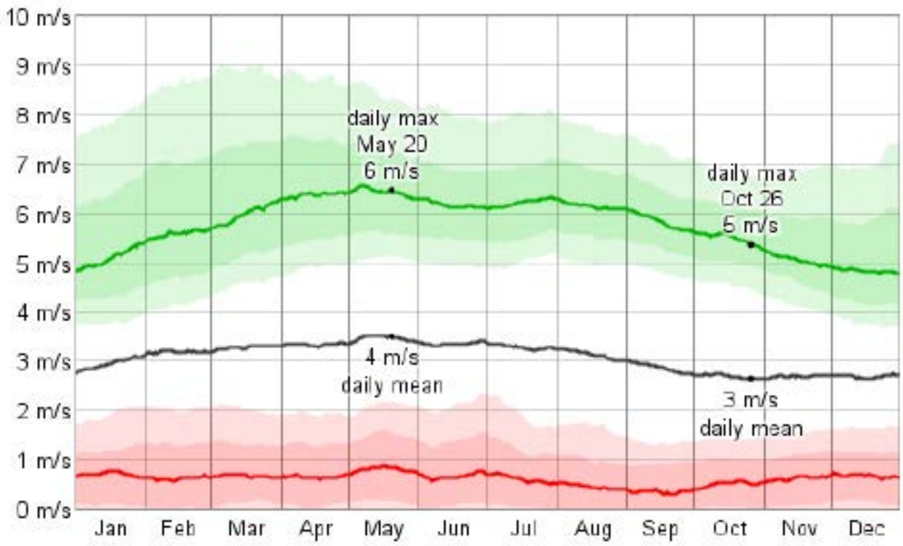


Figure 4: Wind speed

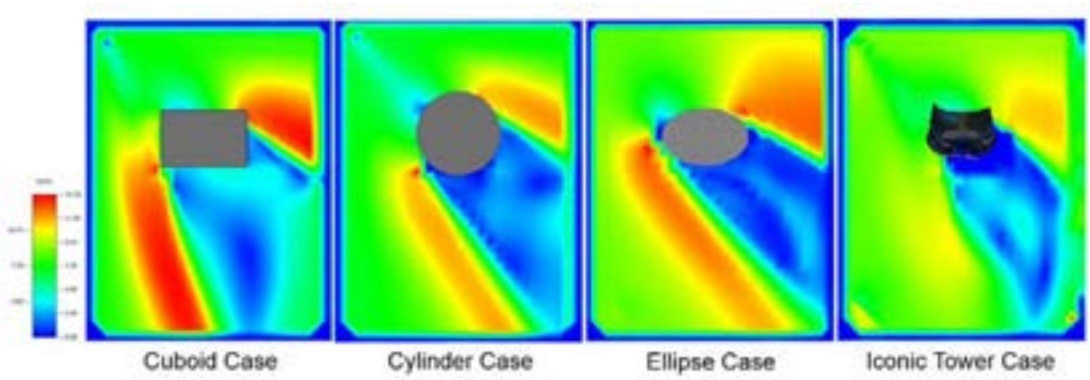


Figure 5: Wind analysis

Table 1: Wind speed of four cases (Generated by Design-Flow-Revit)

	Cuboid Case	Cylinder Case	Ellipse Case	Iconic Tower Case
North	6.6 m/s	10.8 m/s	8.8 m/s	0 m/s
East	3 m/s	1.3 m/s	0 m/s	0 m/s
South	4.2 m/s	1.8 m/s	0.8 m/s	0 m/s
West	12.1 m/s	8.4 m/s	0 m/s	7.0m/s

2.4 Iconic Tower Details

The Iconic Tower is a multifunctional 280 m skyscraper that consist of offices, 7-star hotel, observation deck and sky garden. It has 54 floors and the whole area of the floors is 152,000 m^2. Figure 6 shows the four main elevations, and Figure 7 shows the ground floor plan, an office floor plan and a hotel floor plan. This skyscraper is shaped in a tapering form to save the construction materials. In a plan perspective, it has the shape of ellipse which means the edges of the tower are rounded. A rounded edge makes the tower less resistant to the wind, which leads to a less structure for lateral loads. Minimizing the amount of concrete, steel and glass means that there will be less carbon content and embodied energy in the site. The long axis of the Iconic Tower is oriented east-west. Thus, the most exposed area to the sun is toward south.

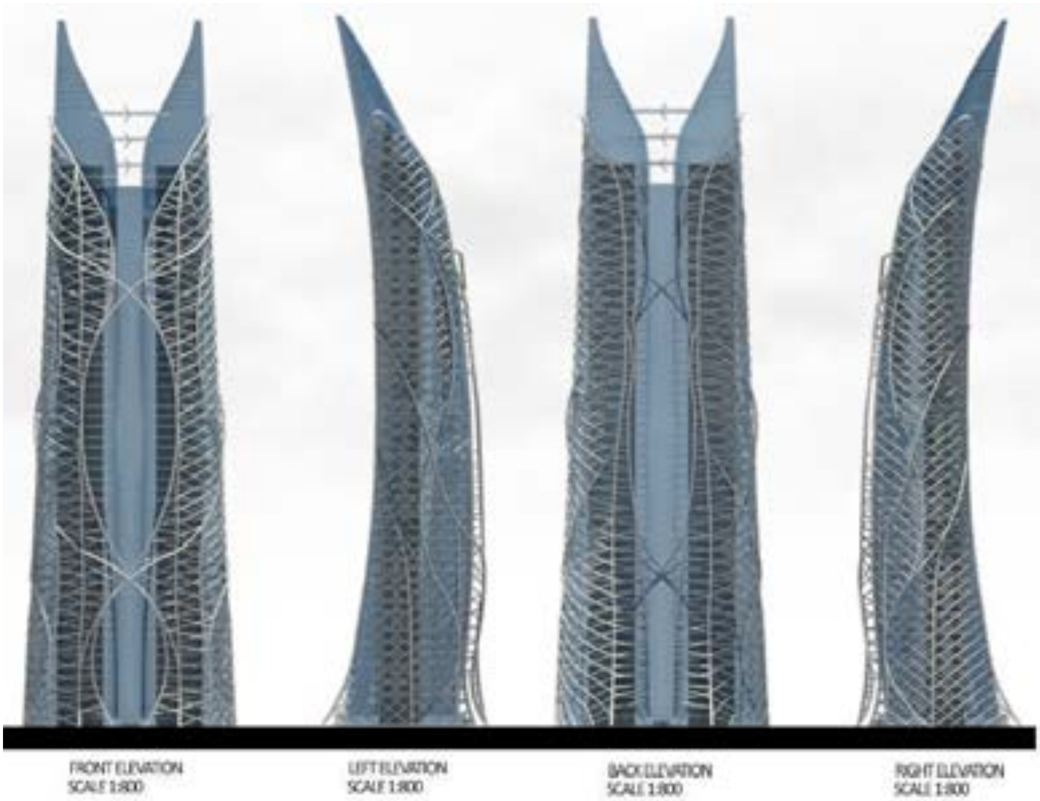


Figure 6: The Iconic Tower elevations

Figure 7: The Iconic Tower floor plans

The exoskeleton structure is the external skeleton that supports the Iconic tower. This structural system resists the live loads, dead loads, wind load and seismic load.

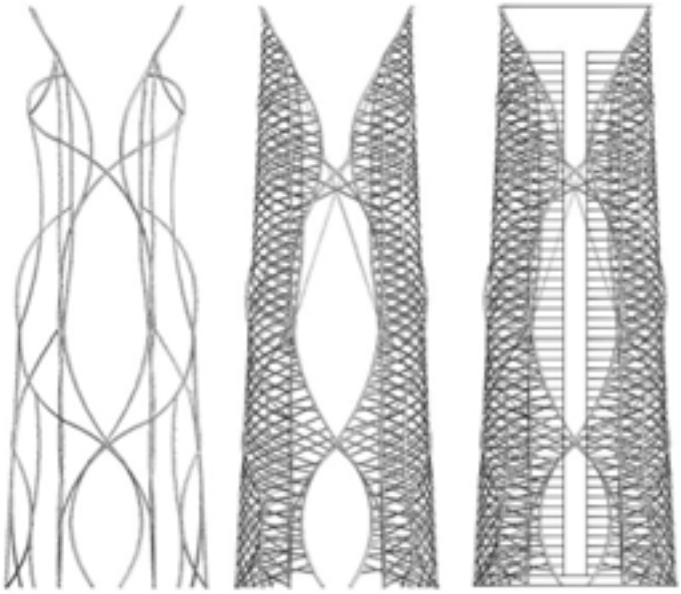


Figure 8: Exoskeleton structure

The material of the Iconic Tower will be Textile Reinforced Concrete. This material is especially significant for prefabricated components and façade engineering. It does a major reduction in thickness and weight, which results in ensuring the economic and ecological construction. As a result, the inner floor space of the tower will be increased when much thinner facades or wall elements are being built. Textile reinforced concrete is a recycled material and it can be reused again if needed, which makes it environmentally friendly. Moreover, the tensile strength is higher than the steel reinforced concrete by six times.

Moreover, a good construction method will be included, which is designing an underground parking floor for the Lagoon Island. This method is environmentally friendly because it eliminates the CO_2 emissions that cars will generate. There are two underground parking floors, the total area is 55,630 m², which can withstand 2500 car parking. The efficiency is around 22 m²/car.

Figure 9: Underground parking

However, the exterior skin will be cladded by curtain wall glazing system. This system consists of a double glazed curtain walls which is highly reflective to the solar heat and consumes 6-8 % less energy than the standard windows. The atrium

space, which is clarified in Figures 10, 11 and 12, indicates the idea of bringing more light to the tower and especially to the middle of each floor to decrease the need of artificial lighting systems. As a result, the CO_2 emission will be reduced. On the other hand, the atrium increases the social sustainability by its moderate cooled temperature and its spectacular views as shown in Figure 10.

Figure 10: The sky garden view forms the atrium

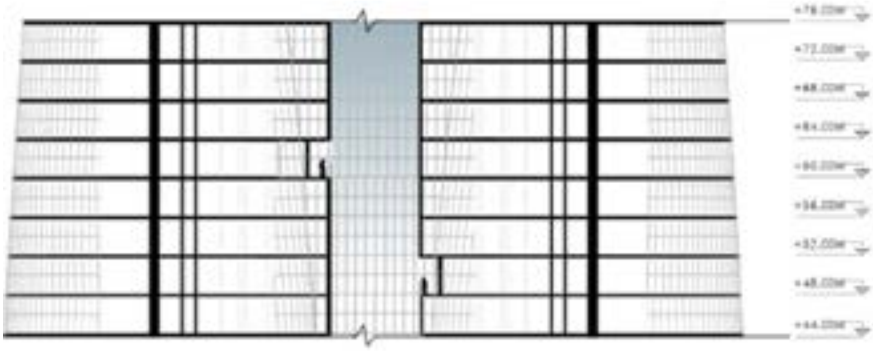


Figure 11: Partial section of the Iconic Tower

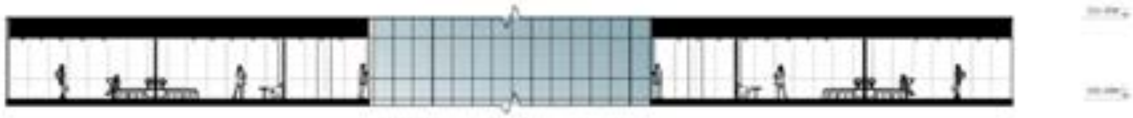


Figure 12: Hotel floor section

Green roofs are energy efficient; they improve the air quality, and last longer. Moreover, they act as an acoustic insulator. This technique increases the thermal insulation, reduce air conditioning needs, creates loveable and comfortable environment for the Iconic Tower visitors and employees. The selected Green roof systems are drained by waffled plastic sheets called drainage plates. Water is retained within pockets on the upper sides; excess water flows through small holes and spills over the edges to be carried off the roof. An air gap between the high-water level of the plates and the top of the plates assures proper soil drainage at all times. Since drainage plates are lightweight and easy to install, they have become the most popular drainage system for green roofs. Drainage plates are recommended for roofs with slopes less than 1:12, which are suitable for the project.

There are aluminum sheets that are placed within the exoskeleton for two uses. First usage is for producing water from humid air. Second usage is for shading; it is 50 %

open for visibility. Also it eliminates more than 30 % of the sun's heat before it reaches the tower. This shading system reduces the energy consumption for cooling and it provides outdoor shade to the main entrance.

The Iconic Tower is a mix-used building/skyscraper with offices and a hotel. Such development is especially beneficial because it creates more customers, supports longer business hours, and enhances the chance of spending valuable time. It increases the possibility of bringing more tourism, and makes the site attractive place to visit. It promotes sustainability, diversity and identity.

3 Harvesting Water

Basically this technique is about condensing humid air to produce water and to purify air from tiny particles. Based on scientific facts, the experiment plan was generated combined with calculations.

3.1 Scientific Facts

Rather than being bothered from the high humidity, it is time to benefit from the small water drops within the humid air. The following scientific facts were the basics of generating the idea of producing water from air.

- The atmosphere of earth contains billion tons of water vapor.
- The volume of water in air equals 12,900 km^3, which covers the whole area of earth by a thickness of 2.5 cm.
- The mass of water that exist in air equals 12.9 * 10^{12} tons.
- The climate of UAE is characterized by the high temperature and humidity during the most of the year's days, which causes disturbance.
- Most of the tiny particles that air carries reach 0.1 * 10^{-6} (from: Volcanoes, Meteorites, Automobile Exhausts, Sea Salts, Pollens and Microbes).
- Over the oceans, every 1 m^3 of air contains 10^9 of the previously mentioned particles. While over big cities, it contains 100 * 10^9 particle.
- Water condensation purifies air from these particles which results in a clear blue sky.

3.2 The Experiment Plan

- The cubic meter of air contains 50 g of water vapor in a temperature of 40 °C. With 60 % of relative humidity and in regular air pressure, as proven in the scientific measurements.
- If 1 m^3 of air has been cooled down to 25 °C, which is the tower's internal temperature, 30 g of condensed water can be produced and 20 g of water vapor will remain.
- The aluminum sheets that are placed within the exoskeleton acts as a water vapor condenser. The exoskeleton acts as a water vapor condenser. The temperature of these sheets can be controlled by using suitable sensors.
- Cooling the aluminum sheet can be done through AC pipes that are connected to the tower's AC system.
- Area of single aluminum sheet: 4 * 4 = 16 m^2. As shown in Figure 13.
- Number of aluminum sheets = 244
- Total area of aluminum sheets = 3904 m^2
- The amount of condensed water depends on relative humidity, the aluminum sheets temperature, atmospheric temperature dew point and wind speed.

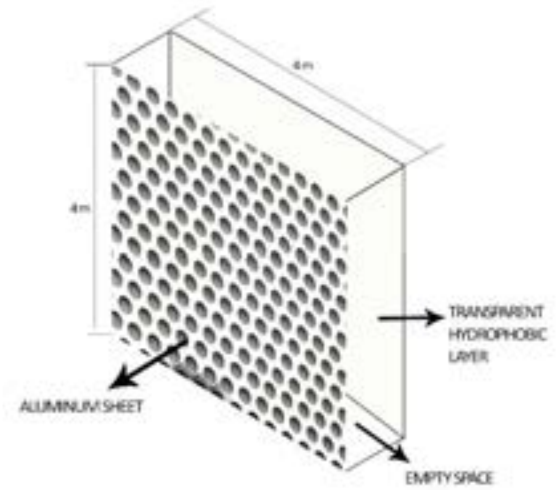


Figure 13: Aluminum sheet structure

3.3 The Experiment Calculations

- An experiment has been conducted in 12-May-2017, tested a cooled sheet of aluminum with dimensions of 1 meter * 1 meter.
- The percentage of humidity was 65 %.
- The temperature was measured by Thermometer; it was 31 °C.
- Using the Graduated cylinder, the condensed water volume was 2 L in 24 hours.
- The temperature has been cooled down to 18 °C.
- 2L * 3904 m^2 = 7808 L = 7.8-ton water.

This amount of water can be produced only when such conditions were provided.

4 Studying Atrium Space

At the beginning of designing the Iconic Tower, the ellipse shape was the basic idea. The long axis of the ellipse is oriented along the east-west direction based on Abu Dhabi Estidama guidelines. The disadvantage of the ellipse plan is that the natural light will not reach the middle of the floor, which generates the idea of including a circle void in the middle of the ellipse plan as shown in the first scenario in Figure 14. By using Autodesk Revit daylight analysis, the result of this scenario can be described as: High amount of natural light will enter the floor as the daylight analysis shows. The second idea was dividing the ellipse into two equal parts as shown in the second scenario in Figure 14. In this case, the natural lighting will enter from all sides into the building but not in an efficient way as you can see in the daylight analysis.

After studying the first two cases and analyzing them, the shape of the atrium was generated. The dynamic shape of the atrium was the main part of enhancing the daylight performance in the tower. It is noticeable that this design brings a reasonable amount of light and less glare. It results in creating a happy and productive environment since the natural light will be considered. This design achieves having spectacular views and sight-lines which allows occupants to have the sense of control of their environment and provides a sense of well-being.

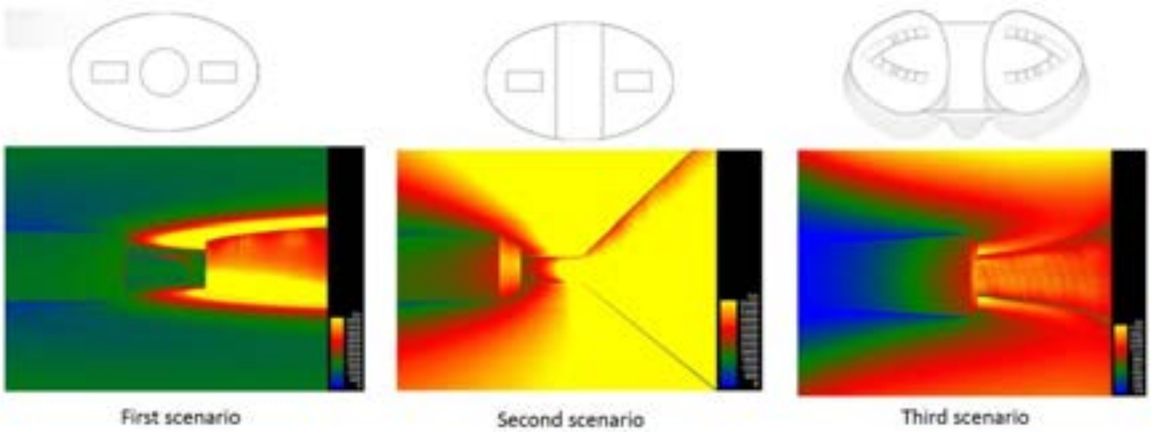


Figure 14: Daylight simulation scenarios

Afterwards, it was a must to study two main cases of the skyscraper. The first case would be the same shaped tower but without an atrium space, and the other case is the designed tower which is with an atrium space. Both cases were modelled using Autodesk Revit. After that, both models were simulated using Revit Energy Analysis tool. Two deferent reports were generated. Table 2 shows the consumed electricity in each model and clarifies how it is related to the floor area. So in the first case, which is the skyscraper without atrium, the floor area is 119,690 m^2. It consumes 4,189,847 kWh. While in the Iconic Tower case, which is the skyscraper with atrium, the floor area is 85,000 m^2, it consumes 3,080,758 kWh electricity. So the larger the floor area, the larger electricity will be consumed. The result of this comparison shows that the atrium provides as energy saving (for lighting) around 27 %.

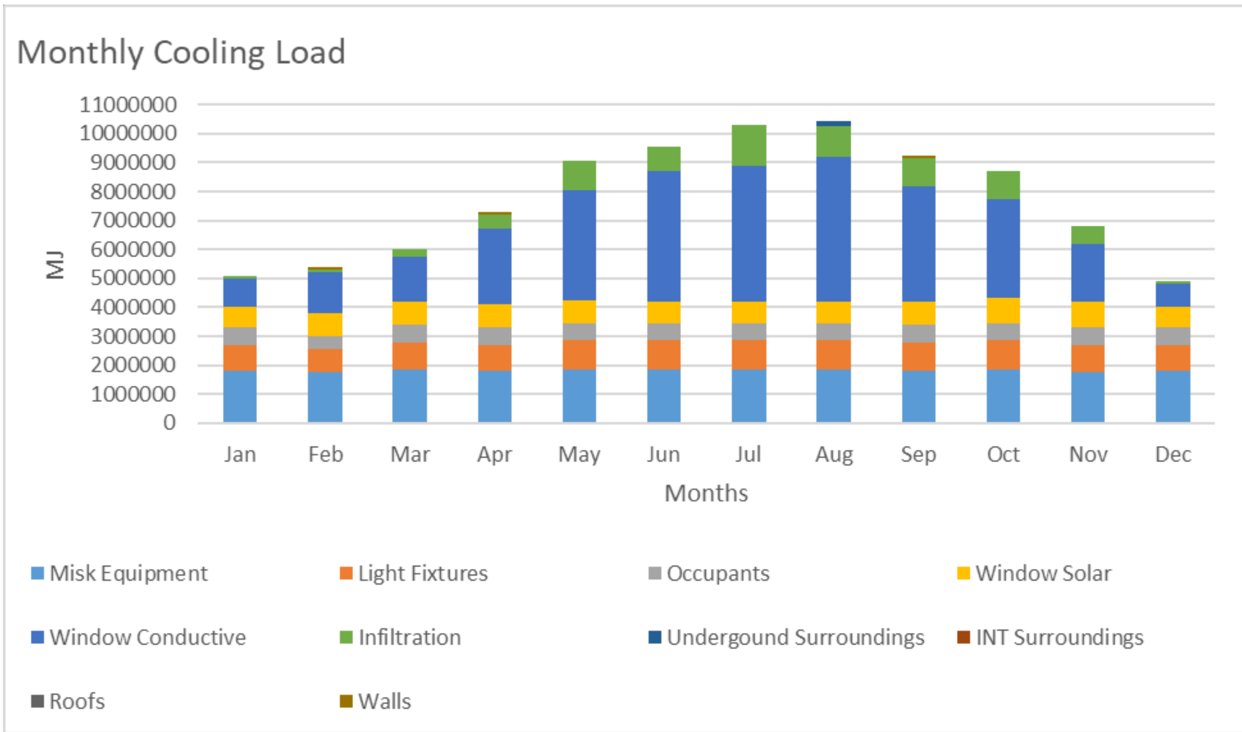
Table 2: Lighting simulation

	Without atrium	With atrium
Floor Area	119,690 m^2	85,000 m^2
Electricity Consumed	4,189,847 kWh	3,080,758 kWh

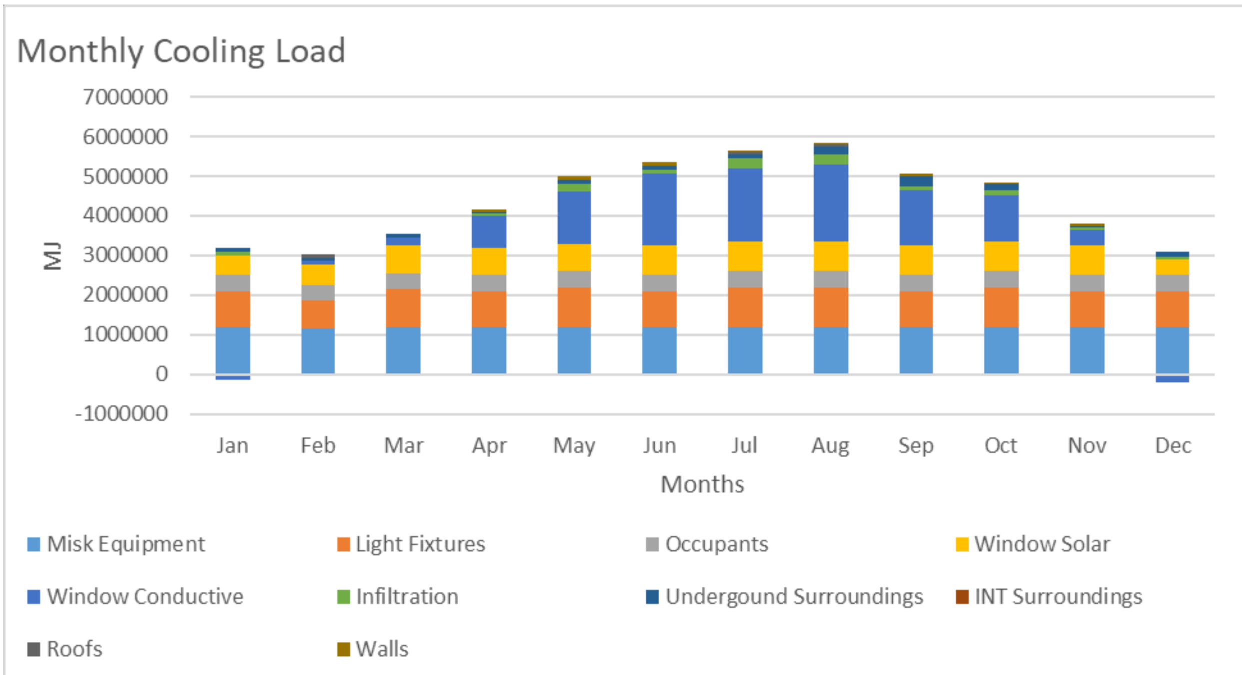
Also from the previously mentioned reports, the peak of cooling load in the first model was 4,000 kW as shown in Table 3 and in Figure 15. While in the Iconic Tower model, the peak of cooling load was 2,250 kW. The result can be clarified as: The atrium provides an energy saving (for HVAC load) = (4000 - 2250) / 4000 = 44 %.

Table 3: HVAC simulation

	Without atrium	With atrium
The peak cooling load	10,200,000 MJ = 4,000 kW	5,800,000 MJ = 2,250 kW
Cooling load for reach floor	80 kW	45 kW



Without Atrium



With Atrium

Figure 15: Monthly cooling load

These comparisons shows that the atrium space works in terms of enhansing the energy performance of the skyscrapper. This technique not only increases the tower's energy saving, but also it increases the social sustainability. The refreshed cool air in the atrium makes a pleasant environment to the tower's inhabitants especially with the spectacular views that can be visualized by the balconies and the curtain walls.The atrium apace starts from the ground floor and continues to the 54th floor as shown in Figure 16. In each mechanical floor there are AC pipes that ejects cool air to the atrium which flows down while hot air flows up and exit the tower from external openings. The air stays fresh by the mechanism of the natural movement of hot-cold air.

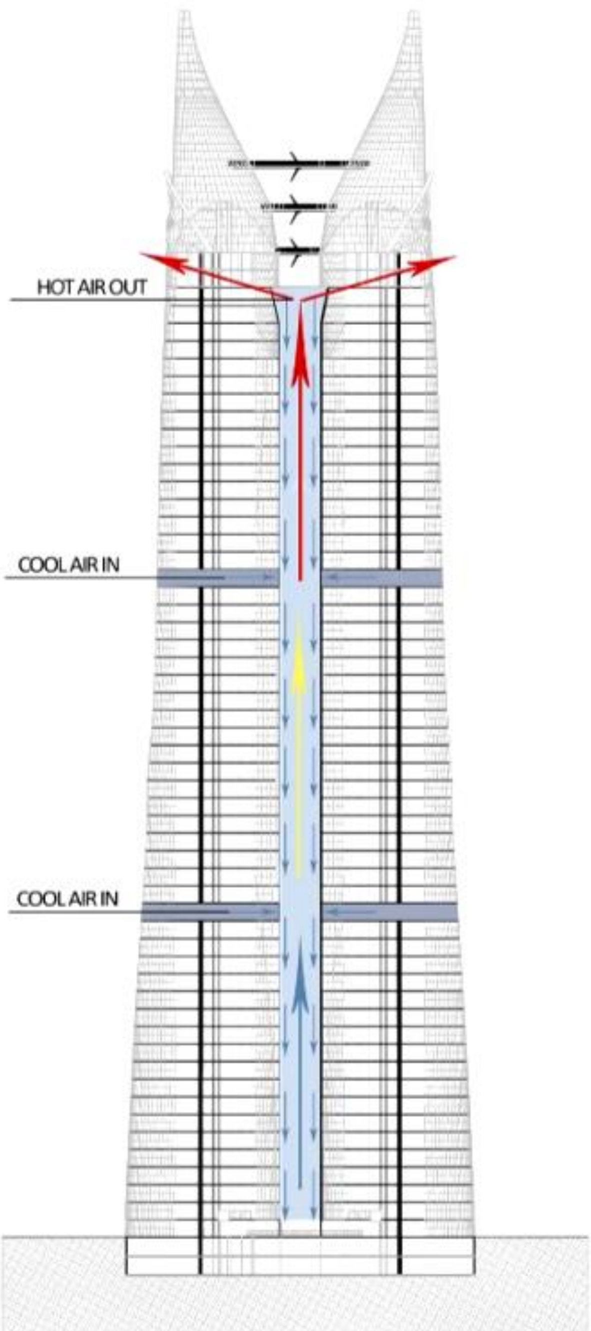


Figure 16: The Iconic Tower section

5 Applying Wind Turbines

Wind energy is considered the most feasible and the most reliable among the renewable energy technologies after hydropower (WSJ 2013). Recent years have witnessed acceleration in wind energy technology development and an increase in the number and the size of investment projects, which contributed in increasing the number of experts and gain large experience in this field worldwide. Also, the utilization of wind energy as a clean natural resource can contribute to reduce the environmental pollution.

Within the highest part of the skyscraper, three wind turbines were placed to generate energy. In this case, the wind speed was considered to equal 17 m/s (DM 2013), and the blade length to be 8 m. The following steps shows how the available power was calculated:

- $P_{avail} = ½\ \rho\ A\ V^3\ cp$
- So the area is $A = \pi\ (8)^2$
- Which means A = 201 m².
- So the power is: P = ½ * 1.23 * 202 * $(17)^3$ * 0.4
- P = 242,928.2 W = 243 kW
- Energy in one year = P* No. wind turbine working hours * 365 * 0.25
- Energy = 242,928.2 * 24 * 365 * 0.25 = 1,064,025,507 Wh
- For one turbine = 1,064 MWh
- For 3 turbines, Energy = 1,064 MWh * 3 = 3192 MWh

As a result, the electricity generated by the wind turbines meets the artificial lighting demand which is 3,080,758 kWh.

6 Conclusions

Economic sustainability can be achieved through the low environmental impact materials that are cost efficient. The tower's tapering form saves the construction materials. An underground parking floor for the Lagoon Island is economic by designing the parking to be exactly under the Iconic Tower. Also, it includes natural openings to bring in the natural light, which saves the artificial lights cost. The LED lighting system is cost efficient. Curtain wall glazing system reflects on a huge amount of heat, which maximize the efficiency of the tower's cooling system. This results in minimizing the cooling energy cost. The economic benefit of the tower's atrium is about bringing more natural light to the offices and the hotel, which results in reducing the artificial lighting costs. The aluminum sheets forming a shading system eliminates more than 30 % of the solar heat that decrease the cost of the cooling energy consumption. Moreover, the aluminum sheets produce water that saves the need of water demand.

Most of the new proposed skyscrapers are designed towards sustainable and green future. They are associated with multiple green techniques. This paper presented a proposal of different solutions to save energy that enhances the energy performance of skyscrapers in such climates like the UAE's. Building Performance Simulation (BPS) studies utilizes tools that are developed for engineers and architects to use in testing different scenarios of the building design until the best case or the most optimal solution is achieved. In this paper, Design-Flow-Revit, Autodesk Revit energy simulation and daylight analysis were used to select the best case scenario (most optimal solution) and to prove that it works.

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ZEMCH NETWORK

PILOT STUDY ON IEQ OF AN AGED-CARE FACILITY IN VICTORIA

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Abstract: *Australian population is ageing. The proportion of Australian population over 65 years old has been increased and it is projected to be 25% in 2042. Although the Victorian Government has promoted ageing in place under home care package services, there is still a genuine need to provide more residential aged care services to satisfy the needs. The indoor environmental quality (IEQ) of residential aged care facilities is closely related to the health and well-being of residents living there. In this pilot study,* the *Adare Supported Residential Services (SRS) in Victoria is selected as the site for investigation. Some sensors are deployed in both communal areas and residents' rooms to collect transient data on IEQ parameters, including carbon dioxide concentration, dry bulb temperature, radiant temperature, relative humidity and illumination level. Data collected is analysed and the links between outdoor environmental conditions and IEQ parameters are investigated. Limitations of this pilot study are discussed and recommendations for the full study are provided.*

Keywords: *Indoor Environmental Quality, Design for Ageing, Residential Aged Care, Environmental Sensors*

1 Introduction

Like most developed countries, Australia's population is ageing. The latest 2016 Census reveals that the percentage of older adults (aged over 65 years) has been increasing from 13% of the overall population in 2002 to 16% in 2016. This percentage is projected to be 25% in 2042 (Pash, 2017). This is a result of sustained low birth rate and increase in life expectancy. The Victorian Government provides home care package services to promote ageing in place and encourage the elderly to stay at home for longer, but there is still a genuine need to provide more residential aged care services. In view of the significant expansion of the ageing population in the coming decades, there is a rapid increase in residential aged care facility development, which is expected to require nearly 80,000 new residential places by 2024 (Creighton, 2016).

The elderly people spend about 19 to 20 hours per day indoors (Aguiar et al., 2014), and the majority of the residents stay indoors all the time at aged care facilities. The indoor environmental quality (IEQ) of the facilities can significantly affect the health and well-being of residents living there. Yet, systematic research on the IEQ of residential aged care facilities in Australia to inform the design has not been well developed. In Victoria, there are 750 government-funded nursing homes (Murphy, 2017) and 131 privately operated supported residential services (SRS) (State of Victoria, 2017).

The main aim of this pilot study is to identify the measurement protocols and explore the capability and reliability of the data collection system. The Adare SRS Facility in Victoria is selected as the building for the study. Data collected is analysed and the links between outdoor environmental conditions and IEQ parameters are also investigated. Limitations of the study are discussed and recommendations are provided.

The building is located in Wantirna South, approximately 35 km to the south-east of Melbourne's Central Business District. It was built in 2000 and it can accommodate 45 residents. As of July 2017, about one-third of residents are English-speaking, while the remaining speak Cantonese, Mandarin, Shanghainese and other Chinese dialects. To accommodate cultural friendliness, room numbers are labelled from 1 to 39, 60 to 63, 65 & 66 (see Fig. 1) to avoid unlucky numbers according to Chinese traditional belief.

Regarding the building layout, bedrooms are located on both sides of three major corridors. Apart from Rooms 16 and 17 which are connected together to accommodate an aged couple, the remaining are single rooms with ensuite. The longer corridor (Rooms 1 to 21) and the shorter corridor (Rooms 22 to 31) run north-southwards, whereas the third corridor (Rooms 32 to 66, together with kitchen and laundry) run east-westwards. The communal spaces (living lounges and dining areas) link these three corridors together with gardens on both sides of the living lounges.

There are no mechanical cooling systems for individual rooms at Adare SRS. Each room has a ceiling fan instead. Evaporative coolers are installed only at communal areas. Wall-mounted hydraulic heaters are installed for both communal areas and residents' rooms. Windows in residents' rooms are open-able for natural ventilation and the curtains can be adjusted to prevent incoming solar radiation and glare. The solar absorptance valve of all external walls (common red brick) is expected to be about 0.6.

2 Methods

In order to measure the indoor environmental quality, sensors were deployed at both communal areas and residents' rooms to collect transient data on site. The sensors were

supplied by HuxConnect (HuxConnect, 2017). Gateways collect carbon dioxide concentration, whereas motes collect various data, including dry bulb temperature, radiant temperature, relative humidity and lighting level. The black-globe of the mote measures the mean radiant temperature, the white hemisphere measures lighting level, while sensors inside measure dry bulb temperature and relative humidity through slots (Figure 1). Measurements are recorded at five-minute timestep. Motes do not have onboard data storage, so data measured by motes were transferred to an assigned gateway via Bluetooth wireless transmission. Gateways are communication relay devices transmitting the data in real time to the online portal by either 4G or Wi-Fi technology. This environmental monitoring system is still under development, so the technical specifications (Table 1) are subject to further enhancement and upgrade.

Table 1: Ranges and Accuracies of the Sensors

IEQ Parameters	Range		Accuracy	Devices
	Minumum	Maximum		
Carbon dioxide concentration (ppm)	0	5,000	± 30ppm ± 3%	Gateways
Dry bulb temperature (°C)	-40	125	± 0.2°C	Motes
Radiant temperature (°C)	-55	85	± 0.5°C	Motes
Relative humidity (%)	0	100	± 2%	Motes
Illumination level (lux)	5	100,000	N.A.	Motes

Motes and gateways were strategically located within the building to collect data. This paper presented the data collected for one week (from 10th June to 16th June 2017). During this one week, a gateway was installed at the dining area (Gateway B) and three gateways (Fig. 2a) were placed in three bedrooms (Rooms 21, 23 and 32). Motes (Fig. 2b) were located near gateways at the dining area and four bedrooms. The experiment design intention was to collect data from four different bedrooms which have windows facing different directions (Room 23 facing east, Room 32 facing south, Room 21 facing west and Room 65 facing north; see Fig. 3). However, the exact locations were still subject to the acceptance of residents and the strength of Wi-Fi and 4G signals there. In this paper, the data collected by Motes A3, B2, B8, B10, C7 and D4 are analysed and compared. For the sake of simplicity, only relevant gateways and motes are shown on the floor plan (Fig. 1).

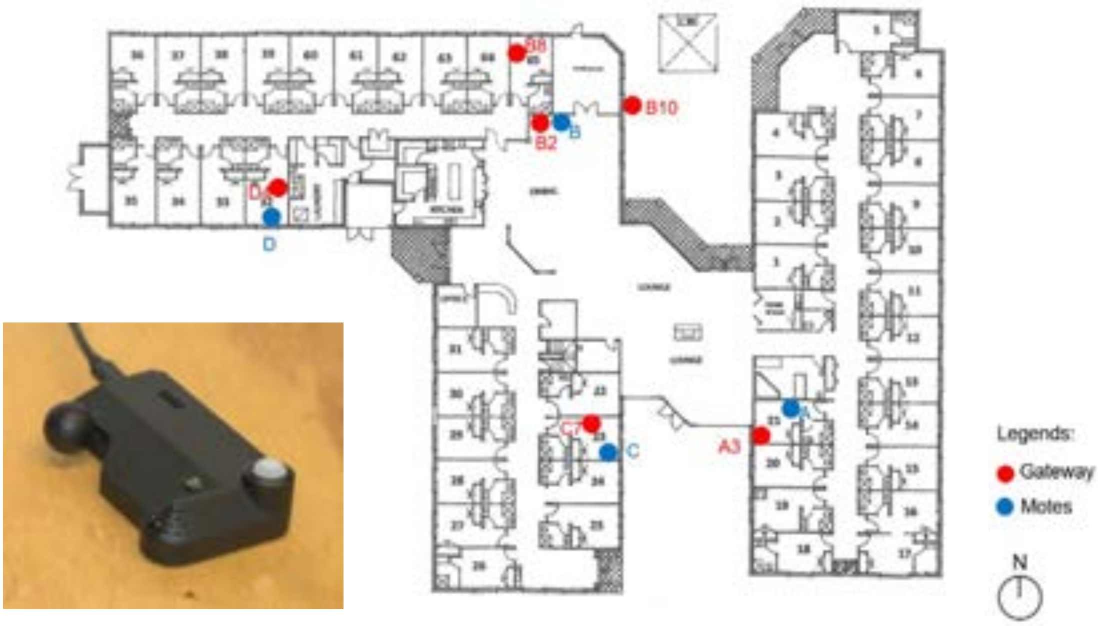

Fig. 1: Locations of Gateways and Motes at Adare SRS

Fig. 2 (a) Gateway on the cabinet & Fig. 2 (b) Wall-mounted Motes

(a) East-facing window, Room 23

(b) North-facing window, Room 65

(c) West-facing window, Room 21

(d) South-facing window, Room 32

Fig. 3 Wall-mounted Motes in various rooms with different window orientations

3 Results

3.1 Dry Bulb Temperature

The indoor dry bulb temperature at dining area fluctuated from 19.4°C to 24.4°C (within a range of 5°C). A daily temperature fluctuation pattern can be easily observed with the maximum at 5pm and with the minimum between 5 and 7am (Fig. 4). The fluctuation patterns of both indoor and outdoor dry bulb temperature were quite similar. Based on weather data (Dark Sky, 2017), the outdoor dry bulb temperature fluctuated from 7.2°C to 16.2°C, which had a wider range of 9°C (5°C internal). A daily temperature fluctuation pattern can be clearly observed with the maximum at 2pm and with the minimum between 4 and 6am. Apparently, the fluctuation of indoor dry bulb temperature was lagging behind the outdoor temperature, which was possibly due to the thermal insulation and airtightness of the building envelope. It also required time to heat up the internal space through the solar heat gain via the single glazing windows.

The indoor dry bulb temperature of the four residents' rooms differed significantly. In general, the east-facing room (Room 23) was maintained at a higher temperature (between 22.6°C and 26.7°C), whereas the west-facing room (Room 21) was at the lowest temperature (between 18.4°C and 21.9°C). For better understanding of the impact of heaters, the dry bulb temperatures at 12 midnight on 15th June of these four rooms were compared: 25.2°C in Room 23 (east-facing), 24.3°C in Room 32 (south-facing), 23.3°C in Room 65 (north-facing) and 20.5°C in Room 21 (west-facing) (Fig. 5). Apparently, the hydraulic heaters at Room 23 and Room 21 were turned on at the highest setting and the lowest setting respectively. The north-facing room (Room 65) sometimes achieved the highest indoor dry bulb temperature, such as 26.8°C at 3pm on 11th June compared to 14.7 °C outdoor air temperature at the same time, which was influenced by both the solar heat gain and the hydraulic heater in the room.

3.2 Radiant Temperature

The fluctuation pattern of indoor radiant temperature was consistent with indoor dry bulb temperature. The radiant temperature of the east-facing room (Room 23) was maintained at a higher temperature (between 23.1°C and 26.9°C), whereas the west-facing room (Room 21) was at the lowest temperature (between 19.4°C and 22.9°C) among the four rooms. Sometimes, the north-facing room (Room 65) could achieve the highest indoor radiant temperature, such as 27.4°C at 3pm on 11th June (Fig. 6). The black cover of the motes facilitates heat absorption for taking radiant temperature readings.

For the dining area, the dry bulb temperature fluctuated between 19.4°C and 24.4°C, while the radiant temperature fluctuated between 20°C and 24.9°C. The graph in Fig. 7 shows the difference between dry bulb temperature and radiant temperature at the dining area. The radiant temperature was within the range of 0.4°C and 0.7°C higher than the dry bulb temperature. Greater temperature differences were observed during night time and before sunrise. For example, at 5am on 11th June, the dry bulb temperature dropped to 19.6°C, whereas the radiant temperature was still maintained at 20.3°C, resulting in the temperature difference of 0.7°C.

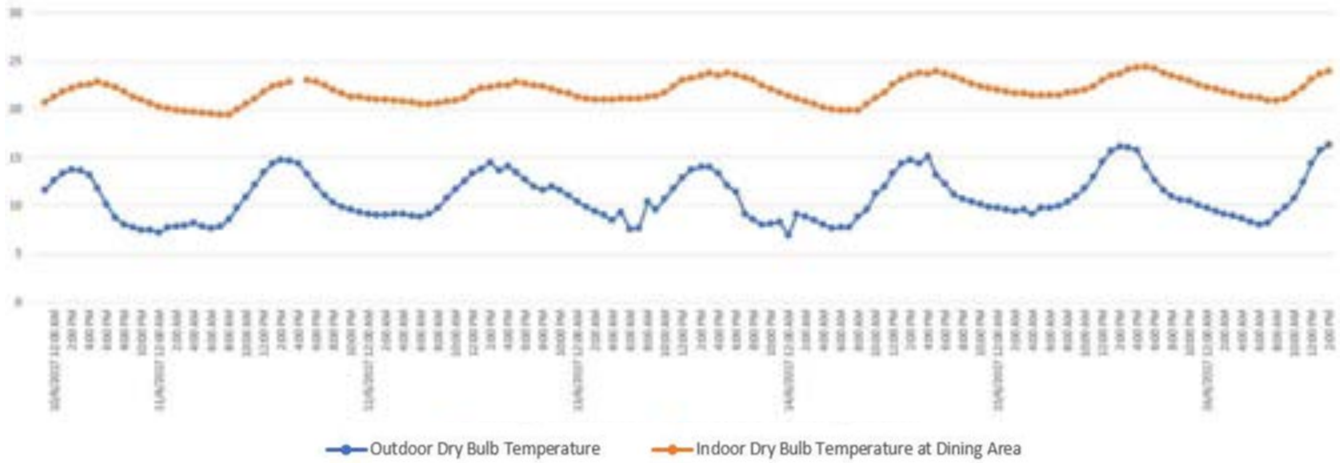

Fig. 4: Dry bulb temperatures indoor (dining area) and outdoor

Fig. 5: Dry bulb temperatures indoor (various residents' rooms) and outdoor

Fig. 6: Radiant temperatures (various residents' rooms and dining area)

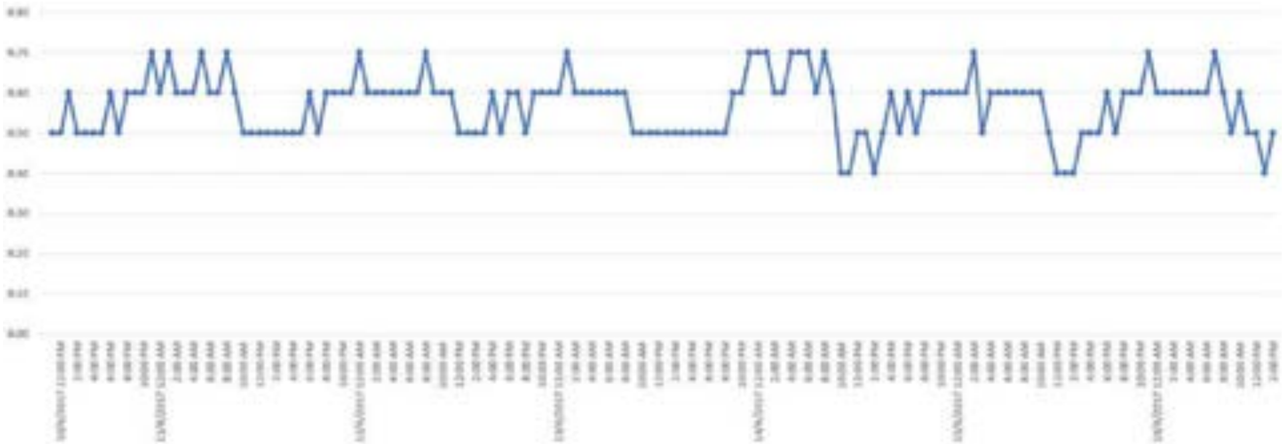

Fig. 7. Difference between radiant and dry bulb temperatures (dining area)

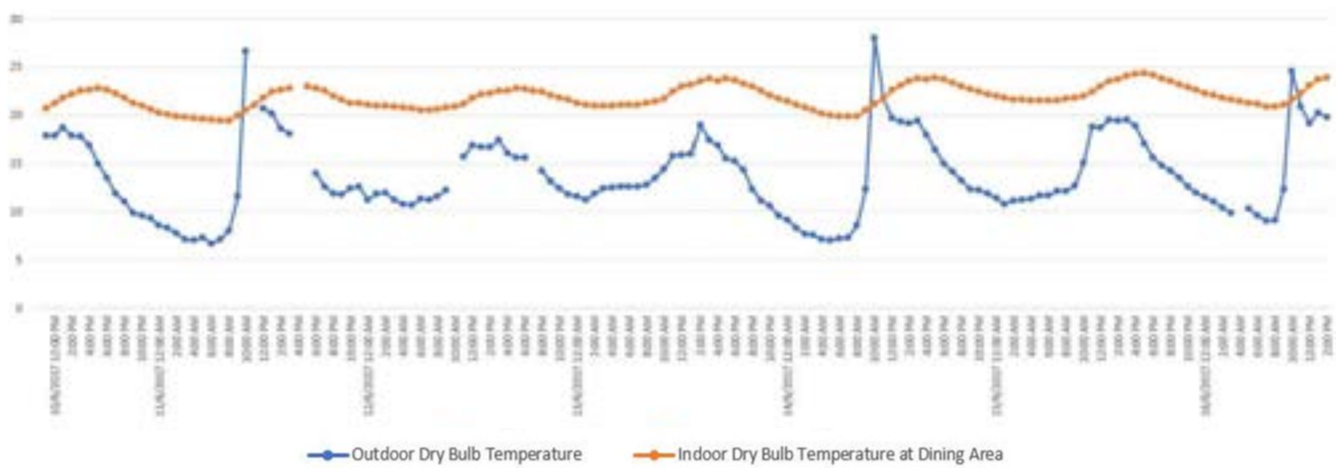

Fig. 8. Dry bulb temperatures indoor (dining area) and outdoor (measured by an outdoor mote)

3.3 Outdoor Temperature

In order to test the measurements of motes outdoor, a mote was placed outside the building near the dining area facing east to an internal garden (Fig. 1). The outdoor dry bulb temperature recorded by the mote is shown in Figure 8. Compared to the weather data (Dark Sky, 2017), such outdoor mote recorded a more drastic temperature fluctuation, such as the significant temperature increase from 11.6°C to 26.6°C from 9am to 10am on 11th June and from 12.3°C to 28°C from 9am to 10am on 14th June. This is probably due to the direct solar radiation onto the black surface of the mote. Based on this observation, motes are not suitable to be used externally and weather data is used instead in this pilot study (Fig. 4).

3.4 Illumination Level

The illumination level recorded by motes reflects the combined effect of both daylighting and artificial lighting. However, in each resident's room, there was only a 12-watt compact fluorescent light bulb installed under the ceiling fan (Fig. 3), so the fluctuation of lighting level during daytime is mainly due to daylighting and window orientation. The north-facing Room 65 obtained the highest illumination of 2,713 lux at 3pm on 10th June, whereas the east-facing Room 23 received 603 lux at 10am on 11th June. Comparatively, the peak illumination values of west-facing Room 21 and south-facing Room 32 were only 232 lux and 137 lux respectively at 12 noon on 11th June, while north-facing Room 65 still maintained 930 lux at the same time (Fig. 9). Among these four rooms, Room 65 received the greatest solar exposure, but too much sunlight penetration could result in glare, high indoor temperature and overheating issue if the indoor environmentally parameters could not be easily adjusted by residents.

During night time, residents' rooms were maintained at around 13-14 lux due to artificial lighting. The lighting level of bedrooms was commonly reduced to 0 lux during sleeping times, which could reflect the behaviour of the residents who often switched off the light at around 7:30pm for sleeping (Fig. 8). The dining area is facing to an internal garden and a building wing in front, so direct sunlight penetration is limited. The highest illumination value of the dining area was 243 lux at 9am on 11th June. As a public communal space, the dining area was illuminated at night and an average of 23 lux lighting level was recorded during night time for safety and visibility reasons (Fig. 10).

3.5 Relative Humidity

The weather data showed a regular pattern of outdoor relative humidity, which fluctuated between 64% and 94% (within a range of 30%). The outdoor relative humidity increased during night time and reduced during daytime (Fig. 11). This corresponds with the fluctuation of outdoor dry bulb temperature as warmer air can hold more water vapour than cooler air, leading to the decrease in relative humidity.

Compared to outdoor data, the indoor relative humidity of the dining area fluctuated between 39.4% and 55.6% (within a range of 16.2%), whereas the indoor relative humidity of the four bedrooms fluctuated between 34.6% and 59.7% (within a range of 25.1%) (Figs. 11 & 12). The fluctuation of relative humidity depends on a number of factors, including the thermal insulation and airtightness performance of the building envelope, solar radiation, heater radiation and human behaviour; so the indoor relative humidity did not show the fluctuation pattern as clear and regular as the outdoor relative humidity.

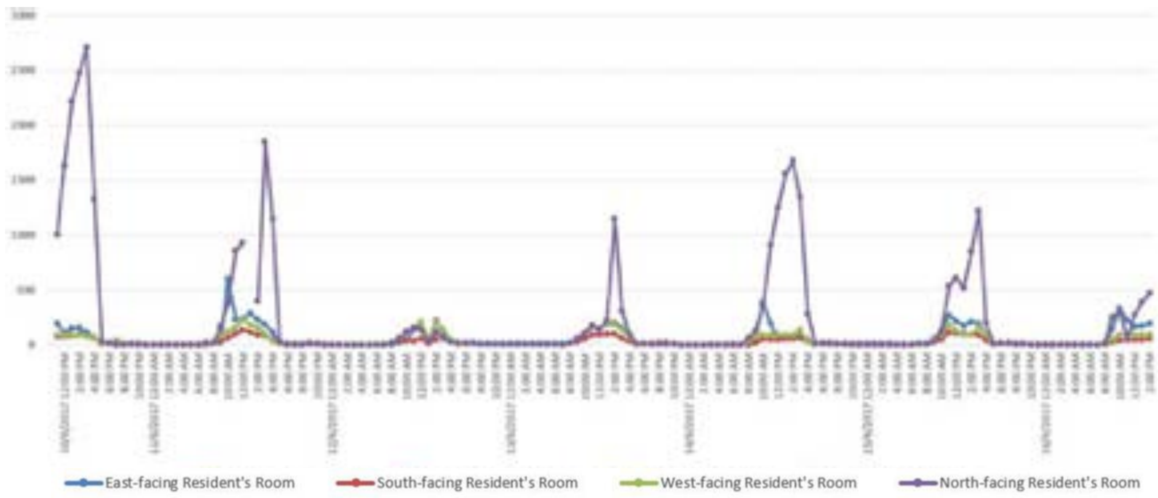

Fig. 9 Illumination levels (various residents' rooms)

Fig. 10 Illumination levels (dining area and various residents' rooms)

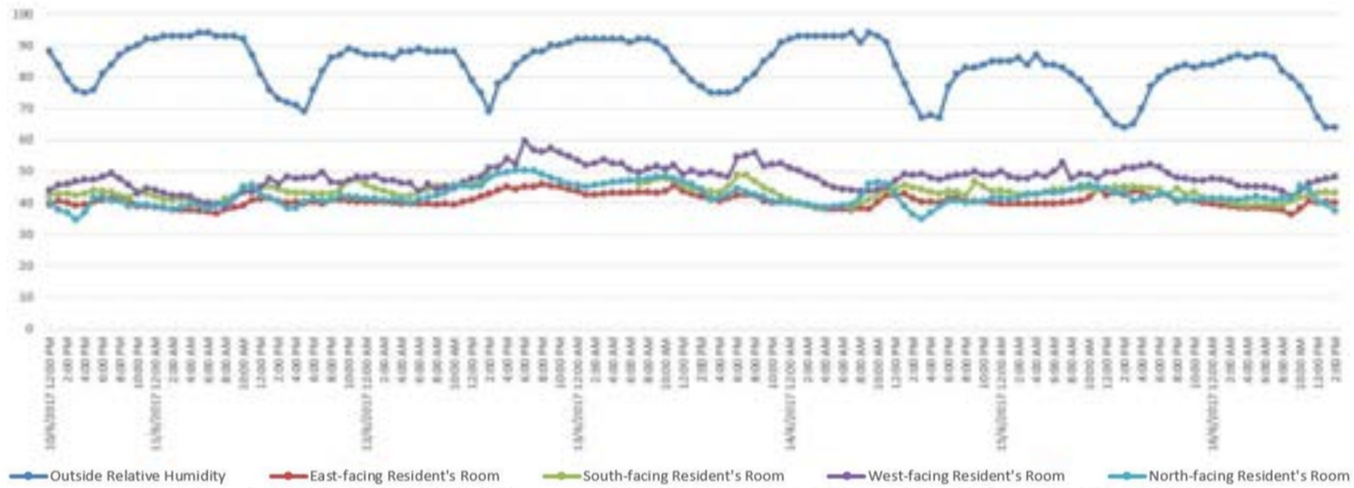

Fig. 11 Relative humidity (outdoor and various residents's rooms)

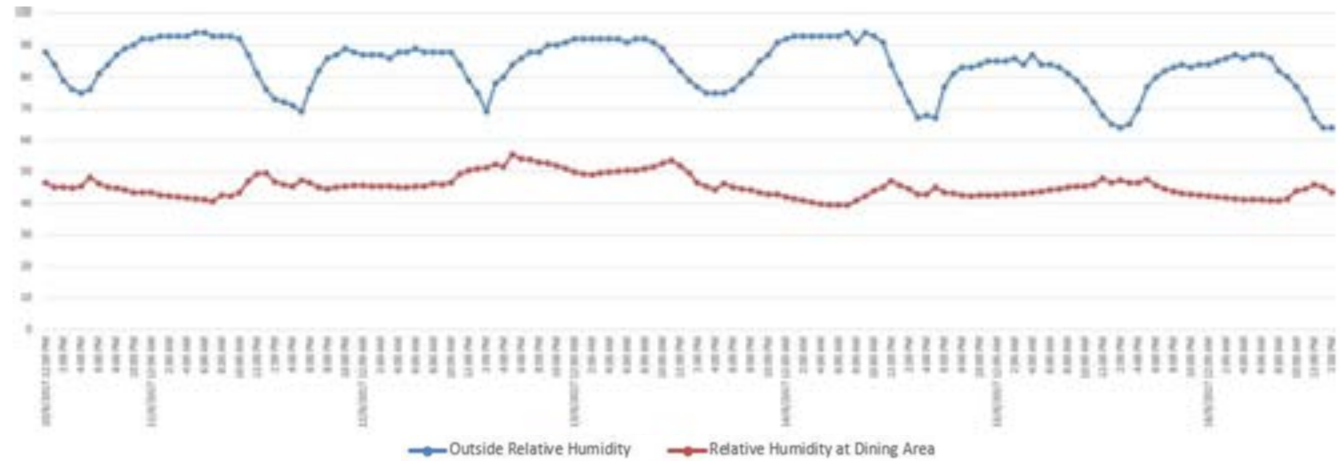

Fig. 12 Relaive humidity (outdoor and dining area)

3.6 Carbon Dioxide Concentration

The carbon dioxide concentration at the dining area showed a regular fluctuation pattern. There were two peaks per day: at 12noon and 5pm, reflecting the gathering of residents at the dining area for having lunch and dinner together. The highest concentration at 12 noon was 752 ppm on 13th June, whereas the highest concentration at 5pm was 640 ppm on 10th June (Fig. 13). The lowest carbon dioxide level at the dining area was 412 ppm at 5am on 15th June as minimal occupants in the early morning.

4 Discussion

Indoor dry bulb temperature depends on various factors, including solar radiation transmitted to the room, heater radiation, human behaviour and air movement. Adare SRS relies on natural ventilation for cooling, but there is no ceiling fan at the dining area and it is not common for the windows to be opened widely, so the impact of air movement to indoor dry bulb temperature is minimal. The wall-mounted hydraulic heaters were frequently turned on during the cold season in June, so the heater radiation impact to indoor dry bulb temperature was consistent. The peak at 5pm can be partly explained by the gathering of residents at the dining area for having dinner together, but the human behaviour seems not to be the decisive factor as significant temperature increase cannot be observed during lunch time at noon daily. Therefore, it seems that the increase of indoor dry bulb temperature at dining area was mainly due to solar heat gain.

Besides, the current arrangement of hydraulic heaters mounted below windows with control knobs at low level close to the floor poses difficulty for users, especially elderly residents, to adjust the heating to suit their needs. Referring to the onsite observation, it was common for some residents (such as in Rooms 23 and 65) to put their cabinets in front of windows, leading to the inaccessibility of the control knobs of the heaters (Fig. 3). If the control knob of the heating can be located at a more user-accessible location, this can facilitate residents to have more autonomy to control the indoor temperature of their rooms. Currently, residents can turn on ceiling fans for cooling effect and adjust the curtains to avoid glare, but solar heat gain to the bedrooms cannot be avoided as the curtains are hanging inside the rooms and solar radiation has already entered through windows.

Another factor affecting indoor dry bulb temperature is the configuration of bedrooms. The west-facing Room 21 has the smallest window area as half of the room is embedded in the living lounge (Fig. 3). The window size of Room 21 is half of the size of the other three rooms (Rooms 23, 32 and 65). Solar exposure of Room 21 is further reduced as it is facing to an internal garden and the sunlight penetration is unavoidably affected by the adjacent living lounge and the building wing in front. This can explain why Room 21 has the lowest indoor dry bulb temperature among the four rooms monitored.

The fluctuation of the indoor relative humidity was within the recommended range between 30% and 60% for any habitable space to minimise the growth of allergenic or pathogenic organisms (Cotterell and Dadeby, 2012: 149). However, Sterling et al. (1985) recommended the optimal conditions of relative humidity to be within a narrower range between 40% and 60% at a normal indoor temperature range of 19°C to 27°C to minimise the health risks caused by pathogens and biological contaminants, including bacteria, viruses, fungi and mites (Fig. 15). Referring to this, viral population and respiratory infections increase at relative humidity below 40%.

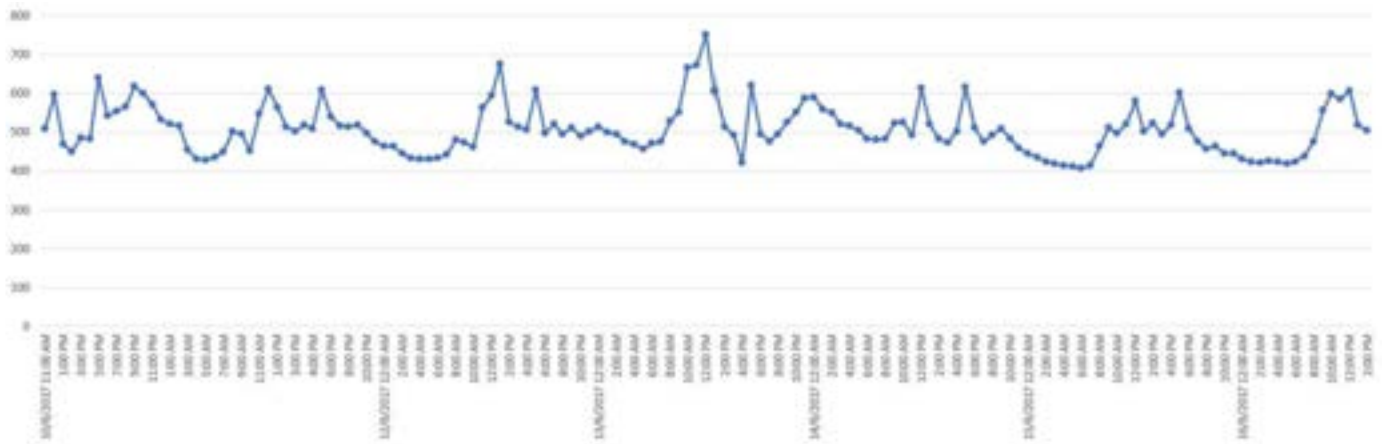

Fig. 13 Carbon dioxide concentration (dining area)

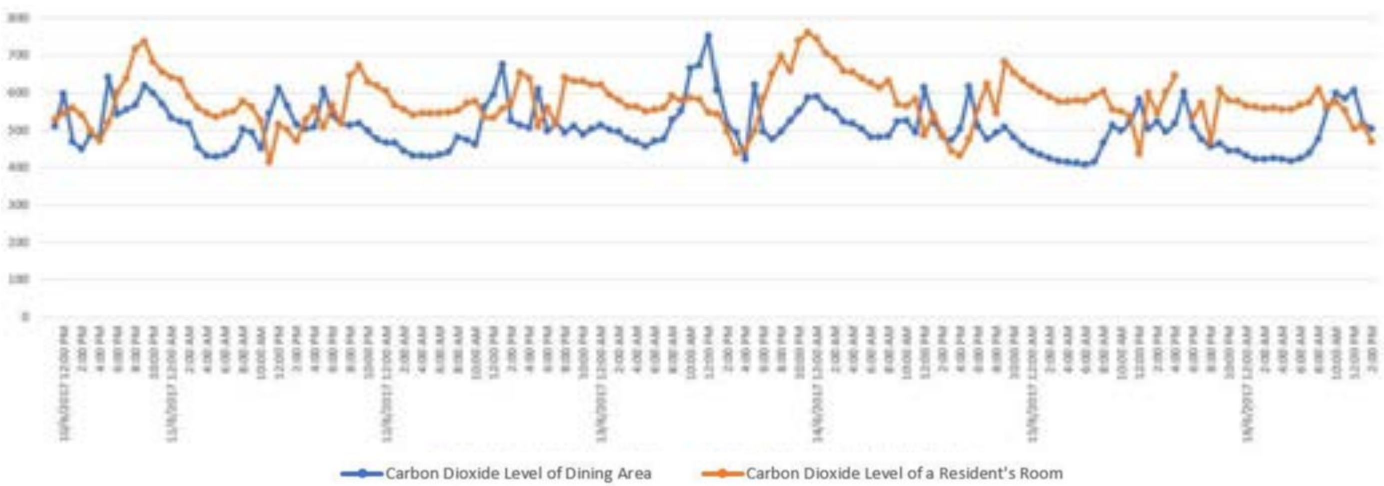

Fig. 14 Carbon dioxide concentration (dining area and room 23)

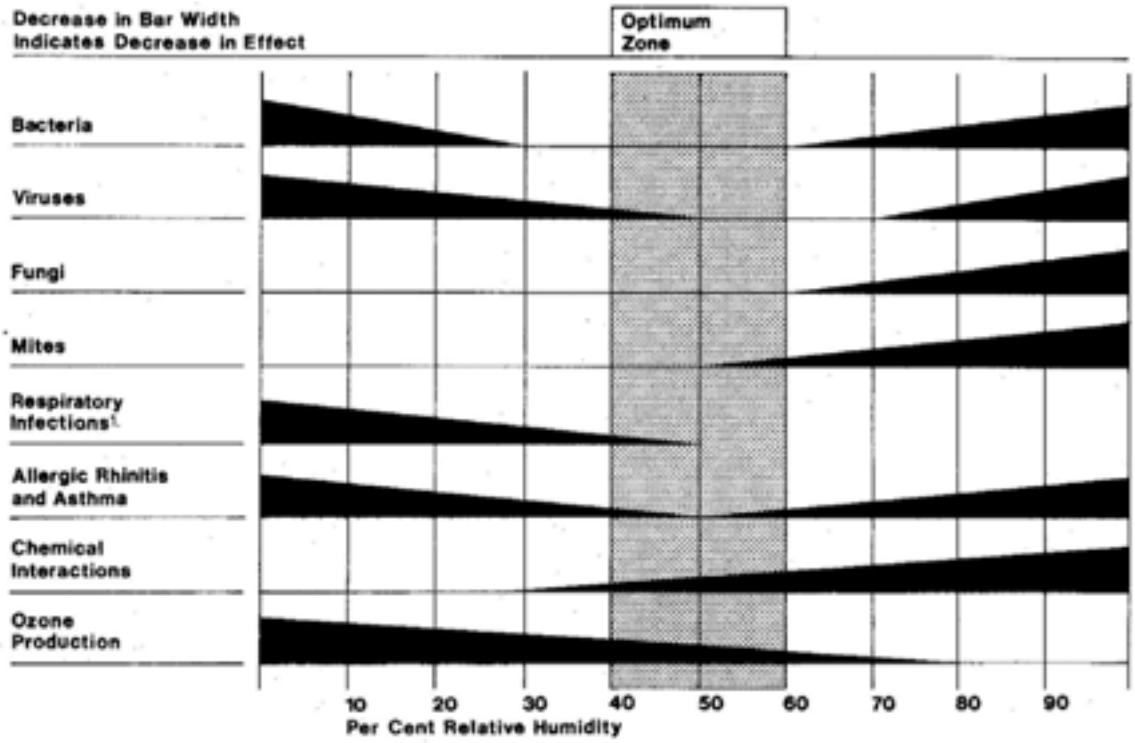

Figure 15: Optimum Relative Humidity Range for Good Health (Sterling et al. 1985: 621)

The carbon dioxide concentration at the dining area below 1,000 ppm (Fig. 13) is an indication of the adequacy of outdoor air ventilation in relation to indoor concentration and occupancy of users. Referring to the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 62 (1989), 'comfort criteria are likely to be satisfied if the ventilation rate is set so that 1,000 ppm CO_2 is not exceeded.' Although 1,000 ppm CO_2 value is no longer mentioned in subsequent editions of ASHRAE 62, this value still serves as a useful guideline value for reference (Petty, 2014).

When the fluctuation patterns of both dining area and a resident's room (Room 23) were superimposed, they were out of phase (Fig. 14). Compared to the daily peaks of the dining area at 12noon and 5pm, the carbon dioxide level at the resident's room was peaked at night (761 ppm at 11pm on 13th June). Due to the small volume of resident's room and the small opening of windows during cold weather, carbon dioxide concentration at the resident's room during night time was higher than the dining area during daytime. Having said that, the carbon dioxide level at the resident's room was still below the guideline value of 1,000 ppm. The lowest carbon dioxide level at the resident room was 414 ppm, which is comparable with the lowest carbon dioxide level of 412 ppm at the dining hall as both areas share similar situation of relying on natural ventilation. As a point of reference, the carbon dioxide level atop Mauna Loa of Hawaii in the Pacific Ocean was measured at 366 ppm, which is regarded as the benchmark for the lowest concentration found worldwide (Schell and Int-Hout, 2001). From this perspective, Adare SRS is well-ventilated without any significant influence from localised sources of combustion or running automobiles.

5 Limitations

There are some limitations in this pilot study. First of all, the connectivity of the gateways and motes is an issue. Motes rely on Bluetooth wireless to transmit data to gateways; however, Bluetooth technology can only allow data transmission over short distance (within 10 m), which can be easily affected by walls and other objects in-between (McClain, 2017). Referring to the physical settings of the building, there are many partitions between residents' rooms and communal spaces, which significantly affect the data transmission.

The data transmission from gateways to the online portal is another issue. Both 4G-based and Wi-Fi based gateways were used in this pilot study, but the data transmission was not so stable. It was common for some gateways to be disconnected and readings not to be shown on the online portal. Further technical upgrade of both gateways and motes is expected and required.

The locations of gateways and motes were also restricted by several factors. Both gateways and motes are required to be connected to power sockets, so the availability of wall sockets and the length of cables restrict the locations of placing those gateways and motes to a certain extent. Some residents did not allow gateways and motes to be placed within their bedrooms, so prior consent from residents was required before actual deployment.

Gateways and motes can only collect dry bulb temperature, radiant temperature, relative humidity, lighting level and carbon dioxide concentration. Sound pressure level for assessing noise parameter cannot be measured by them. However, indoor noise is also a crucial factor of indoor environmental quality.

6 Conclusions and Recommendations

Through this pilot study at the Adare SRS, the measurement protocols have been identified. The capability of the data collection system has been investigated and the reliability of the system are discussed in the previous sections. The wireless data transmission of the existing system via Bluetooth, Wi-Fi and 4G is subject to various limitations. As discussed, the gateways and motes do not have onsite data storage capability. Access to the recorded data is via the online portal. We had difficulties obtaining the full set of recorded measurements at five-minute timestep. At this stage, there is no known explanations and this issue is unresolved. Outdoor environmental conditions should not be measured by the motes; a weather station is highly recommended for this purpose.

By analysing the data collected from 10th June to 16th June 2017, an initial understanding of the IEQ parameters of the Adare SRS building and the link between IEQ and outdoor weather conditions were investigated. In general, the indoor dry bulb temperature is within the acceptable adaptive thermal comfort range (de Dear and Brager, 1998). The dry bulb temperature of some rooms (especially for the ones with window facing north) could reach 26.8°C which may not be suitable for some residents with a medical condition. Such high indoor temperature was influenced by both the solar heat gain and the hydraulic heater in the room. The existing wall-mounted hydraulic heaters can also be improved with easily accessible control knobs for the users to adjust the heating to suit their personal needs. For controlling both solar heat gain and daylighting against glare, the current provision of internal window curtains may not be adequate. External shading devices can be provided to prevent the heat stress. Since the relative humidity

of some residents' rooms were outside the recommended range of 40% and 60%. The room air relative humidity may be monitored and controlled to prevent the potential growth of pathogens and air borne contaminants. It should be noted that, both communal spaces and individual bedrooms of the Adare SRS are generally adequately-ventilated (the carbon dioxide level below 1,000 ppm).

In this paper, only data collected from a restricted period of one winter week (10th June to 16th June 2017) is presented and analysed. Comparison of data over a longer period of time may offer a better understanding of the IEQ parameters of the building as they may change over time. It would be important to collect data from summer months as well especially those data of the north-facing rooms with higher dry-bulb temperature.

In order to further investigate the thermal comfort of the building occupiers (residents, visitors and staff), a questionnaire survey can be developed. The findings of the survey can then be compared with the physical on-site measured data with an aim to identify the gaps between subjective perception and objective IEQ parameters. This can facilitate better understanding of users' individual requirements that can contribute to future design consideration and operation of similar residential aged care facilities in Victoria.

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OVERVIEW OF BUILDING LCA FROM THE SUSTAINABILITY RATING TOOLS PERSPECTIVE

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Abstract: *This study analyses the most representative features of Life Cycle Analysis (LCA) applied to the building sector concerning the environmental impacts of materials and products, through the study of the most shared criteria among four international sustainability rating tools: LEED, BREEAM, DGNB and Green Star. Since 2006, LCA has been internationally standardised with ISO14040 and ISO14044, making it a globally used tool for the environmental assessment of materials, products, building services and whole buildings. The European Commission, through the CEN technical committee (CEN/TC 350), developed the EN15804 and EN15978 standards to stimulate transparent communication about the environmental impacts of buildings and to try to reduce obstacles and limitations in construction industry application. This approach has strengthened knowledge and awareness of environmental impacts, driving designers, producers, stakeholders and policy makers towards more responsible choices and behaviours. Nevertheless, when it comes to buildings, different modalities of usage as well as difficulty in data collection, calculations and projection of service life scenarios, have led to different interpretations of the outcomes, increasing the challenge of accomplishing a comprehensive analysis. Due to this level of complexity, the building sector has not yet been able to exploit the potential of LCA as other sectors, showing a need for simplification and harmonisation.*

This paper aims to identify the most representative characteristics of the LCA approach applied to buildings, through the analysis of the most common/shared features taken into account by four major international Sustainability Rating Systems (LEED, BREEAM, DGNB and Green Star) that are multi-criteria based protocols able to evaluate a number of indicators providing, eventually, an overall score of buildings sustainable performance. The components considered within the analysis include: life cycle phases considered, impact categories and environmental indicators adopted, databases sourcing (involving the integration with EPDs) as well as calculation and benchmarking methods applied, aiming at tracing a way for simplification thus a greater spread and utilization of the LCA approach within buildings environmental performance assessment.

Keywords: *LCA, EPD, Sustainability Rating Systems, Environmental Impact, BREEAM, LEED, DGNB, Green Star, Eco-labels*

1 Introduction

About half of non-renewable resources depleted across the planet feed the construction industry, making it one of the least sustainable industry sectors globally. The EU27 alone depleted between 1.200 - 1.800 Million tonnes of construction materials a year for new buildings and refurbishment between 2003 and 2011 (Herczeg et al., 2014), with consequent adverse impacts on the environment. Buildings also consume almost 50% of energy, 50% of fresh water and exploiting around 80% of agricultural soil (Edwards, 2014). In addition, the global pollution that can be attributed to buildings is estimated to be nearly 50% for greenhouse gas emissions, 40% for drinking water pollution and 50% for landfill waste and ozone depletion (Edwards, 2014).

In order to measure the share of the embodied impacts related to energy consumption, carbon and other pollutants emitted during the production process, Life Cycle Assessment tools (LCA) have been developed to be implemented during different building life stages. This methodology is usually characterised by strict analytical procedures but, at the same time, it suffers from several limitations that hinder a clear interpretation of the assessments; thus not allowing the outcomes from different applications to be directly compared.

LCA has been internationally standardised to stimulate transparent communication about the environmental impacts of buildings and for reducing obstacles and limitations in construction industry application. In the European context, for instance, the standardisation work carried out by the CEN TC 350, has led to the development of the EN 15804 and EN 15978 standards, providing a methodological framework and defining stages and outcomes communication guidelines (Soust-Verdaguer et al., 2016).

Despite these advances, the building sector is still lacking simplicity and clarity about the assessment procedures regarding the environmental performance and hazards related to the embodied impacts of materials and products. Today a variety of sustainability rating tools to perform sustainability assessments that include environmental, social and economic indicators, are available. One of the main aspects of these tools, is the rigour, since they rely on predetermined frameworks and pre-set quality benchmarks for each indicator, therefore allowing different evaluations to be compared within the same system context.

2 Life Cycle Assessment approach: LCA

Life Cycle Assessment (LCA) is the methodology through which is possible to measure the environmental impact of a product or service at all stages of the life cycle: from extraction of raw material, to production, assembling, refurbishment and to possible end of life. For the building sector, thus, is the approach for determining the impact generated by construction products, materials or the entire building.

LCA is intended to account for all relevant environmental impacts throughout a variety of environmental issues with respect to air, water and soil quality, thus including toxicity to human life and to ecosystem, climate alterations and the depletion of resource (renewable and non-renewable), water and energy (Anderson and Thornback, 2012).

2.1 Life Cycle Phases

Even though different studies can have different scopes, when complying with the EN15804 standard at a product level, between all the LCA modules (Figure 1), the production stage (Cradle to Gate) must be always included. Other stages intend to include within the assessment, the transport to, and installation of the product on a construction site, its maintenance, and the impacts of disposal (Cradle to Grave) or, even the recycling potential (Cradle to Cradle).

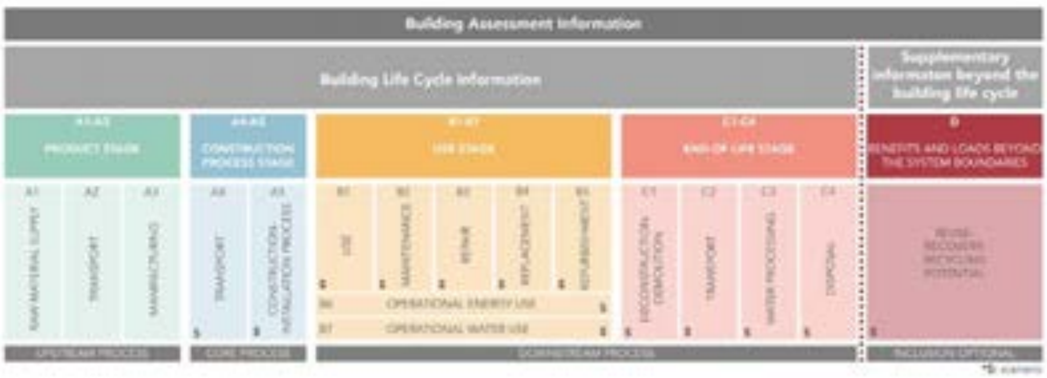

Figure 1: LCA stages and modules EN15804 compliant

2.2 LCA principles and framework

Ding (2014) defines LCA as a "systematic approach to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment over the whole life cycle". Figure 2 illustrates a LCA scheme, inspired by Chastas et al. (2016).

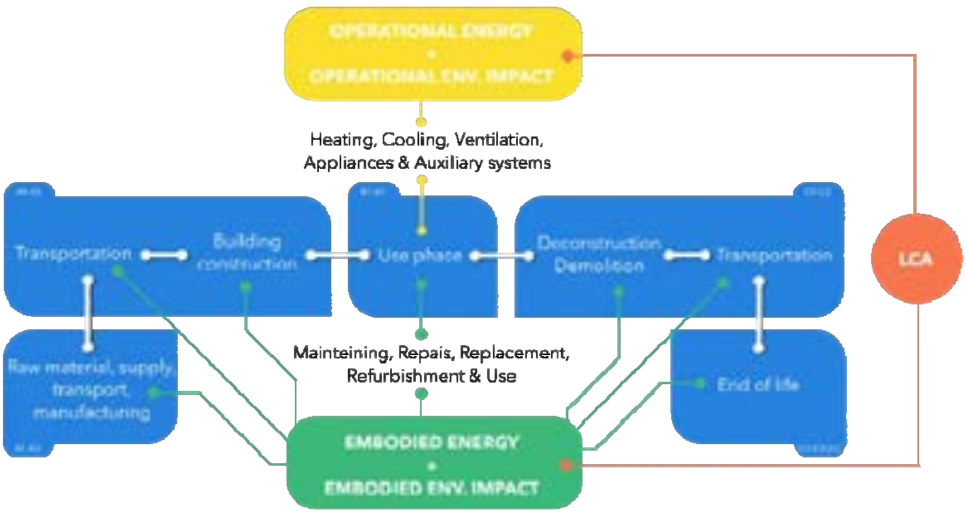

Figure 2: LCA scheme (Chastas et al. 2016), redrawn by the author

Technically and according to the standard, the first LCA steps are: the definition of the functional unit, defined as a quantified description of the performance of the product systems, to be used as a reference (Danish Minister of the Environment, 2004), and a quantitative inventory of all inputs and outputs. Then a classification of the impact and their assessment is required, followed by the evaluation of the environmental impact of the system analysed.

According to ISO14040, LCA has four stages (Figure 3):

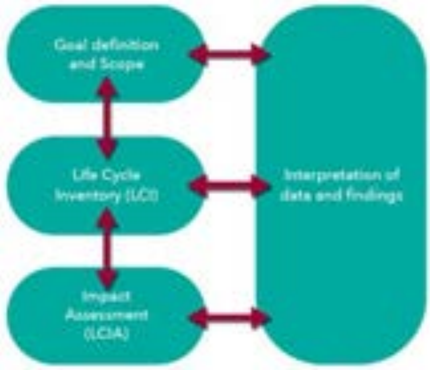

Figure 3: LCA framework, ISO 14040 compliant

1) Goal and Scope: this stage involves the definition of the analysis objectives, products and their alternatives, system boundary, environmental parameters and a data collection strategy;
2) Life Cycle Inventory (LCI): this stage is one of the most critical because it involves scrupulous and precise collection of data and its management, in order to quantify materials, energy inputs and waste emissions (Figure 4). This stage ends with the draft of the inventory tables that include the calculation of the energy and material balance of the system.

Figure 4: System's input and output flows from a life cycle perspective [Ding, 2014], redrawn by the author

3) Life Cycle Impact Assessment (LCIA) / Modelling: this stage provides a quantitative assessment of the environmental impacts based on either endpoint (problem-oriented) or midpoint (damage-oriented) approaches (Ding, 2014) and it consists of the following steps:
   - Classification: after the draft of the inventory, the flow of resources and emissions need to be classified and addressed into impact categories.
   - Characterisation: in this stage, the corresponding impact of the system's output is assessed by assigning standardised characterisation factors to each impact category (Figure 5).
   - Normalisation: some LCA applications might further explain the relative significance of a product's impacts within specific geographic context with regard to specific topics.

In addition, there are two stages, not included ISO standards scope:

- Weighting: this stage is a subjective method of assessing different indicators. It enables to weight and compare different normalised impacts in order to define which is the relative importance of impacts between each other.
- Indirect Normalisation and/or Weighting: Most LCA schemes do not provide normalised or weighted impacts. However, such data is used in building level schemes such as DGNB in Germany and BREEAM NL to provide credits relating to the embodied impact of the building.

(Anderson and Thornback, 2012).

Figure 5: Example of characterisation of impact categories (Anderson and Thornback, 2012)

4) Analysis/interpretation: this phase enable to contextualise the outcomes from the LCIA within the goal and scope of the study. It is an advance assessment involving deeper analysis in order to build a strategy and formulate recommendations for environmental load reduction (Ding, 2014).

An additional stage is characterised by a critical review. This stage involves a critical review to ISO 14044, in case the study has the aim to make a public comparison (Anderson and Thornback, 2012).

2.3 LCA limitations

One of the main criticisms addressed to LCA is that the calculations are excessively complicated and expensive. It is not always easy to model the environmental impacts due to the variety of building techniques even using specific software and tools.

LCA involves a life cycle approach requiring a complex prevision of the service life of building materials since this aspect depends on many variables, such as user patterns, the maintenance cycle, climatic conditions and detailing and workmanship during design and construction.

A further barrier is the deep dependence on the availability and reliability of robust LCI data sources as well as the quality of manufacturing process data as they strictly depending on geography locations (e.g. there is a significant gap in the LCI data in developing countries) and on production plants. (Ding, 2014)

The focus is oriented on material and energy flows and the related impacts, but not all types of impacts are equally well covered in a typical LCA and some issues are not adequately treated such as biodiversity, land use or freshwater source (Ding, 2014).

The products end of life is another delicate topic, since is not easy to provide reliable scenarios in advance about how products can be disassembled and recycled, as well as acknowledging the recyclability level of materials.

2.3.1 The interpretation issue

The interpretation step in the LCA, is a fundamental means for assisting the comprehension and the identification of the most relevant issues and it regards mainly the object of the study either a material or an entire building. Rønnin and Brekke (2014) reviewed the strengths and the weaknesses of LCA within the building sector. In their review, they analysed this matter at two different levels of detail: a macro level and a micro level in order to go deeper in each LCA stage. They believe (Rønnin and Brekke, 2014) that, at a macro level, the main issue is the match between the ambitions of global standardisation and the complexities and ambiguities of the building sector, sustaining the need for a ‘translation processes’ between the two aspects. This macro issue is an aggregate of a number of pragmatic barriers at a micro level such as: the lack of time and the difficulty to collect all significant data, the complexity of comprehending all relevant environmental impacts, the lack of agreement (as well as, a too wide selection of methodologies) about the designation of the relative weight of the environmental impacts and the scarcity of harmonisation about the outcomes comparison. Bribián et al. (2009) have listed a number of weaknesses about LCA that underline the critical issue of the interpretation of results, such as the: arbitrariness of the results, scarcity of cooperation between application manufacturers and potential customers, variety of results displayed by different applications, difficulties in understanding and applying LCA results and the lack of legal requirements and low link with the energy certification applications.

2.3.2 Recommendation review

Rønnin and Brekke’s (2014) review of LCA limitations listed a number of recommended actions, to reduce variations in the results from the LCA method. They suggest firstly, to aim to clarify goal(s) and to provide a detailed and unambiguous definition of scope, with particular attention to the selection of functional units and to the delimitation of boundaries. Consequently, they underline the importance of the data, advising to rely only on transparent, valid and reliable sources. Regarding impact assessment, Rønnin and Brekke (2014) believe a strict and shared selection of important categories can simplify the applications. Finally, with regard to the interpretation stage, they underline the importance of refer the LCA results to the goals and scope of the analysis (Rønnin and Brekke 2014).

Soust-Verdaguer et al. (2016) through their research for a simplified LCA approach for the single-family houses segment, gave several simplification strategies similar to those suggested by Rønning and Brekke (2014). Soust-Verdaguer et al. (2016) recommend the optimisation of data collection process, the reduction of the functional unit, the restriction of the analysis only to significant stages and modules, simplification of the scenario definition and the limitation of environmental indicators. With regard to this last aspect, according to Soust-Verdaguer et al. (2016), life cycle inventory analysis can be restricted to the main components and processes, and the impact assessment phase can be reduced to a few impact categories.

3 LCA based items

3.1 LCA tools

Since LCA is a complex and heterogeneous method, several LCA-based tools have been developed in order to govern all the assessment processes in an easier and more accurate way. These tools usually were designed according to ISO standards and other recognised LCA procedures taking all the material inputs, assigning mass attributes to them and addressing to the mass value, the LCI data relying on one or a number of LCI sources (Ding, 2014).

Ding (2014) indicates three levels in which dividing LCA tools. Tools belonging to the first level operate at the material level, while to the second level, belong the whole building design decision-making tools able to evaluate the environmental performance, elaborating inputs like building geometry and building assemblies and presenting aggregated impacts results. The third level is composed by the also-known: Sustainability Rating Systems (SRT), i.e. building assessment protocols that cover the whole sustainability profile of a building, basing on a set of pre-determined criteria and benchmarks. LEED in the US, BREEAM in the UK, DGNB in Germany, Green Star in Australia and the internationally developed Green Building Challenge (GBC), are just a few examples of the several systems developed and utilized worldwide. One of the main differences is that generally, at the end of the assessment procedures, these systems issue a certification on the basis of an overall rating of the sustainable building performance.

3.2 LCA based Eco-labels

Eco-labelling programmes have been pursued in almost every industrialised country and in some developing countries. The most common voluntary types of ecolabels regarding environmental information, were developed in accordance to ISO and were divided into 3 categories: Type I (certified eco-labels), Type II (product self-declarations) and Type III (environmental product declarations) (Ganzulla Santos, 2014). Even though they all pursue the achievement of environmental goals, only type I and type III eco-labels are LCA based but, in different ways.

Type I eco-labels are regulated by ISO 14024, and aim to certify, through a third party multi criteria evaluation, the environmental preference of products or services within their product category. To achieve this, an LCA approach has to be part of the procedure (as established by ISO 14024), but no specific indications are given about the extent of the LCA methodology to be followed, thus leading to several divergences between schemes.

Type II eco-labels, or product self-declarations, are formulated directly by manufacturers or distributors to provide environmental information about the compliance of their products or services to specific environmental goals. The main differences with the other types of eco-labels are that: they do not provide a certification, but only release a written statement or a symbol, they are not subject to a third-party revision as they are developed internally by companies and, eventually, no LCA approach is explicitly required by ISO 14021:1999 that regulates their development.

3.2.1 Type III eco-labels: Environmental Product Declarations

As reported in Ganzulla Santos (2014), ISO 14025 defines type III eco-label or Environmental Product Declarations (EPD) as an “environmental declaration providing quantified environmental data using predetermined parameters and, where relevant, additional environmental information” (ISO 14025, 2006). Unlike other eco-labels which provides only statements, symbols (as for the type II) or synthetic certifications (as for the type I), EPD provide written reports including both qualitative and quantitative information about the product, and are addressed either to producers (Business to Business - B2B), or to final consumers (B2C) for enhancing the environmental awareness (Ganzulla Santos, 2014).

The quantitative elaboration of the assessment, rely on LCA methodology ISO 14040 compliance and are verified by a third party to ensure transparency and reliability of the results. The results obtained are not subject to rating procedures, or required to satisfy specific environmental quality levels in order to encourage product comparisons within the market thus to stimulate the development of more performing and environmental friendly materials and products.

For the correct execution of fair comparisons and to avoid misinformation, specific rules and standards were developed for supporting the EPD development. EPD have to comply with ISO 14040 concerning inventory results, impact category indicators and other aspects, and to the Product Category Rules (PCR) relative to specific product categories (Ganzulla Santos, 2014). These documents have to be produced in accordance to the ISO21930 (2007) that provides a framework and the basic requirements for their development, as stated in ISO 14025 (2006) and the more recent EN 15804 (2012) (Bovea et al., 2014).

Several national and international programmes globally are undertaking development of EPD and most are related to the construction sector, such as BRE Global (UK), EPD Norge (Norway), IBU (Germany), EPD Italy (Italy), Environdec or International EPD Programme (Sweden/Europe) and Australasian EPD programme (Australia and New Zealand). Generally, these schemes are developed according to ISO 14025, ISO 21930 and EN 15804, although they often differ in content, calculation rules and format because each programme has developed their own programme rules and PCR documents, thereby excluding the possibility to be directly comparable or combinable. Different EPD can be compared only, when the same PCR have been used and all the relevant life cycle stages have been included. The same functionality and use have to be considered when comparing different products.

4 Methodology

LCA is the method currently used to measure the share of the embodied impacts related to energy. The methodology adopted within this study is characterised by:

- the selection of four international Rating Systems (LEED, DGNB, BREEAM, Green Star) through a screening phase of their features with regards to the LCA approach;
- the collection of data from secondary sources (mainly Rating Systems technical manuals, different kind of publications, journal articles and academic theses) regarding the Rating Systems assessment criteria about LCA approach and other related topics such as EDP related criteria;
- the analysis of the collected data through the draft of tables to classify and compare all LCA related components of the selected Rating Systems. The analysis has investigated:
  - the credit potentials of the LCA related criteria and their relative weight in order to outline which Rating System give more importance to the LCA;
  - the LCA framework components considered within the Rating Systems criteria to outline similarities and differences between them with the further aim to identify which components are the most shared and therefore more representative for the building sector.
- the draft of the Rating Systems comparison outcome in the form of statistical graphs and charts;
- the critical interpretation of the findings with the draft of recommendation for further studies and further development of these topics.

4.1 Screening phase

Four international Rating Systems have been selected for the analysis, as a result of a screening phase. The criteria for selection of the rating systems are listed below, they:

- had to include LCA related criteria within their protocols;
- had to be developed in countries with different climate zones;
- had to be suitable for international applications;
- had to be popular and representative of the market choices. For this reason, they have been selected on the basis of the number of certificates issued worldwide (in relation to their release year) and the number of the relative publications within specific databases (such as “Sciencedirect.com”).
- had to provide an English version in case they were developed outside English speaking countries.

The limitations in the selection of the Rating Systems have been:

- the availability of sources and data;
- the clarity and transparency of the available data;

For all these reasons, the selection was the four following Rating Systems: LEED, BREEAM, DGNB and Green Star using, the latest available version for new building construction.

4.2 Data collection and classification

The data about the LCA components within the Rating Systems, have been collected, through a desktop study of the technical manuals of the systems, and classified in two tables. Table 3 has outlined the importance, in terms of credit potential and relative weight, given to the LCA and EPD related criteria by the Rating Systems. In some cases, the listed weights do not come from the simple proportion of the criteria credit potential over the total credits achievable, but result from specific weight assigned by the systems.

The second table, (Table 4) itemises a number of LCA framework components related to the four LCA standardised stages (goal and scope, LCI, LCIA, interpretation) and analyses how these components were considered within the Rating Systems assessment protocols, to outline similarities and differences and identify which components are most shared. A further aim of Table 4 was to identify which components and features should characterise a simplified and shared LCA framework.

Rating Systems Information				LCA + EPD Categories Data				LCA Criteria Data			
Name	Version	Year	Origin	LCA related Categories	N. of Criteria within the Category	Category Credits Potential	Category relative weight [%]	LCA related Criteria within the category	Criterion Credits Achievable	Relative Weight [%]	Total LCA Weight [%]
DGNB	Int. CORE14 Office	2014	GER	Effects on the global and local environment (ENV 10)	3	110	12,4	Env.1.1 Life Cycle Impact Asessment	70	7,9	13,5
				Resource consumption and waste generation (ENV 20)	3	90	10,2	Env.2.1 Life Cycle Assessment - Primary Energy	50	5,6	
BREEAM	Int. New Constr. 2016	2016	UK	Materials	6	14	12,5	Mat 01 Life cycle impacts	5	4,5*	4,5
								Mat 02 Hard landscaping and boundary protection**	/	/	
LEED	V.4 BD+C (New Constructions)	2017	USA	Materials and resources	5+2	13	11,8	Building life-cycle impact reduction	3/5	2,7	2,7
GREEN STAR	Design & As Built v.1.1	2015	AUS	Materials	4	14	14	19 Life cycle Impacts	7	7	7

Table 3.A: Rating Systems LCA and EPD related criteria comparison

EPD Criteria Data				R.S. Data	
EPD related Criteria within the category	Criterion Credits Achievable	Relative Weight [%]	Total EPD Weight [%]	Total LCA + EPD Weight [%]	Total Credits Available
Env.1.1 Life Cycle Impact Asessment	***	/	/	13,5	850
Env.2.1 Life Cycle Assessment - Primary Energy	***	/			
Mat 01 Life cycle impacts	1+1	1,8	1,8	6,3	150
Mat 02 Hard landscaping and boundary protection**	/	/			
Building product disclosure and optimization - environmental product declaration	1/2	1	1	3,7	110
20 Responsible Building Materials	1	1	4	11	
21 Sustainable Products	3	3			100

Table 3.B: Rating Systems LCA and EPD related criteria comparison

LCA Framework Analysed				Rating System			
				DGBN	BREEAM	LEED	GREEN STAR
Goal and Scope	Boundiaries	Raw Material Supply	A1	•	•	•	•
		Transport	A2	•	•	•	•
		Manufactoring	A3	•	•	•	•
		Transport	A4		•	•	•
		Construction Install. Process	A5		•		•
		Use	B1				•
		Maintenance	B2	•			•
		Repair	B3				•
		Replacement	B4	•		•	•
		Refurbishment	B5				•
		Operational Energy Use	B6	•			•
		Operational Water Use	B7	•			•
		Deconstruction - Demolition	C1		•	•	•
		Transport	C2		•	•	•
		Water Processing	C3	•	•	•	•
		Disposal	C4	•		•	•
		Recycling Potential	D	•	•		•
	Service Life			50 years (depends on the DGNB scheme adopted)	N.S.	60 years	60 years (unless otherwise stated)
	Functional Unit			m2 of Net Floor Area (NFT) in a year	1 m2 over 60 years (walls	N.S.	1 m2 project Gross Floor Area (GFA) basis (Additional FU allowed)
	Building Elements Assessed	Footing and foundations		All building elements, stuctural parts, building products, building materials	N.S.	•	Whole-of-Building as defined in EN 15978: "its constituent parts (all building elements, building components, building products, building materials)"
		Structural pillars, columns etc.				•	
		Structural wall assembly (from cladding to interior finishes)				•	
		Structural floors and ceilings (not including finishes)				•	
		Roof assemblies				•	
		Parking structures, exclude parking lots				•	
		Stair constructions				•	
	Impact Indicators | Units	Climate Change	GWP	kg (CO2)eq (100yr)	kg (CO2)eq (100yr)	kg (CO2)eq (100yr)	kg (CO2)eq (100yr)
		Water Extraction	WD	×	m3	×	m3
		Mineral Resource Extraction	TMR/ADP-e	×	tonnes	×	kg Sb eq
		Stratospheric Ozone Depletion	ODP	kg (R11)eq/CFC-11 eq	CFC-11 eq	CFC-11 eq	CFC-11 eq
		Human Toxicity	HTP	×	kg (1.4 -DB)eq	×	○ kg (1.4 -DB)eq
		Ecotoxicity to Freshwater	WTP	×	kg (1.4 -DB)eq	×	×
		Ecotoxicity to Land	LTP	×	kg (1.4 -DB)eq	×	×
		Nuclear Waste		×	mm3	×	×
		Waste Disposal		×	tonnes	×	×
		Fossil Fuel Depletion	ADP-ff	×	MJ (TOE?)	MJ	MJ
		Eutrophication	EP	kg(PO4) eq	kg(PO4) eq	kg N2 or kg PO4	kg(PO4) eq
		Photochemical Ozone Creation	POCP	kg(C2H4)eq	kg(C2H4)eq	kg NOx, kg (O3)eq, or kg (C2H4) eq	kg(C2H4)eq
		Acidification	AP	kg(SO2)eq	kg(SO2)eq	moles H+ or kg (SO2)	kg(SO2)eq
		Ionising Radiation		×	×	×	○ kg(U-235) eq to air
		Paticulate Matter	PMF	×	×	×	○ kg(PM2.5) eq
		Land Use		×	×	×	○ m2
		N. of Indicators		5	13	6	7 + 5

Table 4.A: LCA framework component within Rating Systems

Inventory Analysis	Method			N.S.	N.S.	N.S.	N.S
	Peer Reviewed Data			•	N.S.	N.S.	•
	Databases	Ecoinvent (Swiss Government)		N.S.	N.S.	N.S. (in accordance with ISO 14044)	N.S. (in accordance with EN 15978) Australian data shall take precedence over imported data
		GaBi (PE consulting, Germay)					
		Boustead (LCA consultancy, UK)					
		Idemat (TU Delft)					
		IVAM (University of Amsterdam)					
		BRASUCO		•			
		CHISUCO		•			
		EUSUCO		•			
		UKRASUCO		•			
		EPD Programmes		•			•
		Other		•			•
Life Cycle Impact Assessment	LCIA Methods	ReciPe		N.S.	N.S.	N.S.	N.S.
		CML		N.S.	N.S.	N.S.	N.S.
	Classification; Characterisation; Normalization;Weighting			N.S.	N.S.	N.S.	N.S.
Interpretation	Rating Method	Reduction respect a reference building	Direct achievement of credits	×	N.S.	Reduction > 10% of at least 3/6 impact categories (GWP mandatory) No increase > 5%	×
			Rating based on reduction performance	Rating Points are assigned basing on the performance achieved by each impact indicator, with respect to Limit, Target and Reference values	N.S.	×	• Up to 6 Credits: reduction of 7 impact categories (cumulative percentage) • 1 Credit: 5 additional impact categories (○)
		Impact indicators outputs direct rating		×	N.S.	×	×

Table 4.B: LCA framework component within Rating Systems

4.3 Results

From Table 3, it is possible the Rating System that gives more importance to the LCA criteria in terms of credit potential and relative weight, is DGNB with a share of 13.5%, followed by Green Star (11%), BREEAM (6.3%) and LEED (3.7%). Is therefore possible to observe that, on average, the total share of LCA and EPD related criteria weight is 8.63% over the total.

The analysis of the LCA framework was limited by the scarcity of information released by the Rating Systems within their technical manuals, which was the main source of data. A further limitation is that most of the data relative to BREEAM (new 2016 version) are missing. For this reason and for other missing information, this study has to be considered as a pilot and deeper research using different sources, will have to be carried out. Due to this limitation, only a few findings can be deduced from this study. From Table 4 is possible to outline the following similarities among all the rating systems analysed:

- The LCA boundaries shared by all the rating systems are: Raw Material Supply (A1), Transport (A2), Manufacturing (A3) and Water Processing (C3), while there is still discrepancy on the other aspects;

- The Impact indicators shared by all the rating systems are: Climate Change (GWP), Stratospheric Ozone Depletion (ODP), Eutrophication (EP), Photochemical Ozone Creation (POCP) and Acidification (AP);

- All rating systems rate the outcomes of the LCA through the comparison with the outcomes resulting from a reference building, which, has to be determined in different ways according to each rating system.

5 Conclusion

This study deals with the LCA application within the building sector, the standardised definition of its framework, the barriers and limitations upon constructions and the recommendations for stimulating a greater and easier utilisation among practitioners and decision makers. Following

some key aspects for the simplification of the LCA approach, this study analysed four international Sustainability Rating Systems as a reference: LEED, BREEAM, DGNB and Green Star. Through the comparison of these systems regarding some key components of the LCA framework, this study aims to identify the most shared features, to be considered as the most representative characteristics of the LCA approach applied to buildings, and how these are used within the assessment protocols in order to outline a shared procedure.

The collection and the processing of data about the Rating Systems LCA related criteria, have detected some of the possible simplification suggested in the recommendations such as restricted and simplified boundaries, reduced but significant impact categories and shared outcomes assessment procedure. In addition, the presence of EPD criteria within the Rating Tools, endorses the importance of this item as a reliable source for the Life Cycle Inventory.

On the other hand, available data about LCA frameworks within the Rating Systems protocols, outlined several barriers to the draft of a simplified and transparent approach for the building sector. This study found a lack of clarity and transparency with regards to some important information, essential for performing an exhaustive application and underlined the lack of homogeneity in LCA criteria rating procedures.

For these reasons, this study can be considered as a pilot for further development and deeper research. Being able to bring to completion the LCA framework table with all the crucial data, along with delineation of common benchmarks and rating procedures, would make it possible to draft a shared and simplified procedure to enhance the utilisation of LCA within the building sector, thus overcoming several existing barriers.

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MOVING ASSEMBLY LINE FOR LOW COST MASS CUSTOMISED HOMES

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Abstract: *This paper explores the potential for a mass customised building volume applying lean based moving assembly line method. Past experience would suggest that the moving assembly line stems from a mass production, that reduces customisation through standardisation of processes. However, when combined with a seamless method of design to documentation up front, it is proposed that the moving assembly line could allow for mass customisation. In addition, lean practices suggest that refinements of processes are intrinsically linked to a repetitious assembly process used in producing a homogenous object. We seek to break these moulds and examine the potential for a lean moving assembly line to allow mass customisation and what is required to do so. Moving assembly line offsite building manufacture factories in Australia, Sweden and Japan were visited and observed. A comparative exercise of when, what happens where was undertaken to identify the approaches. It was found that the moving assembly line allows cost and time savings in off-site manufacture of multi storey buildings, and could enable for a mass customised outcome. Lean is the facilitator, or enabler of this process working efficiently*

Keywords: *Lean Construction, Mass Customisation, Moving Assembly Line, Low Cost Housing*

1 Introduction

‘Modular construction offers first-cost savings, a fast-tracked design and construction process, and safer construction methods.’ (Parrish 2012). It can enable faster processes on site, and allow for higher qualities in built form and fabric due to the control afforded to it by a factory process. That said many off-site building manufacturers struggle to implement a finely tuned manufacturing of buildings off-site. In car manufacturing, such as Toyota, we see a line with three different assemblies on the line, using similar base components – engines, transmissions, framework, to assemble a product variant outcome depending on what is ordered. Lean processes allow such a complex product variant to be assembled using a cycle time of as little as 1 minute, 55 seconds in the example of Toyota (Monden 1994). Boeing manufacture their 737 aircraft on a moving assembly line (Lu & Sundaram 2002), yet even though it is an extremely complex product, like the car, it is repeated, so in some ways easier to set up the processes that are repeated on a moving assembly line, and lean framework to facilitate efficiency in the production. This repetition is not so synonymous with building manufacturing.

When considering building manufacture, the question arises that if something simple like a house can be produced in a factory, then can it be produced more efficiently on a moving assembly line, and in a lean framework? Lean construction is well understood, but has limited effect when applied to a building process that is craft based. The dissemination of lean methods to offsite construction was even less clear to us, until relevant factories in Japan were observed. Another question arising out of offsite construction is that of mass customisation. How does one set up a building manufacture facility that can allow for all of the nuanced variables of customer demands in the way individual clients want to live? The answer revolves around mass customisation in building manufacturing, and is discussed in this paper.

In addition, there is a question of building cost. Over the past decade in Victoria there has been a decline in labour productivity, yet an increase in the cost of labour, although in the past two years this has eased slightly (Marosszeky 2013). The nett effect is that by reducing the materials used in the building envelope, the running cost of the building increases. Manufacturing processes in construction could allow for a balancing of cost ratio of envelope to labour. In addition, these processes could allow a house to be customised, cheaper, and more affordable to operate.

The background to this research comes from factory visits through Australia, Sweden and Japan, examining lean production and moving assembly lines for construction of volumetric building modules. The research has also reviewed the literature which is discussed in Section 3.

This paper explores the potential for production of a mass customised building volume within lean moving assembly line for low cost homes. It seeks to determine the effectiveness of a moving assembly line for building manufacture on time and customisation, just as cars are manufactured on a balanced line that moves in a ‘*takt time*’ synchronised across a series of processes and balanced between tasks. ‘*Takt time*’ is the available production time divided by customer demand or the pulse of production (Lean Enterprise Institute 2014). A vehicle consists of some 30 000 parts, yet a house is considerably less complex and should be less challenging to produce.

2 Methods

The research is based on factory visits and observations through Japan, Sweden and Australia. In addition to the factory observations, a literature review was conducted, base on a review and examination of various scholarly articles including journal articles, theses, books, conference proceedings and reports. The following electronic databases have been searched: Scopus, Emerald Insight, Ethos, OATD, ProQuest, DART, and Google Scholar. In the absence of any literature on “Lean moving assembly line for construction”, several search terms have been used that represent the necessary aspects of lean, moving assembly line, and manufacturing of buildings. The following search keywords have been used: lean moving assembly, lean moving assembly line, lean mass customisation, lean house production, lean off-site construction, lean off-site manufacture, lean building manufacture, lean off-site building manufacture, lean construction, design for building manufacture, lean moving assembly line.

Thirteen factories in Australia, Sweden, and Japan were visited and observed. They include five in Sweden, three in Australia, and five in Japan. The purpose of these visits was to obtain better understanding of differences in time, cost, and methods of production. Within each visit, analysis of product produced, process used, time taken, and output quantity was gathered and collated to understand better the spectrum of offsite building manufacture between these three countries.

Table 1 in the results section outlines the key processes, and lean aspects that were observed in each factory. Through the factories visited we were able to interview, often with a translator, the factory manager, or equivalent person on the aspects set out in this table. Visual observation was also used in the assessment of many of the lean principles.

3 Literature Review

The purpose of this literature review is to give a brief background on moving assembly lines for construction as they are defined in the literature, and then identify any links between lean and mass customisation in construction. For clarity, the review has been divided into five thematic sections.

3.1 Moving Assembly Line

The application of a moving assembly line within an off-site construction environment does not appear in the literature. Perhaps it is due to complexity of process or complexity in customisation and setting up a line, that the answer is not yet known.

The moving assembly line has been used in car manufacturing since 1913 when “Henry Ford did not simply devise the physical structure of the assembly line but also the administrative systems that tied sales to production; and ensured that materials and labour were allocated just in time.” (McKinlay & Wilson 2012). The delivery of materials and components, particularly subassemblies could allow for a line to have capacity in mass customisation with appropriate planning. McKinlay and Wilson (2012) also documented that Ford’s inventory system was something akin to what we seen in Toyota today. Stock being at the right levels, and available at the right time. Later in the century Taichi Ohno, the creator of the Toyota Production system, perfected this. Today Toyota can have eight different car models on one line (Cheldelin, Kosuke & Wiggs 2017) customisation is fed into the system early and the line adjusts to suit.

Sims & Wan (2017) identified that “In mass production environments, constraints are usually easy to find; just look for large stockpiles of Work-In Process (WIP), backlogs,

and frequent expediting. But in a lean manufacturing environment, none of these conditions should exist." The paper concludes with three methods for constraint identification in 'mature lean systems' and for this reason, it is expected that this research will pay attention to how this might adapt to a matured lean off-site construction example, if it exists.

Kanaganayagam, Muthuswamy & Damodaran (2015) investigated a direct lean methodology to improve assembly line processes. Though this investigation the research investigated techniques for reducing '*cycle time*' of tasks on assembly line, and in addition, motion studies through spaghetti mapping techniques within a lean facility that manufactures large earth moving equipment. As a real-life study, the researchers were able to identify areas for improvement, and increase their efficiency by up to 50%. Interestingly, the largest areas for improvement were in and around excessive travel (Kanaganayagam et al. 2015).

3.2 Lean Construction

Lean construction is something that challenges the common processes in construction according to (Koskela et al. 2002). It is not one thing, rather a theoretical method for the removal of the eight wastes from the construction process. Lean comes from manufacturing, after World War Two, Eiji Toyoda and Taiichi Ohno at the Toyota Motor Company in Japan pioneered the concept of lean production (Crowley 1998). Since the early 1990's lean has been examined and in some ways forced to fit construction processes. However, construction and manufacturing differ significantly in the physical features of the end product (Salem et al. 2006).

According to Koskela who defined lean in construction as Transformations, Flow, and Value (Koskela et al. 2002)"Lean is a way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value." (Koskela et al. 2002). Koskela suggested that in understanding of the theory of production, there are three views to production, each providing for a number of principles for the production system: transformation, flow and value generation (Koskela & Ballard 2004).

Jayaram, Das & Nicolae (2010) suggested that lean construction is good in method and concept, but the implementation is often flawed through lack of understanding at a cultural level of the people involved in a construction process. If they do not understand or appreciate the principles driving lean, then it is unlikely to succeed. The paper suggested that lean construction is the appropriation of cycle time, quality, cost, and delivery dimensions of manufacturing processes. Through their analysis they found that the direct implementation of Toyota Production System (TPS) based production scheduling initially presented a negative result, possibly, as suggested, because of the nature of plant, supplier, or market driven change which remains outside of the direct control of a construction production facility. However, once this was removed, the processes of implementation saw an increase in production efficiency, and in some cases their research called for a more standardised set of components.

According to Erol, Dikmen & Birgonul (2016) the most significant lean construction principle is "*cooperating with different departments*, which is followed by *organizing regular meetings*, and *establishing long-term supplier relationships*." This is interesting due to the fact this paper suggests the individual aspects of lean cannot be measured, yet if every aspect of it is incorporated in a construction project, then overall there will be a positive outcome in terms of time and cost.

3.3 Lean Off-site Construction

In a lean off-site environment, Zhang et al. (2016) suggested that many companies are implementing lean as a solution in off-site construction to help make production more efficient. One of the barriers that they recognised though is physical limitation to how quickly processes can occur, whether through waste in movement, or waiting. Lean, in off-site construction, is centred on reducing seven wastes. According to Ohno (Ward 2016) these are:

- Excessive transport,
- Inventory,
- Worker motion (ergonomics),
- Waiting or delay between value adding steps,
- Overproduction (making more than the next process needs),
- Over processing, and
- Defects.

Globally, the off-site concept has been operating in the house building sector of many countries, such as Australia, China, the UK, Germany, Sweden, The Netherlands, Japan, and the USA (Mostafa, Chileshe & Abdelhamid 2016). There is a huge amount of literature in off-site construction alone, and the body of information of lean in off-site construction is also growing, but one of the early gaps seems to be a lack of research into mass customisation and off-site principles. The major benefit to off-site manufacture (OSM) is that it provides a controlled manufacturing environment to produce the house components and modules (Mostafa, Chileshe & Zuo 2014). However, the refinement of processes, and standardisation of off-site building techniques becomes a simplification of what is being produced, moving directly away from a customised outcome. According to (Crowley 1998) a lean facility has two focal points, one on the workers who add value, and the other in picking up and resolving defects.

Some research in to lean in off-site construction focuses on Value Stream Mapping (VSM). (Heravi & Firoozi 2016) presented an argument for the use of VSM in an off-site construction facility. It is a technique used to identify the value stream of products in a given system of production. This can be measured in materials in, processing time, storage requirements, and production time, how long they stay after production and when they are created with respect to customer demand i.e. kept in stock or produced on demand.

3.4 Design for Manufacture of Housing

In their paper on DFM and its application to building, Fox, Marsh & Cockerham (2001) argued that the front end of design is ill equipped to handle complex manufacturing techniques in the production of off-site housing. (Sims & Wan 2017) argued not so much for the lack of knowledge but rather the weakest link being the constraint, where manufacturing processes are too rigid and lack flexibility to adapt to differing parameters. For this reason, an understanding of how to break a building down into measureable and identifiable components for production and sub assembly is necessary.

Fox et al. (2001) also suggested that there are “bespoke, hybrid, custom and standard” conditions in building manufacture, and each presents its own challenges in developing a system to accommodate them. They suggested that the use of DFM in construction depends on the definition of these categories. In addition, that whilst some components in a building can benefit from a DFM, others cannot. “Success in simplifying construction would depend on the addition of supplementary design rules and metrics for interfaces with other building components.”(Fox et al. 2001).

When considering mass customisation in off-site construction, the paper Lean and Green Construction (Parrish 2012) Parrish asked “First, can modular construction offer sufficient flexibility to be attractive to owners?” Through a case study analysis of a live project in Long Beach California, the research concluded that flexibility in modular homebuilding was achievable, and afforded increases in quality in other aspects of the build such as increased energy performance. “One particular study focuses on the study of the production system through the application of lean production principles, as an approach to enable mass customization.” (Nahmens 2007)

3.5 Design for Lean Manufacture

Perhaps the most seminal research on lean manufacture as applicable to construction was The Last Planner System. (Ballard 2000) developed this over a period of 8 years and it forms a framework for the application of lean in manufacturing. Ballard recognises the value adding of good design in production control, not just aesthetic or engineering design, but more of a holistic approach to value adding within the early design process.

Mostafa et al. (2016) focused in their paper on housing affordability in Australia, and the value of lean efficiency through the housing supply chain. Interestingly, associated with the supply chain information, they suggest that CAD or BIM would be beneficial in communicating the early needs of a building through the supply chain.

Buildings are usually one off, not repeated, except in the single house market. (Bertelsen 2005) argued in his research for the building to be considered as a product, something that could be designed in a way to take advantage of manufacturing techniques and processes. Similar to Mostafa, his research points out the potential benefits in BIM at early design stage.

Through a case study project, (Yu et al. 2011) tested the effectiveness of lean principles in modular home building. By examining the project within a large offsite building manufacturer, they looked at the effects of lean policy from management to worker. In conclusion, they found lean to enhance the early stages of design for manufacture, but admitted some gaps in the effectiveness to the workers on the shop floor.

4 Observations from Factory Visits

Overall, there were significant differences in the approaches to offsite manufacturing through the different countries. The Swedish were focused on panelised systems, the Japanese on volumetric systems, and the Australians, were using craft based systems, constructing under a roof. The summary of observations of lean practices in factories visited is provided in Table 1.

The Swedish factories visited were producing panelised systems, except for one that was producing a volumetric timber product. The Panelised systems involves typically a 190mm thick stud frame for insulation depth. These are assembled and fixed on a table that would then move down a line of tables and assembly stations in order to fit insulation, internal cladding, external cladding and building wrap, to the end when it would be packed on a trolley ready for shipment to site. Where windows and doors were to be installed in a wall section, they would be made on a sub assembly line, ready to be fed in at the appropriate point in the main line.

Table 1 Summary of observations of lean practices in factories visited.

		S1	S2	S3	S4	S5	J1	J2	J3	J4	J5	A1	A2	A3
Visual Systems	No unnecessary Items or materials	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N
	Shadow Boards?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N
	Everything is stored in its defined place?	Y	Y	S	S	S	Y	Y	Y	Y	Y	N	N	N
	Display boards are used to convey key data?	S	S	S	S	S	Y	Y	Y	Y	Y	N	N	N
Standard Work	Standard Operating Procedures are in place?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	S	Y	Y
	SOP of each process has been visibly posted in each area	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y
	Employees follow SOPs	S	Y	S	Y	Y	Y	Y	Y	Y	Y	Y	S	S
	Mistake Proofing?	S	S	S	S	Y	Y	Y	Y	Y	Y	Y	S	S
Communicat-ion and Cultural Awareness	Managers communicate with all employees	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Employees understand company goals	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Employees Understand KPIs	Y	S	S	Y	Y	Y	Y	Y	Y	Y	Y	S	S
Inventory	Minimum inventory JIT used?	N	N	N	N	N	Y	Y	Y	Y	Y	N	N	N
	Delivery system in place and used?	S	S	S	S	S	Y	Y	Y	Y	Y	N	N	N
	Stock stored and easy access?	Y	S	S	S	Y	Y	Y	Y	Y	Y	N	N	N
	Inventory information collected and tracked.	Y	S	S	S	S	Y	Y	Y	Y	Y	N	N	N

Legend: S-Sweden; J= Japan; A= Australia; Y=Yes; S=Sometimes; N=No

The sub assembly line involved creating the timber frame included lintels. Within the panelised systems, 3 of the 4 factories were using production line techniques. They were achieving high levels of production efficiency, and one particular factory was producing a house every 4 days in a factory. A large difference existed between the panelised and volumetric systems in regards to customisation. In general, customisation was kept to a minimum, but in the case of the volumetric system, was further reduced to being able to change paint colour only. This meant that there is significant homogeneity in what was being produced, and how the resultant building appears on site.

This was in stark contrast to the Japanese methods of building manufacture. Within the Japanese factories visited, there were panelised, component based and volumetric approaches to building manufacture. Each offer differing capacities for mass customisation in the system. Of note is the moving assembly line for volumetric house units exists in one of the Japanese factories, where they produce house modules every 7 hours from start to finish. The line itself finishes a module approximately every 5 minutes. Process cycle times are balanced to match a '*takt time*' and customisation is also possible. One of the benefits to this process is the time saved in the front end of the process. An extensive set of BIM models is used in the early design phase of a project, so the concept design works within a parametric system of components. The advantage of those models is that cost data, and manufacturing data is stored within the model so once the design is complete the building can be costed and sent to ordering and production. In addition, the line is not dissimilar to that of the Toyota factory in Aichi Prefecture, Japan. The line moves through a factory, at some points faster than others depending on processes, with double height and outflow areas for subassembly of more complex components such as stairs, and window fitting.

A significant difference between the manufacturing time between Sweden and Japan is that of paint and plaster. Wet trades typically create a bottleneck in manufacturing due to drying times required. In Sweden finished panels stop on a line, are finished with top coat plaster, left to set for 12 hours, and then fed back into the system. Painting was similar, and done by roller upon completion of the module, which would again sit on the line while the paint dried. In Japan, however we see a different approach. Firstly, they don't paint as much, as the use of wall paper coverings is extensive. Where they do paint though, Seksui House recognised this and reduced their painting time from 18 hours, to 26 minutes by using robotic application, and running the assembly line through large heated rooms. There were several rooms, with painting robots in between to apply the subsequent coat. In regards to plaster, they do not do it. Instead, they use a fast drying, slightly elastic polymer to keep joins flush.

In the Australian context, we commonly see onsite practices replicated under a roof. The systems that were observed in Sweden and Japan are further advanced through time spent developing them over decades. Many of the standard operating procedures seen in Sweden and Japan were non-existent in the Australian context, as can be seen in Table 1. Simple things that help the manufacturing process like visual systems, communication, and staff feedback did not appear to be happening to anywhere near the same level as what was observed in Sweden and Japan. Australian factories were starting to develop sub systems but did not appear to be close to the holistic level being achieved overseas. Offsite construction in Australia was not observed to be taking advantage of manufacturing techniques, rather it was reproducing the same on-site problems in efficiency of time, and as a result cost of production. Excess worker movement was common, access to tools meant walking from one end of the factory to another, where processes weren't scrutinised or designed to suit an optimum time

segment, and where the design for manufacture was virtually non-existent, rather it appeared to be manufacture to the design, and inefficient as a result.

5 Discussion

In Australia, offsite construction represents approximately 4% of the market. It also often replicates traditional construction techniques under a factory roof, and does not yet take into consideration advances that have been made in manufacturing processes through the past century. Where construction processes are replicated under a factory roof there is a saving in time by avoiding weather delays, but that is the limit of the efficiency gain. Lean concepts are not well applied in Australia, and production efficiency in building is often unquestioned. The attitude shift to a manufacturing process is more complex to consider.

In Sweden, offsite building manufacture represents 84% of the market. Driven by climate and necessity to build quickly in the cold weather, the Swedish methods often involve panelised systems that can be taken to site and assembled on site very quickly. They also use a significant amount of timber in their buildings, more as a result of availability and quality than anything else. Their timber grows slowly, and their forestry practices sees their timber thinned out in early years of growth so as to not be full of knots and usable in mechanised processes that allow a depth of insulation to enable more energy saving. As a panelised system timber is good, fast, and then relies on fixings created on site to pin the panels together. In Sweden, we can see the beginnings of a moving assembly line, where one factory has a line and volumetric modules on large trolleys, and there was the beginnings of a lean framework. However, the same mess and clutter of building site was replicated under a roof, albeit arranged in a linear progression.

In Japan, however the predominant driver for material specification is design for earthquake. We see a lot of steel frame housing which is heavily braced, and incorporates various dampers in the structural system. From a manufacturing perspective, this allows for a more volumetric solution, which in turn allows for more automation of processes such as welding of joints, and further efficiencies on site. The Japanese however, are the most advanced in allowing a mass customised outcome within building manufacture. Perhaps due to culture, or inherent expertise in manufacturing processes, the answer is not clear, other than to say they can create a house module completed in 6 hours, which is 3 days faster than the Swedes, and three weeks faster than the Australians.

The common theme between all countries of the usage of panelised systems to produce a customised outcome. The building is reduced into quantifiable components that can be arranged to achieve variability in the built outcome. This method allows for some further flexibility as to where the end point is between what is produced in the factory, and what is produced on site. However, whilst panelised systems are fine for customisation, they are limited in scope of manufacturing efficiency of total building assembly, and do not lend themselves to a moving assembly line.

The moving production assembly line however is better suited to volumetric manufacture. The Seksui Heim model of production allows for customisation in the system, and uses a moving assembly line that ensures a balanced and efficient time in production. The customisation in this case is largely due to the modules being made from steel. The strength of the portal frame allows for sides to be open, so when

attached together in the form of a multi storey house, the room sizes can be adjusted according to the customer's requirements.

There is need for improvement to current off-site construction practices in Australia. The Japanese factories incorporate manufacturing processes, particularly lean methods, which seems natural since they invented it. The fact they are manufacturing and also allowing a customisation in the system is much better than what is happening in Sweden and Australia. The Swedish methods are still advanced, and in their own way making some fast and impressive inroads to building manufacture, but in some ways, are still working in an off-site construction attitude. They still need time and knowledge to perfect their systems. In Australia building manufacture is still embryonic. Often off site processes resemble transferring building processes under a roof. Customised solutions exist, however the time and cost of these solutions is often prohibitive due to the replication of onsite inefficiencies to the offsite environment.

There is little to no documentation written so far on lean moving assembly lines within a factory environment for the production of housing. For this reason, much work has to be done in the research of the benefits of process design for lean manufacturing of housing.

However, if we take the Japanese method, there are manufacturing processes that have been refined to a degree where they are so thoroughly known that customisation in the system is easily done. It works within a framework, but ultimately allows for customisation in the system, and it is manufactured on a moving assembly line.

6 Conclusions

Within the literature there is a knowledge gap that sits where lean off-site construction should be. There is little to no research around a framework for consideration of the application of lean in off-site construction. There is no research on a lean based moving assembly line for off-site construction and there is no research on a moving assembly line for off-site building manufacture.

The terms building manufacture does not bring up much in the current available literature, and this could be seen as indicative of the misapplication of a manufacturing system to a construction system, and ultimately where there is room for improvement.

The literature review revealed potential to explore this topic further, and to move forward in researching into the design for lean manufacture of low cost housing, with an emphasis on understanding the factory processes, before we begin to design for what we do not fully understand yet.

A moving assembly line for the production of housing can allow a customised outcome. This can occur with large savings in time and cost.

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COMPARING MIXING VENTILATION AND DISPLACEMENT VENTILATION IN UNIVERSITY CLASSROOMS

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Abstract: *There are two main types of mechanical ventilation systems: the mixing ventilation (MV) and the displacement ventilation (DV). The aim of this work is to compare their performance in terms of ventilation efficiency, air temperature, relative humidity, size-resolved particle concentrations, carbon dioxide (CO_2) concentrations, and energy consumption. We performed a field investigation in two side-by-side classrooms installed with the two different ventilation systems. The energy consumptions were measured by i) a heat meter to measure the energy extracted by chilled water supplied, and ii) a power analyser to measure energy consumed by the ventilation fan. We also monitor indoor air dry bulb temperature, relative humidity, and CO_2 concentrations in real-time for both rooms. It was found that the classroom with DV system consumed more energy. The unexpected high energy consumption can be attributable to the improved ventilation, CO_2 and humidity control in DV room. Air temperature stratification were observed in DV room, but both room achieved similar volume-averaged temperate. We also found lower particle concentrations in both rooms compared to outdoor levels.*

Keywords: *University Classroom, Mixing Ventilation, Displacement Ventilation, Measurement*

1 Introduction

Classroom environment is a major indoor environment for students. Classrooms are densely populated spaces, often with high concentrations of indoor air pollutants, inadequate fresh air, lack of humidity control, poor thermal comfort, etc. Madureira *et al.* (2015) found that the increase of self-reported respiratory symptoms among students is associated with high concentrations of airborne fine particulate matters and volatile organic compounds. The studies conducted in environmentally controlled spaces (Satish *et al.*, 2012; Allen *et al.*, 2016) revealed that elevated concentration of carbon dioxide (CO_2) can lead to negative impacts on human cognition and decision-making. Sarbu and Pacurar (2015) observed unsatisfactory thermal comfort and high CO_2 concentrations lead to a reduction of student performance.

One major means of achieving a healthy teaching and learning environment is through more fresh air ventilation. There are two main types of mechanical ventilation systems: the mixing ventilation (MV) and the displacement ventilation (DV).

The MV system (Figure 1a) generally supplies air from ceiling level with relatively high velocity to obtain uniform distribution of temperature and fresh air. The DV system (Figure 1b) is designed to achieve better indoor air quality and energy saving. It relies on the buoyance effect to remove heat and air pollutants from the occupied zone. The buoyance force is generated by indoor heat sources, such as human occupants and electrical appliances.

(a) Mixing ventilation (MV) system (b) Displacement ventilation (DV) system

Figure 1. Schematic diagrams of the MV and DV systems (Industries, 2011)

Hu *et al.* (1999) and Lin *et al.* (2011) compared the energy performance between the MV system and the DV system for a range of indoor environments, such as offices, classrooms and retail spaces by computer simulations. Hu *et al*. (1999) applied DOE-2.1C building energy simulation program for different U.S. buildings and climates and Lin *et al*. (2011) applied TRNSYS simulation software for typical office, classroom and retail shop in Hong Kong. Both studies found DV systems consumed less energy. Both studies also indicated that the DV system provide better thermal comfort and indoor air quality (IAQ) compared to the MV system. Qiu-Wang and Zhen (2006) used FLUENT with Re-Normalisation Group (RNG) k-epsilon turbulent model to compare the performance between MV and DV systems. They reported similar findings — the DV system can provide better IAQ in the occupied zone, better temperature distribution and thermal comfort, higher ventilation efficiency, lower concentrations of air pollutants.

It is worth noting that most previous studies were conducted by computer/numerical simulations or performed in experimental chambers. Field studies comparing MV and DV systems are limited. In this work, we present on-site measurements conducted in two classrooms with similar physical dimension, interior layout and furnishing, but one classroom installed with MV system and other one with DV system. The aim of the study is to investigate whether and to what extend the two ventilation systems affect ventilation efficiency, air temperature distribution, concentrations of particulate matters and CO_2, and energy consumption.

2 Methods

Two side-by-side classrooms in the second floor of a building at Nanyang Technological University, Singapore were selected for this field investigation. The classrooms are similar in dimensions, interior layout and furnishing. The dimensions of both classrooms are 8.0 m × 7.5 m × 2.75 m (L × W × H). Each classroom is furnished with one desktop, one projector, six tables, about thirty chairs and six 40" LED monitor. Both classrooms have one door, but no windows. They reply on the chilled water supplied from a centralized air conditioning system for space cooling.

The classrooms are installed with a MV or a DV system.

- Classroom one (denoted as MVR) has the mixing ventilation system. It is equipped with two compact multi-flow (4-way) ceiling mounted cassette fan-coil units (DAIKIN model FWMJC8AV1). Each fan-coil unit has one ducting for fresh air intake but no return nor exhaust duct. Fresh air intakes are located at exterior corners of the room. The ducting has no filter installed. The fresh air intake simply relies on suction by the fan in the fan-coil unit and the air exit through gaps under the door.
- Classroom two (denoted as DVR) employs the displacement ventilation system. The fresh air is drawn by a fan from fresh air intake and then distributed to six rectangular wall-mounted diffusers: three located at the front of the room and three at the back. Similar to MVR, there are no air filters and exhaust duct.

The measurements were conducted for two days in June 2013, one day at DVR and one day at MVR. The classrooms were used for lecture classes during 9:30-11:30, 13:00-15:00, and 15:30-17:30 on both days. They were occupied by ~20 people during the lecture sessions. The data sets collected during lecture period were analysed in this work.

We conducted trace gas decay test before the monitoring to estimate the air exchange rate (AER) of both rooms. AER compares airflow to volume and it is the volume flow rate of air into space divided by interior volume of space. It has units of 1/time. "When the time unit is hours, the AER is also called air changes per hour (ACH). (ASHRAE 2017). In this study, we utilised an InfraRan Specific Vapor Analyzer (Wilkes Enterprise Inc., USA) and sulphur hexafluoride (SF6) as the tracer gas for AER estimation.

On measurement days, we employed Optical Particle Counter (OPC, model 9306, TSI Inc., USA) to measure indoor particle number concentrations (PNCs). The instrument records particle number concentrations in six size bins (0.3-0.5, 0.5-1.0, 1.0-2.5, 2.5-5.0, 5.0-10.0, >10.0 µm optical diameter). The focus was on data recording in the three smallest size bins, covering the optical diameters between 0.3 and 2.5 µm. We conducted the sampling from a location near the centre of the classroom, at a height of 1.2 m, which approximates the breathing height of a seated occupant. Sampling was performed at 2-minute time intervals to capture the transient dynamics.

Concurrently with particle sampling, several monitors were used to collect additional environmental data, including dry bulb temperature and relative humidity (VelociCalc Model 9545-A, TSI, Inc., Shoreview, MN, USA), and CO_2 concentrations (Model CM-0018, CO_2 meter, Inc., Ormond Beach, FL, USA). Each instrument logged data at 2-minute sampling intervals, consistent with the interval which particle data were recorded. We measured dry bulb temperature and relative humidity at four different heights (0.2, 0.8, 1.5, and 2.5 m) to observe vertical variations. The CO_2 was sampled from the same location as particle sampling (at a height of 1.2 m).

The energy consumption of a heating, ventilation, and air conditioning (HVAC) system consists of i) the energy required to produce the chilled water and distribution by pump, and ii) electricity consumed by ventilation fan. We used an iSOLV heat meter (iSOLV BTU981-PT2, Flotech, Singapore) for measuring the heat transfer to the chilled water from room to estimate electricity consumption of chilled water production and distribution. The heat meter measures the flow rate and temperatures of the supply and return chilled water for heat transfer calculations. A power quality analyser (Fluke 43B with i1000s AC Current Probe, Fluke Corporation, USA) for electricity consumption by the ventilation fan. The time interval of both devices was set to 1s.

3 Results and discussion

3.1 Room ventilation characteristics

3.1.1 Required air exchange rate based on ANSI/ASHRAE Standard 62.1-2016

Equation (1) was used to determine required air exchange rate (AER_{req}) for both DVR and MVR. The minimum AER_{req} is 2.05 ACH to meet ANSI/ASHRAE Standard 62.1-2016 (American Society of Heating and Engineers, 2016).

$$AER_{req} = \frac{R_p Occu + R_a A}{V} \tag{1}$$

Where $Occu$ is the number of people during lecture sessions ($Occu$ =20 persons); A and V are the floor area (60 m^2) and volume of the classroom (165 m^2), respectively. R_p and R_a are the outdoor airflow rate required per person and required per unit area, respectively. ANSI/ASHRAE recommends R_p = 3.8 L per (s person) and R_a = 0.3 L per (s m^2) for lecture theatre or classroom.

3.1.2 Empirical air exchange rate

Equation (2) expresses a time-dependent material balance, embodying the conservation principle applied to the mass of a gaseous substance in indoor air.

$$\frac{d(C_i V)}{dt} = E - \lambda V C_i + \lambda V C_o - \kappa V C_i \tag{2}$$

The term on the left-hand side ($\frac{d(C_i V)}{dt}$) represents the rate of change of a gaseous substance concentration in indoor air. The positive term on the right-hand side reflects

the emissions from indoor sources (E) and contribution from ventilating the gaseous substance that exists in outdoor air (λC_o). The two negative terms on the right-hand side reflect the sinks that reduce indoor gaseous substance concentrations: removal by means of ventilation (λC_i) and by means of the first-order decay process ($\kappa V C_i$), respectively.

The variables defined in Equation (2): C_i and C_o are time-dependent concentration of a gaseous substance in indoor and outdoor air, respectively. λ is ACH. V is the room volume. κ is first-order loss rate coefficient for the gaseous substance removal from indoor air by means other than ventilation.

For the trace gas SF6, we used in this study, the indoor emissions ($E = 0$), concentrations in outdoor air ($C_o = 0$), and loss-rate coefficient ($\kappa = 0$) are negligible. We can simplify the mass-balance equation as Equation (3).

$$\frac{d(C_i)}{dt} = -\lambda C_i \tag{3}$$

We can then integrate Equation (3) over the time period t and derive Equation (4) for AER determination. The AER can be estimated as the slope of regression line in $[-\ln C(t)]$ vs. t graph.

$$-[\ln C(t) - \ln C(t + \Delta t)] = \lambda \Delta t + cons \tag{4}$$

Figure 1 illustrates the linear regression of SF6 gas decay in DVR and MVR , respectively. The AER of MVR (0.93 per hour) is far below the required AER (2.05 per h) as minimum set by ANSI/ASHREA Standard 62.1-2016.

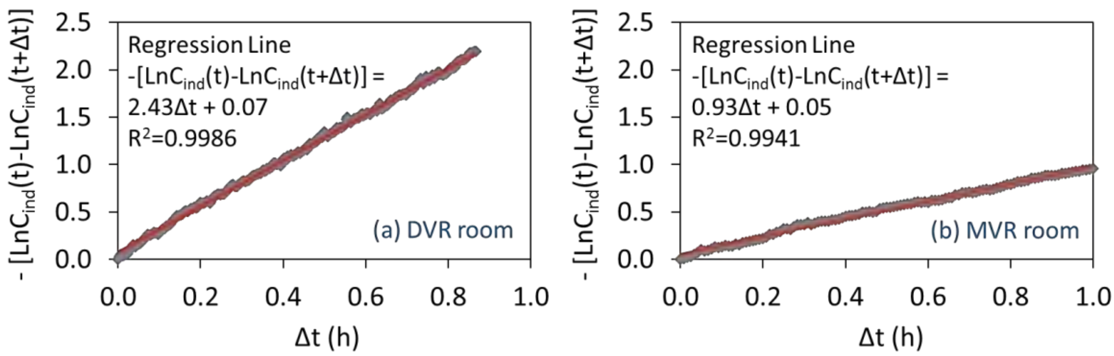

Figure 1: The linear regression graph of SF6 trace gas decay in (a) DVR and (b) MVR

3.2 Time series of CO_2 concentrations

ANSI/ASHRAE Standard 62.1-2016 (American Society of Heating and Engineers, 2016) recommends that indoor CO_2 concentrations should be below 1000 ppm. As illustrated in Figure 2b, we can observe significant CO_2 built-up in MVR during the lecture periods (9:30-11:30, 13:00-15:00, and 15:30-17:00) when the room were occupied by ~20 people. The CO_2 concentrations reached 2000 ppm or even higher at the end of each lecture session. The CO_2 built-up can be attributable to inadequate ventilation in MVR.

Compared to MVR, DVR has lower CO_2 levels. The CO_2 concentrations measured at DVR were below 1000 ppm throughout the whole monitoring period (Figure 2a).

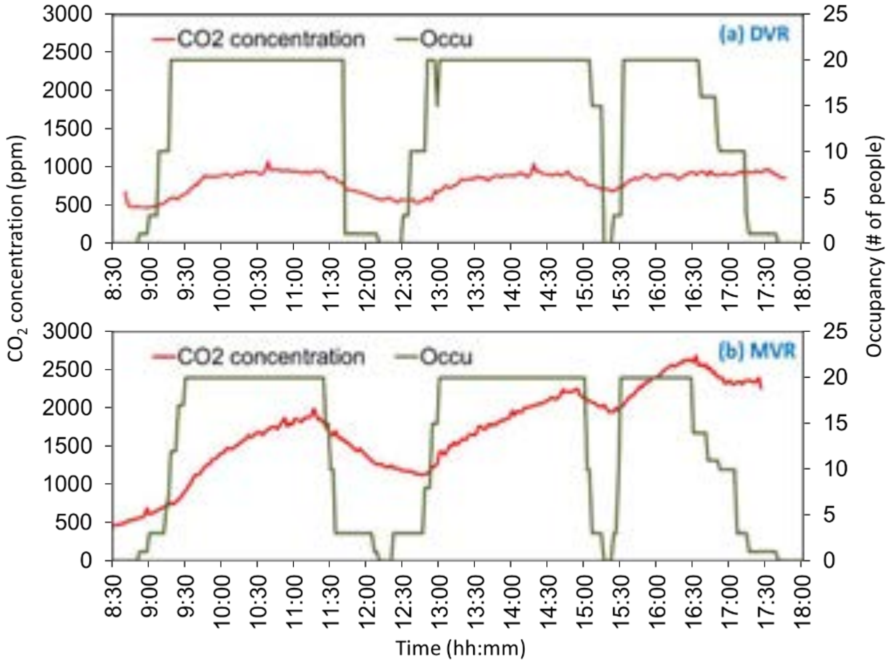

Figure 2: Occupancy and CO_2 concentration measured at (a) DVR and (b) MVR

3.3 Vertical variation of air temperature

Figure 3 shows the temperature variations measured at different height in each lecture period. We observed significant temperature stratification in DVR. The temperature increased almost linearly with the height from the minimum temperature (~21 ^{O}C) at floor level to a maximum temperature (~26 ^{O}C) at ceiling level in the DVR. On the contrary, MVR has relatively homogeneous temperature profile. The air temperature measured at different height ranged 22-25 ^{O}C in the MVR.

The temperature profile observed in this pilot study supports temperature stratification assumption employed in previous computational studies (Gilani *et al.*, 2016). The result is also in agreement with findings reported by Lestinen *et al.* (2016), which found the upper seating area of an arena has relatively higher temperature range 15-17 ^{O}C than at the lower seating area (12-17 ^{O}C).

3.4 Time series of particulate matters' concentration

We converted the particle number concentration recorded by optical particle instrument to mass concentration according to the method described in (Zhou *et al.*, 2015). The conversion was based on two assumptions: i) particles are spherical and have density of 1000 kg/m^3, and ii) mass-weighted size distribution, $\frac{dM}{d(\log d_p)}$, is constant within each particle size bin. Particles with optical diameter less than 0.3 μm were below the detection limit of the particle counter. The concentrations of particles below 0.3 μm could be included in future investigation.

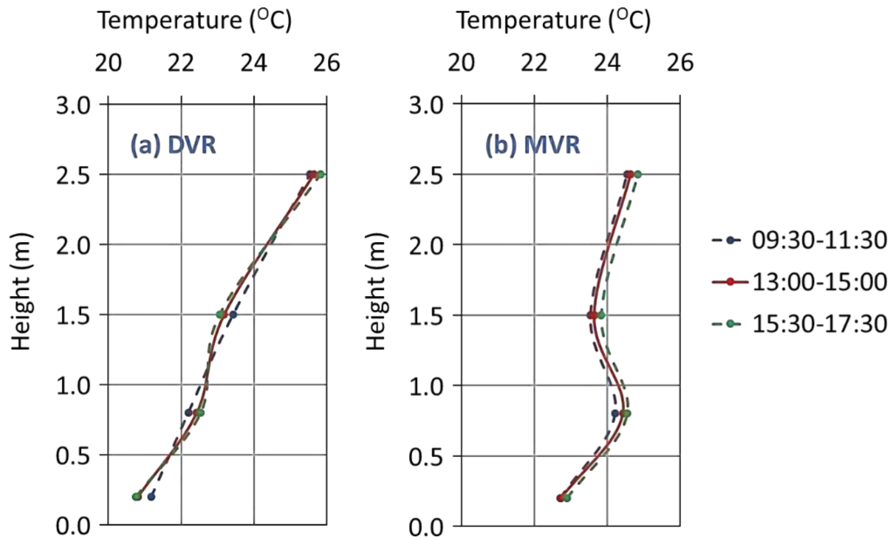

Figure 3. Air temperature measured at various heights in (a) DVR and (b) MVR

Figure 4 and 5 illustrate the time series plots of the size-resolved particle concentrations in DVR and MVR, respectively. We also plotted the variations of outdoor particle concentrations in both figures for comparison propose. Our measurements showed lower particle concentrations in both classrooms than outdoor concentrations, but differences between two rooms was not significant ($p<0.05$). The data also showed a few sharp peaks in $PM_{0.3\text{-}2.5}$ concentrations in DVR during the end of each lecture session. The peaks were mainly associated with large particles shedding from the human body envelope (including clothing) and resuspension from floor. One may expect to observe similar pattern for $PM_{0.3\text{-}2.5}$ concentrations measured at MVR, but surprisingly, the profile revealed quite stable concentrations without significant peaks. The concentration peaks could be attenuated by the full mixing property of the MV system.

3.5 Chiller energy consumption

Equation (4) was used to estimate the time-averaged heat transfer to the chilled water ($\overline{H}_c$, kWh) of the two rooms.

$$\overline{H}_c = \frac{\rho_w C_p \int_{to}^{te} \dot{V}(t)\left[T_r(t) - T_s(t)\right] dt}{te - to} \quad (4)$$

where ρ_w is the density of water (constant, 999.8 kg/m^3 at 10 ^{O}C); C_p is the specific heat capacity of water (assumed constant, 4.192 kJ/(kg K)$^{-1}$ at 10 ^{O}C); $\dot{V}(t)$ is the instantaneous flow rate of chilled water (m^3/s); $T_r(t)$ and $T_s(t)$ are the instant temperature of return and supply chilled water (^{O}C), respectively; to and te are the start and end time of the integration (s), respectively. It should be noted that the electricity consumption of the chiller to make the required amount of chilled water may be estimated by using cooling coefficient of performance (CCOP) of the chiller [$\overline{E}_c = \overline{H}_c / CCOP$]. A typical value for chiller system CCOP is about 2.5.

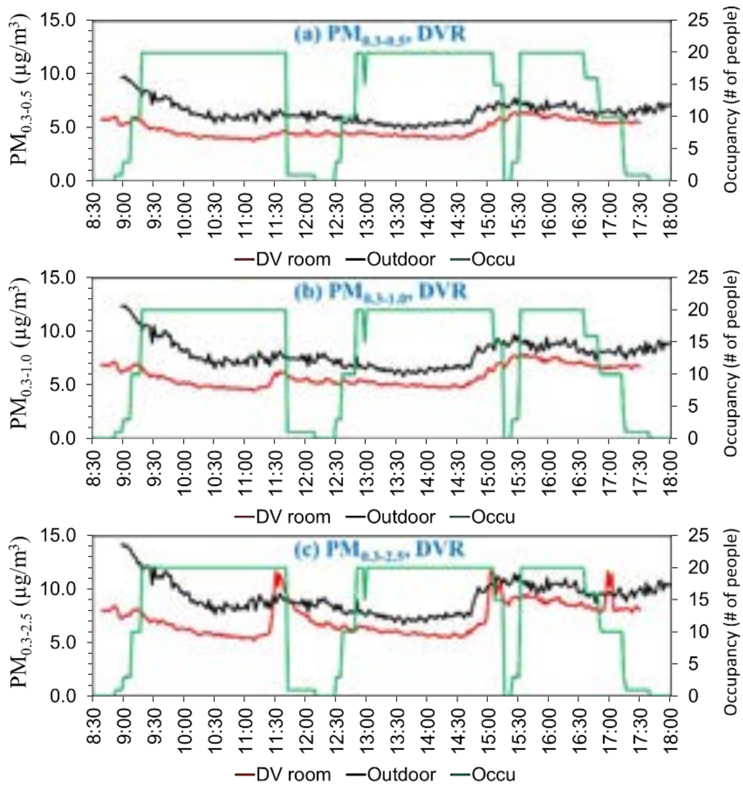

Figure 4. Time series plots of the size-resolved outdoor particle concentrations and the concentrations measured at DVR

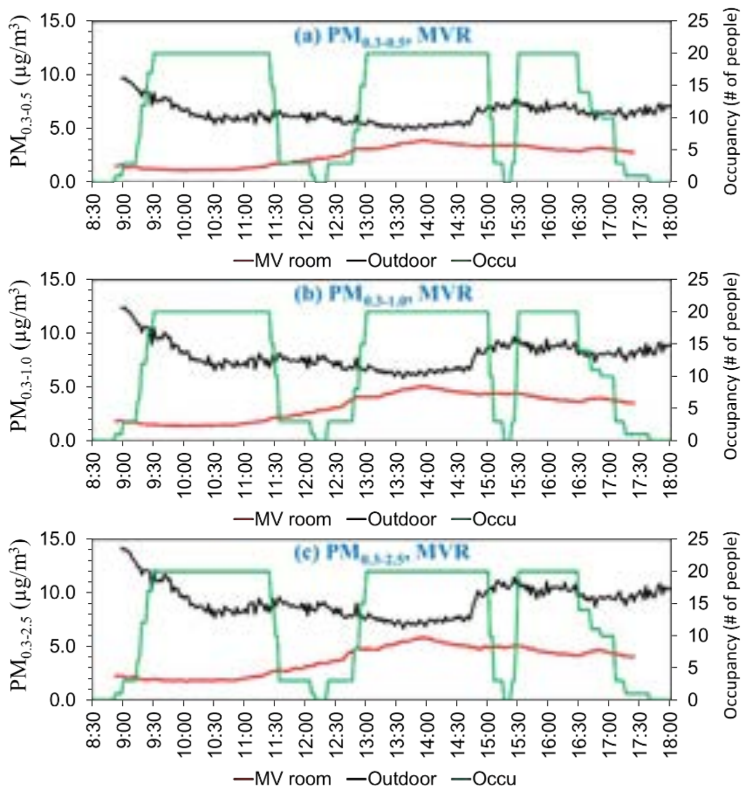

Figure 5. Time series plots of the size-resolved outdoor particle concentrations and the concentrations measured at MVR

Figure 6 illustrates the time series of instant $\dot{V}(t)\left[T_r(t)-T_S(t)\right]$. The area under the plots represents the integration term $\int_{to}^{te}\dot{V}(t)\left[T_r(t)-T_S(t)\right]dt$ defined in Equation (4).

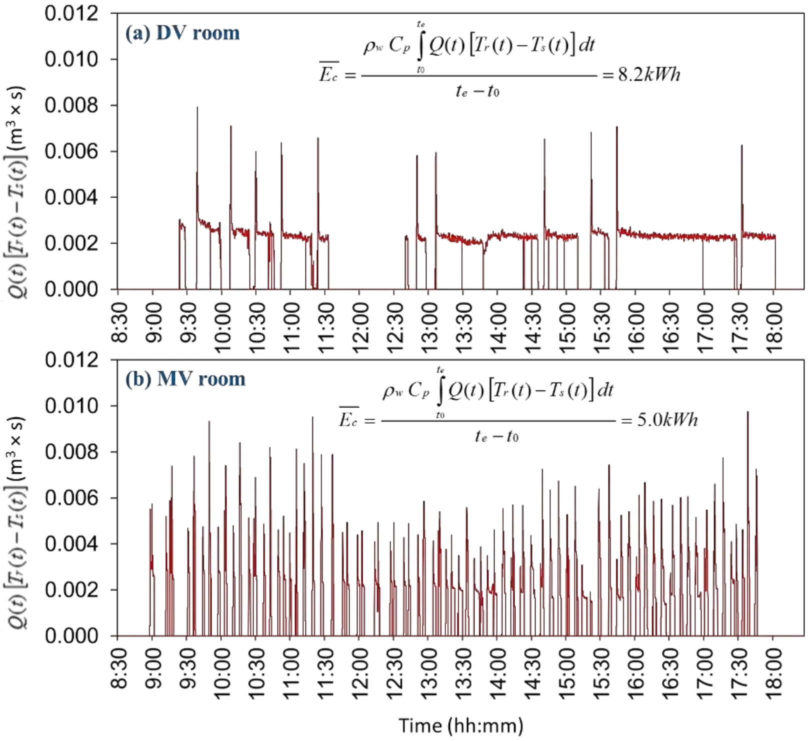

Figure 6. Instantaneous chilled water flowrate × temperature increase in (a) DVR and (b) MVR

Table 1 summarises the averaged energy consumption and environmental quality of two classrooms during the lecture sessions for one hour. Surprisingly, the DV system consumed more chiller electricity consumption than MV system. Given the fact that outdoor weather conditions, indoor facility loads and occupancy are similar between the two rooms, the probable reasons for higher chiller electricity consumption in DVR are:

- DVR has AER about 2.6 times that of MVR (see Table 1), which leads to increased energy consumption to cool the fresh air.
- Higher sensible cooling load in DVR since the indoor volume-averaged temperature is about 1 ^{O}C lower (see Table 1).
- Higher latent cooling load in DVR since the indoor volume-averaged relative humidity is about 19% lower (see Table 1).

Compared to the chiller electricity consumption, the fan electricity consumption is one order of magnitude less for both rooms. The ventilation fan installed in DVR provided adequate ventilation, but it consumed much less energy than that of MVR for the duration investigated. The fan installed in MVR supplied air at high velocity (4.5 ± 0.1 m/s) to enable air recirculation in the room. On the contrary, DVR can reduce fan energy by utilising low speed fan (air velocity of 0.3 ± 0.2 m/s) due to the natural buoyance force. In addition, compared to the continuous-operated fan in MVR, the fan installed in DVR were in operation only during the period when indoor CO_2 concentrations exceed the set point of 1000 ppm. CO_2 concentrations in DVR were rarely above this set point (see Figure 2a) for the duration compared.

Table 1: Per hour averaged electricity consumption and environmental quality measured at DVR on 24 June 2013 and measured at MVR on 25 June 2013 during the lecture sessions

ID	Chiller electricity consumption (kWh)	Fan electricity consumption (kWh)	CO_2 level (ppm)	AER (per h)	Volume-averaged T (^OC)	Volume-averaged RH (%)	Outdoor T (^OC)	Outdoor RH (%)
DVR	3.3	0.02	<1000	2.43	22.9±0.1	57.8±3.4	28.2±1.8	80.7±7.7
MVR	2.0	0.24	>1000	0.93	23.7±0.1	76.6±3.2	28.2±1.0	80.8±7.1

4 Conclusions

In this work, we conducted a field experiment in two classrooms using real-time measurement techniques to compare the influence of the two different ventilation systems on air exchange rate, air temperature distribution, concentrations of particulate matters and CO_2 concentration, and chiller and fan electricity consumptions. Although the classroom installed with DV system consumed more electricity, it provided better environmental quality. The CO_2 concentrations and outdoor fresh air ventilation rate of the DVR complies with ANSI/ASHRAE Standard. The DV system also provided an excellent control of humidity. The volume-averaged temperatures of two rooms are about one degree C difference, their vertical profile of temperatures differed. The temperature in DVR varied almost linearly with the height from the minimum temperature at the floor level to a maximum temperature at the ceiling level, while MVR had relatively homogeneous temperature profile. We did not observe significant differences in particle concentrations between two rooms, but lower concentrations in both classrooms than that of outdoor.

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INTRODUCTION OF THE TSC INTO EMERGING LOCAL MARKETS IN WALES

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Abstract: *This paper investigates the process of implementing a retrofit - type technology (a transpired solar collector) into the convergence areas of Wales which is considered as an economically developing area in terms of sustainable interventions. This paper aims to discuss the disjuncture between the sustainable agenda and the regulation of the free market. The concept of developing a low-carbon environment incorporates the efforts of developing technologies capable of reducing the carbon demand within existing buildings. One of such was the Sustainable Building Envelope Demonstration project which was set out in Cardiff University and supported by the Welsh European Funding Organisation. This project was convened with a industrial partner (Tata steel), which were given significant freedom to introduce the process. The research presented in this paper looks at a project that developed the technology in the specific climatic conditions of Wales and seeks to understand the way in which the industrial partner handled the task of it's introduction with poor availability of skill, infrastructure, awareness and demand. The research looks at the architectural detailing and approach to the design and time-scale of procurement of the sites that the industrial partner was in charge of. The observations suggest that the implementation process follows a free-market model and aims at attracting larger commercial industries as a start. It also suggests the NIMBY (not in my back yard) effect is subject to different regulations which might imply a change in the implementation model. By that the research engages with a discussion set out by Joseph Stiglitz on the role of free market economies in the progress of economically developing regions in Globalisation and its Discontents (2002). The investigation is based on supervision of the implementation process as well as over 100 semi-structured interviews with inhabitants of Wales including by-standers, industrial partners and architects.*

Keywords: *Economy, Sustainability, Retrofit, Transpired Solar Collector, Architectural Detailing*

1 Introduction

Facing a necessity to reduce the environmental damage caused by an unsustainable drain on resources and emission of green-house gasses, architects and engineers seek to develop devices which might reduce the carbon footprint of the built environment. One of such attempts was the development of the Transpired Solar Collector (TSC) technology as a retrofit that is capable of pre-heating ventilation air supply. This paper discusses the process of implementing the TSC into the free market economy of the convergence areas of Wales (see fig 1.) as part of the Sustainable Building Envelope Demonstration (SBED) project. Assuming that the precedent discussed in the text is representative of a larger trend it suggests that large commercial bodies hold a rightfully justified caution in the implementing new technologies. It might be argued that the discussed approach enforces a phenomenon that is similar to the NIMBY (Not In My Back Yard) effect that dampens the free spread of sustainable devices amongst private house owners.

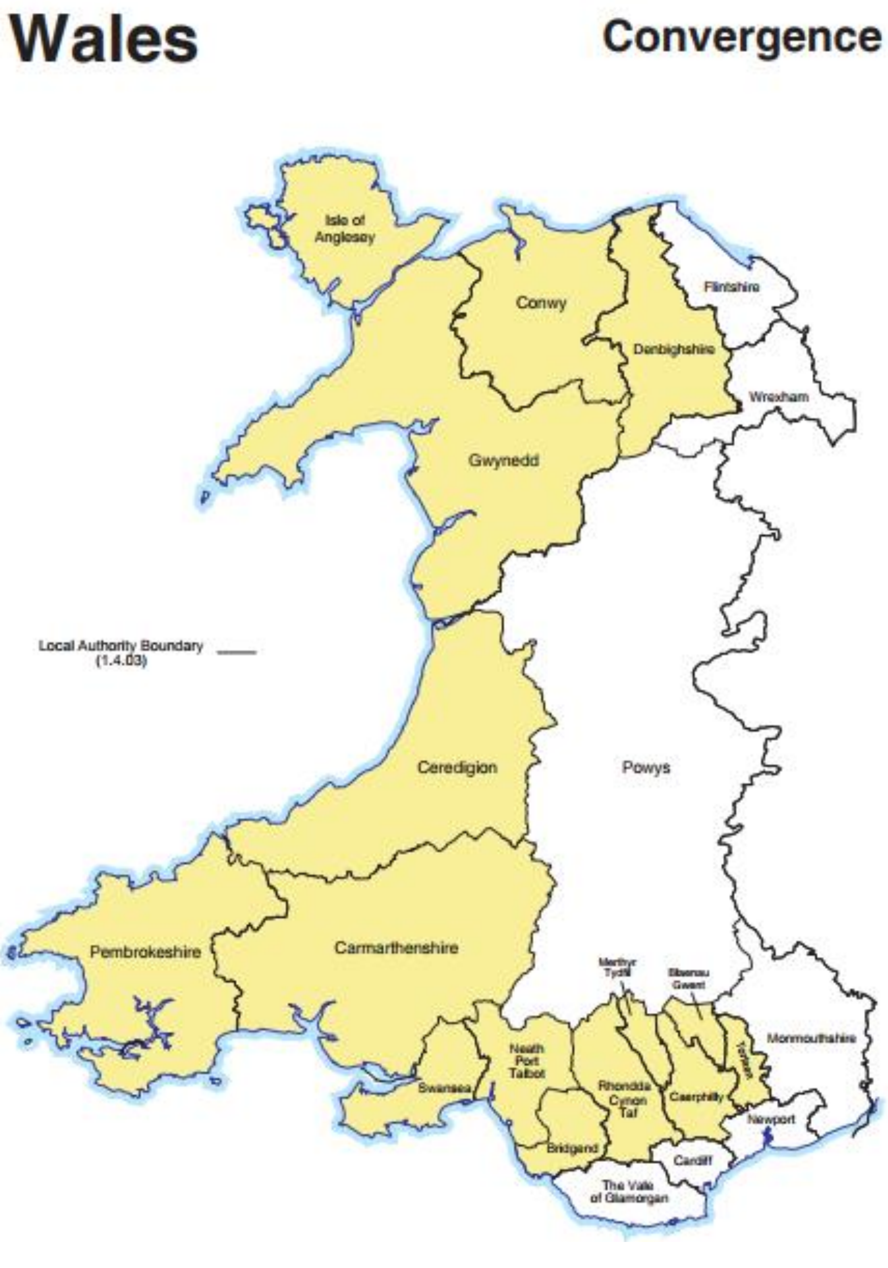

Figure 1: Convergence areas of Wales

The aim of the SBED project was to demonstrate and test the performance of TSC's across a number of building typologies in the convergence area of Wales. This was to ease the introduction of the TSC as a new piece of technology in the area by proving the functionability of the device. The planned buildings that were to be retrofitted with a TSC were to include: two industrial, two institutional, two commercial and two residential cases. This was to ensure that the study encompassed a wide range of data for a broad architectural example and opportunity for a creative exploration of architectural detailing.

All of the material in this paper is an extract from reports submitted as part of the SBED project to Cardiff University and the Welsh European Funding Office (WEFO) monitoring branch. The objective of this paper is to investigate the approach of the industrial partner to the process of developing the architectural detailing of the retrofit and suggest the impact of this approach on the wider public.

2 Background

The TSC is a device capable of using solar energy to preheat ventilation air supply and was widely popularised in Canada. The device comprises of a sheet of (often) corrugated and (always) perforated steel; and a mechanical ventilation systems as seen in Figure 2. An external metal sheet is installed up to 300mm in parallel from the southern-most elevation of a building, preferably one, which is not overshadowed. By doing so the sheet gains exposition to the sun in an orientation that allows it to gain in temperature throughout the day. With the warmth of the sheet the air in the cavity that it encloses between the metal sheet and the old elevation becomes preheated. As the sheet has a multiplicity of perforations - 1.5mm in diameter - (that are spaced uniformly) it allows for a transition of air between the exterior and the cavity. When the air from the cavity is pulled in to the interior of the house via a mechanical ventilation system the pressure pulls the air through the perforations in the warm sheet of steel. In this way the air enters the cavity and then the building already preheated. In the right conditions the air supply in ventilation reduces the amount of energy necessary for heating the space.

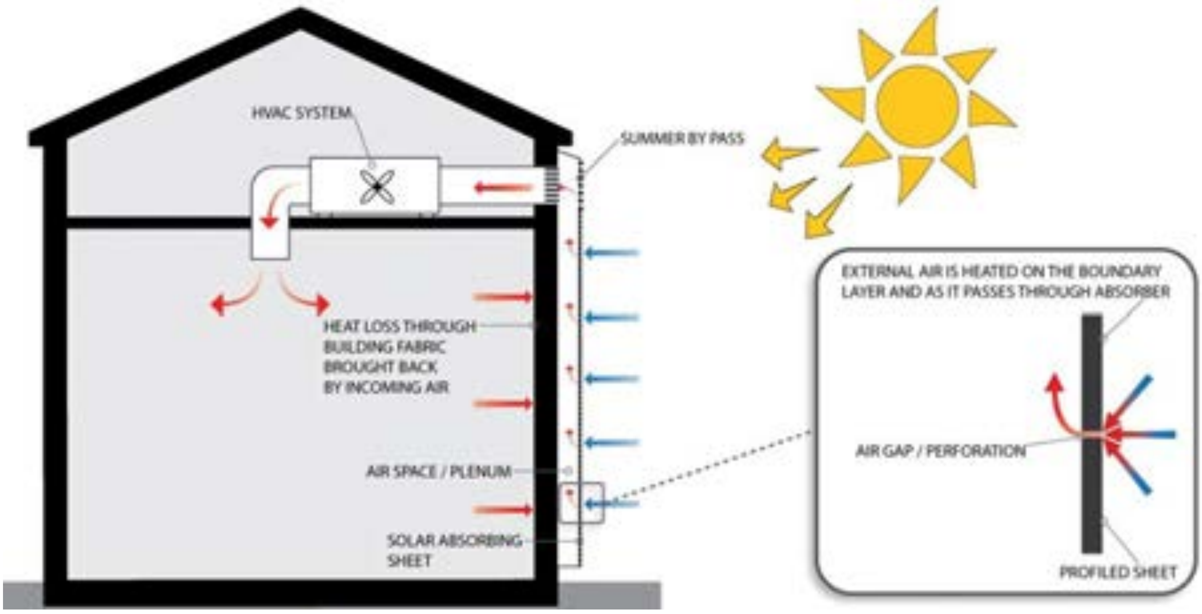

Figure 2: Diagram illustrating the functioning of the TSC

Following the directives of the funding body (WEFO) one of the objectives of the SBED project was to stimulate the economic development of the region and improve it's employment conditions. The goal of the project was to test and present the efficiency of the TSC in the region in hope that it might result in a demand for the device creating a new branch of the market. This demand was to be based on renewable energy that does not harm the environment and reduces carbon emissions.

As mentioned previously in order to convey the task of retrofitting the TSC onto buildings the work was outsourced. The industrial partner which was collaborating with Cardiff University was Tata steel. Tata steel is a large commercial steel manufacturer and supplier. Within this organisation an initiative that was set up to test and advance sustainable ways of utilising steel, this is the Sustainable Building Envelope Centre (Tata Steel). The TSC was adopted as one of such advancements when Tata steel was procured as the industrial partner for the project. The collaboration between Cardiff University and the company relied on the shared paradigm of developing a place in the market for a steel based device that could be retrofitted on buildings and potentially reduce their carbon footprint. The designers of the device were based in Tata as it was assumed that they would have the expertise in working with the material. Because of this the University gave the corporation a great deal of autonomy.

3 Literature review

The focus of the review was the implementation of retrofitted devices capable of generating sustainable streams of energy, strategies aiming to reduce carbon emissions and alternative sources of heat or in short 'renewables'.

The importance of a successful introduction of renewables into local economic markets is argued by Jan Zoellner, Petra Schweizer-Ries and Christin Wemheuer (2008a) who completed a survey in Magdeburg by conducting interviews in and disseminating questionnaires. Their study suggests that the introduction of renewable energy sources in the neighbourhood increases the level of environmental concern in the area and triggers proliferation of the renewables philosophy in the mind-set of the local people. The inhabitants of an area with renewables claim they are incentivised to a lifestyle that is more mindful of the environment. This idea was backed up by a quantitative study conducted by Hiroki Hondo and Kenshi BabaHiroki (2010). Their studies also suggest that the implementation of renewables in a given location with the acceptance of the local community may have a wider impact than expected.

Inaki Heras-Saizarbitoria, Ernesto Cilleruelo and Ibon Zamanillo claim that the successful introduction of any technology needs to coincide with its acceptance by the public (2011). In their collaborative paper on the public acceptance of renewables in media they are analysing cases of sustainable devices installed in Spain. Their study concerns a number of media reports of renewables across a given period of time and presents a positive correlation in public opinion. Their study concerns a case in which the acceptance of renewables increased. A different paper, written by Rebecca Ford, Kathryn Williams, Ian Bishop and Eric Smith (2014) imply that the sustainability of an architectural intervention might hold a deeper impact on the public. It suggests that the sustainable label might lead to a change in judgement and influence its aesthetic perception in a case of deforestation. This suggests that the relationship of sustainability and perceived aesthetic qualities is interlinked and in theory has the potential to be a self-perpetuating machine. The importance of developing an understanding of strategies which might prove to be successful in implementing renewables in a local market is in general assumed to be of great importance. Maria Cristina Munari Probst (2007) argues that the aesthetic quality of a retrofitted device (along with its capacity to produce energy, and durability) is key in determining success on the market.

Nathaniel Coleman, an architectural historian suggests that modern researchers who seek ideal forms (Such as More, or Mannheim) always see them as contextually specific (Coleman 2005). It is Coleman's understanding that the ideal, beautiful form is one which feeds into the network of forms and spaces of a greater context. As Frank Lloyd Wright wrote:

> It [a beautiful object on the façade] is organic with the structure it adorns, whether a person, a building or a park. At its best it is an emphasis of the structure, a realization in graceful terms of the nature of that which is ornamented… without destroying the unity of the object decorated. (Frank Lloyd Wright 1909)

The significance of the specificity of an architectural device to its context is also advocated by Probst and Christian Roecker (2007) who comment that if a retrofitted device is installed in a way that is significantly different from the host building then it will appear unattractive through the differences of inappropriate geometries, colours, size and positioning on the wall. This would suggest that the aim of a designer who is to implement a renewable in a given area must be immensely contextualised and approached with great care to understand the specificity of the local context.

Roecker et al (2007) suggest that an unsightly image of a retrofit might deter from their spread in a given area. One flaw in the retrofit Roecker's team investigated was the abundance of explicitly visible ducting. Roecker et al. suggest ways in which a device, in this case, a TSC might be integrated into the architectural fabric in a holistic way to give it a sense of belonging. They suggest using dummy sheets to cover a whole surface instead of only a functional fragment. By doing so the retrofit might appear like an intentful and controlled architectural intervention rather than an awkward afterthought. This is to suggest an idea that any renewable should be contextual and ought to be attuned to the geometry of the architectural fabric (through spacing, height and width of the openings etc). Probst (2005) goes even further to suggest that the panels should have more than just one function and should play an integral part of the host elevation either as cladding or roof cover.

Probst argues that if the retrofit looks like an afterthought then the whole concept of the building loses its aesthetic qualities (Probst, 2007). The device should therefore be fitted in seamlessly into the architectural composition of the building so that its colours and geometry match the existing conditions on the building and not disrupt the message that is communicated by architecture. The most important in her opinion is to look at size, texture, material, colour, position of the collector as well as the modulation and types of joining. This should all be chosen by the architects as according to her their profession gives validation of what is appropriate.

Tjerk H. Reijenga (2011) is of a different opinion. Reijenga discusses the use of retrofitted solar devices and suggests using their alien nature on the host elevation to its advantage. Reijenga suggests utilising the devices as a shading mechanism and presenting their idiosyncratic quality and site-specific character by a design that is bespoke to the lighting conditions of the specific location. By doing so the devices will gain a new architectural quality that would not need to conform to the geometry of the designed environment.

4 Methodology

The initial challenge of the project was the necessity to find appropriate host buildings for the TSC retrofit. This task was tackled collaboratively and both the Tata Steel and Cardiff University team members contributed. Some building owners were initially approached by the team members of Tata steel whereas some came as a Cardiff University choice. Regardless of the initial approach all buildings had to undergo a rigorous process of pre-installation scrutiny which rendered some insufficient due to geometry of the building, legal

issues or context. The location of the buildings chosen for the project is presented in Figure 3. The pre-installation evaluation ensured that the most favourable examples of buildings were chosen to present the TSC in its full potential.

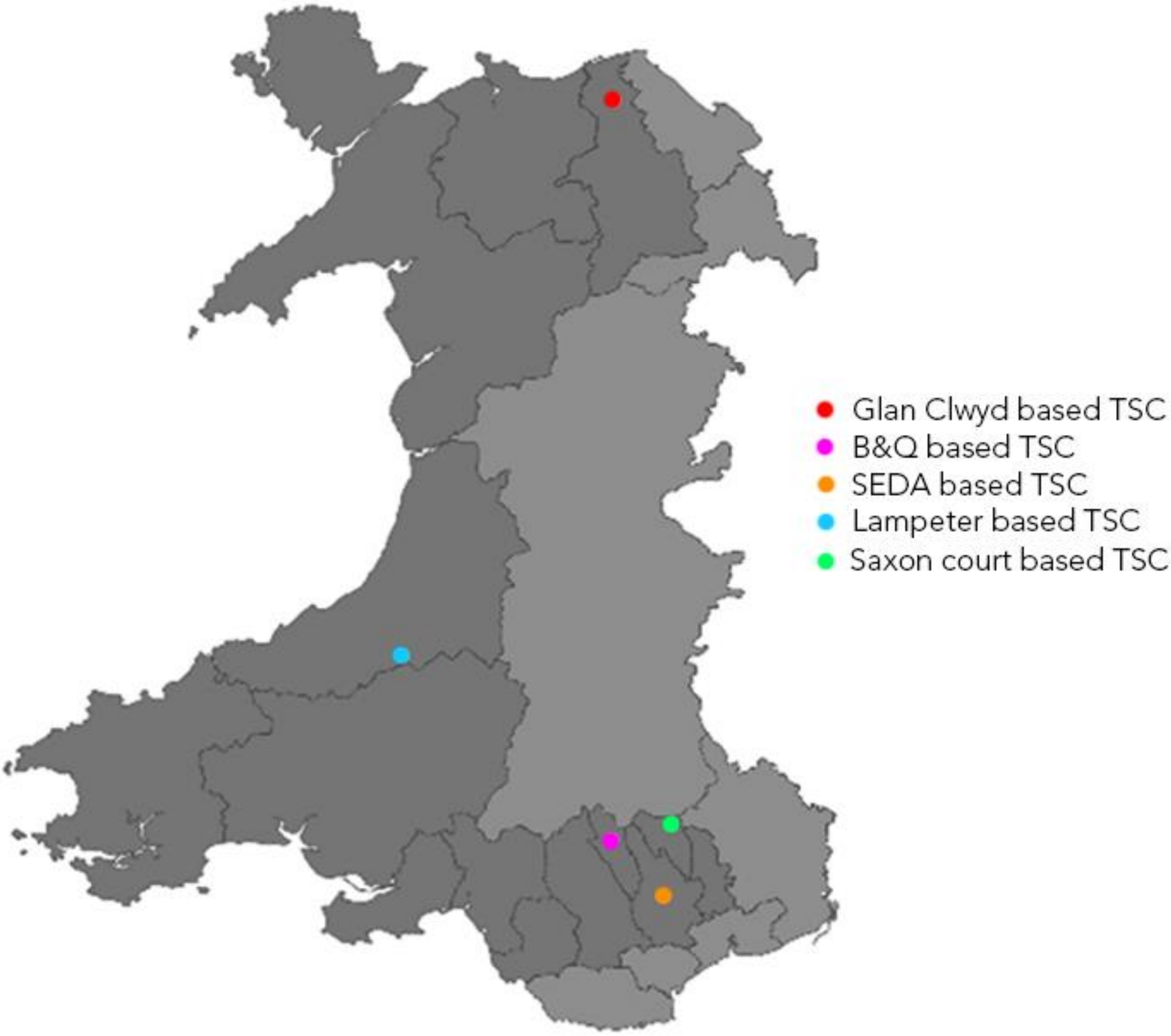

Figure 3: The location of the retrofitted TSC's

After suitable buildings were chosen, the project could unveil and its two fundamental components could be studied. The first outlined the necessity to monitor the efficiency of the device to deliver a potential to preheat air supply for ventilation streams. The second was the importance to study how the public in Wales responded to the quality of architectural detailing of the retrofit. It has to be noted that by using the phrase *architectural detailing* the full extent of designing the form of the device from largest to smallest detail and how it links with its context is at hand.

Monitoring of the architectural detailing took the form of observation of the design process which included visits on the construction site, interviews with interested parties and interrogation of architectural drawings. Monitoring of the architectural quality was an ongoing process and required communication between Cardiff University and the Tata Steel.

The study of public perception required a much less conventional approach. In order to gauge interest in the TSC early on a series of images of chosen buildings from Wales was devised with photoshoped TSC's. The design of the study was based on the A/B-split-testing

technique. This technique relies on establishing key features of an issue, in this case the aesthetics of a TSC. The method asked for images of the TSCs to be presented to a number of groups of people. Each group of people would see images of the device with only one (chosen) feature in several variations and the rest of the features remaining the same (see Figures 5-7). This process was repeated until all the variations of all the features were scrutinised.

In addition to this a complication was included. The TSC's required a host building that would not change the perception of the image as a whole. To achieve this four buildings in Wales were chosen considering the repetitiveness of their typology in the region. The images represented the available technological advancements in the field of architectural detailing that Tata steel were considering. The four buildings, visible in Figure 4, consisted of: a Victorian terrace house in two instances, a modern counsel housing block and a modern (five year old) terrace house. All houses had different treatments of the elevation to introduce variety of backdrops for the TSC: from white plaster, via red and orange brick to stone masonry. The backdrop of each building was retained and did not change in any iteration of the TSC giving the composition architectural context. The images were presented in large scale and small to ensure that a detailed reading and an overall impression were possible (see example in Fig. 5).

Figure 4: The buildings chosen for the test

Figure 5: The photoshoped TSC on one of the chosen houses in different scales

Figure 6: The photoshoped TSC on one of the chosen houses in three variations of the feature of colour

Figure 7: The photoshoped TSC on one of the chosen houses in three variations of the feature of shape

The breakdown of the features was determined by a detailed study of the available literature which suggested that the more contextual the TSC comes across the more successful it will appear.

A significance of colour in the perception of aesthetics was discussed by David Williams and Heidi Hofer (2005) as Williams Yasuki Yamauchi (2005), Banu Manav (2007), Li-Chen Ou, M Ronnier Luo, Andree Woodcock and Angela Wright (2004) and Caroline Paradise (2007). The colour variation was chosen on the basis of RGB colour pallet. The variation was determined by producing versions where the colour was the same as all the primary colours as well as black, the same colour as the elevation and opposite to the colour of the elevation under the RBG scheme (see Fig. 6).

A tentative significance of shapes in the perception of aesthetics was discussed by Irena Pavlova, Arseny Sokolov, and Alexander Sokolov (2005), Sibel Dazkir and Marilyn Read (2012), Zusne (1970), Quinlan (1991) and Chipman (1977). The variations of the texture of the device were: a straight vertical corrugated panel, tongue grove horizontal panelling, cassette panelling, a flat panel and a quilt-like panel as illustrated in Figure 7.

An impact of size in the choice of determining what is beautiful and what is not was implied by Hayward and Franklin (1974). The variations of size were (excluding the window openings): 100% of the, 50% of the elevation, 25% of the elevation. The variations of this feature is presented in Figure 8.

Figure 8: The photoshoped TSC on one of the chosen houses in three variations of the feature of size

The protocol of the interview was to discuss ethical considerations with the respondents, show the respondents all images and go through them all again slowly discussing their aesthetic appeal asking for rating and a comment. After that the respondents were asked a few follow-up questions inquiring about their demographics, attitude towards sustainability as well as possible factors which might have influenced their opinions.

Every variation gained responses from ten people individually to gain good quality full answers from the respondents. This was conducted thirteen times to cover all variations on all buildings as well as images of houses without TSCs. Overall 130 semi-structured interviews were conducted.

The interviews were conducted in Cardiff (the capital of Wales), with members of the public encountered in public libraries (Whitchurch Library, Rhiwbina Library, Cardiff Central Library), on streets (The Hayes, Queens street) In Cardiff University facilities (Arts and Social Studies Library, Bute Library, Welsh Department, Architecture department, Student's Union), leisure centres (Maindy Leisure Centre, Cardiff Central Youth Centre). The places were chosen on the basis of determining the best locations for encountering people engaged in leisure but not busy with specific tasks. This was done to limit disrupting people's daily routines and to gather interest in the study. This meant that the demographics of the study is limited to people who can afford to spend time engaged in non-active leisure during the hours in the day when the interviews were taken (9am – 5pm). All members of the public which seemed willing to partake in the study were approached. The only constraint was the ethical application of Cardiff University which demanded that the participants were over 16 years of age, didn't categorise themselves as persons with learning disabilities or illnesses,

were not people in custody, engaged in illegal activities or vulnerable. Apart from this no discrimination occurred.

Another limitation to the study might have been caused by the presence of the interrogator, who, unwittingly, might have influenced the answers by the way the questions were asked or the way the subject was approached.

5 Case Studies

The discussion herein includes three, chosen TSC's which were retrofitted as part of the SBED project. They show an understandable tendency of Tata steel to favour large-scale implementations of the technology (eg: TSC's retrofitted on industrial or commercial buildings) over domestic-scale retrofits. The sequence of the discussion is determined by sequence in which the managers of the buildings were approached.

The three examples follow a larger trend which was prevalent in the remaining examples discussed in the final report of the SBED project. The examples present an apparent tendency of the industrial partner to think of the installation process with the aim to gain experience and provide a very safe, stable and predictable foundation for their operation within the local market. The information in this section is based on site visits, email exchanges and interviews with the designers and consultants at the Tata Steel.

The first case discussed in this text is a TSC installed on a new-built commercial building owned by the B&Q Corporation. The business was initially approached by the Tata steel team in 2012. The collaboration with B&Q was presented by the Tata steel team as a result of a longer collaboration between them and the owner of the building. Considering that B&Q has an agenda to pursue sustainable sources of energy and make every store as ecologically-friendly as possible this choice was a good start. The relation between the two conglomerates might have meant an established and workforce-generating relationship in the region with a market-stimulating, eco-friendly effect. The location of the building is presented in Figure 3.

The design of this TSC was straightforward as the building was a modern construction which was equipped with provisions to host sustainable technologies on its external fabric. The installation started before the completion of the external walls of the building so it might be assumed that the structure of the building was bespoke to renewables. The final image of the device on the building is presented in Figure 9.

Figure 9: B&Q roof-based TSC.

Figure 10: The lower detail linking the TSC panel to the guttering of the B&Q roof

Figure 11: The detail linking the TSC panel to the ridge of the B&Q roof

The detailing is simple and functional with oversized elements that allow for easy maintenance as shown in Figures 10 and 11. The sizing of the TSC is fit to the requirements of the pre-heating demand as well as the specificity of the geometry of the building. The TSC panel is 280m^2 in area. There are small elements that do not quite meet the geometry of the roof as seen in Figure 11 but the overall concept of mimicking the corrugation of the surface and replicating it with the device seems to integrate the device in an un-obstructive way. The TSC seems to be fitted into the basic concept of the building. The screws on the side of the device are visible and suggest that the detailing is not seamless but since the device is on the roof this did not have a huge visual impact on the perception of the building.

An email communication with the Tata steel designers mentioned that the Tata steel team rightfully started setting up a compilation of standard design drawings for ease of using the knowledge developed in the project for future use on commercial buildings. This was most likely to ease the speed of development in potential future projects.

The next building that was approached was an example of an institutional building; this was the Glan Clwyd school. The initial contact was made by a member of the Tata steel team in 2013 and the location of the building on the map of Wales can be seen in Figure 3.

In contrast to the design of previously discussed buildings this case had a much lower demand for heating and different times of operation that would be required hence the specification of the TSC as well as the design of the detailing had to be altered. This TSC panel is 111m^2 in area.

The first difficulty came from the age of the building which implied that the design of the detailing was not as straightforward as in the previous example. The structure of the roof was not designed to be able to support a future retrofit of a sustainable device nor was it in its prime condition. Above all its geometry was a complex set of interlocking planes which made a single, rectilinear plane retrofit difficult to seamlessly integrate.

Tata Steel decided to install the TSC on one of the sides of the roof as well as on the elevation that encloses a busy staircase. The part of the installation that was visible from public was the elevation based TSC as shown in Figure 12.

Figure 12: The Glan Clwyd school elevation-based TSC

The size of the panel on the elevation could have any given dimension as the designers intended the axillary roof-based TSC to compensate the size of the elevation-based device. This gave the designers the opportunity to follow the lines of the elevation so as to not compromise the original intent of the architect of the building. The element as a feature on the façade also picks up on the colouring of the panels below the windows. The positioning of the panel additionally seems appropriate as it divides the old fabric of the building from an extension that is visible due to change in the colour of the bricks used in both. Corrugation is used, which gives the installation an industrial character and the sizing of the elements that meet the old fabric is the same as in the case of B&Q based device.

The intention of the designers was to conceal the roof-based TSC but they did not consider the height of the neighbouring buildings that the roof was clearly visible from. The installation stands out as an obvious afterthought and distorts the roofline in a clumsy way with no apparent attempt to conceal the awkwardness with non-functioning (or dummy-) panels as suggested in literature by Roecker et al (2007). The side of the roof-based TSC is also enforced with what looks like metal brackets that makes the installation appear as a temporary adjustment to the architectural fabric.

The interior of the building was also dealt with in a wide-brushed way as the visible ducting inside the busy staircase (as seen in Figure 15) explicitly breached the existing fabric. Figure 15 is a photo taken before the installation was complete but the size of the duct makes the installation look intrusive and out of place.

Another drawback of the retrofits came from the use of the spaces around the school. The elevation-based TSC, even though seemingly attractive and contextual seems to have identical brackets supporting the panel throughout the installation. Ideally there would be more reinforcement for the panels at the bottom of the installation. This is due to an expectation that children might damage the surface with idle play and accidentally applied lateral loads. An example is a trace of dirt on the device left clearly after a ball had impacted the surface (seen in Figure 16).

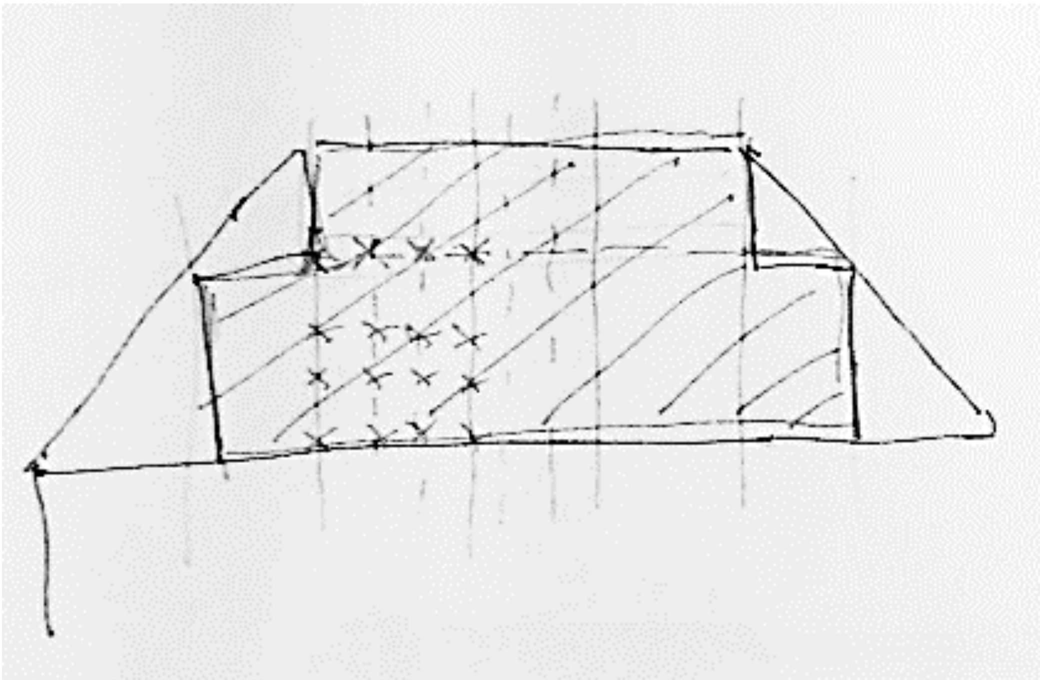

Figure 13: Hand drawn sketch of the Glan Clwyd school roof-based TSC with a conceptual framework of the brackets that would be supporting the installation.

Figure 14: The Glan Clwyd school roof-based TSC

Figure 15: The Glan Clwyd school TSC ducting in the staircase

Figure 16: Dirt from an impact of a ball on the Glan Clwyd school TSC elevation-based TSC that someone humorously altered into the shape of a skull.

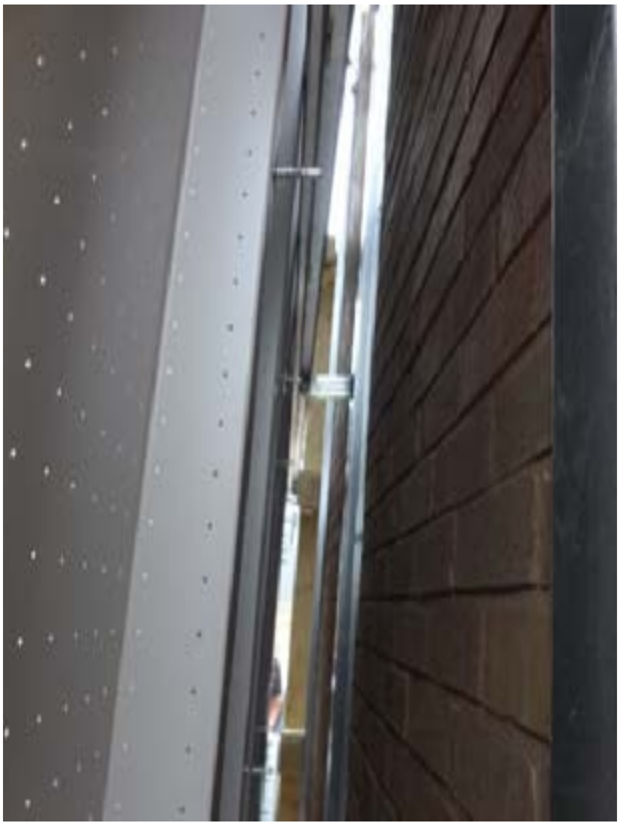

Figure 17: Spacing of the brackets behind the TSC panel on the Glan Clwyd school TSC elevation.

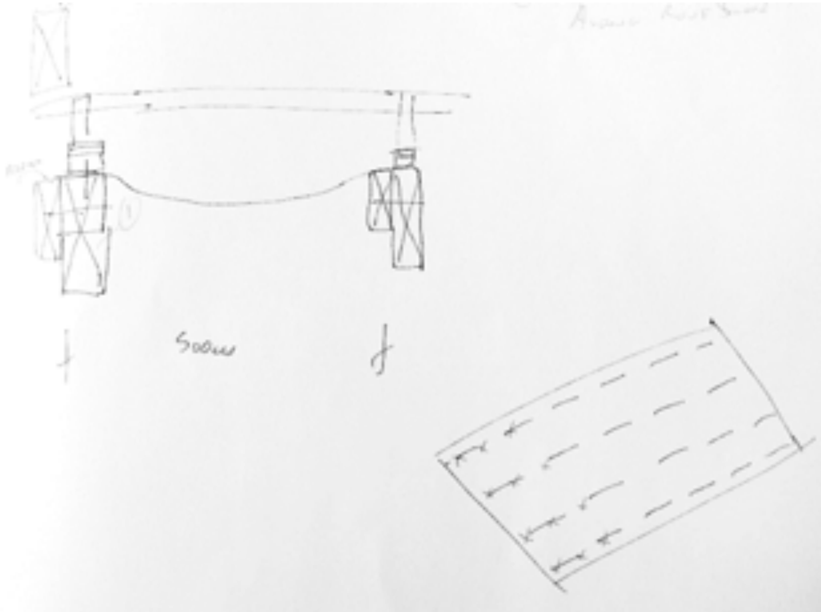

Figure 18: Hand-Drawn sketches, solutions to the structural problem on the Lampeter school presented by a Tata steel designer.

During a discussions about the design of retrofits for dated, institutional buildings in the Tata Steel centre one of the Tata steel designers presented a deep structural problem of rooftop durability. The issue concerned the rafters sustaining the roof and their loadbearing ability. The designers suggested that the rafters are too weak to support the weight of the panel. Several options were discussed as seen in Figure 18 but in the end the one that was chosen as the most common-sensical solution was least-costly. The designer we met presented this as *a matter of fact* that cost-effective solutions are the most common-sensical approach in a free-market economy.

The final building that came to be retrofitted with a TSC that the Tata steel designers tackled was a multi-residential building, Saxon Court. This was a building that was initially approached in 2014 by the team in Tata steel. The location of the building can be seen in Figure 3.

The geometry of the panel is fully elevation-based and covers the entire south-most elevation. Dummy panels were used to avoid surfaces that expose the old fabric of the elevation. This was done to unify the materiality but this made the TSC overwhelming as shown in Figure 19. The impression of the device, rather than seamlessly integrating into the domestic character of the building comes across as industrial.

Figure 19: The complete TSC on the Saxon Court building

The detailing of the installation seems to present a standardised way of approaching the design as seen in the previous examples. Corrugated steel is used which is usually associated with warehouses or container sheds. This is a sterile and economic way of implementing the device by copying the detailing solutions used in previous examples. This approach fails to mediate the aesthetics of a domestic scale of Welsh dwellings. The most awkward places in this design come across in moments where the device meets the geometry of the existing fabric such as the eves (as seen in Fig. 19) and the pavement. The design implies that there was not enough metal to cover the entire elevation so the panel cannot reach the ground nor can it frame the second floor windows. This way of looking at detailing suggests that it was not investigated in a small scale. The device looks bespoke in a drawing in 1:100 or 1:200 scale where the gaps between the window and the eaves or at the bottom of the building are of a millimetre but not from up close.

In a conversation about this retrofit one of the Tata steel designer expressed awareness of the financial constraints of the projects (discussed in this text) which might lead to solutions pushing the economic drive of a TSC panel on the Welsh market. He mentioned that his thinking is also guided by the knowledge of the manufacturing process that the material has to undergo in order to take a desired, cost-effective form. He commented that there is a number of options that the design team was discussing and eventually the most *common-sensical* one, as he described it, was chosen.

In a final note the designer also mentioned that in the spirit of developing the technology for a domestic scale the Tata steel team came up with an idea that might solve the cost issue and make the product available as an 'off-the-shelf-solution'. The designer quoted the solution to be quick, simple and effortless to install. He designed the TSC to be a 1 by 2 meter compact, self-contained hexagon. This box-like feature could potentially be attached to an external surface of a building and further into the mechanical ventilation system of the dwelling. In his understanding the virtue of this approach is the accessibility of the panel and its affordability. This idea was drawn for me and presented in Figure 20. The lack of forethought of context and the assumption that a solution will fit all buildings suggests lack of care for aesthetics and implies that the *domestic box* was an underdeveloped design proposal.

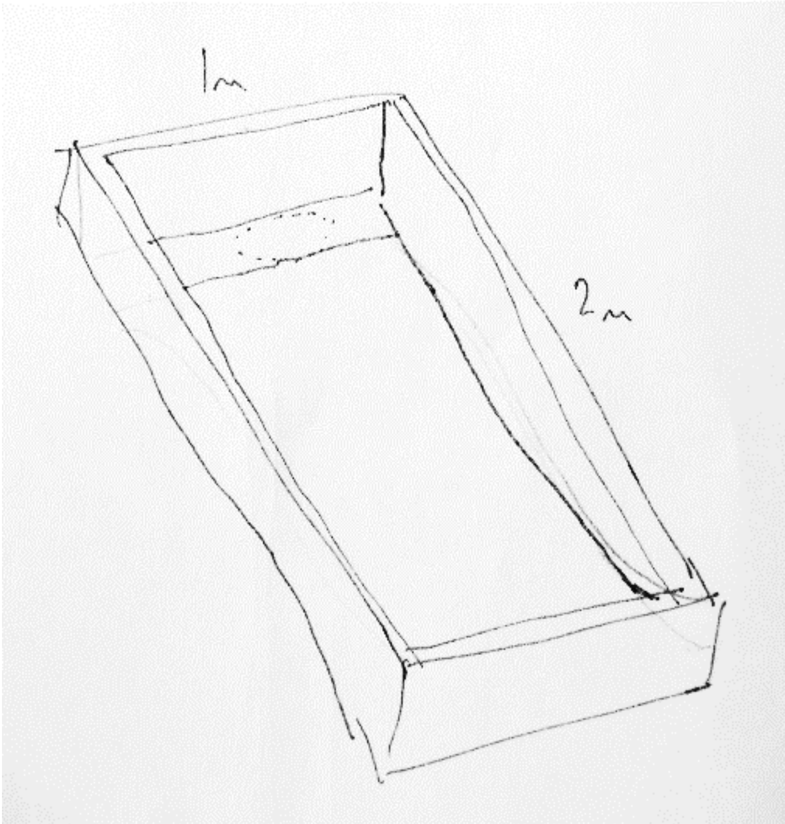

Figure 20: A hand-drawn conceptual axonometric for the domestic TSC. Hand- drawin by one of the Tata steel designers

6 Public Perception

The images which respondents of the study were presented with were an adaptation of the architectural detailing that was at the disposition and in the toolset of the Tata Steel team. One of the features of the TSC that was exemplified in this study was its capacity of the device to generate sustained stream of energy without draining the earth's resources. A paper, written by Rebecca Ford, Kathryn Williams, Ian Bishop and Eric Smith in 2014 suggests that the meaning of an architectural intervention might lead to a change in judgement and influence its aesthetic perception. The case in our investigation might be seen as similar. The expressed perception of the TSC was negative but was in most cases followed up by comments praising the initiative for its capacity to reduce carbon emission. A preliminary online questionnaire suggests that there is an overwhelming support for solar devices capable of generating sustainable sources of energy amongst the respondents.

A vast majority of the respondents suggest that modern buildings might be more in-tune with the aesthetic of the presented TSC's, in particular factories and shopping centres were suggested as buildings that would be best for the retrofit. People were more open to presenting their dissatisfaction with the aesthetics of the device in cased of domestic TSC's. Their interviewees were negative but almost immediately differed from negativity to reinforcing our expectation of their positive attitude towards renewables. They kept hinting that: '[They] would like to install something that was sustainable but not as obtrusive or obvious.' and 'the devices help[s] make the environment more liveable and friendly […] aesthetics [is] not my personal concern here.'

One of the respondents commented:

> They're ugly but if they save the world [and therefore] we'll have them. Solar panels are ugly, wind turbines are ugly, what we have to remember is that sustainable devices are unattractive but power stations are as well. We just need to accept that energy is not pretty.

One of the features of the TSC's that was identified immediately was the *common-sensical* approach of the Tata steel's designers which was commented on as: '[the discussed TSC] looks like a shed' and '[the discussed TSC] looks cheap.'; '[the discussed TSC looks] quite commercial.'

The questionnaire's findings identifying the inappropriateness of the retrofit on a historic structure also came across strongly in the interviews as a number of the respondents kept referring to the age of the host building. One of the respondents said:

> ' [The aesthetics of the device] would depend on the way they are fitted and on what type of property/if it was in a city where everyone has one it would be ok. [I d]on't want it to stand out. It's ok on modern buildings but not old.'

A notable comment that was presented was that: '… [TSC's] can be designed as a feature of a building which camouflages with the form.' This statement reinforces the general ethos of the responses that were gathered. It suggests that, in spite of the negative impression of their aesthetics the TSC's as well as other renewables are welcome in Wales.

7 Conclusions

The review of the available literature which touched on the aesthetic presence of renewables suggests that the perceived appearance is dependent on the level of appropriate integration of the installation.

This inspired the methodology and informed the way we gathered information on the public perception as well as the approach that was taken whilst interrogating the design process of the Tata Steel design team.

Tata Steel's designers' approach appears to be aimed at achieving a standardised approach that seemed to have placed larger industries at its core. The approach of the Tata Steel's team was presented as *common-sensical* and appears to be a reasonable response to the geographical and economic context. This approach has the potential to develop the economic position of the TSC in the region but is strengthening the preconception of the inappropriate aesthetic of the device in a domestic environment. It could be argued that this approach is developing a phenomenon similar to the NIMBY effect.

The approach that Tata Steel's designers seems to have adopted was safe and oriented around the difficulty of introducing the device into an emerging economy. Their approach was to minimise the risk, cost and time taken for designing a TSC by standardising the elements of the retrofit. It could be understood that this take was to satisfy the demand for renewables (in this case TSC's) for larger corporations. The sequence of the approach to each building typology also follows the premise of prioritising larger corporations. It is reasonable to assume that those were expected to generate demand and a steady revenue stream in Tata Steel's investment in developing the skillset amongst its designers. B&Q has a growing demand for renewables that might pay off in years of cooperation with Tata Steel. This approach might lead to new jobs and the development of a skillset in the region that might develop the economy of the convergence areas and establish a place within it for renewables. In the context of the time (during the economic crisis started in 2006) and place (economically less developed area), that the SBED project was run, this approach might have been a good solution.

This prioritisation of larger economic bodies can be seen in the care for the detailing (which almost did not change across the typologies of buildings) as well as the timing of the choice

of buildings. The drawback of this approach is the lack of differentiation of the presented TSC's concerning the architectural detailing techniques that were to integrate the device with the host building fabric on a domestic scale. The public perception survey studied the reactions of the public to the architectural detailing that Tata Steel were using. This study suggests that in spite of the fact that people are positive towards the notion of renewables they are not supportive of the design approach presented by the TSC's. It might be argued that the lack of bespoke qualities in the presented TSC's (through the lack of available detailing types) was responsible for this negative reaction. Following Probst (2007) the lack of bespoke solutions in domestic cases disallowed the TSC to integrate into the architectural fabric in a convincing way and was rejected by the community. It might be said that in this case, the mind-set of the people exposed to the TSC in its current form was rightfully recognised as 'industrial' and 'cheap' as opposed to integrated with the architectural fabric. Much like suggested by Roecker et al (2007) the strategy of architectural detailing lead to eventual rejection of the device from the market or at least its (domestic-scale) sector. The problem with TSC's is that unlike power-plants their operation needs to be localised otherwise the efficiency of the device decreases.

Looking at the matter under a different light, from the perspective of Jan Zoellner, Petra Schweizer-Ries and Christin Wemheuer (2008a) it might be said that the lack of integration of the TSC was an attempt to exemplify the presence of the device. By its explicit aesthetics it might be said that it will eventually inspire sustainable lifestyles in the nearby area. Unfortunately, given the lack of immediate associations with renewables that the TSC lacks this scenario is possible but highly unlikely.

The NIMBY effect relies on a preconception of architectural languages and affiliation with the character of the traditional designed form in the area. A retrofit that is not in-keeping with the same ethos or following the geometry of the already existing architectural fabric is seen as an afterthought or an unsightly intruder. Tata steel seems to have presented an approach that follows the NIMBY effect by targeting non-residential and out of sight locations for the TCS instead of challenging it by creating a bespoke an attractive retrofit.

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ZEMCH NETWORK

A MINIMUM VIABLE PRODUCT DESIGN OF VOLUMETRIC BUILDING MODULES

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Abstract: *This paper explores the adaptation of an IBM approach to product development emphasising user experience and critical requirements. The potential of this approach to be applied to offsite building manufacture is identified. Minimum Viable Product (MVP) has helped IBM validate key hypothesis about a product, thus increasing its probability of success, before completing its development. This paper attempts to answer the question of whether an MVP of manufactured building unit can aid cost awareness at early design phase of building and also facilitate a mass customisation. Since about 80% of a building's cost is determined in the concept design phase and the front-end design of manufactured buildings is seemingly unaware of costs, time and processes associated with the methods, this can cause unnecessary cost increases. The investigation involves the design of a parametrically constrained building system of an MVP of space requirement to program. The Victorian apartment design standards, logistic constraints, and user customisation to room sizes are considered to define spatial limitations in the case study. The effectiveness of the system is examined through a case study analysis to identify the possibility for variation of volumetric unit in an apartment building scenario. It is expected to develop a new understanding of modular building constraints at early design stage yet still allow for a mass customized outcome without the expense of variation through lack of front end knowledge of the manufactured system. It is also expected to produce a better understanding of base building costs and time associated with a mass customisable manufactured building system, suggesting possible cost data inputs to the system. It is anticipated that an MVP approach to early building design can help determine design and cost viability of building projects to stakeholders in the early design phase.*

Keywords: *Mass Customisation, Housing, Minimum Viable Product, Prefabrication, Building Manufacture Costs.*

1 Introduction

Eighty percent of a building's cost is determined in the first 20 percent of the design phase (Anderson 2004). Considering the impact of early design decisions on the cost of a building, it is necessary to consider methods and approaches to making accurate understanding of cost and user experience at schematic design phase of a building. We investigated critical requirements and user experience at the schematic design phase of a modular building design process, to find out if these aspects can be improved, and made clearer.

IBM uses a Minimum Viable Product (MVP) approach to test key hypothesis of a new product, enabling it to determine the product's success with minimum investment. The approach is to produce the bare minimum required in order to see if something will work. Often this is applied to application software (or) app development, where the investment is large, and the future return on investment sometimes uncertain. By implementing an MVP approach, developers are able to determine the viability of a product before investing valuable resources in detailed programming or design.

The question in this paper is "Can this idea of a minimum viable product be adapted to offsite construction?" in a conventional construction sense, probably not due to current processes of designing and constructing buildings. However offsite construction, where modular and prefabricated techniques are used, might provide opportunity, and this is discussed throughout this paper. Bertelsen (2005) argues that a building could be considered as a product, allowing for better manufacturing techniques and methods to be applied. When considering volumetric modular forms of construction, there are parameters evident and required that do not appear in conventional construction. These parameters if known and defined at an early point in the design process, could contribute to a successful MVP approach before excessive time is spent in developing a design or documenting the construction drawings. At an early stage, it could be possible to incorporate cost data, manufacturing information, as well as input from structural engineers, HVAC, building services engineers, energy modelling data, and other consultant information that could help aid the development of a product and reduce the unexpected risk. Alam (2015) argues that there is benefit to reducing waste in the processes of early design in order to create better outcomes.

Building information modelling (BIM) could also allow for this as a solution to early cost modelling. However, BIM objects can be complex, and do not always have enough flexibility to allow for mass customisations. The proposal in this investigation is to develop a parametrically constrained system for design for manufacture and assembly (DfMA) of modular building volumes that have enough cost data attached that they can be designed with freedom. It is envisaged that there could be other data associated with the BIM objects to allow for a known and flexible set of attributes associated within a manufacturing environment. Each attribute could then be defined as required, whether it be cost data, engineering input, energy data around building envelope, or systems and services data. For the purpose of this paper, we focus on cost and space.

IBM defines this approach to problem solving as the identification of a problem, writing and testing of a hypothesis for it, and then doing the minimum amount of work required to get it over the line for finance (IBM 2017). Translating this approach of MVP to construction, the question becomes; what is the least amount of work we have to do to determine the development potential of a site? In addition to this, it would be necessary to know what cost is associated with the proposal and what the proposal is. Often cost

models are taken from square meter rates and inaccurate in the early stages of design. Without specificity in the process, little can be done to predict the cost of materials and trades that have not been defined. This is amplified when considering traditional construction methods, and the variable costing that goes with it depending on method, contractor, site, or stage of economic cycle. User experience at the beginning of projects is often lacking in the same specificity of spatial outcome, sizes, or costs as design processes are not often integrated with information from other consultants. Ripperda and Krause (2017) argued that modularisation is isolated to geometric break up, and unaware of other factors such as time and cost.

Building cost data is not well understood at the beginning of a project as is customisation in a modular building environment. Often customisation is seen and experienced as a hindrance to a manufacturing system, where changes increase cost and time in a project. With advances in technology over the past century however, it does not have to be this way. An MVP of building unit could have the capacity to provide a costed structural unit where size can be client determined, and combined. In addition there is potential flexibility in the cladding system of how it looks, generating a mass customised outcome in production.

This paper also seeks to open for discussion the issues around customisation in a modular method of building assembly by breaking it down to a minimum viable product, specific to what is required spatially at early building design stage of a modular building project. It delivers an understanding of customisation within volumetric building elements and how early user input into the decisions on space might customise this, and how a unit might be arranged. This does not suit every type of building. The idea of mass customisation sits within a building that provides a framework and flexibility for plug in modules that identify things like flexible electrical, mechanical and hydraulic services in a building, and how these might adapt to a change in use or more importantly position within the building.

2 Methods

The research is based on literature review, site visits of 13 factories through Australia, Sweden and Japan, and a case study of MVP applied to early design of a modular building. Site visits to factories identify those that produce volumetric units and panelised systems. In addition, it was identified how they translate design to manufacture, and further to that how they translate customisation through this process to their customers.

A case study is undertaken to determine the potential of customisation in an offsite environment, and where this could occur in the process. It is based on the Victorian apartment design standards, and on transport logistic and manufacturing constraints. The division of space can lead to ultimate customisation of spatial outcome through the insertion of temporary supports in construction, so once joined, larger spaces both horizontally and vertically can be achieved. The method for understanding the potential of MVP in construction also refers to the available literature on and around the topic for input.

The literature review is intended to uncover what is known about a minimum viable product of building module and whether it is understood as a way of facilitating mass customisation. The literature review plan and the search for terms comes from a review and examination of various scholarly articles including journals, theses, books, conference proceedings and reports. The following electronic databases have been searched: Scopus, Emerald Insight, Ethos, OATD, ProQuest, DART, and Google

Scholar. In the absence of any particular literature on "Minimum Viable Product for buildings", several search terms have been used to find literature close to the topic. The following search keywords have been used: Minimum Viable Product, Minimum Viable Product construction, MVP, MVP Cost modelling, Early cost modelling in construction, schematic cost, BIM cost data, BIM cost, Parametric cost data, Architecture as Product.

3 Literature Review

The purpose of the literature review is to identify any literature on a Minimum Viable Product for construction. In addition, it seeks to define any literature on the early cost modelling of modular construction and potential benefits of it when considering project viability. For clarity, it has been broken in to thematic sections.

3.1 Minimum Viable Product

In their paper title MVP Explained: A Systematic Mapping Study on the Definitions of Minimum Viable Product, Lenarduzzi and Taibi (2016) reviewed the definitions of MVP throughout the literature, and in the grey literature as well. Through a methodical process, they derived that 22 articles stood out as having definition, and further to that, they examined how this has changed over time. The results they uncovered were then divided in to sections describing intent, and then effect of the various definitions. Their conclusions were that by definition, MVP had 'minimum features' as the most recurring term associated in current literature, but this did not exclude other definitions of it as being valid.

They confirm the first definition of MVP by Frank Robinson in 2001, and then a redefinition of it in 2009 by Eric Ries by interview firstly and followed up in a book by him in 2011 titled "The Lean Start-up" (Lenarduzzi & Taibi 2016). In his book, Ries (2011) refers to the MVP as a feedback loop of "Build-Measure-Learn" and for this process to happen in the shortest amount of time. Interestingly, Ries (2011) emphasised how the MVP approach is about learning as fast as possible.

Pease (2015) also argued in his thesis that the MVP is defined by the minimum features required to understand and test a product. There is a common definition amongst the small amount of literature available that the MVP is the shortest path in determining the success of a product. It seems that within the literature there is no application yet of MVP directly to construction, or building projects. Within the searches, MVP is common in computing and software development, but there is a small amount of literature pointing of MVP to physical product design.

3.2 MVP in Construction

One paper stands out in MVP that has some relationship with construction and that is by Echeveste and Mossé (2017) who set about using MVP to determine what a target market is willing to pay for an innovative smart home system. They combined the use of MVP with choice based conjoint analysis of customer surveys. In their research, they interviewed industry professionals such as architects and engineers in an attempt to get to a market that understood the cost benefit of energy saving solutions in building design and innovation. Whilst no other literature is currently available on the use of MVP in construction, we might draw links later on the building as a product, and then explore how the application of MVP might occur.

3.3 BIM in Construction

When considering volumetric building units, Wikberg, Olofsson and Ekholm (2014) discussed the use of architectural objects in a BIM environment. Objects are predefined

but have some flexibility to change or adapt to a client's, or designers requirements. There are arguments for and against the use of BIM objects and the main arguments against are due to the redundancy in the object as the technology or the product develops. It seems that there is no automatic method of updating BIM model objects to keep up with development of a product. If we take a step back an MVP approach however, this becomes less necessary, and has the potential to facilitate a mass customised outcome.

An MVP approach to construction is a simulation of what could be built, without fully building it. In construction, and architecture/design, this occurs in practice, however at the moment it takes a long time, as the simulation is based on drawings, and sketching, which lacks in information around cost, manufacturing, and time. Jeong, Hastak & Syal (2006) identified in their research that in a factory setting there are a multitude of processes that contribute to a single order, and that this adds significant complexity to the supply chain as a result.

3.4 Mass Customisation in Modular Buildings

Mostafa, Chileshe and Zuo (2014) described offsite building manufacture as a method, which can increase quality, whilst decreasing price of the end build. Their research however suggests that a mass customized outcome is sometimes reduced by manufacturing processes, and that the user engagement and choice available are limited. Globally, the offsite concept has been operating in the house building sector of many countries, such as Australia, China, the UK, Germany, Sweden, The Netherlands, Japan, and the USA (Mostafa et al. 2016). There is a large number of literatures in offsite construction alone, and the body of information of lean in offsite construction is also growing, but one of the early gaps seems to be a lack of research into mass customisation and offsite principles. The major benefit to offsite manufacture (OSM) is that it provides a controlled manufacturing environment to produce the house components and modules (Mostafa et al. 2014). However, the refinement of processes, and standardisation of offsite building techniques becomes a simplification of what is being produced, moving directly away from a customised outcome. Heravi & Firoozi (2016) argue that there are significant differences between construction and manufacturing, mainly around onsite and offsite parameters, and how this affects every process that takes place during construction.

In their paper on simulation in manufacturing, Mahayuddin & Tjahjono (2011) put forward the idea that as manufacturing systems evolve, so do the problems that go with them. If this is the case then the design methods must evolve to overcome such scenarios and have the flexibility to allow for multiple solutions to a problem. In regards to building manufacturing processes, Kanaganayagam Muthuswamy & Damodaran (2015) investigated a direct lean methodology to improve assembly line processes. Though this investigation their research investigated techniques for reducing the cycle time of tasks on assembly lines and motion studies of factory processes. The suggestion coming out of both papers is that manufacturing processes for buildings require flexibility and speed in order to be successfully applied to buildings.

3.5 DfMA in Construction

In their paper on DfMA and its application to building, Fox et al. (2001) argued in traditional architectural processes there is a lack of technical knowledge about DfMA methods for modular construction, and as a result, problems occur in the manufacturing process. They argued that the front end of design is ill equipped to handle complex manufacturing techniques in the production of offsite housing.

Sims and Wan (2017) identified that there needed to be a focus on efficiency in a whole system, not just individual processes. The approach then becomes lean, and as a result more efficient. In relation to a building, understanding how to break a building down in to measurable and identifiable components for production and sub assembly is necessary. Fox et al. (2001) argue in their research into DfMA, that architects have never been able to benefit from production systems in the same way that design engineers working with production systems have been. In some ways, the customisation of buildings and their specificity to site limits how a building can be modularised when maximising site coverage and development potential. Their research however did not take into consideration a global context, particularly when we see DfMA of buildings occurring already with excellent efficiency in Japan. In Sweden, they break this problem by using large panelised systems where an eight-storey building can be erected in less than two weeks. Fit out occurs afterwards in this case, as they have a strong emphasis on building sealing, air tightness and generally a higher necessity for well insulated buildings. Fox et al. (2001) also suggested that there should be different processes for different actions in the development of a manufacturing process for buildings, arguing that they needed categories for "bespoke, hybrid, custom and standard." They suggested that the use of DFM in construction depends on the definition of these categories. In addition, they argue that whilst some components in a building can benefit from a DFM, others cannot.

3.6 Modular Buildings and Mass Customisation

When considering mass customisation in offsite construction, the paper Lean and Green Construction, Parrish (2012) asks whether modular forms of construction can offer any flexibility to potential clients. Through a case study analysis of a live project in Long Beach California, the research concluded that flexibility in modular homebuilding was achievable, and afforded increases in quality in other aspects of the build such as increased energy performance. Another particular study focuses on the study of the production system through the application of lean production principles, as an approach to enable mass customization (Nahmens 2007). In respect of the skills required by workers in offsite construction however, Arashpour et al. (2016) argue that having a multi skilled work force can allow for better responsiveness to problems which might arise.

Within the literature, there is a consensus that buildings created offsite are not customisable, and if they are then they defy the boundaries of a manufactured building. Stump and Badurdeen (2012) however recognised that it can happen, but they suggested that if manufacturing is to offer a mass customisation then the system needs to have enough flexibility in it to be successful. Without any literature on an MVP in relation to offsite construction, there is a need to determine and examine a case study into the potential effectiveness of such a system on mass customisation at early design phase. This has to relate to spatial outcomes first. From there, further consideration is given to how cost and manufacturing data is combined to such a system of constraints is found through location based and proprietary cost data dynamically linked to the type and method of building manufacture of the project.

4 Case Study

An analysis of modular space breakdown has been considered. In this case, we investigated timber framed building modules, and the same could be applied to steel framed or composite structures. The user experience here is defined by the ease at which the system can respond. It is noted that the user control over MVP does not

preclude the overall building from responding to all standards under Section 55 Requirements of the Victorian Planning Scheme.

4.1 Victorian Apartment Design Standards

The Victoria Planning Provisions state that "A single aspect habitable room should not exceed a room depth of 2.5 times the ceiling height." (DEWLP 2016); see Figure 1.

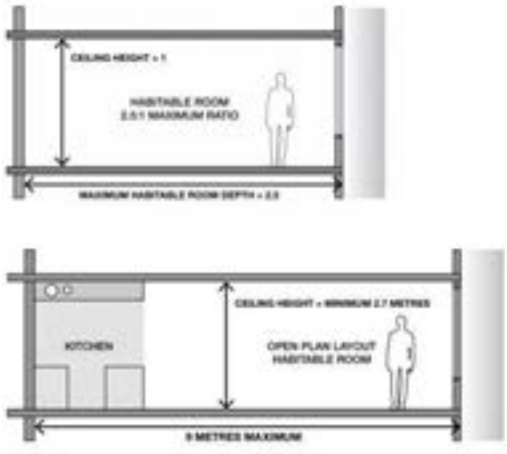

Figure 1. Room depth and ceiling height dimensions (Source: DELWP 2016, p.15)

Other dimensions articulated in the Apartment Design Standards are:
Bedroom Dimensions:
- Main bedroom 3 m x 3.4 m;
- All other bedrooms 3 m x 3 m.

Living Room dimensions:
- Studio and one bedroom dwelling 3.3 m, 10 m^2;
- Two or more bedroom dwelling 3.6 m, 12 m^2.

There are no minimum requirements for bathrooms so 4.5 m^2 is assumed as a minimum for the case study, based on a unit 1.2 m x 3.6m that can hold toilet, shower, and vanity unit.

4.2 Logistic Constraints

In Victoria, a load wider than 3.5 m requires a pilot vehicle (VicRoads 2017). Between 3.5 m and 4.5 m this pilot is lesser qualified and cheaper than that of a load between 4.5 m and 5.5 m wide. The length of a load not requiring a pilot is 26 m. Longer than that, the same levels of pilot vehicle apply. Since manufacturing volumetric building modules is unlikely to reach 26 m, we assume length is not an issue. Other states in Australia have slight variations on these constraints (VicRoads 2017). Some consideration has to be given to crane capacities and relate more to site specificity and weight as opposed to overall length. Height is constrained to a maximum of 4.6 m without escort.

From the information gathered for the constraints, the workable width for a modular house unit is between 3 m and 4.5 m. The workable length of the same unit is between 3 m for the smallest allowable bedroom, to 26 m for the easiest and cheaper transport allowable.

The model constraints are set with these parameters and the user experience guided within them. Based on the transport logistic constraints, and minimum design standard constraints, the definitions of minimum and maximum X, Y, and Z dimensions can be seen in Table 1.

Table 1 Minimum & maximum dimensions

Measure	Minimum (m)	Maximum (m)
X (internal)	3.0	4.5
Y (internal)	3.5	26.0
Z (external)	2.4	4.6

Note: Z depends on the structural requirements.

For example, an apartment might be then described dimensionally as follows:

$2(X = 3.1 \times Y = 4.6) + (X = 3.2 \times Y = 4.2) + (X = 3.8 + Y = 3.1)$ and $Z = 3.3$ all in m.

This equates to an apartment of an area of 53.75 m^2 as an example of the modules being assembled into a layout that could form a larger housing unit or apartment. If we consider 'C' as the cost input data then we attach this to the equation to achieve an equation that looks like this:

$$(2(X = 3.1 \times Y = 4.6) + (X = 3.2 \times Y = 4.2) + (X = 3.8 + Y = 3.1) \times Z) \times C$$

where C is a cost defined by minimum structural product and minimum building envelope relative to respective building code requirements. The user is able to understand the cost implication of a particular spatial outcome. Further development could occur around the equations associated with mass customisation of internal fixtures and fittings.

The effect of variation of user driven decisions is simulated and can be seen here through a series of floor plans (Figure 2). The user decisions are made within the limits of the X, Y and Z values defined in Table 1. Refined variations can be obtained through the overall floor plate of the building, providing the potential for a mass customisation in the floor plan of each level, and in the resultant building form.

4.3 User Defined Constraints

In addition to legal and logistics requirements, the MVP approach could address the customer desires upfront. The opportunity to enhance user experience in early design phase provides further opportunity for user identification and control of the space that they would like to inhabit. Using an MVP approach to building design could also have flow on effects to the sale of space, where if a person wants to pay more for extra space, they can, and likewise less. The choice around space allows the user some control in the overall experience of multiunit development. Typically, this does not happen in apartment buildings. We see a space divided in to cells and the cells divided further around daylighting opportunity and services locations. The user's customisation in design is lost where spatial limitations are set early by constraints and other priorities. By enabling users input in the early stages of design, allowing them to experience and influence design at an earlier stage within the necessary parameters, the users have opportunity for customisations in room size, quality, and price.

Spatial quality is not easily measured, as it is subjective, and this is why offering the individual customisation and flexibility could be beneficial to the overall opportunity in design. Several examples exist of such a system in the Open Building Concepts (Kendall & Teicher 2010; Schmidt et al 2010). Where a building is designed to be adaptable, that

it has an openness and flexibility designed into the overall volume, but where the user has control over how it is fitted out, or finished. One of the major benefits of this approach is that a family can build what they need when they can afford it. This means that a family could start with a one or two bedroom apartment and potentially expand it when they need it, and also when they can afford it. The potential prospect of financial benefits to the expandable housing is enormous, and when considered in the context of increasing building costs, it is highly relevant.

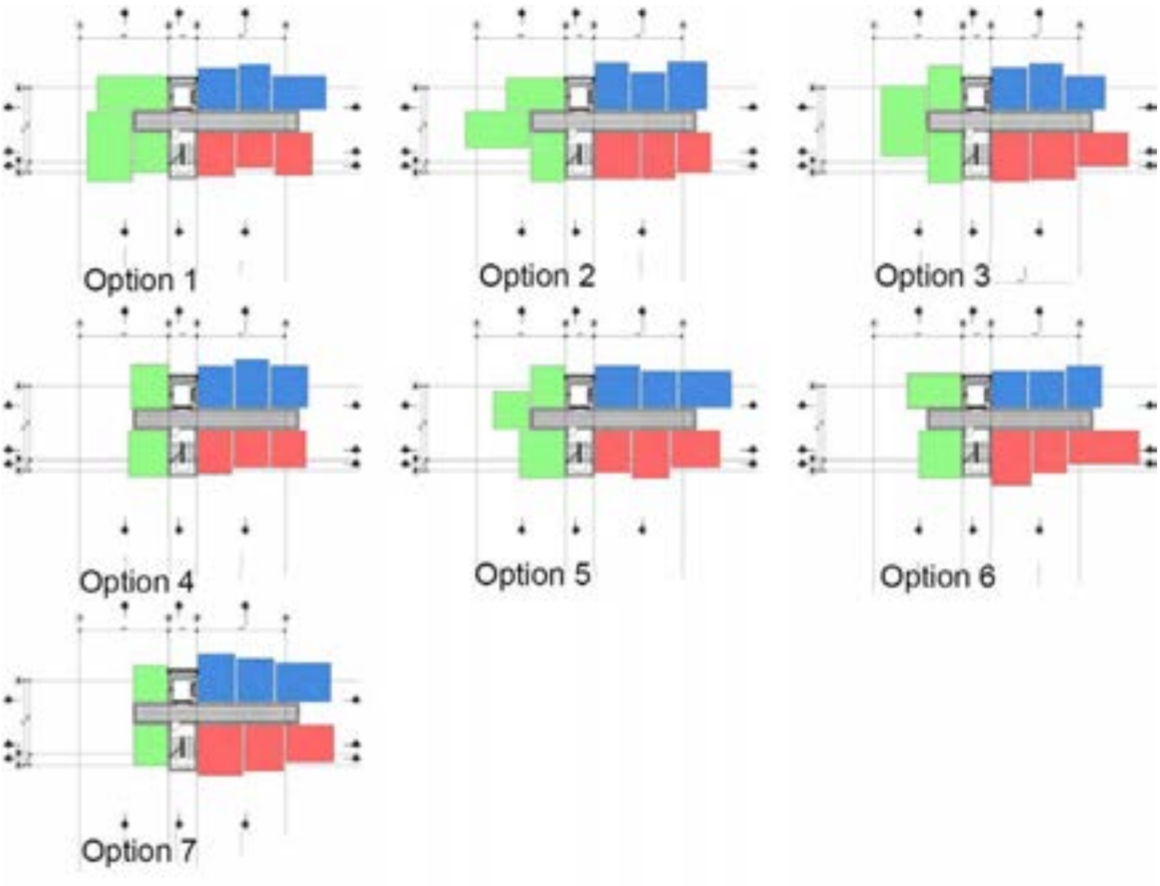

Figure 2 Example of user defined variation across a floor plate

Here, the MVP approach also extends further to subjective appreciation of space, or spatial quality, but also to spatial affordability, where the user has the opportunity to customise what they can afford now, with some potential to have space on reserve, for when they can afford it later.

5 Findings & Discussion

The MVP approach to design of volumetric building units logically aides a mass customized outcome by allowing the user to operate within a dimensional range set by the constraints as identified in Section 4. By allowing this, the user experience is tailored to the operator, and the outcome has the capacity to be varied through user influenced variations or selection of spatial determination. The MVP model also has capacity to connect to data sources that represent cost, and construction detailing in BIM and time associated with offsite manufacturing methods used to create the object. The knowledge of this at early design phase can aid a more accurate estimate of cost to client at early design phase and facilitate speed in procurement of building outcome as a result.

Interestingly though the Japanese factory offers a customised product, with known cost at the early stages of design through cost data being associated with an extensive BIM library. They have a modular system of design that within the design phase of production, the BIM model is used for design, and contains manufacturing and cost data, so once the design is complete, the cost is known and the manufacturing drawings already completed and ready for ordering and production. Considering this, the MVP model is arguably already in use, although not described as MVP. They have been doing this for a long time, and this appear in the literature as far back as 1996 when Gann (1996) studied the Japanese building manufacturing market and found them to be producing high quality, mass customised, and mass produced housing.

Further to basic customisation of spatial outcome, there is opportunity for customisation in the parts components that create a housing unit. These continue into joinery, paint colour, lighting, the position of fixtures and fittings and then the further question of how this is communicated to the assembly line. Often when considering assembly line processes, we contemplate how a process of producing an object is repetitious, where the design has been refined to create efficiency gain in manufacture that is unarguable and predetermined.

The position and determination of fixture and fittings does not generally happen until later in the process of design. However it is essential to give consideration to building services earlier, rather than later in the design of volumetric units. In regards to the processes available in an offsite construction environment Hermes (2015) recognised that there is work to be done in this area, as many of the services are manually handled with little to no automation. The process of identifying broader spatial outcome comes in earlier in the MVP method as a way of identifying what is possible and could aid in understanding the cost implication of such a process before a client sets down a road of indecision and lack of clarity. An additional benefit of an MVP approach to building module is that it effectively identifies a potential of cost data to parametrically relate to geometry in a way that furthers understanding of early cost implications of design decisions.

The focus has been on the client and early decisions. When considering this impact on the manufacturer, the most valuable aspect of an MVP building unit is the potential of manufacturing and cost data to be associated with a dynamic BIM model. BIM models typically have the capacity to allow such data to be shared through consultants. However, without the use of third party software that allows this, it is harder to implement effectively. By using an MVP approach, the building is broken into smaller components and becomes capable of holding such data. The capacity for this data to be then shared and manipulated by the various stakeholders that are involved such as engineers, energy consultants, building surveyors, mechanical and services consultants and fire engineers.

6 Conclusions

A minimum viable product approach to building can be useful for identifying cost associated with design decisions early in the process of procuring a building and providing better user experience. It can determine cost and design flexibility of building early in the process, which in turn can aid decision-making processes by the user of the system. It is anticipated that the user experience in this case has the potential to be better, and more transparent when designing with a known and well-defined framework that is suitable for modular mass customised construction. Additionally, some key user pain points can be addressed upfront through constraints setup in the MVP modelling.

The MVP approach also identifies the spatial composition of a building quickly, by designing with a kit of parts that has a set number or variations, and that provides ultimate flexibility in the configuration so as to arrive at a mass customised outcome. This approach is a subtle but necessary departure from the arrangement of predefined BIM objects into the shape of a building. The experience of this method leads to potential user control over the space required and desired, set within the systems parameters, but still with some flexibility to change within them. Because of this, flexible options for the end user are identified early in the process. A part of future work to follow this could be to explore how the MVP approach to building design relates to a minimum marketable product (MMP).

An MVP approach in the DfMA of housing would be highly appropriate for mass customised houses. The reason being that it reduces waste that could arise from overdesign at the initial stages. At schematic design stage, a more lean approach would be to only consider what is essentially necessary to meet the customer's needs.

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THE SECRET FORMULA DETERMINING AMBIENT TEMPERATURES OF TROPICAL PASSIVE BUILDINGS

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Abstract: *One of the five undebatable basic core elements of a Passive House in every climate is air tightness. It is not only a feature derived from passive design. By expelling the intruding outside air as an intervening parameter, such buildings respectively rooms pose an excellent testing ground and indicator to what extent "passive" insulation of a building against cold or hot outside air works. As a result, a "secret" regression formula can derive the required surface temperatures of all enclosures (wall, windows/ doors, roof/ceiling and floor) to "create" the necessary ambient temperature and humidity needed to jive with the occupants' thermal comfort banding. The experiments at the "triple green mock-up building park" showcase in a longitudinal study which surface temperatures are required to live up to the tropical maximum passive residential benchmark standard of 28.6 °C. If the radiant temperatures of single or all enclosures mentioned above still exceed the standards for a residential passive house with or without radiation, it is showcased how further heat insulation can help (passive cooling). If not sufficient, active cooling must come into the play.*

Keywords: *Insulation, Air Tightness, Green & Energy Efficient Building, Passivhaus, Carbon Footprint*

1 Introduction – the ”high 5” Contributors

The research in the art of greening a tropical building is to look at the ability of the material of 5 contributors (walls, windows, roofs / ceilings and floor) to reduce the overheating effect. The inner surface temperature of these five contributors can be measured with direct intermittence of the air in an airtight building with no moderating effect of the air conditioning or any other cooling system. In addition, what we will call the “secret formula” to determine the contribution of all building enclosures, is an indication whether passive design based airtightness is effective or not to defeat the typical overheating of tropical buildings. Hence, we will compare an airtight with an open-windows building in terms of overheating the 5 contributors during different days and weather conditions. It is firm to say that if the air is expelled as a heat contributor for the ambient temperature, then the heat intake would be up to our 5 contributors. Hence, our main hypothesis is that the overheating effect is slower in passive design, and faster in a conventional building. Furthermore, among the “high five” we can determine the critical contributors in specific situations that effect the ambient temperature to exceed the tropical upper space limit that is set to 28.6 °C in residential buildings.

2 Literature Review

How cold has a building envelope to be to create thermal comfort? How does it react in different weather conditions? Usually, residential rooms in tropical countries for those who do not run air conditions in part or all the time, are ***open air*** style at least for the living area. Especially during the daytime, it is encouraged by green certification tools to make use of natural ventilation with the windows open (Green Mark, 2015). However, warm air is drawn in which culminates in the fact that during sun-lit conditions the temperature of the intruding air is not 31-32 °C (which is a typical upper highest daytime shaded temperature in tropical countries like Singapore or Malaysia), but 55 °C. Not only the cooling load is tremendously higher, the building also needs to digest the influx of a temperature that is not issued by the metereological departments’ logs. The walls harvest and retain the heat during night, until the next daytime heat wave renews the effect of overheating.

Expelling the air as one component of a tropical passive house is also advantageous for the experimental design of our following experiment that removes the conductive impact of the outside air by insulation up to air tightness (IPHA, 2016).

The Operative Temperature in a room where the air in no longer an independent variable depends on the following factors WINDOWS,DOOR, ROOF @ CEILING and FLOOR.

The formula we devise here is based on a specific regression and factor analysis. In theory, the formula to calculate the operative Mean Radiant Temperature looks like the following measurement and analysis the surface temperature by the used building materials (Prado & Ferreira, 2004:298):

$$T_{mr} = T_1A_1 + T_2A_2 + \ldots + T_NA_N / (A_1 + A_2 + \ldots + A_N)$$

where,

T_{mr} = mean radiant temperature,

T_N = surface temperature of surface N, (calculated or measured)
A_N = area of surface

The mean radiant temperature depends on the individual contribution of all single parameters mentioned above (cf. Bretz, Akbari & Rosenfeld, 1998).

3 Methodology

3.1 The secret formula for Green & Energy Efficient Buildings (GEEB)

The secret formula is an indication whether airtightness is effective or not. Hence, we compared an airtight building (M3) with an open-windows building (M4) in terms of overheating during different days. It is firm to say, if the air is expelled as a heat contributor for the ambient temperature, then it would be up to the 5 "high five" parameters mentioned above to determine the ambient temperature:

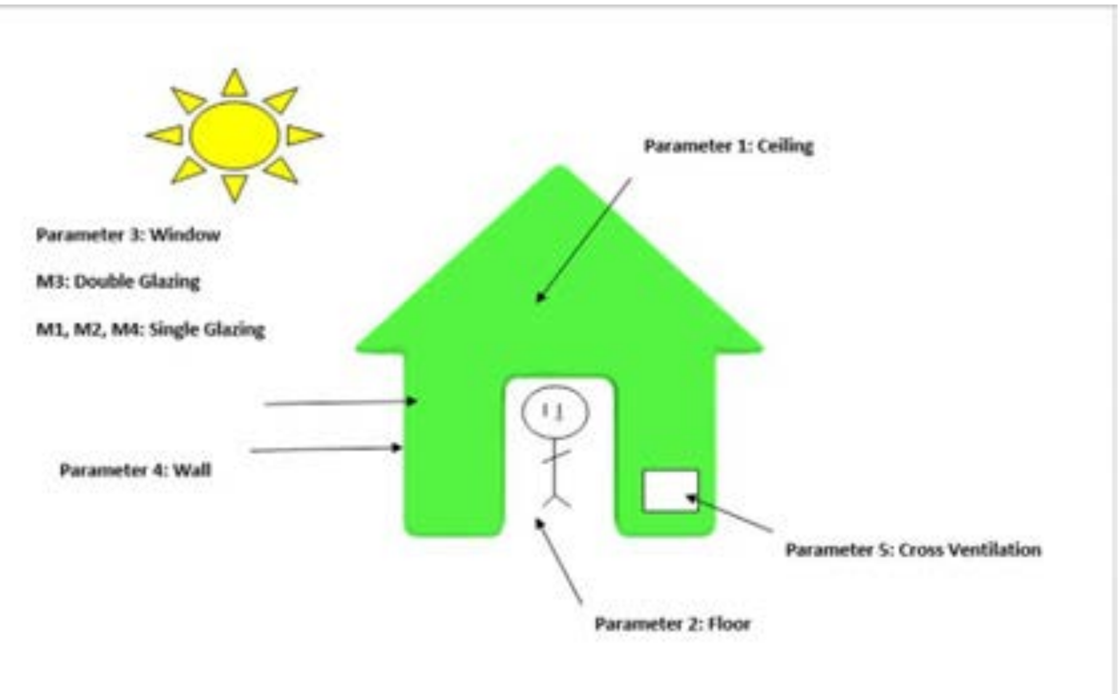

Figure 1: High five Independent variables to determine ambient heat generation in an airtight building

a) With open air (M4) b) without (M3)

In our experiments below, we want to showcase the real heat prevention features beyond the theoretical values above. The novelty is that under different weather conditions in a longitudinal

study we created a solidly growing database that later can be utilized for computer simulation to determine the effect of different material in terms of heat and also humidity prevention.

The research project from different schools at University of Kuala Lumpur (MICET, BMI, ICOLE, MFI and IPROM) had been initiated in 2012 and was called 'The Making of a Proto-Tropical Passive and Low-Energy Residential House'. It included the construction and experiment of 3 passive designed demo houses (MUB 1, MUB 2 and MUB 3) and one conventional control house (MUB 4). Positioning was identical and shading was almost equal, a few compromises in terms of the sun path had to be made due to space restrictions.

This is how the area looks like at this point in time, with the yellow-marked MUB5 building proposed with recycled LCD-screen material still to be constructed:

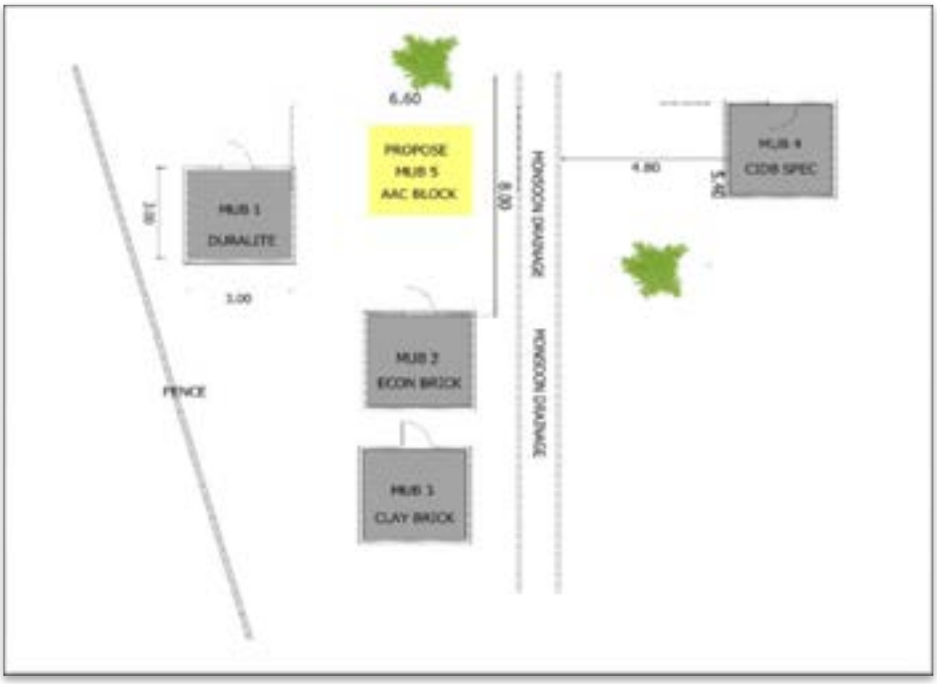

Figure 2: Layout Plan Triple Green Mock-Up Building Park Kuala Lumpur

3.2 The candidates for the secret formula testing

In the following, we will only focus on two buildings, M3 (the best insulated one) and the M4 (the worst insulated one):

3.2.1 M3 – cavity gap clay building

Clay as fully natural material has been used for walls in millions of low-cost houses not only around the tropical belt, At first sight, in Singapore and Malaysia this material seems to be restricted to quite high-priced clay tiles on the roof. But at a closer look, this is not at all true. As a second note, several producers can be found within an association in Selangor and Johor accompanied by quite professional information on their websites. Interestingly, beside normal applications, this material is marketed in the shape of double layers with air cavity gap.

However, as it has to go through the CO_2-triggering burning process, and unlike the natural abundant river clay material, it is uncertain if the environmental costs can still be considered green. In our experiment, we used clay bricks wall to prove that with a low U-value the building's interior will be quite cooler compared to the conventional material. For another experiment in the future, we would choose virgin material, or material with less carbon footprint with double layers, e.g. wood wool or fibre material with vapour barriers:

Figure 3: Virgin clay material and burnt clay brick stones

Among all other mock-ups, in its double layer feature, clay had the best heat prevention rate. If we consider the anyhow low costs of $ 0.06 in Perak/ Malaysia per piece and build a second layer, including plaster and the finishing, the U-value will be as low as 0.88. As its tradition has two layers and an air buffer, according to a Malaysian website the time lag is 7-8 hours before the heat wave from outside dissipates through the wall. That was verified in the following graph where it is visible that the time lag is heating up the clay walls on sunny cloudy days primarily during the hot afternoons.

Only a small proportion of heat striking a west-facing cavity brick wall passes. If the following depiction is correct, most of the heat is reflected and some is absorbed, allowing less than one percent (5-6 W/m2) to penetrate the wall at the time of sunrise. This can be compared to the massive 120W/m2 measured to enter through a shaded north-facing window.

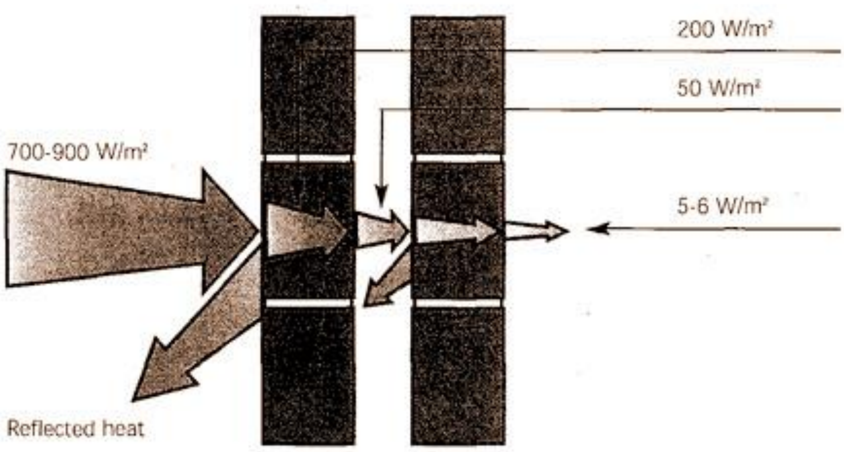

Figure 4: Less than one Percent of Heat penetrates a west-facing Clay Cavity Brick Wall

That might the case when the sun arrives. The longer the heat outside persists to gain access into the building, the more questionable is this protection. And if the days are hot during a period of days, If clay has to compete as a single layer against its potential green competitors, its heat reduction rate is only slightly better (U-value of 5.6 compared to 8 of the conventional bricks which would hardly use the cavity brick principle as the tradition for clay-bricks probably as strategy for their market entry or survival).

3.2.2 M4 – Conventional Building

The common, typical control unit for the wall experiments is the Standard Low-Cost House"MUB4 / M4". It uses basically sand cemented bricks or concrete. Ferrolite uses iron inside as a derivation of concrete applications. With high heat transmission rates and no insulation, this kind of building has both a tremendous heat intake and long daily heat retention cycles to digest. Putting one's fingertips onto the wall might cause a deceiving cool perception as the building envelope does not feel extraordinarily warm like e.g. the extremely hot awnings or the windows. Measuring their temperature log, along with the floor slab, will unveil this as a fallacy: The temperature is constantly and consistently increasing to 30-32°C during the daytime of a typical sunny-cloudy day. The walls store the heat and typically remain slightly below the same level during night until a new heat wave hits again during the next morning. Literally speaking, the wall cannot unload the heat intake it had harvested the day before.

Figure 5: Mock-Up Building in British Malaysian Institute

3.3 Calculation of the Secret Formula

These are the necessary steps to calculate the secret formula:

Step 1: After tabling out the 5 main parameters contribution to heat intake, the m² will be calculated and their proportion will be expressed in %.

In our mock-up buildings, the calculation appears like in the following table:

Table 1: TOTAL MATERIAL= % OF PARAMETER X TEMPERATURE

Number Parameter	Parameter	m²	%
1.	Wall		
1a)	Wall North	: 6.69m²	12.5%
1b)	Wall East	: 7.1568m²	14.3%
1c)	Wall West	: 7.1568m²	14.3%
1d)	Wall South	: 7.089m²	12.5%
2.	Ceiling	: 9.0m	17.9%
3.	Floor	: 9 .0m²	17.9%
4a)	Window .West	1.2432m²	2.4%
4b)	Window East/	: 1.2432m²	2.4%
4c)	Window South	: 1.2492m²	2.4%
4d)	Cross Vent Area Fan	: 0.9.m	1.8%
5.	Door		3.3%
	TOTAL	51.6m²	100%

Step 2: Calculation of Contribution of every parameter by temperatures

This step is a simple calculation of the "contributor value" which multiplies the percentage and the temperature with every 30 minutes reading (exemplified only in the yellow cell 14.3% * 29.3 °C = 4.10):

Table 2: Example for the Calculation of the Contributor Value (M3 Wall East)

Time of measured temperature	M3 Wall East % of Building Envelope	Temperature of the Enclosure, (here M3 Wall East)	Contributor Value
7.30 am	14.3%	29.3	4.10
8.00 am	14.3%	29.4	
8.30 am	14.3%	27.9	

Step 3: Calculation of all temperatures of the enclosures on average at each measuring point

Calculation like presented in table 2 for all parameters according to table 1

/ number of parameters

= GRAND TOTAL ("**PREDICTED AMBIENT TEMPERATURE"**)

Minus REAL ambient indoor temperature

= differential

=> cooling demand can be calculated and measures planned to passively cool the building further

3.4 Chosen Reference Days

Prior to our research, we classified the following generic types of days:

Table 3: Weather Conditions factored into the Secret Formula Research

Type of Day	Description
A	Sunny - Cloudy
B	Cloudy – Sunny (overcast)
C	Mostly Cloudy
D	Haze
+	Rain (differentiated in Little Rain, Heavy Rain, Flash Flood, Thunderstorm, isolated Thunderstorm)

The weather conditions A and B are the most common ones in tropical countries, with mere sunny days only appearing 10 times a year. Hence, the **selection of days o**ut of our data base in 2017, are more stable A or B-days without the **interference** of heavy rain. However, at this point in time we were not able to yield any *sequence* of 3 or more non-rainy days as this year the intermonsoon season was untypically rainy.

Table 4 : 5 References Days Comparison (I) Determination of Secret Formula within the Green Building (M3)

Dates	Type of Day
March 12th 2017	A
March 15th 2017	A
April 3rd 2017	A
April 12th 2017	BA
April 19th 2017	BA

In a second comparison, we chose another reference day

Table 5: Reference Day Comparison (II) Green and Red Building

Date	Type of Day
October 31st 2016	AB

4. Findings

4.1. 5 days (Time Series Plot)

We measured the average temperature of all independent variables (inner surface temperatures of all 5 enclosures as demonstrated in methodology) and then compared it with the dependent variable (indoor temperature).

Figure 6 shows that both buildings' inside temperatures (n=124) are significantly lower than the independent variables' temperatures (26.47 °C , S= 3.61 compared to 31.89 °C, S= 2.58)

However, the following time series plot shows that the difference between all the parameters of the green building is more than double as high as the red building's difference.

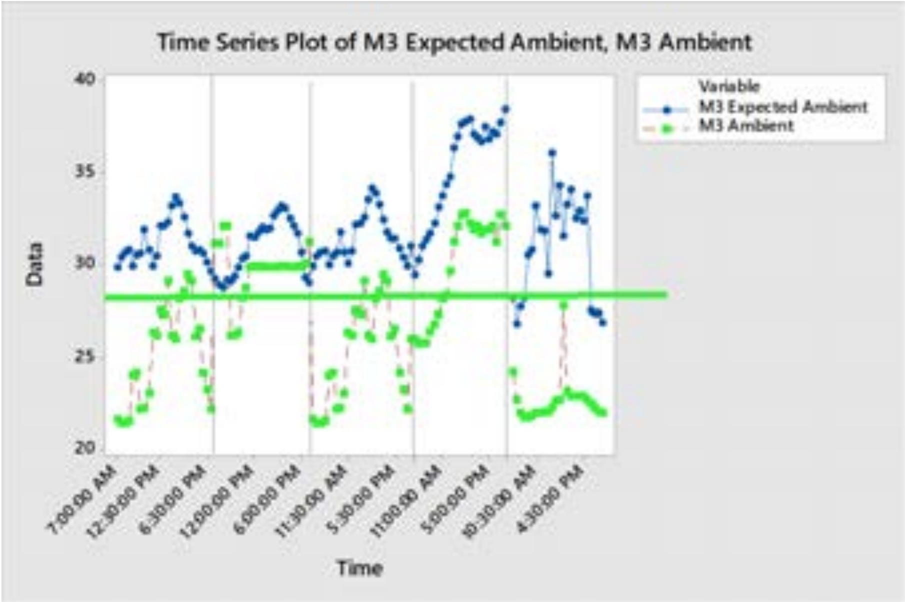

Figure 6: 4 days comparison Secret Formula for the "passive" insulated green building (M3) in March-April 2017

In the pilot run above, the correlation is IKMAL 1. It can be shown that if the ambient temperature is below the USL of 28.6 °C, nothing has to be looked into. In all cases of exceeding, the "should be" maximum temperature of the enclosures needs to be calculated. For example, day 2 it is firm to say that if the maximum temperature is not 33, but 31, the ambient temperature still wold be below 28.6 °C. Even clearer on day 4 it becomes evident that a decreasing surface temperature from 37 to 33 would be hypothesised to be sufficient to pull the ambient temperature below the USL. On the last day, astonishingly, the likewise high surface temperature index does NOT lead the ambient temperature to surpass the thermal comfort zone.

***4.2. 1 Day Comparison** (31st October 2016)*

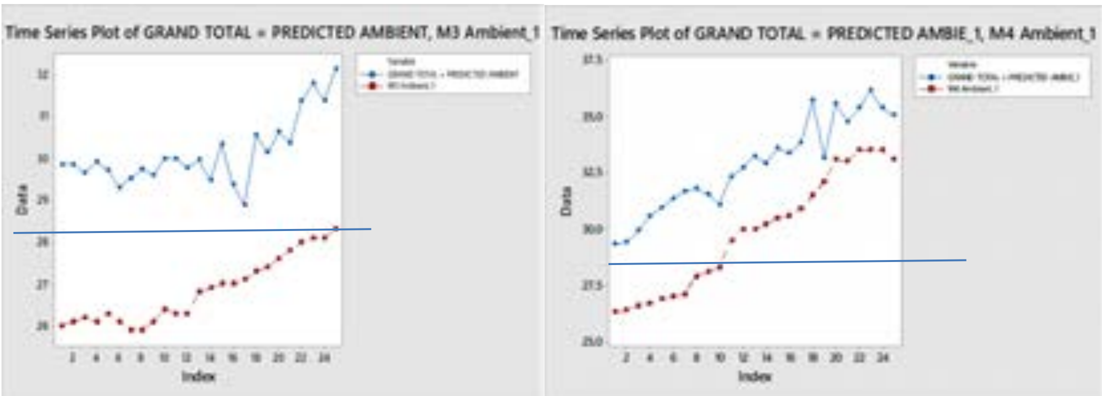

Figure 7: Averaged a) "passive" insulated Green (M3) and b) the uninsulated Red(M4) Building

The graphic a) shows that in case of the M3 building at a maximum temperature of 28.6 °C, the average score of all the 5 contributors for the expected ambient can be 2-10 °C higher. It means the air stays much cooler than the reading of the five parameters. In case of the “red” open building the differential is about 1-3 °C only.

As a consequence to improve passive design, we can determine what parameter needs to be improved, in case it exceeds from the necessary benchmark. Green means that the parameter itself has a temperature which is low enough to fall below the Upper Space Limit (USL) of 28.6 °C. Yellow would mean it is between 28.6 and 30 °C, and the meaning of Red is that it would be above 30 °C. In the tabled example below, along a scale of the rainbow colours, in July 2015 according to the secret formula calculation the roof (orange colour) and the window were still highly critical (red colour). 9 months later, during thermal improvements of the materials we applied, the ceiling remained orange. By shading and setting up a different kind of glazing we succeeded to turn the window from red into orange.

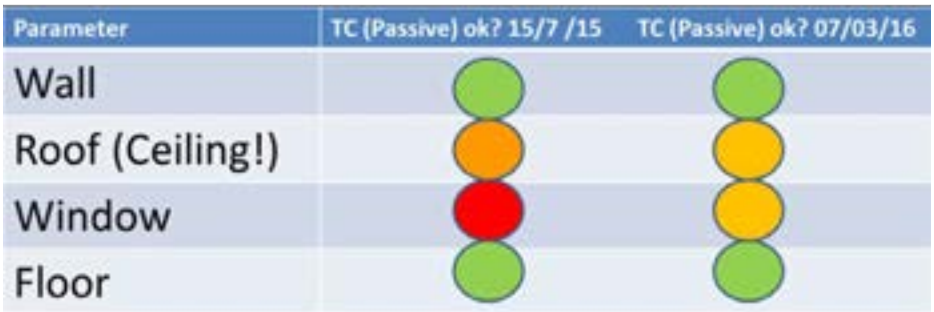

Figure 8: Single Assessment of the enclosing Parameters

5. Conclusion and Recommendation

The (not longer secret) formula is helpful to gain an understanding of how cool the parameters of a green airtight building need to be in order to keep the intruding heat to a non-disturbing level to achieve passive cooling, or at least reduce the cooling load tremendously

Other projects to confirm the experiments for different kinds of buildings could be conducted, following this SOP:

Step 0: Describe parameters (WALL, WINDOWS/DOORS, ROOF or CEILING, FLOOR)

Step 1: Describe and Apply formula (%)

Step 2: Decide on DoE Application (day/night, number of occupants, temperature set point)

Step 3 Devise the model based on a whole year (2017..) -> Calculation of cooling load

Step 4: Along the traffic light colours, define the critical parameters above the upper allowable temperature & determine costs of retrofitting

Step 5: Steps of Improvement from RED to ORANGE to GREEN

Step 6: Define rest of active cooling load and devise a respective smart system

Hence, if the secret formula becomes less secret, but more a common standard to define and redefine green buildings by a specific energy audit rating, it is suggested that it can even become part of the certification standards. The first steps to do so have not yet been specified as the formula is still under probation. A model for "insulation" as one of the four factors of the tropically adopted Energy Performance Certificate (TEPC) can easily be devised (Wagner, 2014ff.). However, with a temperature of above 26.5 °C the higher humidity in tropical buildings might decrease the thermal comfort and dehumidification might be deemed necessary. Whether this can be achieved conservatively by desiccant technology (e.g. Silicate), is still subject to ongoing research at institutions like the University of Kuala Lumpur and the National University of Singapore.

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AFFORDABLE WASTE MANAGEMENT SOLUTIONS FOR COMMUNITY HOUSING

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Abstract: *Urban housing has developed rapidly in most cities in India. In most places, the growth has also been unplanned. Both high and low rise developments have posed many challenges to creation of sustainable built environments. Towns and cities in Assam suffer from the same challenges: high consumption patterns; open dumping of waste; unregulated disposal; pollution. There are several issues which need to be addressed to achieve sustainability. One of the key issues is solid waste management [SWM] in these urban developments. Designing an effective waste management system integrated into the construction of new developments could offer a sustainable environment for these new communities. The essential elements for an effective SWM system for urban developments in India are simplicity, affordability and sustainability. An in situ semi-mechanised SWM system was designed for a new development in the city of Guwahati, in Assam, India. The pilot scale model was a community led initiative incorporating components of segregation, processing and composting of waste. The design was based on the philosophy of a zero waste society based on energy and revenue generating principles. Design and development of the SWM model also considered the reuse of construction materials from locally generated construction waste. The model demonstrates the reduction of emissions compared to traditional systems and low carbon consumption due to its affordable and integrated design. The design could offer sustainable SWM solutions to new constructions and can be replicated as well as adapted to different situations or cities.*

Keywords: *Sustainability, Zero Waste, Affordability*

1 Introduction

In today’s industrialized world the production of different products in order to satisfy consumer’s changing lifestyle has increased to a great extent in the last few decades. Industries are using complex and composite materials for manufacturing of products which are disposable in nature. People have now formed the habit of using these products in the day to day life and are getting inclined more towards packaged food, packaging of products for ease in transportation etc. The rise in people’s living standards especially in the developing countries has compounded the problem of solid waste generation (Song et. al, 2015).

There has been a parallel increase in the amount of waste generated and has become one of the top priorities to deal with for sustainability all over the world. The authorities are also under high pressure to manage the waste sustainably (Shekdar, 2009; Cheng & Hu, 2010). The total waste generated is estimated to be around 1.3 billion tons per year which is expected to increase to 2.2 billion tons per year by 2025. The land available for dumping of waste is decreasing day by day and it is high time to think of some alternate solution to the problem of waste management.

Countries like America, United Kingdom, and Australia are trying hard and implementing different technologies to solve the problem of waste management. Also, in India different techniques have been adopted in different parts of the country but the problem of solid waste management is still a challenging task for the authorities. People are in the habit of dumping waste on the roadside and are still practicing NIMBY (Not in my backyard) philosophy.

This paper discusses about one of the models developed for solid waste management which could be a feasible solution to tackle the problem. The major component in the model is a designed segregation bin used for waste collection from the individual households has been experimented. Integration of a waste management system in the housing with an approach towards zero waste management has been the guiding principle in this paper. Resource efficiency and circular economy are being prioritized for tackling the problem of global resource scarcity (Zaman 2014).

2 Literature review

The heterogeneity of the waste generated in households poses greater challenges to its further utilization as a raw material. Hence, fractionation of the waste is imperative before they can be subjected to any meaningful treatment process. Sorting or segregating the waste at source is one of the traditional fractionation methods and fundamental steps in an integrated waste management system. Data regarding the quality and quantity of waste generation and its fractions can be obtained from source segregation.

Bernstad (2014) made trials on household food waste separation behaviour and the importance of convenience in Sweden. Two trials were made with distribution of written information amongst households and installation of equipment for source segregation of food waste. Paper and plastic bags were provided for source segregation of food waste. Food waste was disposed into the paper bags and recyclables into the plastic bags. It was found that in the second trial using two separate bags in households increased the quantity of collected food waste as well the source separation of recyclables.

Edjabou et al (2015) studied the factors affecting source segregation of food waste in office areas in Denmark. Source sorted food waste and residual waste was collected on a daily basis for 133 working days and investigated the efficiency of the source sorting campaign. It was found that food waste generation equated to 23 kg/employee/year of which 20 kg/employee/year was source sorted. Residual waste amounted to 10 kg/employee/year which consisted of mainly paper and plastic. Moisture content of food waste collected and the potential methane production was also investigated.

Rispo et al (2015) conducted a waste audit and household questionnaire survey in a deprived area in London. It examined source segregation and food waste prevention activities of residents in high rise, high density dwellings. The results showed that contamination was low for recyclables and percentage of food waste was low due to their disadvantaged economic circumstances. 38% of the total audited waste was recyclable but only 15% was correctly disposed into the recyclables bin while in the mixed residual waste 28% was recyclable.

3 Methodology

3.1 Selection of area

The area selected for setting up the pilot scale model was primarily a residential housing colony in Basista area of Guwahati, Assam, India. The plant was set up in a small plot of land in the vicinity of the apartments measuring about 1000 sq. ft. Handing over of the plot of land for setting up a waste management plant itself showed a sense of participation for such a project.

3.2 Household survey

The area was surveyed for the type of community residing in the households, type of waste generated and the quantity of waste. The residential colony was occupied by people from different parts of India and with a cultural mix and different food habits. There are total of 25 towers with 25 apartments in each tower. Two of the towers were selected which was a total of 50 households for the study. The households were selected which was nearer to the site of the plant. The variability in the type of waste collected from the households was not seen. The households were almost of the same income group.

3.3 Distribution of dustbins

Two dustbins were distributed in the households for collection of waste and data was collected for the amount of waste collected. It was found that it was not very efficient and the residents made mistakes in disposing the waste in separate bins.

A specialized dustbin was designed and was distributed in the households for collection of waste generated. The bin consists of two chambers for disposing biodegradable and non biodegradable waste separately which are enclosed in one bin.

3.4 Waste collection

Biodegradable and non biodegradable waste was collected separately from the individual households and brought to the pilot plant. The biodegradable waste was collected everyday and the non biodegradable waste was collected after 2 days.

3.5 Data collection method

Various qualitative and quantitative research techniques were considered in this paper. Therefore different data collection methods for gathering of qualitative and quantitative data were adopted. Data collection at the household level consisted of questionnaire survey and checklists. Data collection related to waste characteristics and waste quantity was based on experiments, recording and observation. Data from waste collectors, scrap dealers, consultation with experts related to Solid Waste Management, Guwahati Municipal Corporation & Pollution Control Board was collected through interviews. It gave an insight into their objectives and the strategies adopted that have proved to be helpful in functioning of the system and the strategies that have failed and the challenges they face in the implementation process. Following is the description of the various structured questionnaires/ data sheet used in the research.

3.5.1 Datasheet on Waste using Two Bin System

Datasheet was used for collection of data on waste using two bin system. Data was collected from 50 households for 90 days from the selected area at Games Village Campus, Borsojai, Guwahati. Data on biodegradable waste, non biodegradable waste and contaminated waste was taken into consideration.

3.5.2 Questionnaire Survey on using of Two Bin System

Questionnaire survey was done for the households using two bin system. Feedback was taken from the households on the problems, suggestions for improvement, size of the bins, explanation on handling of the bins on using two bin system.

3.5.3 Datasheet on Waste using Segregation Bin System

Datasheet was used for collection of data on waste using segregation bin system. Data was collected from 50 households for 90 days from the selected area at Games Village Campus, Borsojai, Guwahati. Data on waste collected from the biodegradable chamber and non biodegradable chamber. Data on waste contaminated in both the chambers was also recorded.

3.5.4 Questionnaire Survey on using of Segregation Bin System

Questionnaire survey was done for the households using segregation bin system. Feedback was taken from the households on the problems, suggestions for improvement, size of the bin and explanation on handling of the Segregation bin.

3.5.5 Datasheet on Segregation of Waste using Belt Conveyor System

Datasheet was used for recording the segregated waste into different categories viz. PET bottle, glass, plastic, steel/ tin, aluminium etc using belt conveyor system. Waste collected from the 50 households using segregation bin system was feed to the belt conveyor for segregation. A total of 4 trained people were used during the trials.

4 Data tabulation and analysis

Structured questionnaire was administered to collect primary data at various stages of the research. Data tabulation and analysis was performed using Statistical Package for Social Science (SPSS). Various descriptive and inferential statistical analyses were conducted for data analysis. Altogether three master data sheets were developed for database of (1) Two bin system and segregation bin system (2) Segregation of recyclables for belt conveyor system and existing waste disposal system (3) Parameters of waste collection for belt conveyor system and existing system

4.1 Two bin and segregation bin system

Master data sheet was prepared in SPSS for the two different bin design system. The variable was taken as numeric with nominal scale. Data on biodegradable, non biodegradable and contaminated waste was recorded for a total of 180 days, 90 days for each bin design system. The variables were taken as numeric with a measure of metric scale in kg for the different types of waste. One way ANOVA was performed for biodegradable, non biodegradable and contaminated waste for two bin and segregation bin system.

4.2 Segregation of recyclables for belt conveyor system and existing waste disposal system

Master data sheet was prepared for different types of recyclables for two waste segregation system viz. belt conveyor system and existing waste disposal system. Data on different recyclables were collected for 90 days for each of the system. The variables for different types of segregated recyclables were taken as numeric with a measure of metric scale in kg. Descriptive statistics for mean, median and mode was calculated. Normal distribution curve was observed for all the recyclables for both the waste segregation system.

4.3 Parameters of waste collection for belt conveyor system and existing system

Master data sheet was prepared for different parameters of waste collection for two waste segregation systems viz. belt conveyor system and existing waste disposal system. Data on parameters were collected using seven point semantic differential scale for 30 trials for each of the system. The variables for different parameters were taken as numeric scale.

5 Assumptions and limitations

The study of SWM may constitute a large number of aspects from the viewpoint of researchers and professionals associated in this field. Varied aspects like characteristics, processing technologies, collection and disposal techniques, energy recovery, landfills, management and other relevant phenomena on solid waste may be included in the study. However, depending upon the importance, necessity, current state of issues, available expertise in the field, academic background, ground limitations, government regulations, only a few aspects of the subject can be studied. No scientific research on the design of a MSW model for Guwahati had been done earlier.

Sampling of waste is to be done on random basis from different target groups of the community with the understanding of it being representative of a typical locality and the total population of Guwahati. It is understood that variations in waste generation would have been there based on time, year, seasons, locality and cultural differences in the city. However the flexibility of the MSW design evolved in this research would be able to accommodate such variations without affecting the outcome to a great extent. Table1 shows the percentage of different waste generators and domestic source as the highest contributor.

Table 1: MSW generated from different sources in Guwahati

Sl. No.	Source	Unit Generation/day	Total waste tons/day	% of Total

1	Domestic source	348.63 gm/cap/day	271.95	54.39
2	Commercial Establishment	1.49 kg/unit	89.25	17.85
3	Restaurants	8.33 kg/unit	14.85	2.97
4	Hotels	83.89 kg/unit	4.25	0.85
5	Market	15 kg/unit	18.95	3.78
6	Schools & Institutions		4.75	0.95
7	Street sweepings		75.5	15.16
8	Temples		1.65	0.33
9	BMW (Domestic)	1.13 kg/unit	6.5	1.30
10	Construction		3.95	.79
11	Others		7.9	1.58
	Total Waste Generated tons/day		499.5	100
	Combined per capita generation		417.40 gm/capita/day	

Per Capita generation (PCG) is defined as the ratio between the total quantity of waste generated by all sources and total population (2011) of Guwahati. PCG= 499500000/1196690 = 417.40 gm/cap/day

Source: Guwahati Municipal Corporation (GMC), 2011

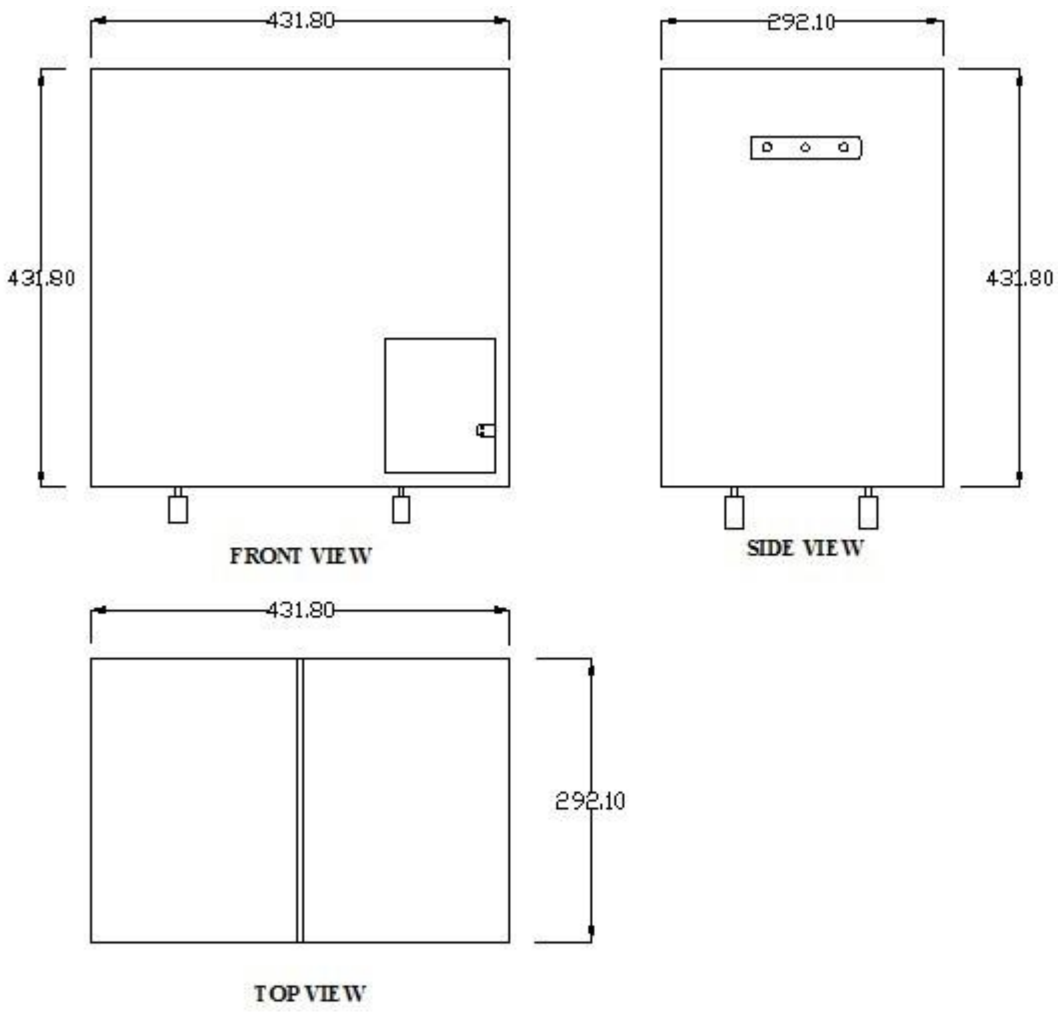
6 Designing of the segregation receptacle

The segregation receptacle has been designed keeping in mind the ease of handling of waste primarily for households. The major problem of segregation of waste found in the households was due to keeping of too many receptacles at home. Two bin system with colour coded bins was also trialed on the same population. People prefer to keep a single bin at home for disposing all types of waste into the same bin. This multiplies the problem of waste management which is the most important bottleneck for proper waste management. Source segregation of waste could simplify the waste management process and cost of disposal. The major strength of the design lies in the fact that it is a single bin with provision for disposal of biodegradable and non biodegradable waste separately. Both the compartments are covered and colour coded. The biodegradable compartment has a facility of un mounting it separately as it is to be collected everyday for preventing odour and flies. The non biodegradable compartment can be un mounted as and when required. In this attempt to design the segregation bin the underlying facts of simplicity of design, affordability, cost, carbon footprint and nature of waste produced locally has been taken into consideration.

The bin has been made from locally available material of galvanized sheet metal and painted with rust proof paint. It is potable mounted on wheels which can be easily maneuvered and tipped easily for unloading of waste. The size of the bin can be adapted as per the size of the kitchen space available. Dry waste can be collected by opening a side door which also works as a safety catch to prevent users from disposing liquid or wet waste into this chamber. The design has been kept simple so that it can be fabricated easily involving local expertise.

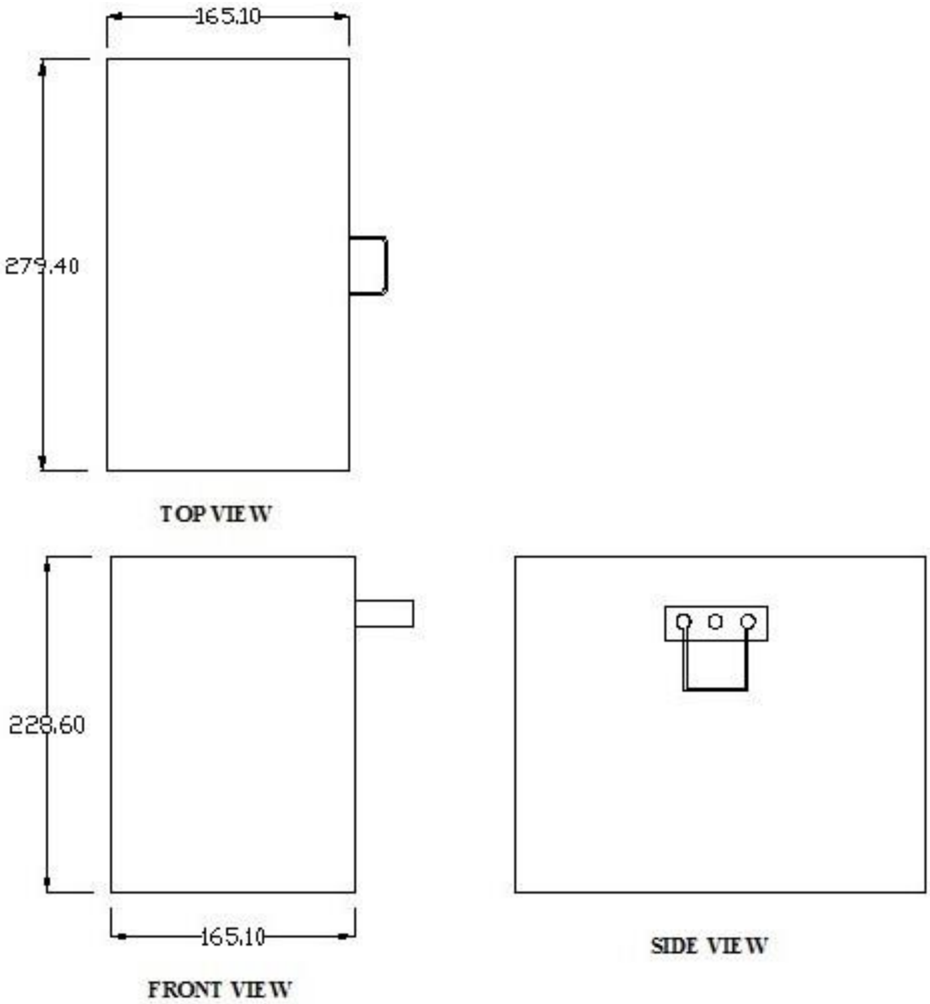
6.1 Dimension of the segregation receptacle

The dimension of the segregation bin was calculated based on the collection of data on waste from the households. Data of biodegradable and non biodegradable waste was taken into account and the dimensions were fixed based on it. Figure 1 shows the line diagram of front view, side view and top view of the segregation bin with dimensions. In the front view the door for collecting non biodegradable waste also used as a safety catch is seen at the lower right hand side corner. Figure 2 shows the line diagram of the biodegradable or wet waste chamber with dimensions which is fitted inside the segregation bin. This chamber can be separately removed from the segregation bin for collection of biodegradable waste. Figure 3 shows the isometric view of the segregation bin with the lids for biodegradable and non biodegradable chambers in open condition.



(Dimensions are in mm)

Fig. 1 Line diagram of segregation bin



(Dimensions are in mm)

Fig. 2 Line diagram of biodegradable chamber

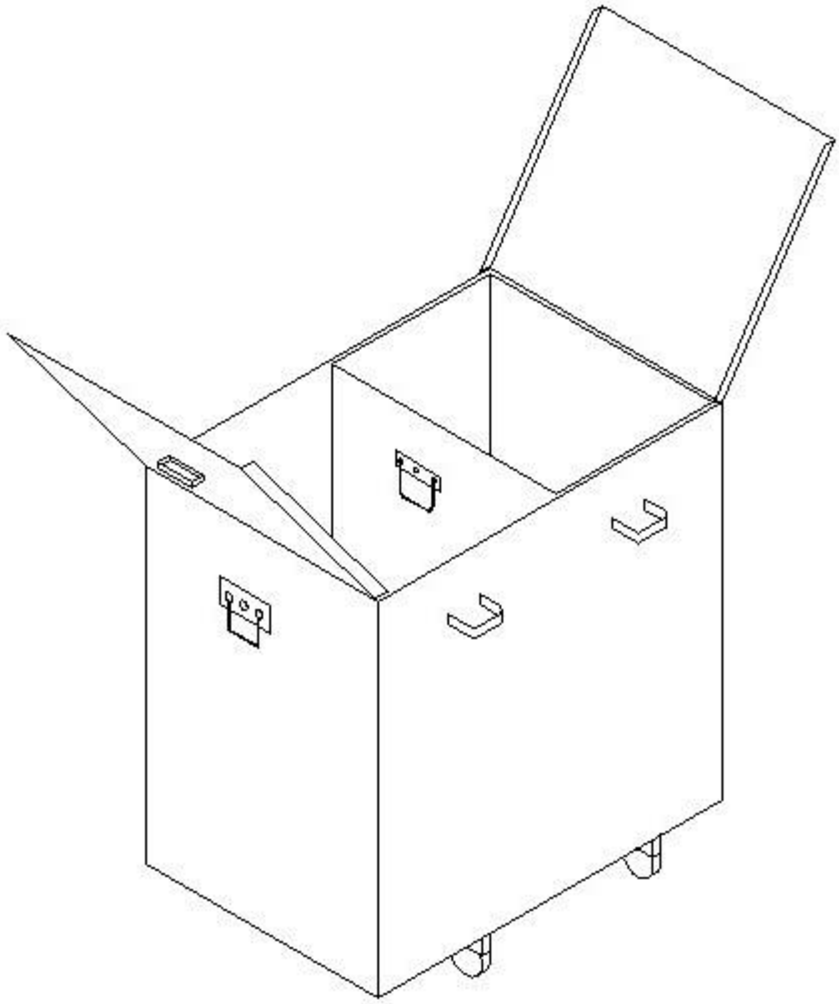


Fig. 3 Isometric view of segregation bin

7 Non biodegradable waste segregation system

The non biodegradable waste consist of primarily dry recyclables such as PET bottles, glass bottles, paper, cartons, plastic and metal. Apart from these it also consist of non recyclable item like multilayered polythene and some inert materials. The non biodegradable waste segregation system consist of mainly semi mechanized segregation equipments. This section consists of conveyor belts on which the dry waste will travel and get sorted in terms of size, nature and physical characteristics. Trained manual handlers with appropriate gear and clothing will sort out the waste and segregate.

8 Experimental results

The experimental results and discussion has been divided into three parts. The first part consists of the data collected using the two bin colour coded system for the households. The second part consists of the data collected using the designed segregation bin for the same households. The third part consists of the data on the amount of recyclables collected from the dry waste chambers of the segregation bin. The dry waste is further segregated using belt conveyor into different fractions and sold to recyclers.

8.1 Two Bin System

Two colour coded bins were distributed to the households which consisted of blue bin for disposing recyclables or dry waste and green bin meant for disposing biodegradable waste. Data was collected from the 50 households on the quantity of waste collected as biodegradable, non biodegradable and contaminated waste which was statistically analysed using SPSS.
Table 2 below shows the mean values of biodegradable, non biodegradable and contaminated waste derived from the statistical analysis using SPSS.

Table 2: Mean values of type of waste using two bin system

Sl. No.	Type of waste	Mean (kg)
1.	Biodegradable	42.19
2.	Non biodegradable	5.23
3.	Contaminated	9.07

It is seen that there is contamination in both the bins biodegradable and non biodegradable bins as shown in (fig.4). The quantity of waste with contamination was higher than the quantity of non biodegradable waste by weight. It was mainly due to the mixing of biodegradable waste with non biodegradable waste. The bin allocated for dry waste was found to be mixed with food waste and contaminated polythene bags as the major components. Also the bins allocated for disposing biodegradable waste was found to be contaminated with disposable plates, cups etc.

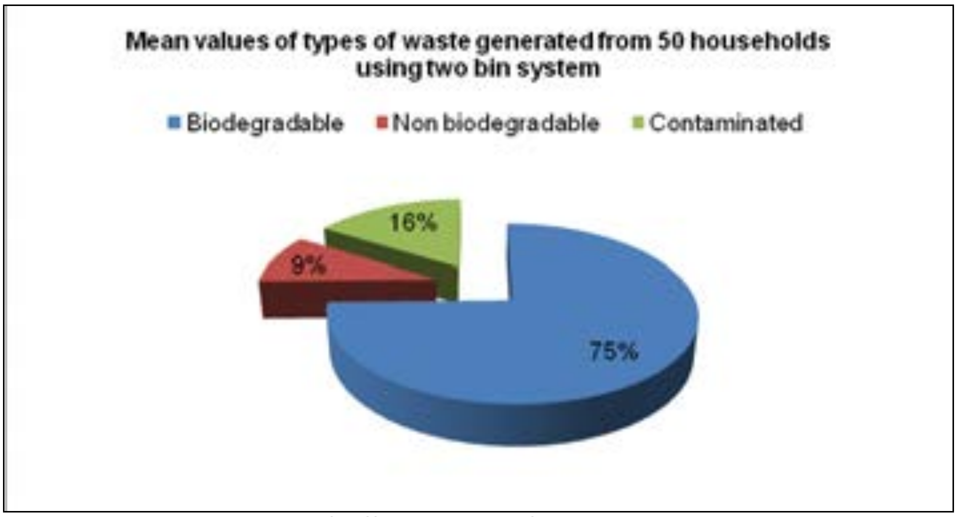


Fig. 4: Percentage of different types of waste using two bin system

8.2 Segregation Bin System

The designed segregation bin was distributed among the 50 households. Data was collected on the quantities of biodegradable, non biodegradable and contaminated waste for 90 days. Table 3 below shows the mean values of biodegradable, non biodegradable and contaminated waste for the designed segregation bin derived from statistical analysis using SPSS.

Table 3: Mean values of type of waste using segregation bin

Sl. No.	Type of waste	Mean (kg)
1.	Biodegradable	44.05
2.	Non biodegradable	6.53
3.	Contaminated	5.42

It was found that biodegradable waste consists of the highest fraction as 78% followed by non biodegradable waste at 12% as shown in (fig.5). The contaminated waste was found to reduce to 10% which is to be disposed into the landfill. This can be further reduced by introducing washing facility.

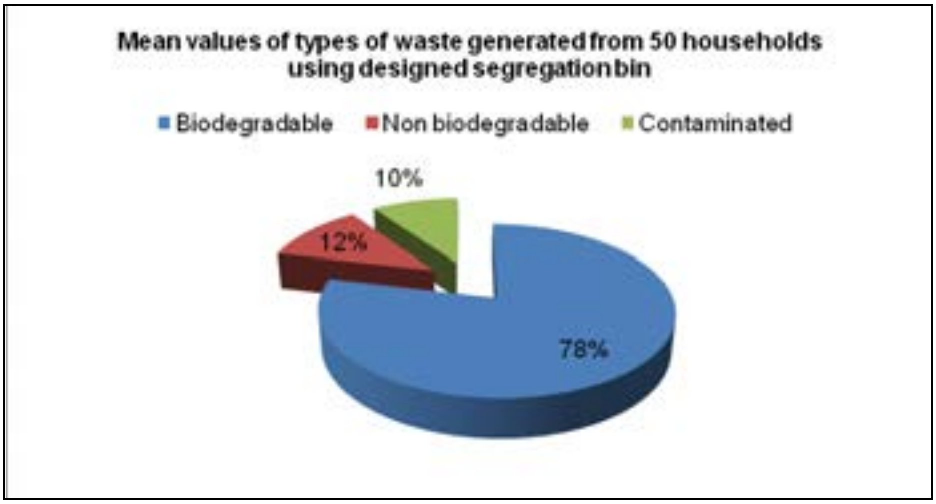


Fig. 5: Percentage of different types of waste using segregation bin system

8.3 Comparison of Two Bin System and Segregation Bin System

On the basis of the collected data inferential statistics has been conducted to study the variance of amount of various types of waste viz. biodegradable, non biodegradable & contaminated waste with respect to two different designs of segregation bin. In this paper Null Hypothesis for only biodegradable waste has been presented.

Null Hypothesis:

There is no significant difference in the amount of biodegradable waste collected with two different ideas for collecting waste viz. two bin system and improvised segregation bin.

One way ANOVA was conducted for a significance level of 0.05. The null hypothesis was rejected (significance level 0.048) and concluded that there was a significant difference in the amount of biodegradable waste collected with two different ideas for collecting waste viz. two bin system and improvised segregation bin.

The descriptive statistics showing the mean values of two bin system and segregation bin system for biodegradable waste is shown in table 4.

Table 4: Mean values of two bin & segregation bin for biodegradable waste

Biodegradable Waste				
	N	Mean	Minimum	Maximum
Two Bin System	90	42.19	30.52	67.73
Improvised Segregation Bin	90	44.05	31.48	70.72

Comparison of two bin system and segregation bin system in the amount of biodegradable waste collected from 50 households for 90 days taking the mean values are shown in fig.6.

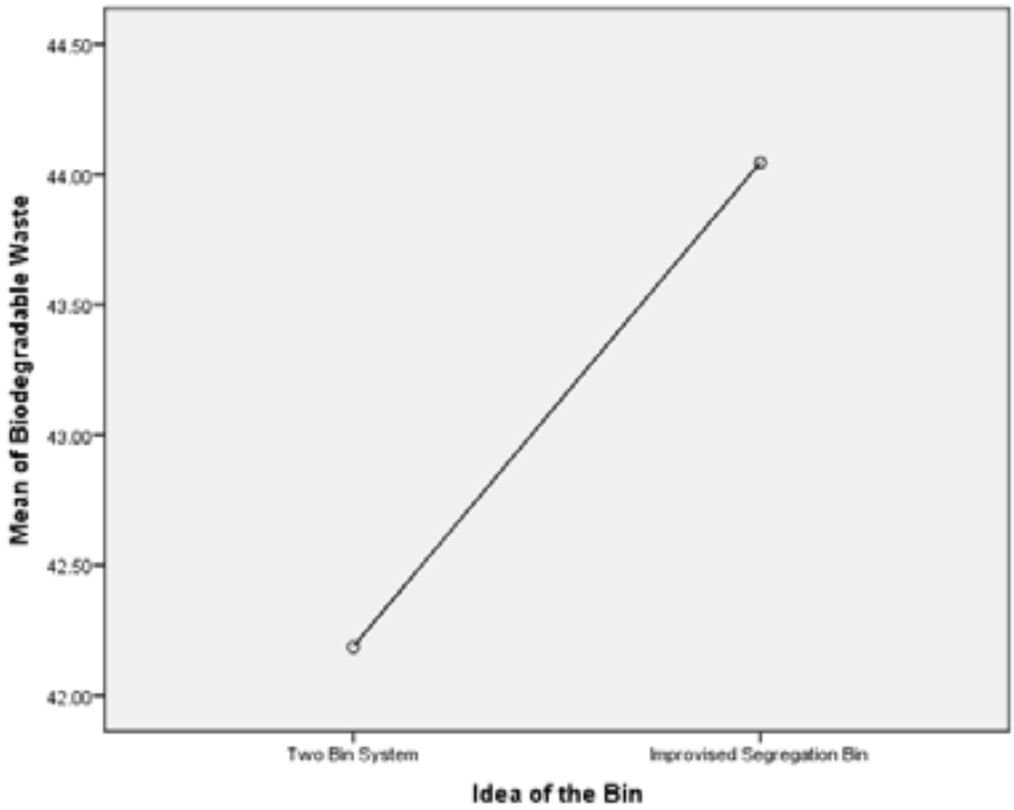


Fig. 6: Comparison between two bin system and improvised segregation bin for biodegradable waste

8.4 Collection of recyclables

Recyclables were collected from the non biodegradable waste collected separately from the 50 households using the segregation bin. This was done by loading the non biodegradable fraction of waste into the conveyor belt which was also a part of the designed set up for municipal solid waste management. The belt conveyor was tested for 90 days of operation. Data was collected on the quantity of recyclables collected along with the different fractions of the recyclables. The data collected was fed into the software SPSS and the mean value was obtained. The mean values of the different recyclables collected from 50 households for 90 days are as shown in table 5.

Table 5: Mean values of recyclables from trials in the belt conveyor

Sl. No.	Type of recyclable	Mean value (kg)
1	PET Bottle	0.62
2	Glass	1.97
3	Plastic	0.99
4	Carton	1.52
5	Steel/ Tin	0.13
6	Copper/ Brass	0.04
7	Aluminium	0.06
8	Polythene	0.38
9	Paper	0.67
10	Multilayered Polythene	0.11

The different fractions of recyclables collected in this system was found to clean as there was no contamination which could save a lot of money incurred for cleaning of the recyclables. Out of all the recyclables glass bottle has the highest fraction by weight followed by cartons, plastics of different grades, paper, PET and other as shown in (fig.7).

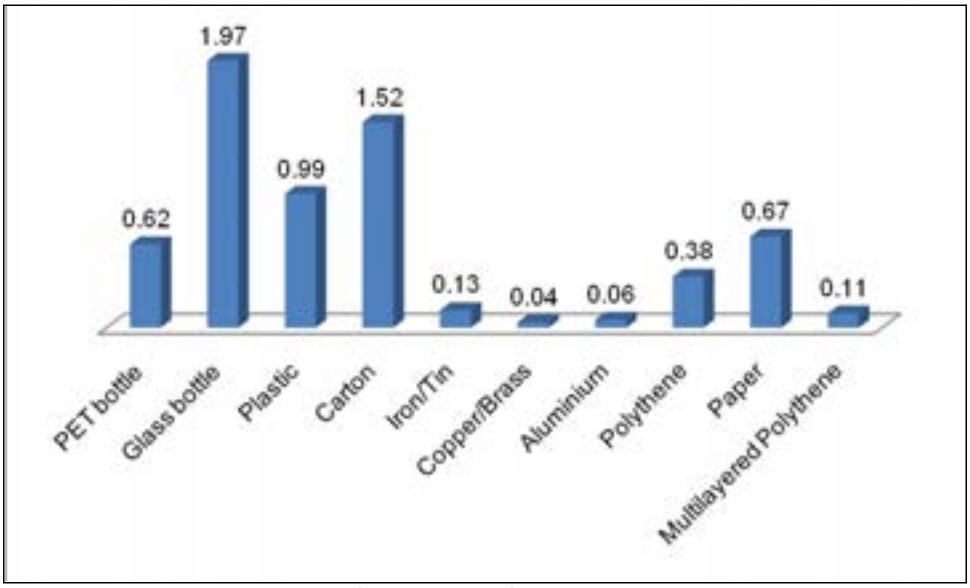


Fig. 7: Mean values of recyclables from trials using belt conveyor

8.4.1 Revenue generated from the dry recyclables

For calculating the revenue generated from each household per month the equivalent percentage of each type of recyclables were calculated from the mean values as shown in table 6.

Table 6: Type of recyclables, mean values and the equivalent percentage

Sl. No.	Type of recyclable	Mean values from 50 households/ day (kg)	Equivalent percentage
1	Pet bottle	0.61	9.43
2	Glass	1.97	30.43
3	Plastic	0.99	15.3
4	Carton	1.45	22.4

5	Iron/Tin	0.20	3.1
6	Copper/Brass	0.04	0.62
7	Aluminium	0.06	0.93
8	Polythene	0.38	5.9
9	Paper	0.67	10.35
10	Multilayered polythene	0.10	1.54

Table 7 below shows the average revenue generated per household per month from the different recyclables. The rate per kg of the recyclables has been considered taking the prevailing market rates locally. Revenue generated from recyclables per household per month has been calculated taking the mean values of the corresponding recyclable item for 90 days.

Table 7: Revenue generated from recyclables per household per month

Sl. No.	Item	% by weight of each recyclable	Weight (kg)/ household	Rate per kg (Rs)	Revenue per month/ household (Rs)
1	Plastic	15.30	1.33	15.00	19.95
2	Carton	22.40	1.95	10.00	19.50
3	Pet bottle	9.43	0.82	20.00	16.40
4	Glass	30.43	2.65	3.50	9.27
5	Copper/Brass	0.62	0.05	175.00	8.75
6	Aluminium	0.93	0.08	90.00	7.20
7	Paper	10.35	0.90	5.00	4.50
8	Steel/Tin	3.10	0.27	10.00	2.70
9	Polythene	5.90	0.51	5.00	2.55
10	Multilayered polythene	1.54	0.12	For RDF	-------
Total revenue per month per household from different recyclables					90.82

The revenue generated from the households was used for paying the wages to the people engaged in the waste management plant. It was sufficient for payment of wages to the waste handlers which makes the model self sustaining.

9 Discussions

The results obtained out of the segregation at source process demonstrated the importance of the process in waste processing. Even though local authorities have financial constraints and unscientific dumping of waste is resorted to as a convenient option, the segregation of waste at source will have to be given high priority. Segregation at source data stresses the urgency to integrate the process in the waste management process to minimize the impact and damages to the environment which are irreversible.

The design of the waste processing facility delivered the desired outcomes of a waste processing plant in terms of efficiency and material recovery. It eliminated the issues associated with the current system with regard to its unscientific handling in dumping grounds by unskilled people and low recovery of recyclables. In the current scenario of waste management in the city total manual handling versus totally mechanized sophisticated system brings out a lot of interrelated social and economic issues.

It demonstrates a solution to the SWM problem involving simple technology, local materials and fabrication, affordable, socially responsible. The SWM model addressed the concerns of big finance required for installation of sophisticated waste management facilities. It also opens avenues for local entrepreneurs to get involved in design and

development of facilities for the waste management sector. Adoption of local skills and materials has made the model cost effective and early recovery of capital costs from revenue earned from recyclables.

It also offers a blueprint for zero waste planning of places and shows the potential to be integrated in community housing. The successful running of the facility and delivery of the desired outcomes brings out a feasible sketch of a model which could be replicated in other places. With initiatives taken by other local authorities, the model in this research could form the basis for the creation of zero waste places in other cities.

10 Conclusion

The disposal system of waste in a city is the key to sustainable urban development and to render sustainable living. Urgent action is needed to find scientific waste disposal solutions in majority of Indian cities. Design of a robust system from the point of generation to disposal is vital to maintain health and wellbeing of the citizens and the personnel in the process. In situ waste segregation system in an urban development which is affordable and operationally simple is demonstrated to be viable economically and functionally. There is seen to be lack of awareness among the public regarding safe and environment friendly waste disposal practice. Introduction of in situ waste segregation systems combined with waste awareness for responsible waste disposal can create sustainable housing developments thereby restoring the aesthetics of a place as well as civic pride.

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DEVELOPMENT OF A HOME ENVIRONMENT VISUALIZATION AND MANAGEMENT SYSTEM

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Abstract: *HEMS (Home Energy Management System) is attracting attention as one of home energy conservation measures and its introduction example to smart houses and apartment buildings is increasing in late years. The function of the HEMS is, as the name suggests, centered on energy management such as control of home electronics, measurement and showing of power consumption. On the other hand, control of indoor environment is one of the most important factors for living a comfortable life in the house, but most of the HEMS does not show indoor environments such as temperature and humidity. In these situations, as a device for increasing residents' interest for indoor environment and promoting utilization of passive technologies depending on residents' ingenuity and seasons, "home environment visualization and management system" was developed by author's laboratory. Then the effect of energy conservation and improvement of indoor environment were confirmed by test installation in an apartment. In this study, as the next step of the development, enhancing the versatility by downsizing and packaging the devices in a kit was conducted. In addition, measurement contents and means for transmitting information were improved in view of the residents' health and safety such as alert of ventilation, heatstroke, over desiccation, and outdoor dust. In the means for transmitting information, small LED indication light that color and blinking changes with indoor environment was incorporated. From the results of test installation of this system in several houses, various passive activities were promoted and the effects of improvement of indoor environment were confirmed.*

Keywords: *HEMS, Energy Saving, Indoor Environment, Passive Activity, Life Style*

1 Introduction

In recent years, HEMS (Home Energy Management Systems) have got attention as an energy-saving measure, and are being adopted in an increasing number of cases in smart houses in Japan. Japanese government aims to put HEMS into every home in Japan until 20301).

Their main focus is energy management functions such as control of appliances, measurement and display of electric power (2-10). On the other hand, adjustment of the indoor environment is an important factor for comfortable living in the home, but it is extremely unusual that indoor environment are displayed.

Therefore, my laboratory has previously developed a “home environment visualization and management system” as a means of raising interest in the indoor thermal environment, and promoting use of passive control method (11-14).

As the next step in development, for this report we improved the versatility by packaging devices more compactly, and developed a system with additional innovations to take into account factors of health and safety. This presentation reports the result of a subject experiment using that system.

2 Overview of a Home Environment Visualization and Management System Kit

Based on the results of previous operation experiments using a prototype system, the authors developed an indoor environment visualization kit that can be easily installed in existing homes. The main concepts are indicated below.
1) Improved awareness of the indoor/outdoor environment (measurement items and screen innovation)
2) Health and safety warnings (heat stroke alerts, etc.)
3) Convenience of installation (can also be installed in existing homes)
4) Power-saving design (long-term drive using batteries)
5) Simplification of data gathering (use of Internet line in each home)
6) Screen for comparison between homes (continuation of interest)

Figure 1 shows the configuration diagram of the system. It was decided to adopt the following measurement items for the prototype kit: (1) Indoor temperature/humidity and globe temperature, (2) Wall/floor surface temperature (radiation temperature), (3) Carbon dioxide concentration (+ temperature/humidity), (4) Dust concentration, (5) Indoor temperature/humidity, (6) Outdoor air temperature/humidity, (7) Total power consumption (smart meter), and (8) Outlet power consumption (outlet sensor for air conditioners). It was decided to adopt specifications making it possible to ascertain the indoor vertical distribution of temperature by installing the sensor terminals for (1)–(3) at three different heights (high, medium, low). (1)–(4) are installed in a typical room (living room), and in addition sensor terminal for (5) was prepared for installation in any desired room by the resident. Measurement of the thermal environment is conducted every 30 seconds, and measurement of power every minute. In addition, the view count is collected for each page.

The indoor environment and power consumption are sent from each wireless base unit to a web server via the in-home Internet line, and the data is processed into easy-to-view graphs and the like. These can then be viewed from a smartphone, tablet or PC. An existing product was used as the power consumption measurement device. Compact boards (Arduino15)) were used for the sensor terminals newly developed and fabricated

this time, and ZigBee16) communication was used as the communication standard with the system's base unit (Raspberry Pi17)). Power-saving design was carried out for each board, and dry cell drive was adopted in the sensor terminals for (1), (5) and (6).

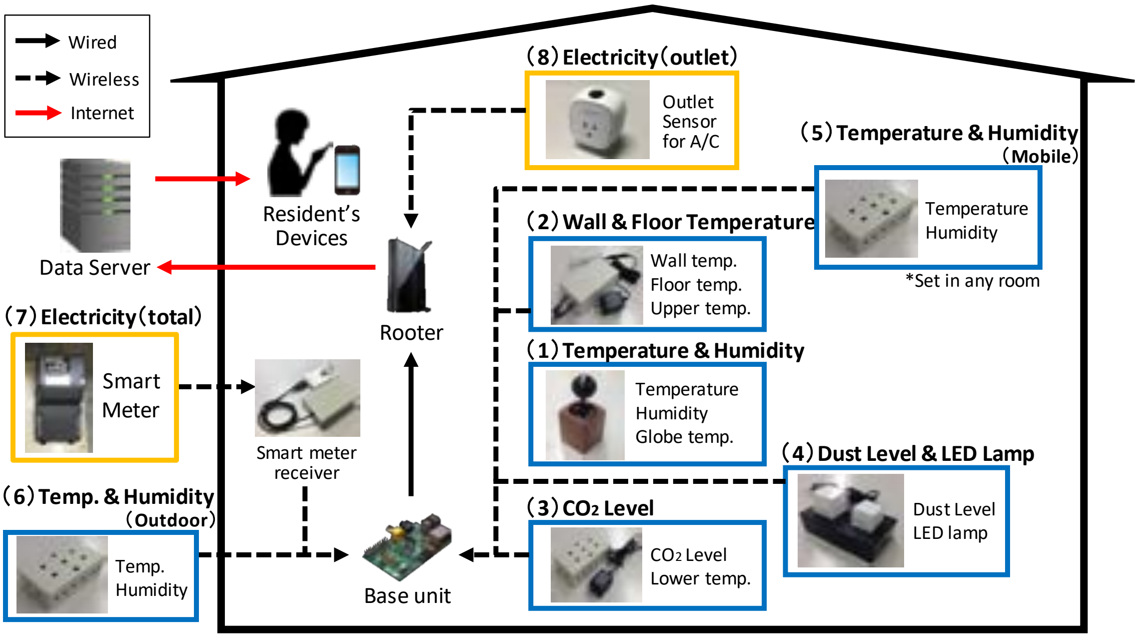

Figure 1: Configuration diagram of the system

Figure 2 shows the functions of the "LED lamp indicator" which is a major distinguishing feature of this system. This indicator provides a real-time display of the measured indoor/outdoor temperature information using the color level of an LED lamp. This allows the user to intuitively ascertain the indoor/outdoor thermal environment even without looking at a smartphone or other device. In addition, the system has a function to enable display of various alerts for ventilation, heatstroke and dryness using a flashing LED display when measurements of temperature/humidity, CO2 concentration or other values exceed a fixed threshold. Internally, the system has a built-in dust concentration sensor.

Figure 3 shows a sample screen from the "Uchi-Repo" viewing site. "Uchi-Repo" means "Home Report". Various monitoring data and graphs of each home are displayed at Uchi-Repo viewing site. The home screen displays the weather forecast for 3 days starting today and real-time values for measurement data, and the system is designed so that information on the indoor environment can be understood at a glance. At the room temperature screen, graphs are displayed of the indoor temperature, window/floor surface temperature, vertical distribution of temperature, and outdoor air temperature, and at the humidity screen, graphs are displayed of the indoor humidity and outdoor humidity. This enables indoor/outdoor comparison, comparison of times series for 1 week from the current day, and so on. Time series graphs are also displayed for CO2 concentration and power consumption. Also, using the comparison screen, it is possible to compare the indoor environment and power consumption with other households, and to ascertain the whether the indoor environment in the home is good or bad, and where power usage is high or low. The system is designed so that an LED flashes simultaneously when sensor measurements exceed fixed thresholds, and warnings on ventilation, heatstroke, and dryness are displayed on the home screen of the "Uchi-Repo" site. This helps promote quick response. To ascertain differences in the sense of

heat/cold in each household, a function is also provided to enable reporting of the current degree of comfort.

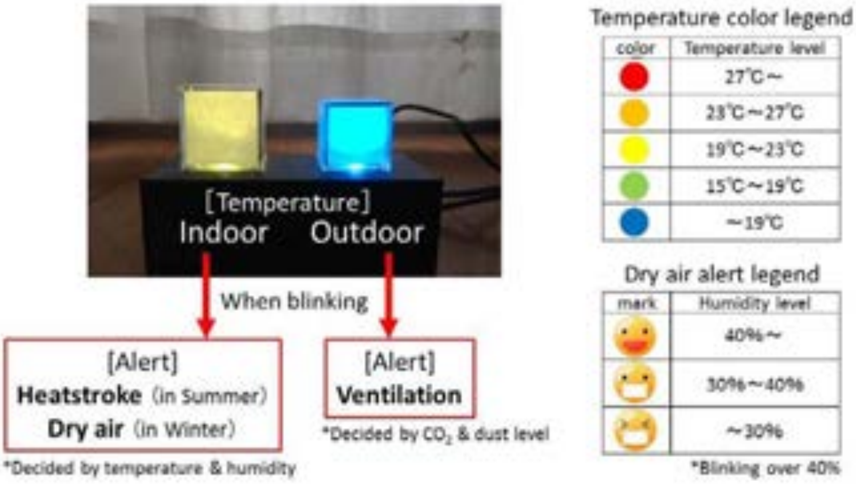

Figure 2: Functions of the "LED lamp indicator"

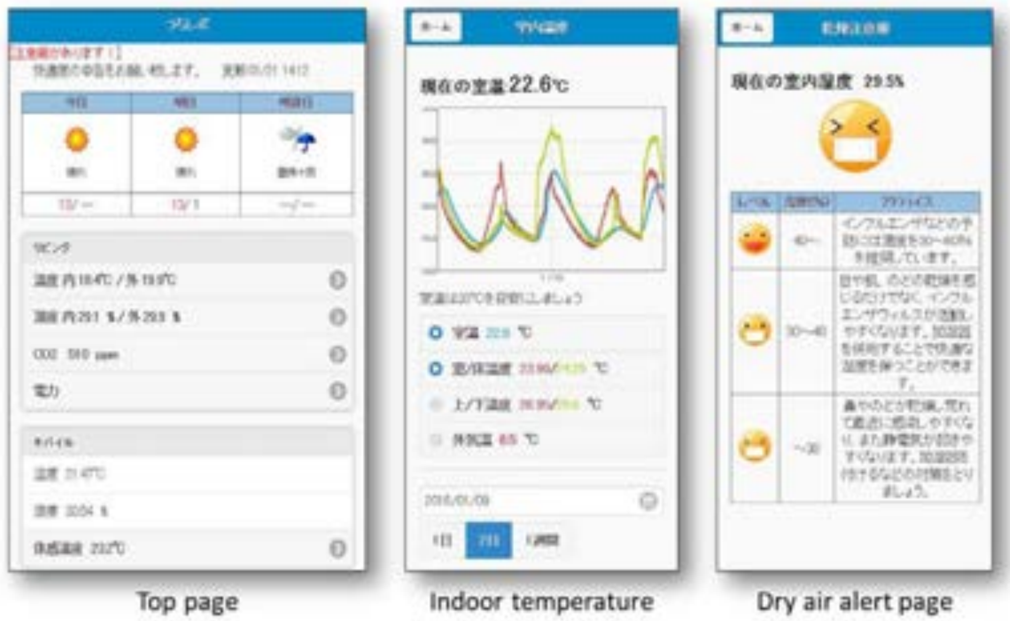

Figure 3: Sample screen from the "Uchi-Repo" viewing site

3 Subject Experiment Using System Kit

3.1 Overview of experiment

Table 1 provides an overview of the homes for the subject experiment. Experiments were conducted by installing 6 of the systems improved and developed in the previous section in 6 households. Data was collected for at least more than 1 week subsequent to installation of the equipment. After that the viewing site "Uchi-Repo" and how to use it were explained, and then data was collected again for at least more than 1 week while performing visualization. The experiment period was from August to September, 2016, at the latter half of summer. After the experiment was finished, a questionnaire survey was

administered regarding how the subject usually spends the same period each year, changes in awareness due to system adoption, and views on the system itself.

Table 1: Overview of the homes for the subject experiment

	Location	Numbers of residents	House type	Construction type	Before visualization period	After visualization period
A	Tokyo	4	Apartment	RC	Aug 5 - Sep 4, 2016	Sep 5 - Sep 18, 2016
B	Tokyo	2	Apartment	RC	Sep 4 - Sep 11, 2016	Sep 12 - Sep 30, 2016
C	Kanagawa	3	Detached house	Wood	Sep 4 - Sep 12, 2016	Sep 13 - Sep 25, 2016
D	Tokyo	4	Apartment	RC	Sep 4 - Sep 12, 2016	Sep 13 - Sep 25, 2016
E	Tokyo	3	Detached house	Wood	July 31 - Sep 3, 2016	Sep 4 - Sep 18, 2016
F	Tokyo	4	Detached house	Wood	Aug 16 - Sep 5, 2016	Sep 6 - Sep 20, 2016

System viewing and evaluation

Figure 4 shows screen viewing counts for each day and time band in each household, and Figure 5 shows the viewing percentage for each type of screen without top page. It is evident that there are differences in the view count and percentage depending on the lifestyle, interest and concern of the subject. As can be seen, in homes with a high view count (B and F), viewing is done throughout the day.

About viewing percentage, top page accounts for around 60%. Real time monitoring data is displayed on the top page, so it is expected that residents often view only top page and know their environmental situation.

In Home A and B, their viewing percentage of indoor environment (temperature, humidity and CO2) are about 60%. It seems that they care much about indoor environment. On the oter hand, in Home E, power consumption page accounts for about 40%, so it is believed that the residents are interested in energy saving or cost saving. In Home F, comparison pages account for more than 50%.

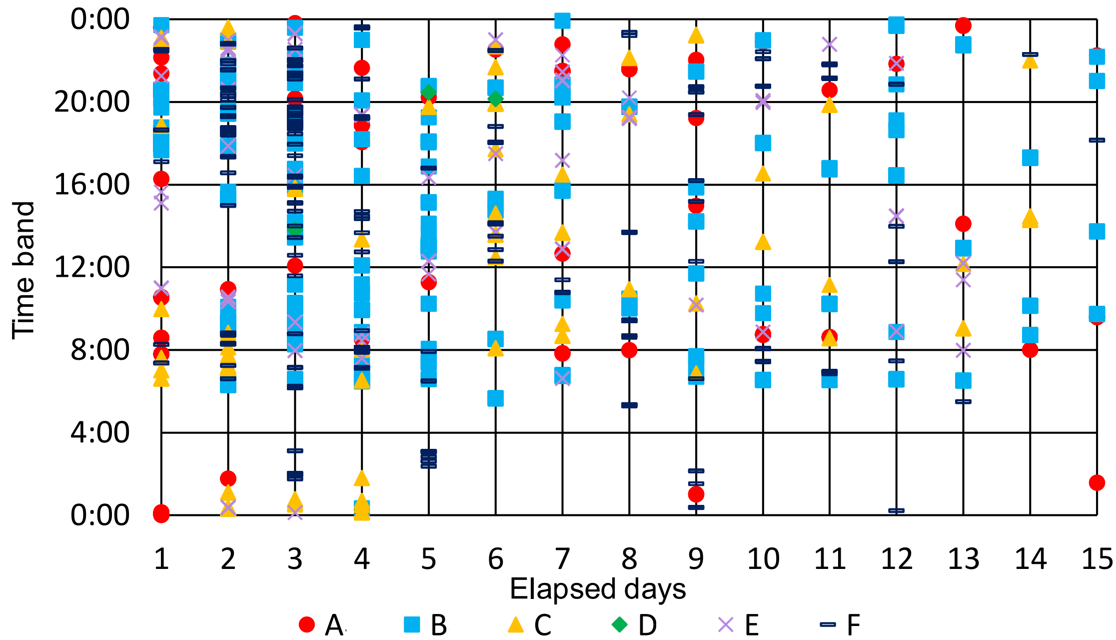

Figure 4: Screen viewing counts for each day and time band

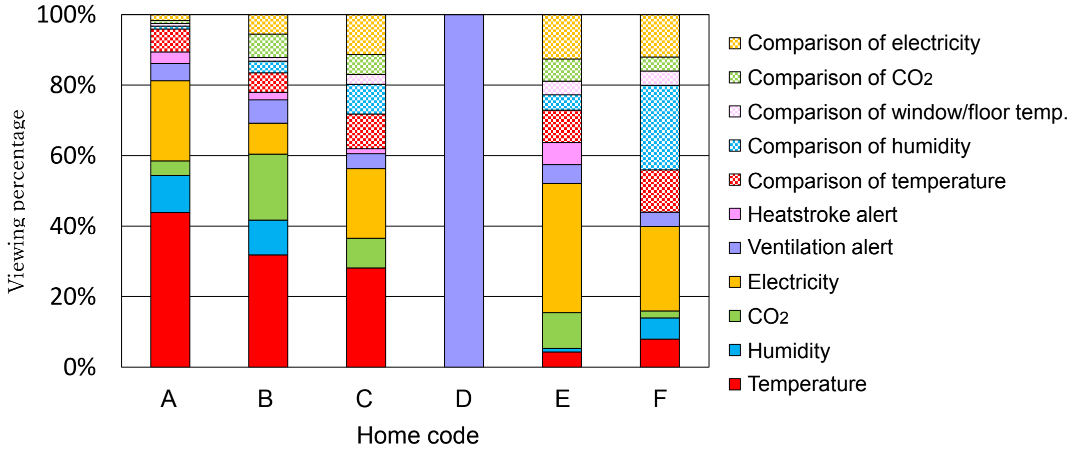

Figure 5: Viewing percentage for each type of screen

3.2 Changes in environment awareness due to visualization

Table 2 shows results regarding the changes in environmental awareness of each household according to the questionnaire. In most households, the items "a. I began to worry about temperature control.", "d. I could control indoor temperature without cooling.", "f. I began to worry about ventilation.", and "l. I could open windows and ventilate rooms well." were answered "Yes". This can be regarded as confirmed by the results of interviews indicating that the subjects periodically engaged in the ventilation behavior of opening/closing doors and windows while looking at the color level and flashing of the LED lamp. In addition, in most households, power saving items were translated into action, and the needs of the alerts were high.

On the other hands, environmental control actions about forecast indoor climate such as "h. I began to worry about indoor climate before going out." and "i. I began to worry about indoor climate before going to bed." were not translated into action in this short period of this subject experiment.

In addition, there were also comments such as "I confirmed with the LED color that maybe the current room temperature was too hot for my child and dog," and "I determined the timing for using cooling based on the LED color." This can be regarded as confirming that this sort of visual device has high potential to aid in proper prediction and regulation of the indoor environment.

Table 2: Questionnaire results regarding the changes in environmental awareness

Classification		Questionnaire list	A	B	C	D	E	F	Point
Temperature	a	I began to worry about temperature control.	△	○	△	○	○	△	9
	b	I learned to be able to predict current indoor temperature.	△	△	○	○	○	△	9
	c	I learned to be able to know my comfortable temperature.	△	△	△	○	○	△	8
	d	I could control indoor temperature without cooling.	○	○	×	○	○	○	10
	e	I began to worry about opening and closing curtains.	×	○	×	○	△	△	6
Ventilation	f	I began to worry about ventilation.	○	○	×	○	○	△	9
Indoor climate	g	I began to worry about indoor climate from the outside.	×	△	×	△	△	○	5
	h	I began to worry about indoor climate before going out.	×	△	×	△	×	×	2
	i	I began to worry about indoor climate before going to bed.	×	×	×	○	△	△	4
	j	I began to worry about heatstroke in the house.	△	△	○	△	△	×	6
	k	I could use air conditioners and electric fans well.	△	×	○	△	○	○	8
	l	I could open windows and ventilate rooms well.	○	○	○	○	△	○	11
Electricity	m	I began to turn the temperature settings down of AC.	○	△	○	○	△	○	10
	n	I began to worry about using appliances.	○	△	×	○	△	○	8
	o	I began to reduce wasteful electricity use.	△	○	○	○	△	○	10
	p	I began to turn off the TV when no one is watching.	—	○	○	△	△	△	8
	q	I began to disconnect the plug of unused appliances.	○	○	○	○	△	×	9
Alert	r	I think I need heatstroke alert.	○	△	△	○	○	○	10
	s	I think I need ventilation alert.	○	△	○	○	○	△	10

○ : Yes   △ : Maybe yes   × : No   — : Non-use of the appliances

4 EFFECTS OF IMPROVING INDOOR ENVIRONMENT

4.1 Prevention of heatstroke

Figure 6 shows the variation of temperature, WBGT (Wet Bulb Globe Temperature) and AC (Air Conditioner) use of Home E. It is found that the residents turned on the air conditioner when they saw the flashing LED lamp of heatstroke alert and viewed Uchi-Repo site. According to the hearing after the experiment, they have a dog and a child, so they often controlled indoor environment by reference to LED lamp indicator.

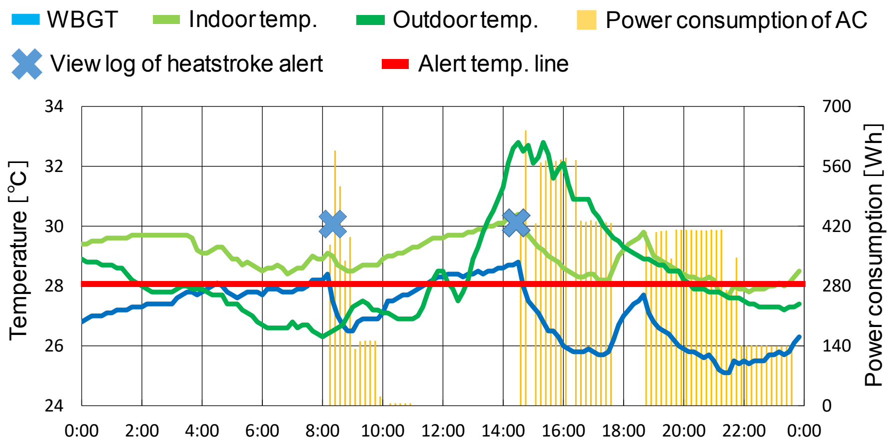

Figure 6: Temperature, WBGT and AC use of Home E

4.2 Ventilation behavior

Figure 7 shows changes in CO_2 concentration and CO_2 screen viewing before and after viewing period at Home C. Before viewing period, CO_2 concentration often exceeded 1,000 ppm, but no action was done. In viewing period, it is found that residents took a ventilation behavior when they saw the flashing LED lamp of ventilation alert, viewed Uchi-Repo site and noticed the high value.

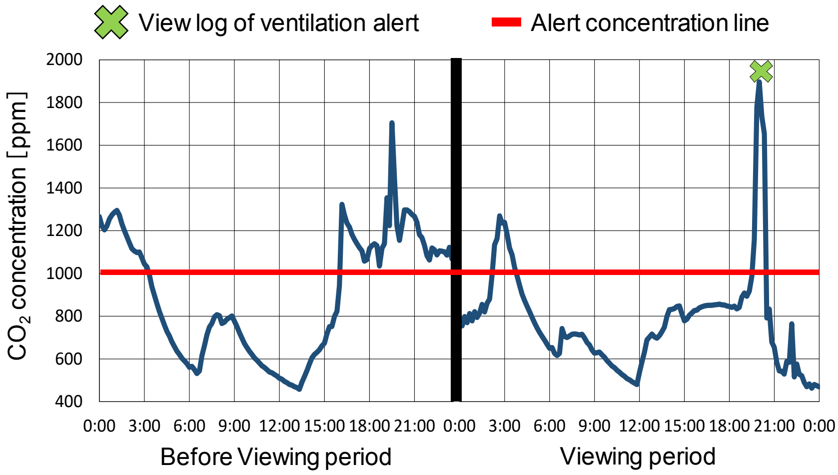

Figure 7: CO2 concentration of Home D

4.3 Energy consumption

Figure 8 shows the daily average of power consumption before and after adopting the system at each home. Home C data is omitted because Home C has PV panels and the power generation amount was not sure.

As the result, mean daily outdoor temperature were about 1 degree lower in viewing period than before viewing period, but the daily average of power consumption was reduced by an average of 8%.

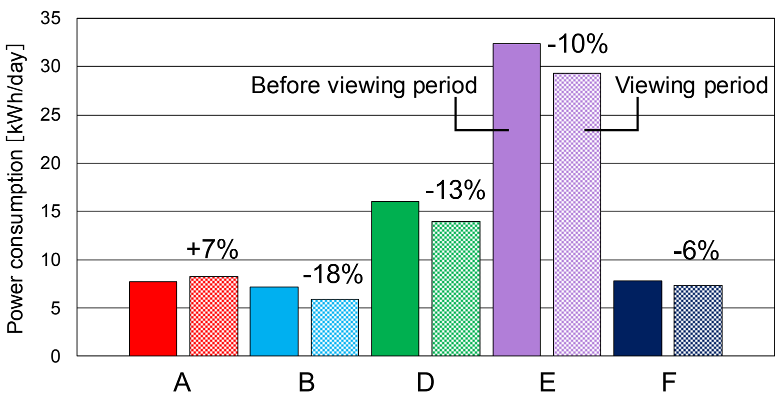

Figure 8: Daily average of power consumption before and after adopting the system

4.4 Effect of improving indoor thermal environment

Figure 9 shows the correlation diagram of indoor and outdoor temperature in Home A and C whose viewing logs are relatively high. Outdoor temperature values are higher in before viewing period than in viewing period, but in comparison at same outdoor temperature level, it is found that indoor temperature values in viewing period are about 1 degree lower than in before viewing period.

It is considered that residents began to do various actions for environment control and the indoor environment were actually improved by using this environment visualization and management system.

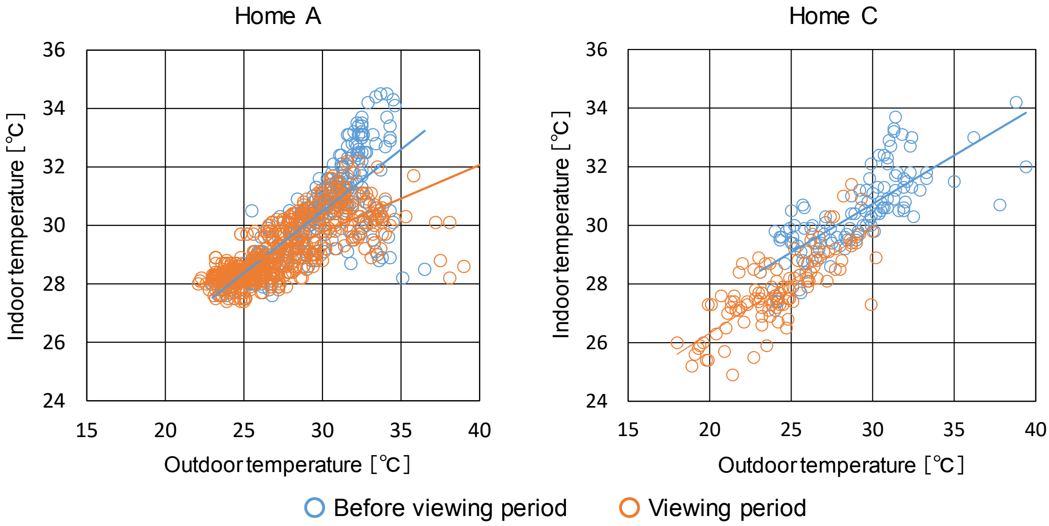

Figure 9: Correlation diagram of indoor and outdoor temperature

5 Conclusion

This research is a pilot project, but the following summarizes the main findings obtained as a result of a subject experiment with the developed system for home environment visualization and management.

1) A tendency was evident for use of the system kit to lead to various types of awareness, interest, and concern toward the indoor/outdoor environment, and cases were seen that were linked with specific passive behavior.

2) It was confirmed that the LED lamp indicator promoted routine awareness of the indoor/outdoor environment in almost all households, and helped to warn about alert items such as heatstroke and ventilation.

3) It is considered that residents began to do various actions for environment control and the indoor environment were actually improved by using this environment visualization and management system.

Going forward, the authors will increase the number of subjects, lengthen the experiment period, conduct detailed verification of the results of improving the environment through communication of information such as warning displays, examine effective comparison screen content, improve to a system and design with less trouble and resistance to installation, and so on. The author's plan is to proceed with development to make this a system for promoting energy-saving and environment control behavior, and a tool for management of energy consumption, and safety, health and comfort.

Acknowledgements

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16) ZigBee: Zigbee is the wireless language that everyday devices use to connect to one another. http://www.zigbee.org/
17) Raspberry Pi: Raspberry Pi is a single-board computer with ARM processor for promoting the study of basic computer science in schools. https://www.raspberrypi.org/

EMBODIED CARBON AND THE DECISION TO DEMOLISH OR ADAPT

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Abstract: *Embodied and operational carbon are both an important part of the built environment's impact on climate change. Two mitigation strategies identified for reducing embodied and lifecycle emissions include refurbishing existing buildings or demolishing existing buildings and replacing them with more efficient new buildings. This paper explores existing literature assessing the decision between demolition and adaptation, then through a quantitative analysis assesses three factors regarding lifecycle assessments which were identified through a critique of existing research. The analysis concludes: embodied emissions associated with the existing structure should not be included in decision-making, as they have already been 'spent'; the decarbonisation of the grid is important to consider when comparing strategies, as the cumulative emissions from a less efficient refurbishment are likely to take longer to exceed emissions associated with new build; absolute values for emissions (the total amount for the whole building) should be considered when comparing adaptation to new build projects, since many existing papers focus on emissions per square metre and like-for-like replacements which are deemed to be unrealistic. The quantitative analysis is supported by a qualitative analysis of two focus group with industry and academic experts in the built environment. These focus group discussions showed that there are still methodological issues with life cycle assessments, such as uncertainties with lifespans and data reliability. Participants felt these need to be addressed before legislation and financial incentives can be introduced. A commonly mentioned suggestion to improve the current methodology included collecting more data through case study investigations. Both the qualitative and quantitative analyses build upon the existing research identifying key concepts which need to be addressed and improved upon if considering embodied emissions in the decision to demolish or adapt existing buildings.*

Keywords: *Embodied Carbon, Demolition, Adaptation, Decision-making, Life-cycle Assessments*

1 Introduction

Embodied and operational carbon are both an important part of the built environment's impact on climate change (Brown et al., 2014; Cuéllar-Franca and Azapagic, 2012; Hacker et al., 2008; Monahan and Powell, 2011). Both Oregi et al. (2017) and Weiler et al. (2017) report that the building sector contributes approximately 30% of the annual global greenhouse gas emissions, referencing the report from the Commission of the European Communities (2014). To try and reduce this contribution, Ibn-Mohammed et al. (2013) describe the introduction of a mandatory carbon reporting scheme for companies in the UK. The UK Government has indicated that embodied emissions are likely to become key metrics to be addressed when considering the whole-life sustainability of a building, and Ibn-Mohammed et al. (2013:240) concludes "*its inclusion in the decision-making process is therefore of the utmost importance*".

Pomponi and Moncaster's (2016a) systematic review of the academic literature indicates that there are several mitigation strategies to reduce embodied emissions in the built environment. One of these includes retrofitting the existing housing stock to improve energy efficiency, while another includes the opposite, demolishing existing buildings and replacing them with new, with the authors (Boardman, 2007; Dubois and Allacker, 2015) stating that the life-cycle emissions are lower for particular scenarios.

This paper explores these two mitigation strategies by comparing when the environmental impact is higher or lower for the demolition or adaptation of existing buildings. A literature review summarises and provides a critique of existing research. This is followed by a quantitative analysis to show how a building's lifetime emissions can vary when considering different factors such as: whether or not to include existing emissions in the analysis; decarbonisation of the energy grid; and increasing floor areas. These factors were identified through critiques of existing research. A qualitative analysis of two focus group discussions is then used to investigate current attitudes towards embodied carbon's inclusion in decision-making and to suggest potential improvements.

2 Literature Review

2.1 Embodied carbon and life-cycle assessments

2.1.1 Life cycle stages

Embodied emissions are associated with every stage of a building's lifecycle. The Commission of the European Communities' (2014) TC350 framework defines the life cycle stages shown in Table 1. Ideally, all stages should be considered through a 'Cradle-to-grave' or even a 'Cradle-to-cradle' concept to ensure correct decisions are made (Pomponi and Moncaster, 2016a). For example, if the focus is only on stages A1-A3, a strategy may be chosen which has fewer emissions for this product stage but more over the building's lifetime.

If conducting a life cycle assessment (LCA), operational emissions should be considered alongside embodied emissions. Existing research has tended to focus on operational energy because this is where policies have previously focused. Szalay (2007) discusses the European Commission's Energy Performance Directive which only encompasses operational emissions and recommends embodied energy is taken into account during assessments. Although authors such as Cuellar-Franca and Azapegic (2012) found that 90% of carbon emissions were associated with the use-stage and only 9% with

embodied carbon, others argue that as embodied emissions are calculated for each life-cycle stage and operational energy decreases, embodied energy will contribute a higher proportion of overall emissions (Ibn-Mohammed et al., 2013).

Table 1: Life cycle stages of a building. Data source: BS EN 15978:2011 (BSI, 2012)

Stage	Code	Sub-stage
Product Stage	A1	Raw material supply
	A2	Transport
	A3	Manufacturing
Construction process stage	A4	Transport
	A5	Construction installation process
Use stage	B1	Use
	B2	Maintenance
	B3	Repair
	B4	Refurbishment
	B5	Replacement
	B6	Operational energy use
	B7	Operational water use
End of life stage	C1	De-construction/demolition
	C2	Transport
	C3	Waste processing
	C4	Disposal
Benefits and loads beyond the system boundary	D	Reuse, recovery and recycling potential

2.1.2 Uncertainties and sensitivities

A current issue with LCAs is the sensitivity and uncertainty of the methodology (Dixit et al., 2013). A recent study by Oregi et al. (2017) assesses emissions for 775 refurbishment scenarios. Their sensitivity analysis included alterations to: the service life of the building and its components; transportation distances; climatic zones; embodied energy calculated for products; uncertainty regarding occupancy and conversion factors from energy to carbon. Their results are shown in Fig. 1 and demonstrate the range of values which emerged for each life-cycle stage.

Pomponi and Moncaster (2016b) conducted a project aiming to ‘bridge the gap’ between whole life carbon theory and its practical implementation. Three specialist carbon consultants assessed five case studies, four new build and one residential refurbishment. The consultants used the BS EN15978 standard (BSI, 2012) as a framework and the same data as a starting point, including a bill of quantities and technical drawings. The final report and subsequent paper (Pomponi et al., In Press) discusses methodological issues identified through a comparison of the three consultants’ LCAs as the results showed significant variations. These were caused by various assumptions including: the study period; type of floor area (gross external, gross internal or net internal); and material/spatial boundaries (Pomponi and Moncaster, 2016b). Although the report’s intention was not to compare adaptation to demolition and new build, if the results are normalised to emissions per m^2 (Fig. 2), the consultants’ results have different conclusions for which strategy has the lowest emissions, reiterating concerns that there needs to be methodological improvements.

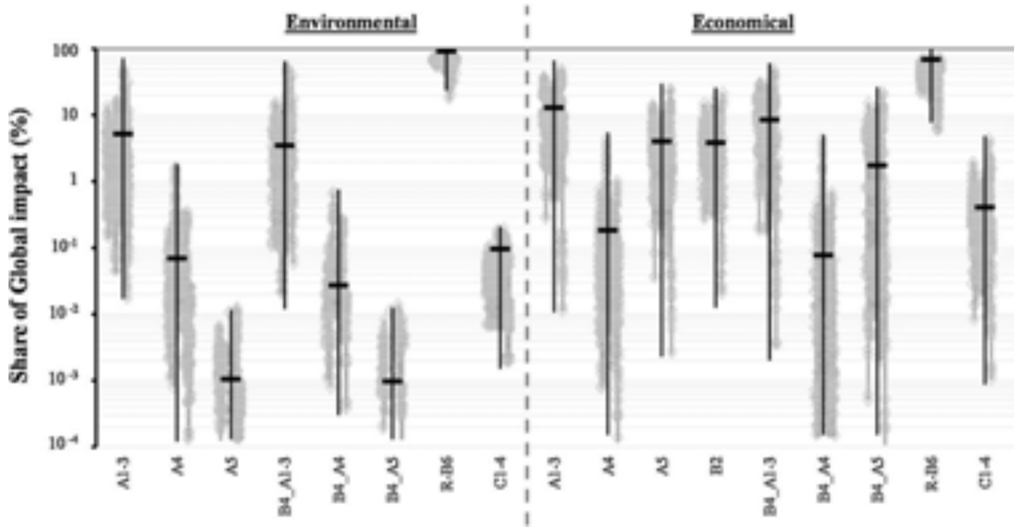

Figure 1: Percentage of global impact for each life-cycle stage (see Table 1) for refurbishment scenarios and their sensitivity analysis. Source: Oregi et al. (2017: 22)

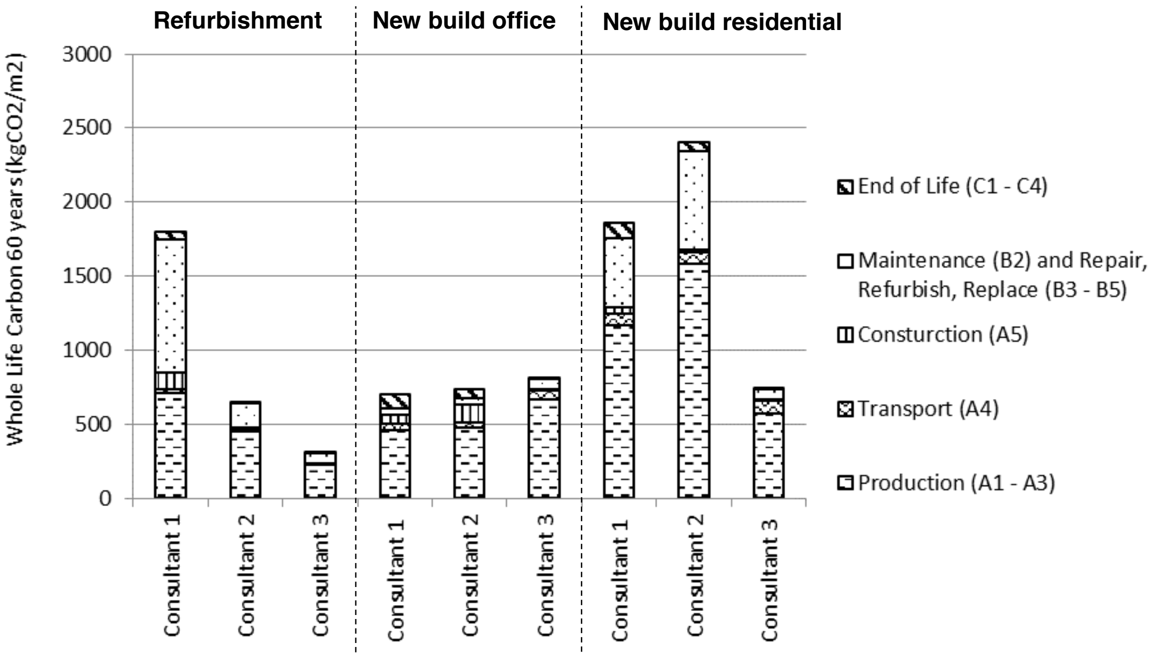

Figure 2: Consultant responses for whole life carbon assessment of three case studies using 60year lifespan (excludes B6 lifecycle stage). Reproduced and adapted from Pomponi and Moncaster (2016b).

2.2 Demolition versus adaptation (refurbishment)

Demolition refers the end of a building's lifespan caused by man-made destruction (Thomsen and Flier, 2009), whereas adaptation typically refers to retaining part or all of an existing structure (Wilkinson et al., 2014). Adaptation can vary from a change in the internal space; the performance (e.g. energy efficiency), function, size or even location (Schmidt III et al., 2010). Within the literature there are various terms used including retrofit, refurbishment and renovation; which are often interchangeable with adaptation.

This section reviews literature focusing on embodied emissions and/or LCAs alongside the decision to demolish or adapt. It is structured in three parts which reflect factors affecting this decision. These factors/sub-headings were identified through a critique of existing research papers' methodologies and results.

2.2.1 The inclusion or exclusion of existing emissions ('sunk costs')

Existing buildings will have emissions associated with their past construction, however their inclusion in the decision-making process is debatable as they are emissions which have already been 'spent'. In some academic papers they are considered, whereas in others they are dismissed.

Gaspar and Santos (2015) evaluate a family dwelling in Portugal for its embodied carbon. Their analysis includes a quantification of the material in the existing structure as well as the new material required for a new build replacement or the refurbishment of the existing building where 64% of the initial structure is demolished. They found that refurbishment has lower embodied emissions than the new build. However, if these historical costs are included, there can be additional complications with calculations. This was found during a study by Bin and Parker (2012) who tried to quantify the embodied emissions of an early 20th Century house in Canada.

In other studies, such as Erlandsson and Levin (2005), the historical emissions, are not seen as relevant today and are referred to as 'sunk costs'. Weiler et al. (2017) assessed four scenarios for a multifamily house in Germany using a 50 year lifespan. These included: an existing 1975 house with no refurbishment; the existing 1975 house with medium refurbishment (corresponding to a standard between kfW70 – kfW100[1]); an advanced refurbishment to passive house[2] standards; and a newly constructed 2016 building with kfW70 standard. They used two approaches to calculate the embodied emissions for the refurbishment strategies. In the first, they include the emissions associated with the existing building and the additional emissions required for refurbishment, stating that this allows the refurbished building's environmental impact to be compared to a newly constructed building. Their second approach only considers the energy used for refurbishment, which they say allows the refurbishment to be compared to demolition and new build, which is the focus of this paper. Weiler et al's results showed that an advanced refurbishment (excluding sunk costs) had the fewest emissions (1.42 million kgCO2e); followed by new build to 2016 standards (1.66million kgCO2e); then a medium refurbishment excluding sunk costs (1.70 million kgCO2e); followed by doing nothing (3.14 million kgCO2e).

Overall, the majority of papers reviewed for this paper did not include calculations for the existing building's emissions which can be used as an indication they are not commonly considered (Hacker et al., 2008; Olsson et al., 2016; Wastiels et al., 2016). The impact of their inclusion is explored further in Section 4.1.

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[1] KfW-70 = maximum annual primary energy requirement 70 kWh/m^2 & KfW-100 = maximum annual primary energy requirement 100 kWh/m^2 (energiesparen im haus halt, 2017)

[2] *"A Passivhaus is a building, for which thermal comfort can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air"* (Building Research Establishment Ltd., 2011)

2.2.2 Variations in operational energy standards

Depending on the level of retrofit, the operational energy standards will vary and can lead to different decisions regarding a renovation's environmental impact compared to new build. For example, Dubois and Allacker (2015) highlighted that previous papers (Morelli et al., 2014; Power, 2008) found refurbishment to have a lower environmental impact than new build but only focused on 'deep retrofit' strategies, which they define as a 60% or more reduction in operational energy. Using a series of equations they argue that focus should be either on replacing existing buildings with higher performing new build or using deep retrofit strategies. They feel that there should not be small scale subsidies for renovation as this locks in energy and prevents improvement in the future. However, this conclusion does not consider the decarbonisation of the fuel supply. Although operational energy will remain the same, the carbon associated with this is likely to reduce (Alderson et al., 2012; Kannan and Strachan, 2009). In addition, operational energy is not just a technical matter and is influenced by the users and economic valuations. Various authors including Greening et al. (2000); Brännlund et al. (2007) and Chitnis et al. (2013) explore the 'rebound effect' which can offset potential energy savings. Despite this critique, Dubois and Allacker's paper does highlight the importance of considering the level of intervention and refurbishment, as also seen in Weiler et al's (2017) paper discussed in Section 2.2.1.

Rather than comparing adaptation against new build, other papers focus solely on the lifecycle impacts of different refurbishment strategies. For example, Brown et al (2014) evaluated refurbishment measures identified in a survey of 1,400 single and multi-family dwellings. Results showed the measures which contributed the highest proportion of emissions were replacing the windows and mechanical ventilation strategies. In a study by Schwartz (2016), two social housing blocks on the same estate in Sheffield, UK, were evaluated to compare the actual refurbishment measures to the optimal refurbishment measures. The optimal result showed that the operational emissions of Building A could have been reduced to 795kgCO_2/m^2 compared to the original refurbishment which was at 923kgCO_2/m^2, showing that decision-making at the initial design stage regarding environmental impact could have been improved. The study showed that emissions were significantly reduced by insulating thermal bridges and increased by using brick cladding. A comparison between the two buildings indicated that one used less CO_2 over the lifetime and this is assumed to be because of the different spatial arrangements, orientations and solar gains. These factors would be easier to control with new buildings.

A limitation linked to the possible level of intervention for refurbishments is heritage, a key factor considered in the decision to demolish or adapt existing buildings (Baker et al., 2017). In some refurbishment scenarios, such as those outlined by Wastiels et al. (2016) external wall insulation was not allowed because of urban development rules and in Oregi et al's (2017) analysis they assume there was no historic or urban restrictions. In reality, as acknowledged by Olsson et al (2016:30) "*cultural heritage values make some building envelope measures impossible*". Work by organisations such as Historic England, formally known as English Heritage are conducting research to try and overcome these constraints (Historic England, 2017).

The variation in the operational energy standards is also important to consider in the new build scenarios. Alba-Rodríguez et al. (2017) evaluated the environmental footprint (EF) for the refurbishment of a multi-family housing block compared to demolition and new build using global equivalent hectares (gha) as the units over a 25 year lifespan. Although, the housing was in very poor condition, the EF was 0.093gha/m^2 for refurbishment compared to 0.214 gha/m^2 for the new build. If that new build reached

newer standards for operational energy at the time the paper was submitted for publication in 2016, rather than when the decision was made in 2006, the environmental impact would have been 0.200 gha/m^2.

Operational energy standards will have a significant influence on the LCAs of buildings. This section has shown that it vital to consider the effect of different levels of intervention for refurbishment and standards for new build, as well as considering what will affect operational emissions in the future, such as the decarbonisation of the grid and the uncertainty of user behaviour.

2.2.3 Floor areas

Existing literature regarding demolition and adaptation tends to focus on like-for-like replacements (Alba-Rodríguez et al., 2017; Gaspar and Santos, 2015; Weiler et al., 2017), which seems to be unrealistic. Baker and Moncaster's (2017) case study of a masterplan regeneration site in Cambridge, showed it is often desirable for developers to demolish existing buildings to build back bigger because of economic viability. Morelli et al. (2014) evaluate the decision of demolition versus adaptation economically. Their evaluation favoured the renovation of a multi-family 1850-1930 house in Denmark over new build. However, values given are per m^2, it is likely that the square meterage will be increased for new buildings. If this is the case, there will then be higher returns on the building due to the higher floor areas.

Changing floor areas were acknowledged by Wastiels et al. (2016) who evaluated different options for a single family house in Belgium. Although the house remained at three stories, in the new build option the basement and attic became useable creating a 78% increase in useable floor space from the renovation strategy. Their results showed that the environmental impact of the new building was approximately 20% higher than the box-in-box renovation. At the end of their paper, they discuss how the new build performs better per square meter of heated floor space. Although this is true, this type of analysis needs to be treated with caution. If the existing building is replaced by a larger building and not a like-for-like construction the absolute figure for environmental impact will be higher and unrepresentative if viewed on a CO2e/m^2 basis.

3 Methodology

This paper reports on part of a 3-year PhD project assessing the decision to demolish or adapt existing buildings on masterplan sites, where the consideration of embodied energy has been identified as an important aspect to consider (Baker et al., 2017). A quantitative analysis is used to demonstrate how the inclusion of different factors can influence LCAs and a qualitative analysis reflects current viewpoints towards the consideration of embodied energy in decision-making.

3.1 Quantitative analysis

The quantitative analysis uses secondary data to assess how the inclusion of 'sunk costs'; decarbonisation of the grid; and changing floor areas, affect the outcome of LCAs. Data was selected by evaluating whether appropriate figures required to assess the factor were included in the paper/report. Primary data was not used because the purpose of this paper is to demonstrate different concepts and how LCA figures can change depending on the inclusion or exclusion of these factors, thus wasn't deemed necessary.

3.1.1 Potential impact of 'sunk costs' (emissions associated with existing materials)

Using data from two papers: Weiler et al. (2017) and Gaspar and Santos (2015), the effect of including 'sunk costs' was evaluated by calculating the percentage change in the embodied emissions with and without its inclusion.

Weiler et al. (2017) provide scenarios including and excluding emissions calculated for the existing structure. These values have been used to calculate the 'sunk costs' (see Equations 1-3). Gaspar and Santos (2015) provide data for three scenarios, these are outlined in Table 2. The values determined as 'sunk costs' for the purposes of this paper are identified.

$$\text{Medium Refurbishment Sunk Costs} = R^M\text{ALL:P} - R^M\text{RefOnly:P} \qquad (1)$$

$$\text{Advanced Refurbishment Sunk Costs} = R^A\text{ALL:P} - R^A\text{RefOnly:P} \qquad (2)$$

$$\text{New Build Sunk Costs} = 1975\text{:P} \qquad (3)$$

Where:

1975:P	Production emissions: 1975 existing structure
R^MALL:P	Production emissions: Medium refurbishment including embodied emissions in existing structure
R^MRefOnly:P	Production emissions: Medium refurbishment excluding embodied emissions in existing structure
R^AALL:P	Production emissions: Advanced refurbishment including embodied emissions in existing structure
R^ARefOnly:P	Production emissions: Advanced refurbishment excluding embodied emissions in existing structure

Table 2: Scenarios and values identified as 'sunk costs' using Gasper and Santos (2015) data

	Scenario E (Existing structure)	**Scenario N** (New build structure)	**Scenario R** (Refurbishment)	
			Outputs (emissions associated with remaining structure)	**Inputs** (new materials required for refurbishment
Embodied energy (GJ)	New build sunk costs		Refurbishment sunk costs	

3.1.2 Operational energy levels and decarbonisation

Using values from Weiler et al's (2017) paper, the effect of decarbonisation is analysed.

Weiler et al. (2017) provided final figures for:

- Primary energy during the whole lifecycle (50 years) in kWh
- Greenhouse gases emitted during the whole lifecycle (50 years) in kgCO_2e

An approximate emission factor was calculated using Equation 4 producing a value of 0.279 kgCO_2e/kWh (see Table 3). In the UK, the Government aims to reduce carbon emissions by 34% by 2020 and 80% by 2050 compared to 1990 levels (HM

Government, 2008). Table 4, displays the adjusted emission factors and annual emissions if these values are used to decarbonise the grid and applied to the initial emission factor. It is important to note that these emission factors and decarbonisation figures are unlikely to be accurate, however they are being used to demonstrate a concept and the potential effect of decarbonising the grid. Annual operational energy and emissions have been calculated using Equations 5 and 6. The method used to calculate cumulative emissions on a yearly basis is shown in Fig. 3, this was applied to Weiler et al's scenarios (excluding existing emissions).

$$Emission\ factor = \frac{Greenhouse\ gases\ emitted\ during\ the\ whole\ life\ cycle\ in\ kgCO_2e}{Primary\ energy\ during\ the\ whole\ life\ cycle\ in\ kWh} \quad (4)$$

$$Annual\ operational\ energy\ in\ kWh = \frac{Total\ use\ stage\ energy\ using\ 50\ year\ life\ span}{50} \quad (5)$$

$$Annual\ emissions = Annual\ operation\ energy\ in\ kWh \times emission\ factor \quad (6)$$

Table 3: Calculations for emission factor and annual operational energy using data from Weiler et al (2017) study. See equations 4 and 5

	Figures provided by Weiler et al (2017)		Calculated figures for this paper	
	Greenhouse gases emitted during 50 years (use stage only) - $kgCO_2e$	Primary use stage energy during 50 year life-cycle - kWh	Emission factor calculated (see equation 4) - $kgCO_2e/kWh$	Annual operational energy (see equation 5) - kWh
Original construction	2,950,200	10,570,900	0.279 (3sf)	211,418
Medium refurbishment	1,554,000	5,568,250	0.279 (3sf)	111,365
Advanced refurbishment	1,259,350	4,512,500	0.279 (3sf)	90,250
New build	1,410,400	5,053,650	0.279 (3sf)	101,073

Table 4: Approximate emission factors and average operational annual emissions taking into account decarbonisation (see equation 6). Original data used: Weiler et al (2017)

		<2020	2020-2049	>2050
Emission factor used* $kgCO_2e/kWh$ (3sf)		0.279	0.184 (34% reduction)	0.056 (80% reduction)
Average annual operational emissions calculated for this analysis (see equation 6) - $kgCO_2e$*	Original construction	59,004	38,943	11,801
	Medium refurbishment	31,080	20,513	6,216
	Advanced refurbishment	25,187	16,623	5,037
	New build	28,208	18,617	5,642

*Use with caution. Rough results obtained for the purposes of demonstrating a concept

	A	B	C	D
1	**Year**	**Medium refurbishment cumulative emissions – <u>including decarbonisation</u>**	**Medium refurbishment cumulative emissions – <u>not including decarbonisation</u>**	**Description**
2	2016	103921	103921	Production emissions for medium refurbishment
3	2017	=B2+31080	=B2+31080	Production emissions + annual operational emissions
4	2018	=B3+31080	=B3+31080	"-"
5	2019	=B4+31080	=B4+31080	"-"
6	2020	=B5+20513	=B5+31080	"-"
7	2021	=B6+20513	=B6+31080	"-"
....	...	...	...	...
35	2049	=B34+20513	=B34+31080	"-"
36	2050	=B35+6216	=B35+31080	"-"
37	2051	=B36+6216	=B36+31080	"-"

Change in annual emissions when decarbonisation considered. Assumption that emission factors reduce in 2020 and 2050 (see Table 3).

Figure 3: Method used to calculate cumulative emissions. Data used: Weiler et al (2017)

3.1.3 Floor areas

In Weiler et al's (2017) study the building is a like-for-like replacement. This paper uses values obtained per m^2 to assess absolute (total) values for environmental impact and at which point the medium refurbishment, which currently has the highest environmental impact is equal to the new build's impact as the new build's floor area increases. The same method is then applied to the values obtained in Pomponi and Moncaster's (2016b) study.

The useable heated floor area provided in Weiler et al.'s (2017) paper is 1635m^2, this was used to calculate the emissions per m^2 for the new build scenario using equation 7, equation 8 shows the actual values used. A calculation was not required for the refurbishments as it is assumed their floor areas remain constant. The method used to calculate the effect of increasing floor area and when the absolute value of new build exceeds the refurbishment strategy is shown in Fig. 4.

$$New\ build\ emissions\ per\ m^2 = \frac{Total\ emissions\ for\ new\ build\ scenario}{Useable\ heated\ floor\ area} \quad (7)$$

$$New\ build\ emissions\ per\ m^2 = \frac{1{,}657{,}793\ kgCO_2e}{1635\ m^2} = 1013.9\ kgCO_2e/m^2 \quad (8)$$

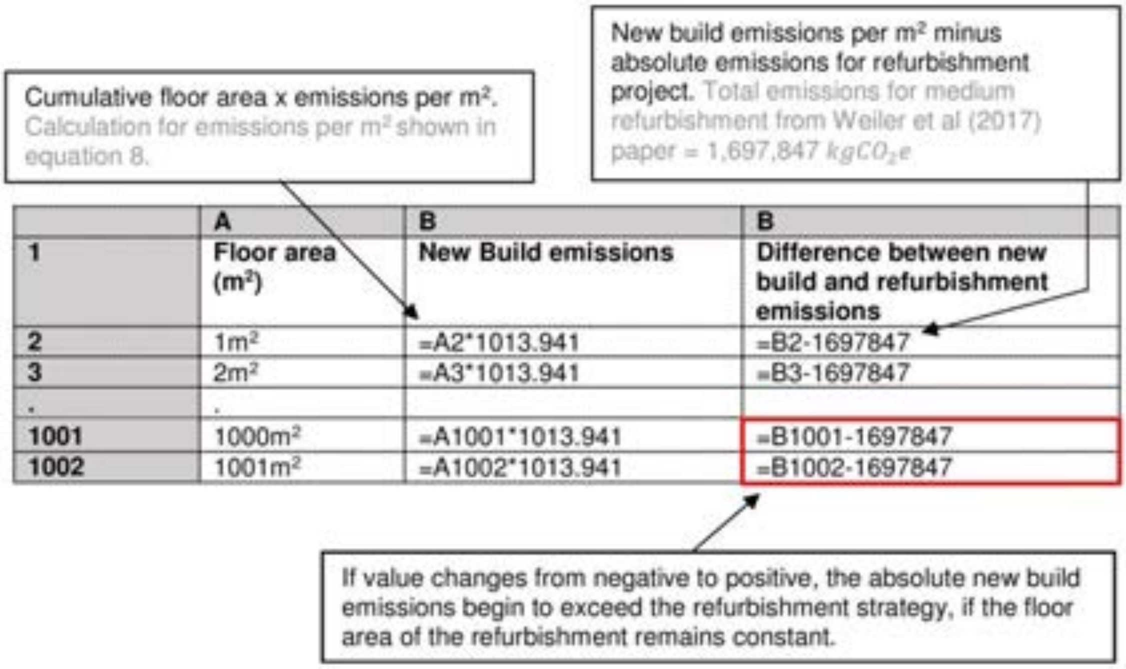

Figure 4: Method used to calculate absolute carbon emissions as floor area increases.
Data used: Weiler et al (2017)

3.2 Qualitative analysis

Two focus group discussions were analysed to investigate current attitudes towards embodied carbon. These focus groups took place as part of a UK embodied energy symposium in April 2016 with industry and academic experts in the built environment (see De Wolf et al., 2017 for more details). Each focus group lasted 40 minutes and included 8-9 people. The question discussed was:

"*How can embodied energy be incorporated in the decision to demolish or retain existing buildings*?"

Initially everyone was asked for their viewpoint 'one-by-one' and then the topic opened up for discussion. The focus groups were recorded (permission was obtained by participants) and transcribed. These were analysed to evaluate what key themes emerged using grounded theory methods, where qualitative data is coded (Silverman, 2013). Two iterations of coding have been completed to date. In the analysis these codes are referred to as 'discussion points'.

4 Analysis

4.1 Quantitative analysis

4.1.1 Potential impact of including existing emissions

Figure 5 shows two bar charts indicating the embodied emissions for the production lifecycle stages with and without the emissions associated with the existing structure (sunk costs). The overall values increase by 36.7-49.0% in Gaspar's study and 73.8%-89.0% in Weiler et al's. Although their inclusion does not affect how the strategies of refurbishment measures and new build rank against one another, there is a percentage change in the difference between them. For example in Gaspar and Santos's study, if

the existing emissions are included the percentage difference between the two strategies is 28.3%. If the 'sunk costs' are excluded the percentage difference is 17.8%. This is unsurprising as the new build strategy considers 100% of the existing structure and the refurbishment strategy only includes 64%. As shown by Figure 6, when the whole life cycle is taken into account the proportion of emissions is significantly reduced to 5.4 – 9.3% in Weiler et al's study, but still affects final figures for LCAs.

This paper agrees with Erlandsson and Levin's (2005) viewpoint that these are historical emissions and should be dismissed and with Weiler et al. (2017) who state that the emissions associated with the existing building should not be included when comparing a refurbishment strategy to demolition and new build. The existing emissions are difficult to account for and have already been invested. The changes in values that they cause may lead to misleading results. Instead, the energy required to demolish the existing structure should be included in the calculations for replacement buildings as these emissions have not already been invested.

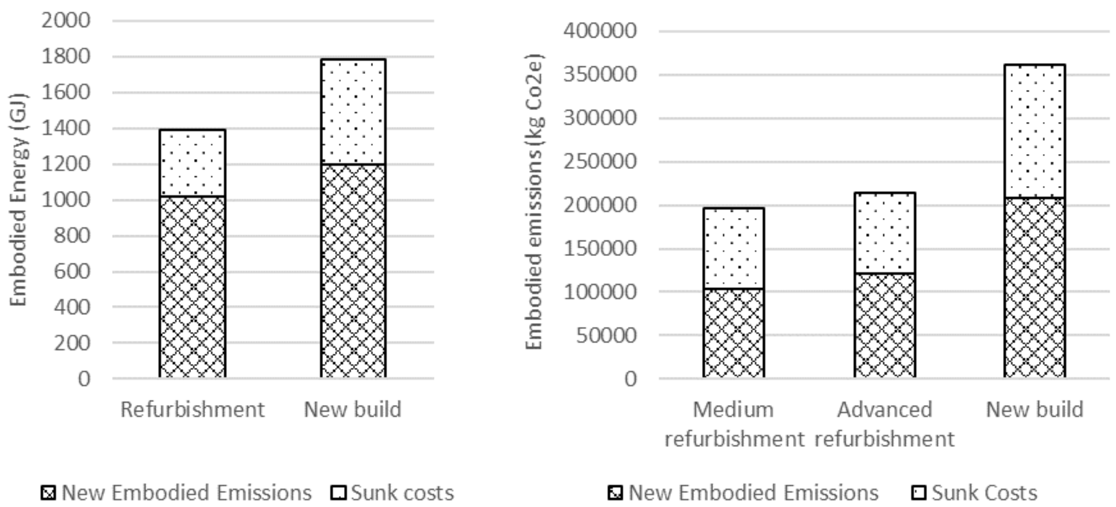

Figure 5: Inclusion of existing emissions (sunk costs) in the production lifecycle stage.
Data sources: Left: Gaspar and Santos (2015); Right: Weiler et al (2017)

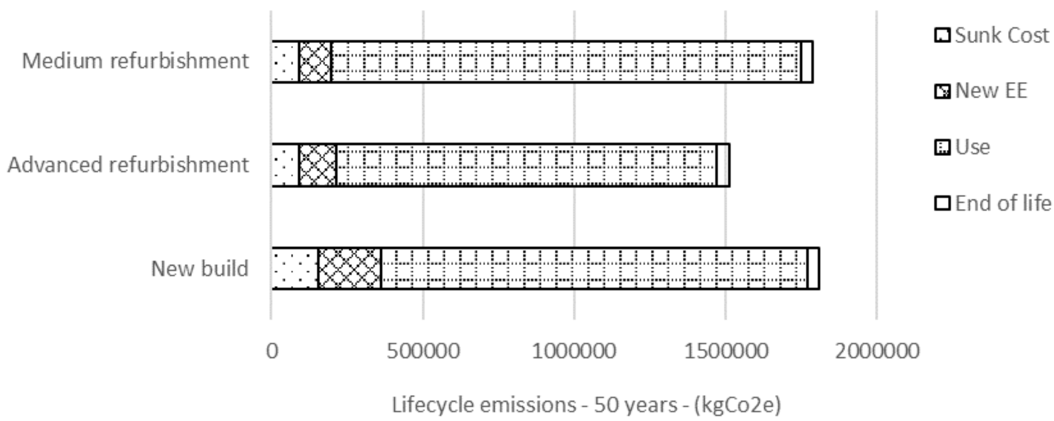

Figure 6: Inclusion of existing emissions (sunk costs) in whole lifecycle.
Data source: Weiler et al (2017)

4.1.2 Operational energy

When decarbonisation of the grid is included in the annual operational emissions for Weiler et al.'s study, the overall lifecycle impact of all three scenarios reduces. In the original scenarios which excluded decarbonisation (Figure 7), the existing 1975 building with no change had the highest environmental impact; followed by the medium refurbishment; new build and then advanced refurbishment. In the example shown, the cumulative emissions for the medium refurbishment exceed the new build after 37 years, because the value calculated for the operational energy is 10.2% higher than the new. When decarbonisation is included, the cumulative emissions for the medium refurbishment do not exceed the new build (Figure 8) within the 50 year lifespan. Although the new build continues to use less operational energy, the carbon emissions associated with this are lower. A rough calculation shows that in this scenario the medium refurbishment's emissions will exceed the new build after 90 years, also emphasising the importance that lifespans can have on decision-making.

This simple analysis is important as it indicates that less intense refurbishment strategies may have lower life cycle impacts than more energy efficient new build over set lifespans if decarbonisation is included. However, it must be acknowledged that the calculated figures are approximations to demonstrate a concept, in reality they will be subject to uncertainty related to LCA and the decarbonisation of the grid. For example, it cannot be guaranteed how the grid will decarbonise in the future and issues such as the 'rebound effect' referred to in this paper's literature review are not considered.

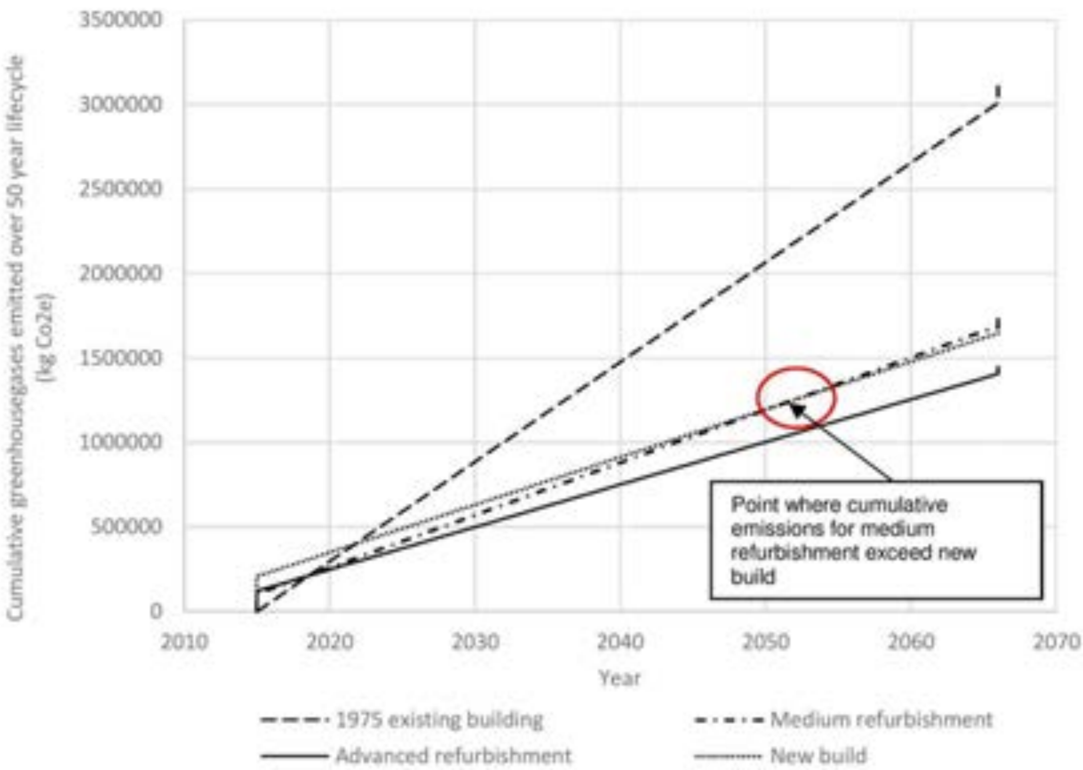

Figure 7: Cumulative emissions over 50 year lifespan <u>excluding</u> decarbonisation of the grid. Original data source: Weiler et al (2017)

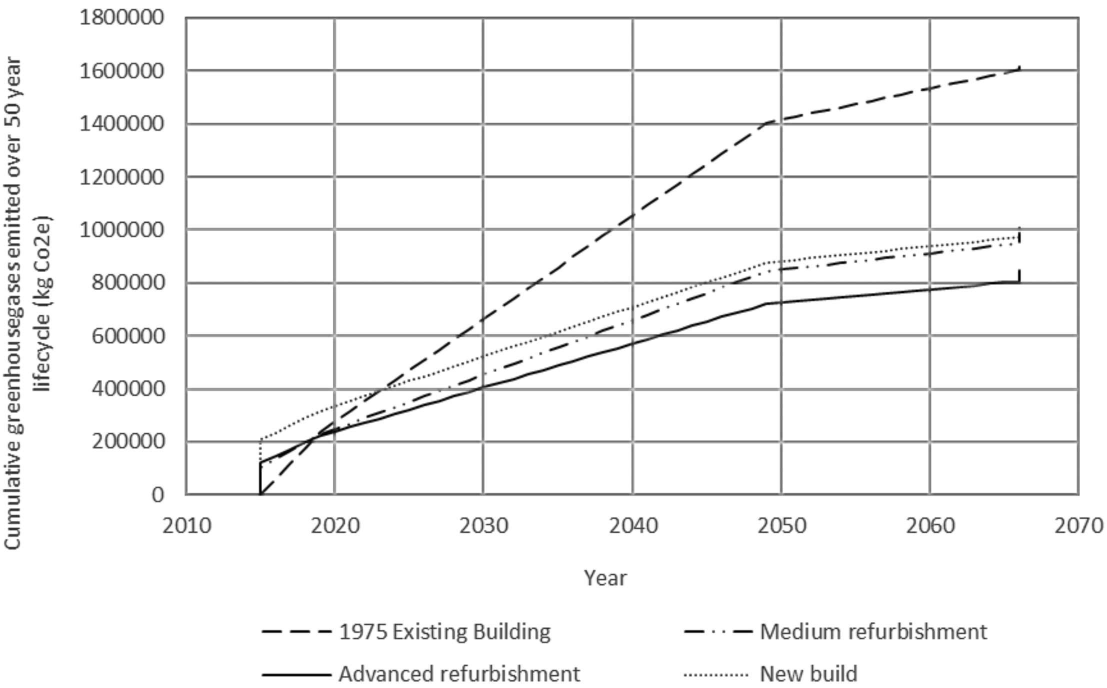

Figure 8: Cumulative emissions over 50 year lifespan including decarbonisation of the grid.
Original data source: Weiler et al (2017)

4.1.3 Floor areas

Figure 9 indicates when absolute (total) emissions for the new build scenario exceed the refurbishment scenario by increasing the floor area of the new build and keeping the floor area of the refurbishment constant. In Pomponi and Moncaster's (2016b) study the average floor area for the original refurbishment was 398 m^2, producing 367,000kgCO_2e (average value across the three consultants). At this floor area, the new build refurbishment produces 298,000kgCO_2e. In reality, new buildings are built bigger than the existing building which is demolished. The total emissions for the new build equal the emissions of the refurbishment (with 398 m^2 floor area) when the new build's floor area increases to 490m^2, a 23% increase.

In Weiler et al.'s study, the existing building's useable floor area was 1635m^2, with absolute emissions of 1.70million kgCO_2e for the medium refurbishment and 1.66million kgCO_2e (3sf) for the new build. If the new build's floor area increases to 1766 m^2, an 8% increase, absolute/total emissions begin to exceed the emissions for the medium refurbishment (1.66million kgCO_2e) where the floor area has remained constant.

These simple calculations have emphasised the importance of not just considered like-for-like replacements and values per m^2. If looking at the environmental impact of a new build against refurbishment, it is likely the floor area will increase, thus the absolute (total) emissions should be considered.

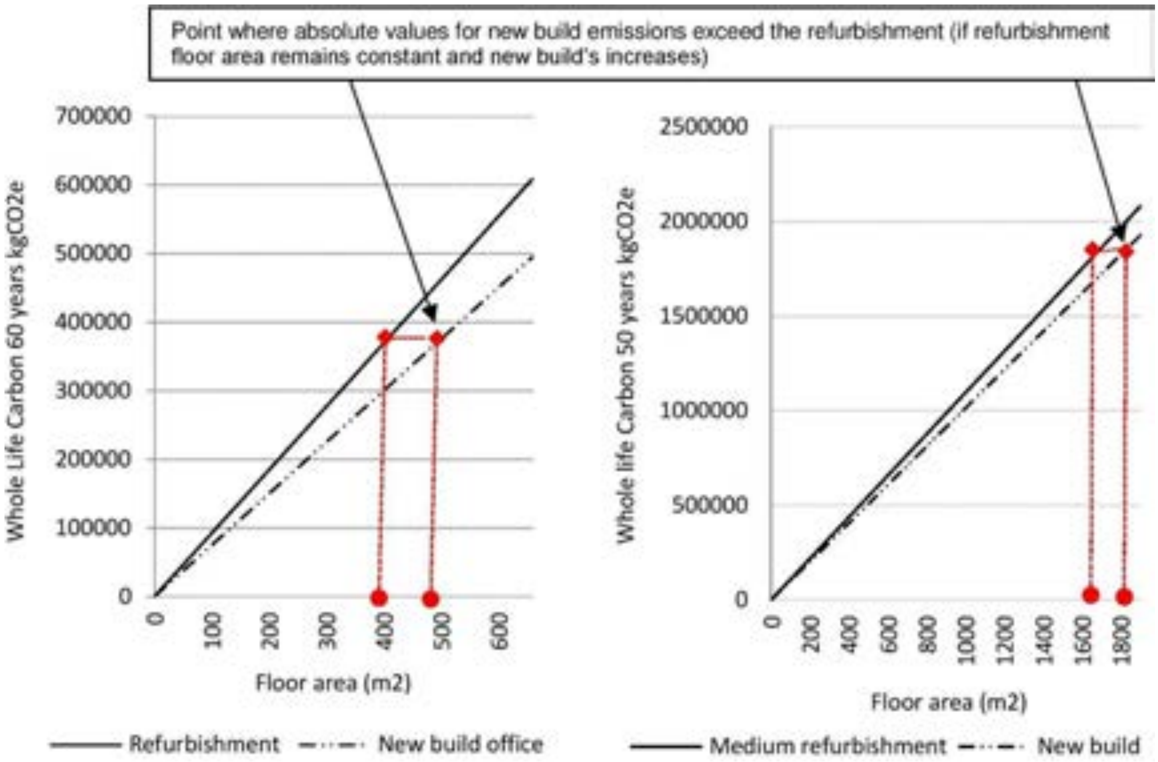

Figure 9: Increasing floor area and the associated emissions for refurbishment and new build.
Data source: Left: Pomponi and Moncaster (2016b); Right: Weiler et al (2017)

4.2 Qualitative analysis

The focus group discussions covered a range of discussion points related to embodied emissions including: current practice; problems; general statements; suggested changes and potential issues with the suggested changes. Overall 48 separate codes were defined. Fifteen of the topics were only raised once and other topics more frequently, topics raised five or more times are shown in Fig. 10.

The participants felt that the decision to demolish or adapt existing buildings is currently influenced by other factors including: economics; floors areas and heritage values. If embodied emissions are considered, it comes after these factors. One of the reasons given for the lack of consideration was the difficulty in valuing embodied emissions. If evaluating operational energy, it is seen as easier to link with economic savings. In some cases, the participants felt that embodied emissions are reduced as a consequence of other factors, for example reducing material to save on capital costs, consequently reducing embodied emissions.

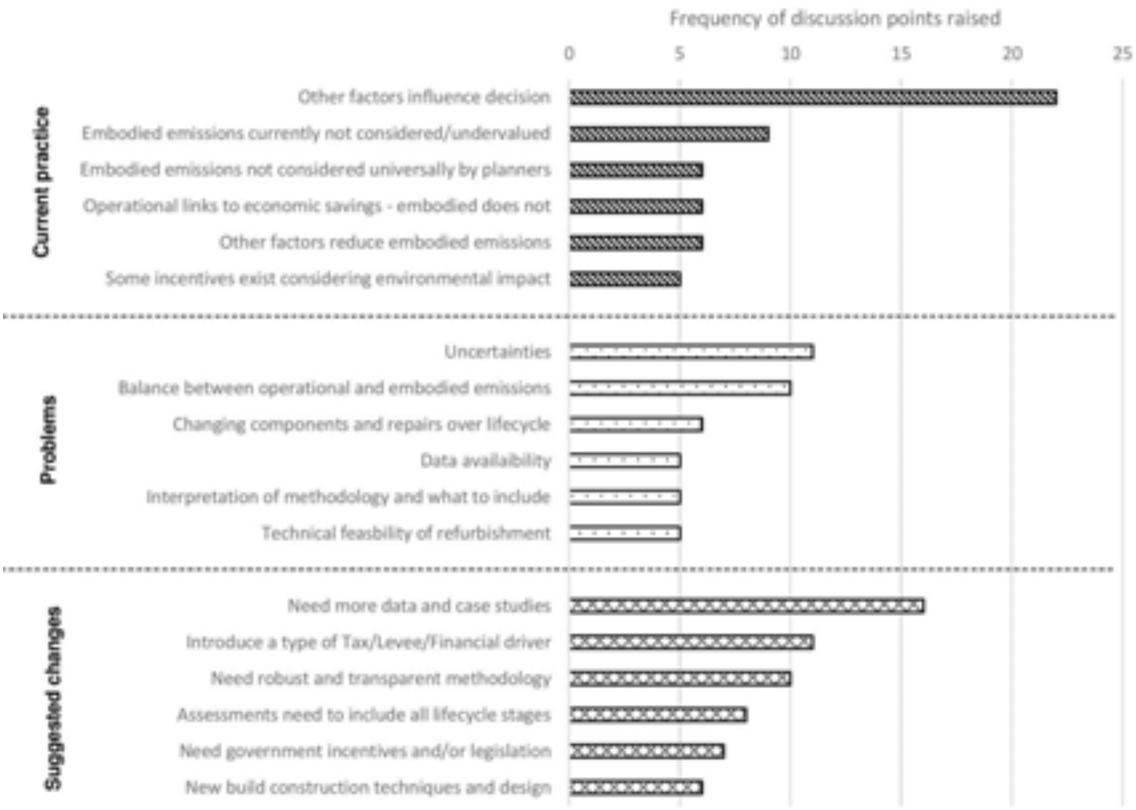

Figure 10: Points of discussion during focus groups. Only showing those with frequency of 5 or more

The problems identified helped to explain why embodied emissions are not yet universally considered, although the majority of participants felt that they should be. A regularly discussed problem was factoring in uncertainties, such as unknown lifespans and changing occupancies. Participants felt that there is still a lack of data regarding emissions over building lifecycles for new build and refurbishment. As a result, participants felt more data is needed to help reduce uncertainty and improve the transparency and robustness of the methodology, a topic regularly discussed as requiring change. These changes are required to implement other suggested improvements including: government incentives; requiring an LCA assessment as part of planning and/or introducing taxes or other financial drivers.

Overall this qualitative analysis has emphasised that the consideration of embodied emissions sits within a complex network of other factors that need to be considered. For it to have more weight in the decision-making process, problems identified such as uncertainties with the methodology and lack of data need to be overcome. One way this could be accomplished is through more cases studies.

5 Conclusions

Embodied and operational energy are important to consider in the built environment because of the emissions associated with them and link to climate change. This paper has reviewed existing literature assessing the life cycle impact of adaptation compared to demolition and new build. The majority of papers reviewed found that over a given lifetime, usually between 50-60 years, refurbishment strategies had lower environmental

impacts than demolition and new build. However, as identified by Dubois and Allacker (2015), these tend to be significant renovations, rather than smaller retrofits. From the literature review three factors were identified as a critique of existing research methodologies. These included: whether or not emissions associated with the existing structure should be included; operational energy levels and whether decarbonisation of the grid should be included; and considering absolute values for emissions rather than per meterage as new build is rarely a like-for-like replacement. These three factors were then assessed through a quantitative analysis and the following conclusions were made:

- Emissions associated with the existing structure should not be included in assessments comparing refurbishment to demolition and new build as they are historical. However, it is important the emissions associated with the demolition of these structures is included in the calculations for the new build as these have not already been 'spent'.
- Various levels of refurbishment and standards for new build's operational energy need to be considered.
- Commonly the operational emissions of new build are lower than medium and less intense refurbishment scenarios. Although, there is a higher investment of embodied emissions for new build, over the lifecycle of buildings, new builds may be favourable to medium refurbishments. However, the UK and other countries are aiming to decarbonise the grid, if this happens, the emissions associated with the operating energy of these buildings will be reduced. This may favour less 'extreme' refurbishments as they often begin with a lower investment of embodied emissions.
- Absolute (total) values for lifecycle emissions should be considered when comparing refurbishment to demolition and new build because it is common for replacement buildings to have larger floor areas. Like-for-like replacements are unrealistic in urban development scenarios.

A qualitative analysis concluded that for embodied carbon to be considered in decision-making, there still needs to be improvements in the methodology. This can be achieved by collecting more data and conducting additional case studies. Once improved methodology and data are available, legislation can be introduced equivalent to that for considering and reducing operational carbon.

Overall, the literature review and quantitative analysis showed that there are methodological issues when comparing refurbishment to demolition and new build projects, including which factors should be considered. This statement is supported by the focus group discussion where problems related to current methods and the need to improve the robustness were regularly discussed. Both the analyses build upon the existing research identifying key concepts which need to be addressed and improved if considering embodied emissions in the decision to demolish or adapt existing buildings.

6 Limitations and Further Work

This paper has demonstrated how particular factors affect environment assessments using secondary data and assumptions outlined in the methodology. The aim was to demonstrate whether these concepts should be considered in decision-making, not to provide accurate quantitative figures. Further work will include a new case study investigation comparing the decision between demolition and adaptation whilst taking the recommended factors into account. The qualitative assessment will be extended to

include viewpoints provided during interviews conducted for the PhD project which this paper forms part of looking at the decision of demolition and adaptation holistically.

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SUSTAINABLE CONSTRUCTION IN THE CONTEXT OF SMART VILLAGES IN ASSAM

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Abstract: *The state of Assam comprises an area of 78440 sq. km, and is considered to be an epicentre for the economic development of the North-eastern states of India. Urban renewal receives considerable Government and industry attention, aimed towards the creation of smart cities. However, 85.90% of population of Assam lives in rural. This demands a shift in emphasis towards rural empowerment. While the rural households are generally made of locally available materials, such as bamboo, the recent trend for using the reinforced cement concrete has been growing among the middle class. The Assam Type House, a common housing typology, was introduced during the colonial rule and is constructed by using locally available materials such as bamboo, wood, Ekra and mud, with the roofing made of Kher (a type of grass), asbestos or iron sheets (where available). However, the use of the traditional materials is currently being replaced by bricks, cement plaster, and reinforced concrete pillars. This trend is due to the general belief that concrete structures are generally stronger and more durable as compared to the traditional Assam Type House. Currently, there is no any scientific evaluation on the use of modern materials in the context of sustainability and the triple bottom line (TBL) assessments. This research provides first-hand insights of the present situation in the state of Assam regarding the construction and management of these two forms of housing, and provides an in-depth analysis and comparison in the context of an international best practice. The findings are expected to provide a clear guide for establishing a benchmark for promoting sustainable practices among the local industries.*

Keywords: *Assam, Kher, Ekra, Assam Type House*

1 Introduction

Assam is a state in the north-eastern part of India comprising an area of 78,440 sq. Km, with its capital located at Dispur (26.14°N, 91.77°E). Geographically; it is located to the south of the eastern Himalayan mountain range. The mighty river Brahmaputra flows through the heart of the state of Assam from the east to west, dividing the state into south bank and the north bank. Assam is well known for its Tea and Silk. It is the home of Indian one horned rhinoceros; Digboi in Assam is the place where the first crude oil well was drilled in Asia in the late 19th century and a refinery was setup in the year 1901 and is still in operation. The main economy of Assam evolves around the Tea, Wildlife Tourism and Oil Industry. However, a recent change in the economy towards construction industry, agricultural production has been observed, with the government prioritising the infrastructural development in the North-eastern part of India due to economic and strategic reasons.

The population census of India, 2011, reports that the population of the State of Assam is 31,205,576. Table 1 and Figure 1 below provide a statement of parameters associated with the population status of Assam.

Table 1: Population status of Assam

Population	Growth rate (%)	Area (sq.km)	Population Density	Sex Ratio (female per 1000 males)	Literacy ratio	Rural Population
31,205,576	17.07	78438	398	958	72.19	26,807,034

Source: www.census2011.co.in

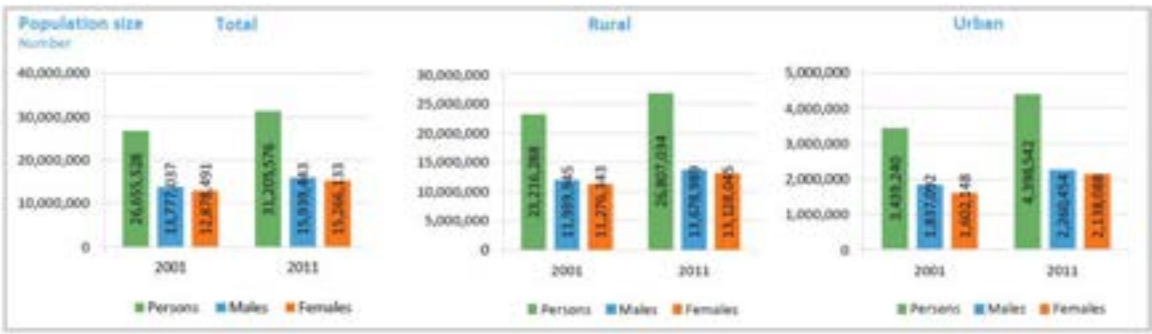

Figure 1: Comparison of Census data of 2001 and 2011 of urban and rural population of Assam (Source: www.pnrdassam.nic.in/documents/IND018_Assam.pdf)

85.90 % of the population of Assam lives in the rural areas, and there are 26395 villages in Assam (source: pnrdassam.nic.in). The main livelihood of the rural population of Assam is agriculture. However, with rapid increase is the population and decreasing livelihood avenues in the rural areas, migration of towards the urban areas seeking a better livelihood have been observed. This has caused many problems, the urban centres has become over populated with the increase of the migrant population and are not being able to provide the basic civic amenities to the citizens. Further, not all the migrant population finds a better livelihood. Alternatively, if the rural population can be provided better options of living in the rural areas, it may stop the migration of the rural masses to the urban areas.

2 Objective

This research attempts at providing a first-hand insight of the present situation in the state of Assam regarding the construction and management of two forms of housing, viz, Reinforced Cement Concrete (RCC) type and Assam Type Housing (ATH). This paper also attempts to provide an analysis and comparison in the context of an international best practice. The findings are expected to provide a clear guide for establishing a benchmark for promoting sustainable practices among the local industries.

3 "Assam-Type" House (ATH) and its construction in Rural Assam

The various traditional construction practice and housing types prevailing today in different regions of the world have evolved based on technology transferred from one generation to the next by word of mouth or by some documentation by practicing masons and end users (Patwari, 2017). What is important is that these construction practices often have characteristics that address the prevalent local conditions of weather and other environmental and natural hazards viz. earthquakes, flood, and cyclone (BMTPC, 1999). There is much to study and learn from these housing practices. The ATH is one such construction practice which has the potential to emerge again as one of the most sustainable, flood resilient and earthquake-safe housing in the north-eastern part of India.

This form of construction was promoted by the government in the past, and the Assam Public Works Department had the specifications for such buildings in their standard and schedules, encouraging this practice in the constructions by various government departments. It has been a matter of concern that in the last decade, this earthquake safe construction practice has lost its applicability in the housing sector owing to the emphasis on vertical expansion of the urban centres., However, the sub-urban and semi-urban areas still provide an opportunity for this construction practice as the best alternative for sustainable and earthquake resistant housing where adequate spaces are available for planning (Nath et al., 2010). This can be substantiated from the fact that more than 80 % of the population of Assam lives in the rural areas.

3.1 Assam Type House (ATH)-a brief review

The Assam Type House, a common housing typology, was introduced during the colonial rule. This construction type is in use for the last 200 years in Assam (Kaushik and Babu, 2009). This type of houses is a common feature in the north-eastern states of India. The Ekra type houses (as in Figure 2) is also found in the Gangetic plains of Central India, Bangladesh, Myanmar, Thailand, Cambodia etc. (Kaushik and Babu, 2009). However, based on the local conditions and customs the houses may be a bit different in their planning and layout. The Ekra type houses is no longer used in the urban areas, however, in some rural areas where Ekra is available it is still used in the rural areas, but is not a preferred mode of housing.

The Assam Type house is generally a single storey house; however, two storey store houses are also built. Assam type houses of more than two storeys are rare. The following points discuss in general the components of an Assam Type House.

Plinth: They are generally constructed on a raised plinth. The raised plinth is provided to avoid reptiles, marshy land, dense vegetation, and stagnant water, floods etc.

Frame: The main frame consisting of the pillars and bracings etc. of the building is made up of bamboo or timber or steel depending on the purchasing level of the owner. While the bamboo frame one is generally erected by the house owner themselves with help of

their family members, the timber ones need the specific inputs of a specialist. Figure 7 below shows an Assam Type House nearing 100 year of lifespan, where steel has been used for the frames. The steel used was imported from England about 100 years back (Hazarika and Verma, 2017). Another example where steel was imported for construction of the pillars is the Haflong Circuit House in Haflong, Assam as shown in Figure 8. The pillars were manufactured and shipped from M/s Dorman Long Technology, a British Consultancy Company.

Figure 7: Assam Type House in Guwahati, Assam. (Hazarika and Verma, 2017)

Figure 8: Steel pillar of Haflong Circuit House

Walls: The walls are generally made up of mats of ekra or bamboo weaved together. On top of the mat mud and cowdung mixture or cement plaster is used to give a smooth finish. In some cases the walls are constructed of bricks up to the sill level and above that the provision of walls as mentioned earlier is provided.

Windows: Windows are generally made of timber and may or may not consist of glass panels for the lighting purposes.

Ventilations: Ventilators are generally provided in the roof level. The ventilators are openings made up of timber in most cases.

Roof Truss: Roof truss made of timber, however in modern days trusses made of steel is also prevalent.

Roofing: Roofs made of thatch leaves, Kher, steel sheets and asbestos sheets are found in the Assam types of houses.

Sanitation Facilities: Generally the sanitation facilities are provided separately from the main structure. However, in the present days, attached sanitation facilities can be seen in most of the houses.

Heating and Cooling: Provision of heating and cooling are generally not an integral part of the Assam Type House as the climate is not so extreme. However, in some areas where the temperature dips to very low ranges people who can afford do install a fire place inside the house.

Materials used: An Assam Type House typically is constructed by using locally available materials such as bamboo, wood, Ekra and mud, with the roofing made of Kher (a type of grass), and asbestos or Galvanized Iron sheets (where available). However,

the use of the traditional materials is currently being replaced by bricks, cement plaster, and reinforced concrete pillars.

4 Reinforced Cement Concrete (RCC) and its construction in Assam

The Reinforced Concrete Frame Buildings type of housing is becoming increasing popular across the country, particularly for urban construction. The construction of reinforced concrete buildings with brick masonry infill walls has been a very common practice in urban India for the last 25 years. It employs beams–columns frame structure with slabs to form the basic backbone for carrying the loads. The vertical walls made of masonry or other materials are used as infill in between the beam-column grids to make functional spaces. These houses are expected to be constructed based on engineering calculations. However, in a large part of the country, such buildings are being built with little or no engineering intervention or design. In many areas, most of this construction has been designed for gravity loads only, in violation of the Code of Indian Standards for earthquake-resistant design. These buildings performed very poorly during the Bhuj earthquake of January 2001 and several thousand buildings collapsed. The seismic vulnerability of this construction is clearly demonstrated by the collapse of about 75 RCC frame buildings and damage to several thousand others in and around Ahmedabad, which is over 250 km from the epicenter (Jain et al., 2001). The state of Assam and the entire north-eastern region of India lie in the seismic zone V(BIS-2002) and hence the challenge for any construction practice is its sustainability regarding both safety and economy. The RCC type housing in the rural areas is very limited and is generally constructed after going through the three stages of planning, design and construction. Indian standard codes NBC-2016, BIS-2000, BIS-2002, SP 16-1980 are followed for the design and construction of the RCC type houses in Assam. This construction process is generally monitored by regulating agencies in the urban and semi-urban areas. However, in the rural areas there is a lack of any regulating agency for regulating the construction of RCC type houses.

5 Housing Types in rural Assam: Recent trend

While the rural households in Assam are generally made of locally available materials, such as bamboo, the recent trend for using the reinforced cement concrete has been growing among the middle class. This trend is evident both in the urban, semi urban and rural areas. This trend is due to the general belief that concrete structures are generally stronger and more durable as compared to the traditional Assam Type House.

Two common types of housing type found in the rural Assam are the Assam Type House which is built on a raised plinth and the second type of house which is built on elevated platforms. The former type of house is commonly built in the plain areas of rural Assam where the area is highland and not subjected to floods. However, the second type of house is generally preferred by the tribal people generally living in the flood plain and on the hilly areas.

Das et. al. (2014) had differentiated and discussed about four distinct type of traditional houses in Assam, viz., Ikra House, Mud House, Chang House and Bamboo House and has been described pictorially in Figure 2, 3, 4 & 5 respectively.

Figure 2: (a) Ikra in the foreground for construction of walls, an Ekra house behind (b) A constructed ekra wall panel for use. (Source: www.db.world-housing.net)

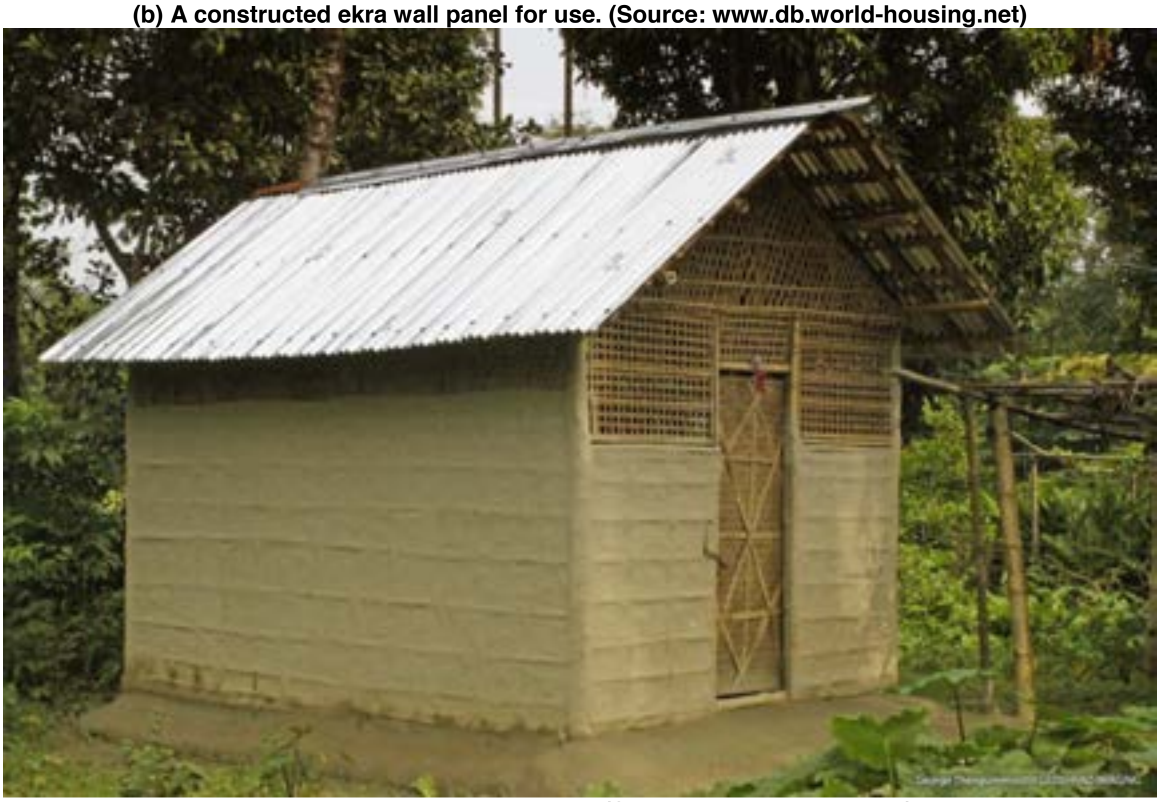

Figure 3: A Typical Mud House (Source:www.theindia.info)

Figure 4: A Typical Chang House (Source:www.downtoearth.org.in)

(a) **(b)**

Figure 5(a): A Typical Bamboo House (Source:www.zogam.com)
(b) A Typical Bamboo House in elevated platform

Das et al (2014) has identified four distinct types of house types is would be best to define the housing types as basically of two types, one on raised plinth and another on raised platform. The above two may be divided in various subcategories depending on the level of finishing given to the housing types. For example, a house owner may not choose to give a finishing of mud on the walls, while another may go for use of cement plaster on the walls. The walls itself may be made either of ekra or bamboo, the two most preferred form of wall materials for construction of wall panels in the rural area owing to it low cost and easy availability. The wall panels are them plastered with

two/three layers in case of a mud house. First layer consists of wet mud-cow dung mixture, a second layer of mud-cow dung layer may be provided in case the first layer is not of sufficient thickness. The mud-cow dung layer is then topped with only a wet mixture of mud to give a better finish and colour. The floors are also finished using the same mixture. However, in case of houses on elevated platforms, floors may be made of timber (depending on availability) or bamboo.

However, with the passage of time the rural masses have started building various modified types of the so-called Assam Type House. Figure 6 (a) to (f) provides a glimpse of a few types of the Assam type houses generally prevalent in the rural areas of Assam in the present time.

(a) Assam Type House
(Source: igsss.org)

(b) Assam Type House
(Source: earthquakeengineeringblog.worldpress.com)

(c) Assam Type House
(Source: thetelegraph.com)

(d) Assam Type House
(Source: www.housing.com)

(e) Assam Type House
(Source: downtoearth.org.in)

(f) Assam Type House
(Source: nelive.in)

Figure 6(a), (b), (c), (d), (e) & (f): Various forms of Assam Type house found presently

6 Smart villages

Smart Villages can be defined as a village where the system enables the common people access to better housing facilities, good education, healthcare, clean drinking water, sanitation, healthy nutrition, gender equality, demographic engagement and better avenues for the growth of productive enterprises to boost incomes, and enhanced security (Smart Villages, 2017). After the success of Millennium Development Goals (MDG), the world community is moving towards adopting Sustainable Development Goals (SDG). The United Nation General Assembly's Open Working Group on sustainable development forwarded to the Assembly its proposal contains 17 (Sustainable Development Knowledge Platform) goals with 169 targets covering broad range of sustainable development issues including ending poverty, hunger, improving health and education, making cities more sustainable, combating climate change, and protecting ocean and forest (United Nation Open Working Group, 2014).

6.1 Smart Villages, Sustainability and TBL assessment with a comparison to international standards

Considering the fact that more than 80 % of the population in Assam lives in the rural areas; holistic, inclusive and sustainable development of Assam is only possible with the sustainable development of rural Assam. As such various factors are required to be considered before moving forward in creation of a smart village. One such factor which plays in the creation of a smart village is provision of the basic need of a house for each and every household in the village. Sustainability in construction has to be achieved while pursuing for the provision of housing facilities to the rural masses. Assam is a land of many tribal populaces and each has their own customs which are quite different from each other. Various factors like the social acceptability, economic status etc has to be taken in to account while creation of housing facilities for the rural masses in the state of Assam. This will satisfy one factor leading to the creation of smart villages.

Sustainability is one of the most discussed and talked about but least understood words (Lafarge Holcim Foundation, 2015). Bruntland Commission (1987) report defines sustainable development as meeting the needs of the present without compromising the ability of the future generation to meet their own needs. Construction industry in case of building involves huge utilization of energy and resources. Buildings worldwide consume 30% of the planet earth's energy and 40 % of its resources generating about 40 % of the waste and emitting 35 % of the greenhouse gases (Vestian-Assetz Report, 2016). Considering the above fact it is imperative that a sustainable development policy for achieving sustainability in the construction industry is drafted.

A sustainable construction (development) involves the three broad themes of environmental, social and economic accountability, often known as the Triple Bottom Line (TBL).

- Economic sustainability: increasing profitability by providing for more efficient and judicial use of resources
- Environmental sustainability: protecting the surrounding environment from the terrible impact of emission, effluent and waste generated due to construction.

Social sustainability: recognising the needs and requirements of everyone impacted directly or indirectly by construction, from inception of a project to demolition.

Construction of houses in rural Assam is generally carried out often by unskilled / semi skilled construction workers. Very often the rural masses build their own houses made of

locally available materials the sustainability of which has yet to be established in detail. However, with the change in trend of the rural masses to build a brick and concrete house, the earlier housing types made of locally available materials have declined in acceptability.

The Triple Bottom Line (TBL) assessment for the housing facilities in context of smart villages in Assam holds importance as that will be set the acceptability criteria of the housing types developed based on various socio-economic and environmental aspects. This will give the rural masses a choice of getting themselves a suitable house based on their economic status, social relevance and religious acceptability. Table 2 provides the ratings of various performance based indicators. The performance based indicators adopted and provided in Table 2 are as proposed by Kamali and Hewage (2015). This basic table shows that although the current trend indicates a shifting toward the RCC type housing, it might be better to go for an ATH.

Table 2: Performance Indicators for TBL assessment

Performance Indicators	RCC House	Assam Type House
Economic considerations		
Cost of construction	High	Less compared to RCC
Materials Cost	High	Less
Design and construction time	High	Less
Design and construction costs	High	Less
Maintenance Costs	Relative	Relative
Durability of the Building	High	High
Flexibility	Not Known	Not Known
Integration of supply chain	Well organised	No well organised
Environmental considerations		
Electricity consumption	High	Less
Solid waste generation	High	Minimal
Change in land use/land cover	High	Minimal
Renewable energy use	Relative	Relative
Embodied energy	High	Less
Use of Regional (Local) Materials	Less	High
Green house gas emissions	High	Low
Indoor air quality	Relative	Relative
Daylight and viewing comfort	Relative	Relative
Thermal comfort	Low	High
Acoustic (noise) comfort	Low	High
Social considerations		
Health, comfort and well-being of occupants	High	High
Influence on the local economy	High	High
Functionality and physical space usability	High	High
Aesthetic options and beauty of the building	High	High
Construction workforce health and safety	Relative	Low
Community disturbance	High	Low
Influence on local social development	High	Not Known
Cultural and heritage conservation	Low	High
Affordability	Low	High
Safety and security	Relative	Relative
User acceptance and satisfaction	High	High

Further, in comparison to the international best practices the construction scene can be said to be at par with international standards in case of RCC type houses. But, it would be premature to draw a comparison of the Assam type houses as it is site specific. However, it is certain that more studies need to be conducted to discuss various issues of declining social acceptability and sustainability of the ATH in comparison to the RCC type houses in the rural areas of Assam.

7 Conclusion

The above study essentially tries to submit that sufficient study needs to be conducted for the Assam Type house considering the sustainability of the traditional materials that has been used in the construction of the house. Various other parameters including the cultural, social and religious aspects also have to be taken into consideration while proceeding with the study. A sustainability study of the construction materials used, as well as the construction methodology used in the construction of Assam Type house may be conducted. Further TBL assessment of the Assam Type house is required in greater details for in-depth understanding of the suitability of the housing type in context of the area of study.

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HOUSING DESIGN SOLUTIONS FOR REFUGEES EMERGENCY: ITALIAN STUDY CASES

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Abstract: *With reference to the current research within HousingLab - DiAP, Sapienza University of Rome, the present investigation considers the role architecture can play in the immigration emergency in Europe, trying to identify housing solutions supporting integration in our cities. The aim is the definition of an effective project able to transform a dramatic situation into an opportunity, enriching the debate on the welcoming of immigrants in Italy with new ideas and solutions. This work proposes case studies, which may constitute a reference model to be used also in other contexts, facing similar conditions, inspired by the common guidelines following:*

- Promoting a model of hospitality, based on the idea that the first step towards integration depends on the possibility for individuals to have a "home", a space to identify themselves.

- Favouring relations with the urban fabric of the city and avoiding setting marginal areas.

- Including services and spaces allowing integration, based on different activities able to create opportunities for employments and exchanges between inhabitants. The starting point of this study is that housing emergency is more critical in Rome than in other Italian city, both in numerical terms and in relation to the capacity of hospitality structures. Therefore, to face up to the current situation, this paper proposes design solutions for the second phase of hosting immigrants and also to meet the demand for housing expressed by the local population in similar homeless conditions. In particular, the objective of the research is to promote housing strategies and projects for variable durations of stay, from short- to long-term, by adopting the fundamental requirement of social mix.

Keywords: *Refugees Emergency, Housing Design Solutions, Integration, Urban Transformation, Immigration.*

1 Introduction

1.1 The Migrant Crisis and New Forms of Poverty

The chronic housing crisis affecting Italy for many years has recently been aggravated by two primary events: economic recession with rising unemployment and an exponential increase in migratory flows caused by conflicts and poverty. Comparing the data presented in the "*Dossier Statistico Immigrazione 2015"* (Caritas italiana 2015: Web page) with those from the thirteenth report on poverty and social exclusion in Italy released by Caritas Italia (Caritas italiana 2014: Web page), makes it possible to delineate a framework of reference for identifying key issues tied to a lack of quality and affordable housing solutions for disadvantaged social groups excluded from the Italian real estate market.

In 2014 the number of global migrants (232 million in 2013 according to the UN) most likely reached 240 million, accounting for 3% of the global population. Since 2011 the European Union has been overrun by unprecedented levels of mobility, which are not forecast to reduce in the immediate future.

Also in 2014 more than 170,000 people arrived in Italy in search of asylum or a better life (similar numbers are forecast for 2015). Many more arrived in Italy for family reunification and other reasons (religious, healthcare, education, etc.) through official channels. A total of 64,625 requests for asylum were received. In 2014 30,906 illegal immigrants were intercepted by law enforcement (source, Italian Ministry of the Internal Affairs with a repatriation percentage of 50.9% (15,726). During the first five months of 2015 47,463 people arrived by sea, and 46,714 in 2016 (source, UNHCR 2016). Of foreigners residing in Italy, while the majority hail from Europe (2.6 million), the number of non-Europeans continues to rise (3.5 million) and demonstrate a strong trend toward permanent settlement, with over half in possession of long-tem residency permits. The agricultural sector, one of the most exposed to exploitation, employed a total of 327,495 foreign-born workers.

Faced with this situation, the Italian system offering hospitality to asylum seekers and those afforded international protection remains fragmentary. In June 2015 the structures of the SPRAR network (host structures of the Protection System for Refugees and Asylum Seekers, in accordance with Law n. 189/2002, consisting of a network of local entities supported by national funds for asylum policies and services) hosted only 25% of a total of 78,000 asylum seekers and refugees, while 62% were housed in temporary structures.

To summarise, at the beginning of 2015, according to estimates by the IDOS study and research centre, Italy was home to 5,421,000 registered foreigners.

This situation must be considered together with the new forms of poverty and new demands on society highlighted in the Caritas report on seven of the European Union's "weak" countries: Italy, Portugal, Spain, Greece, Ireland, Romania and Cyprus.

Many categories are now at risk. In addition to economic poverty, unemployment caused by job loss and a shrinking job market is now a potential cause of homelessness.

The most vulnerable social categories are: the elderly, single-parent families and young couples searching for affordable housing suitable to their needs. The housing problems

faced by immigrants are less a question of availability and cost and more an issue of ethnic and cultural barriers. For immigrants, like the other categories at risk, the availability of a home plays a determinant role in fostering opportunities for integration. It has been shown that enduring housing issues may accelerate the passage toward social exclusion and marginalisation.

Beginning with this last consideration, coupled with a study of problems tied to the housing crisis in Italy described above, the research intends to offer a contribution through the study of design models and housing solutions able to satisfy today's complex and multifaceted demand, not only for quantity but above all for quality.

The home, intended as the primary fundamental right of any individual belonging to a civil society, must be rethought in relation to new economic and political dynamics; a basic component of a more complex system of social and urban relations, the home must be accessible to all social groups.

2 Method

2.1 Toward a New Model of Social Housing

The demand expressed today by new social groups is no longer tied to the traditional concept of permanent home. There is a shift toward new forms of flexible dwellings whose spaces can be adapted over time. Housing is now an integral part of a vaster system of services and opportunities. One of the fundamental features of this dwelling model is the importance assigned to human relations and the construction of a community: the home is seen as a space for the elaboration and production of social relations and environmental, social and cultural wellbeing. This requires the study of formal models that reconsider the structure of the home not only in its internal layout, but above all in terms of the system of relations binding the more intimate and private realm of domestic space with the collective dimension of public and urban space. New models of dwelling must investigate the means and forms of housing with an ability to create urban systems "at the human scale". Virtuous experiences, both national (cf. "Housing First programme") (Busch-Geertsema 2013: 13-94) and international (cf. cohousing for migrants and refugees in the Ixelles district of Brussels) (Josefa Foundation: Web page) demonstrate that it is possible to transform an emergency, such as that related to housing immigrants, into an opportunity for today's society. The research presented here has the objective of identifying strategies and best practices, starting from the immigrant housing crisis, to reconsider current residential typologies and the offering of housing. The final aim is to study sustainable and affordable housing solutions that reconsider the domestic space in relationship to use, respecting ethnic and cultural differences, and in the organisation of collective spaces designed to favour social integration. Permanent though reversible solutions, adaptable to changing demands over time; flexible enough to form diversified housing systems, both collective and not, and sufficient for guaranteeing individual dignity and privacy, benefiting from the advantages of sharing common spaces and services. Models must respond to the following requirements:

- diversification of dwelling solutions (from single rooms to mini-apartments, from small communities to traditional dwellings) to satisfy the need for temporary and long-term housing;
- the adaptability of spaces and functions to respond to current demand;
- the variation and composition of threshold spaces between public and private to stimulate a sense of belonging to a community.

The methodological premises of the research include:

- the adoption of the city of Rome as an operative context, given its characterisation as the Italian city facing the greatest housing crisis;
- testing the inclusion of a new offering of housing within the existing urban fabric, favouring the rehabilitation of currently abandoned public housing stock (former schools, warehouses, barracks, etc.) and private constructions (buildings confiscated from organised crime) and the reconversion of urban voids or abandoned sites.
The principal objectives of the research include:
- reducing construction time and costs and, consequently, rental fees;
- containing the number of residents within a minimum and maximum value, in relation to the availability of community services, avoiding concentrations in oversized structures and privileging models disseminated across the urban fabric;
- employing technologies of modular, dry-assembled prefabrication, particularly suitable to guaranteeing environmentally friendly and energy efficient, flexible and reversible residential structures;
- introducing systems of assisted self-construction to favour the involvement and participation of residents and create opportunities for training and employment.

3 Results

3.1 Proposals and Study Cases for Housing Emergency in Rome

Considering that the imposing wave of migratory flows experienced over the past two years is only destined to increase exponentially in the coming months in Italy, and in Rome in particular, this paper proposes a study of solutions designed to provide for the second phase of hosting immigrants and meet the demand for housing expressed by other social categories in analogous positions.

In particular, the research intends to promote housing intervention strategies and projects for variable durations of stay, from short- to long-term, adopting the fundamental requisite of a social mix. The aim is to provide a stock of contemporary and quality housing suitable to the dynamics of today’s society. Dynamics ranging from impoverishment to social exclusion, from a lack of housing alternatives for transitory subjects (commuters, students, etc.) to the emergence of new social groups facing serious difficulties, such as refugees and asylum seekers.

The closest reference to this model is that of the "collective dwelling" (Dall'Olio, Mandolesi 2014: XVII-XXIX), in which the private spaces of individual life overlap the public spaces shared by a community. Important typological experiments from the twentieth century include the work of such remarkable architects as Le Corbusier and Aldo van Eyck. In 1929, Le Corbusier completed the Cité de Refuge in Paris (Hallen Brooks 1993: 174-175), commissioned by the Salvation Army to host the poor and the homeless. This theme was approached by the Swiss-French master as an occasion for experimenting with typology, language, technology and building systems. The ground floor consists of different volumes juxtaposed against the thin blade of the dormitory, summarising an underlying theme in a clear image: the coexistence in one place of a community of people united by a common destiny. Also clearly belonging to a catalogue of communal housing, though based on different principles than those of the Cité de Refuge, is the “Mother’s House” in Amsterdam by Aldo van Eyck, form 1973-78 (Dall'Olio, Mandolesi 2014: XXVI). Inserted within the city’s historic fabric, the house provides each resident with a specific space: mothers, new-borns and children are arranged in three independent groups, with dedicated spaces designed to meet their particular needs. The complexity and variation of paths, spaces and details has led some critics to consider the building as “a miniature city”.

The reference that best adapts to the multiform needs of contemporary residents appears to be that proposed by A. van Eyck. A model based on the articulation of circulation and the complexity and differentiation of different environments, reinterpreted today as "cohousing": a form of organising dwelling spaces that is gaining ground in Italy and which aims to establish a positive cohabitation in a new organisation of residential structures, combining the advantages of domestic privacy with those of shared services and obligations shared by groups of people with similar needs and lifestyles. These models of organisation may constitute a valid starting point in the search for new solutions able to reconcile individual needs, increasingly more variegated and difficult to adapt to standardised building typologies, with a collective dimension.

Based on these considerations, at least two aspects of the present research can be considered innovative. The first is to consider the problem of welcoming refugees and immigrants within the more general housing crisis in Rome. This crisis affects other social groups, owing to elevated rental costs and a lack of alternative models to traditional housing. Furthermore, confronting the problem in these terms makes it possible to reduce the known sources of social conflict deriving from the separation, if not the opposition, between immigrant and autochthonous populations and consequent phenomena of discrimination and segregation.

The second aspect is the intention to compare the housing emergency (caused in Italy other than by massive migrations above all from North Africa, by evictions, employment problems, the reduced economic possibilities of students, the elderly, etc.), by overcoming the logic of assistance and short-term urgent solutions, focused uniquely on providing a place to sleep, in order to test solutions that consider the problem in its entirety. In Rome, the housing emergency is more critical than in other Italian cities, both in numerical terms and in relation to the capacity of hospitality structures to face up to the current situation. One of the objectives is to transform the housing emergency linked to welcoming migrants and disadvantaged social groups into an opportunity for urban renewal through diffuse grafts of new elements with the power to reactivate abandoned or underutilised structures across the city. The following section looks at two study cases in Rome, which serve only as examples. The first proposes to arrange services and temporary housing for immigrants and students in a void area in San Lorenzo neighbourhood. The second intends to reuse the abandoned facilities of the old Rome Fair Grounds in the EUR neighbourhood, to create a housing settlement and services for migrants and local residents (Carrano 2016: 102-109).

3.1.1 Cohousing in San Lorenzo, Rome

This project offers a response to the problem of second phase shelter, favouring integration between refugees and creating a small structure offering services and temporary housing (maximum one year), primarily for unaccompanied minors. The homes can also be used by students and other users requiring temporary and short-term lodgings. The area of San Lorenzo as selected because it is a neighbourhood with an elevated concentration of young people and a notable percentage of immigrants, in addition to the fact that it offers a number of unoccupied areas in need of reuse. The new project integrates the services offered by Civico Zero, a daytime hospitality centre for migrant minors created in Rome by the international association Save the Children and offering temporary housing. The proposal features a "fixed" and permanent structure, on the ground floor, with common services (dining, library, meeting rooms) open to the entire neighbourhood, connoted by the use of more solid materials. Grafted onto this element is a flexible system of small apartments for 2 to 4 people. The apartments are

constructed using prefabricated wood components assembled in situ that reduce construction times and facilitate eventual implementations or modifications over time.

Figure 1: Cohousing in San Lorenzo, Rome. Bachelor's Thesis Project: Pellegrino Capiraso Supervisor: prof. D. Mandolesi. Sapienza University of Rome, 2016-2017. The project site in the context of the San Lorenzo neighbourhood.

Figure 2: Cohousing in San Lorenzo, Rome. The new project integrates the services offered by Civico Zero, a daytime hospitality centre for migrant minors, with temporary housing and new public services open to the entire neighbourhood.

Figure 3: Cohousing in San Lorenzo, Rome. The new project integrates the services offered by Civico Zero, a daytime hospitality centre for migrant minors, with temporary housing and new public services open to the entire neighbourhood.

Figure 4: Cohousing in San Lorenzo, Rome. A flexible system of small apartments (2 to 4 people) constructed using prefabricated wood components assembled in situ.

3.1.2 Homes and Services Inside the Old Rome Fairgrounds

The project proposes the creation of a second phase shelter for migrants and new homes and services for a variegated user base.

Situated between the high-density Ardeatino district and Via Cristoforo Colombo, a traffic artery connecting central and southern Rome, this central site is well connected with the city's infrastructural network. The area is currently occupied by 12 pavilions distributed across 75,000 square meters, 63,000 of which are covered, for the most in a discrete state of conservation and thus suitable for reuse. Existing structures can be repurposed and integrated with new constructions along the edge of Via Cristoforo Colombo. The principal residential interventions include a hospitality migrant centre, located inside one of the existing fair structures, and a system of temporary modular homes replacing the wall enclosing the area with a more porous and permeable structure. A prefabricated wood modules system subdivide the existing building into smaller residential clusters to host migrants. These residential clusters are connected by outdoor filter zones that also serve to bring natural light into various common living areas. The new homes are made of a multi-level steel truss structure, containing the circulation system providing access to the dwelling units. This structure hosts four different prefabricated dwelling modules, similar to containers and designed to be assembled in situ. The housing system communicates a new image for the site. The elimination of physical edges in favour of a functional and architectural hierarchy of buildings is the underlying idea of the project, which aims at an encounter and cohesion between immigrants and local populations through the exchange of goods, activities and services.

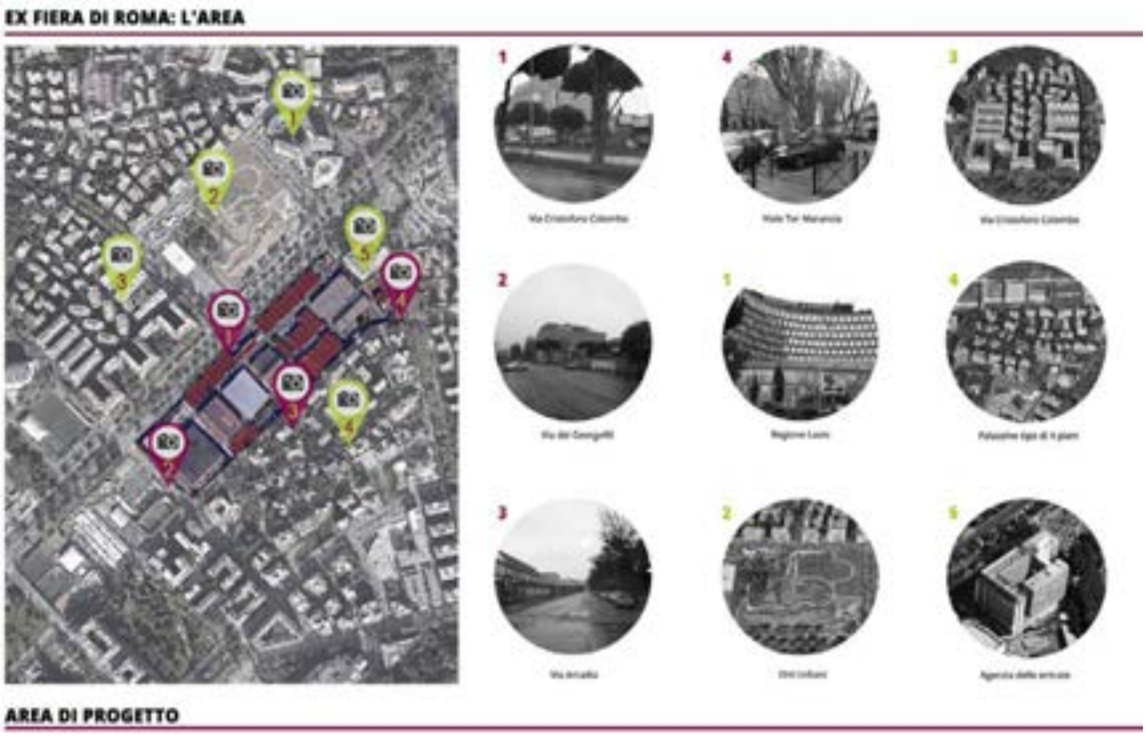

Figure 5: Homes and Services Inside the Old Rome Fairgrounds. Bachelor's Thesis Project: Elena Lorenzetti - Supervisor: prof. D. Mandolesi. Sapienza University of Rome, 2015-2016. The project site in the context of southern Rome.

Figure 6: Homes and Services Inside the Old Rome Fairgrounds. The area with new uses of existing pavilions and new homes buildings on the margin along Via Cristoforo Colombo.

Figure 7: Homes and Services Inside the Old Rome Fairgrounds. Made of a multi-level steel truss structure, the structure host four different prefabricated dwelling modules, similar to containers and designed to be assembled in situ. The design of this new housing system communicates a new image for the site.

Figure 8: Homes and Services Inside the Old Rome Fairgrounds. Section of housing system.

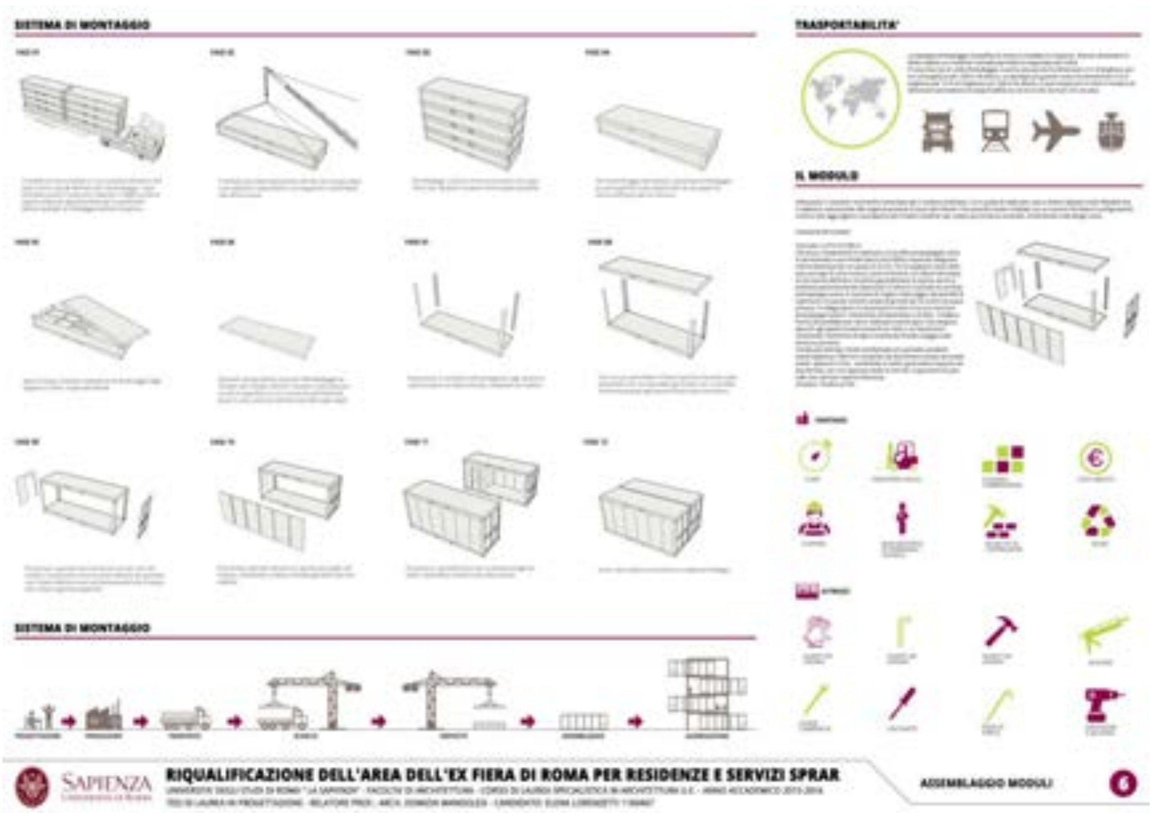

Fig. 9: Homes and Services Inside the Old Rome Fairgrounds. The prefabricated dwelling modules: transportation and assembly system.

Figure 10: Homes and Services Inside the Old Rome Fairgrounds. Prefabricated wood modules subdivide one of the existing pavilions into smaller residential clusters.

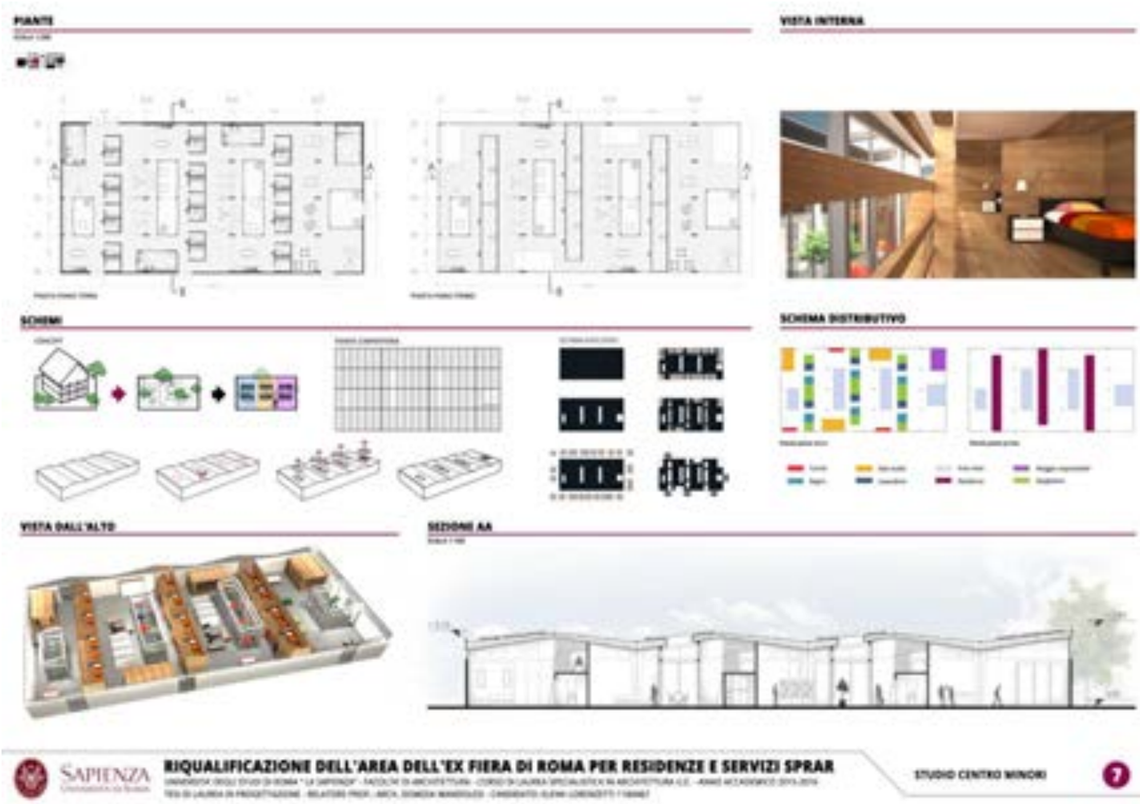

Figure 11: Homes and Services Inside the Old Rome Fairgrounds. The hopsitality migrant centre, located inside one of the existing pavilions.

4 Conclusions

Despite a growing availability of homes on the private market, Rome hosts a “weak” population made of families with low incomes, the elderly, young people, students and immigrants, all denied access to a proper home for economic reasons. The work presented here intends to respond to the demand expressed by these disadvantaged social groups through the definition of flexible and sustainable residential systems designed to be inserted within the urban fabric of Rome.

This new model of *social housing* is based on four primary requisites.

The first is the control of the costs of renting and maintaining a home. This may in part be favoured by the model of *cohousing*, which involves sharing selected maintenance and operating services, costs and fees.

The second involves *social mix* and *urban integration*. The insertion of a new offering of residential solutions into void or abandoned parts of Rome, based on a logic of “urban acupuncture”, may favour a rebalancing of social disparity and reduce phenomena of segregation.
The third requisite is represented by the *dimension of settlement*. This dimension must be tied to the human scale and limited to a size that allows the growth of communities. The arrangement, variation and correct dimensioning of buildings and voids act to reduce the feelings of alienation and to favour a sense of belonging among residents.

The fourth is tied to *architectural quality* and *flexible structures*. This requisite applies to both space and time, and in equal measure to the home and systems of aggregation. The proposed model is an alternative to the more rigid traditional home. The structure of domestic space is modelled to the principles of flexibility and adaptability. Residential functions are viewed as part of a wider system of services and opportunities.
Once these base requirements have been established, the research unfolded in 5 different phases.
1. A study of international literature, by exploring this issue to identify design guidelines and requisites useful to the definition of dwelling solutions.
2. Analysis and interpretation of demand through a comparative study of forms and models of dwelling.
3. Design and dimensioning of dwelling models and aggregation types based on the results of phases 1 and 2.
4. Identification of abandoned and/or void public or private areas in the city of Rome in which to locate new residential structures.
5.Verification of the types and models proposed during phase 3 through the development of a project for the areas identified during phase 4: *Cohousing in San Lorenzo Rome* (case study 1); *Homes and Services Inside the Old Rome Fairgrounds* (case study 2).
As applications of the research methodology, the two case studies provide useful tools that can be replicated in analogous urban areas.

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THE NATURE OF SUSTAINABILITY IN ARCHITECTURAL DESIGN

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Abstract: With reference to the current research of the LaMA - DiAP, Sapienza Unversity of Rome, the aim of this paper is to present a system of design strategies that endeavor to create more environmentally and socially sustainable architecture. This requires a critical departure from traditional practices, starting at the formative stage, as defined by Edward Mazria's 2030 Challenge (http://architecture2030.org/): first a change is required in education, making ecological literacy a central tenet; then a change in design, to reduce CO2 emissions by building activity by 50 %. The methodology of research has been developed through teaching and research experience and assumes an alternative approach to design education, to deliver different results making the education process itself innovative, interactive and sustainable, and demanding smart buildings with the same characteristics. The building process must constitute the epicenter of innovation in the study of sustainable tech- nologies, representing in itself a testing ground for advanced "solutions in progress" which are continually integrated, evaluated and replaced. The result of this sustainable education model is the design of an architectural organism conceived according to bioclimatic strategies for minimal environmental impact, using recycled materials and meeting the highest standards of energy efficiency. The knowledge base on sustainable design is constantly expanding, requiring active research contributions that will be explained through the presentation of different case studies.

Keywords: *Sustainable Education, Sustainable Design, Research Project, Ecoliteracy*

1 Introduction

When in February 2007, the architect Edward Mazria launched the 2010 Imperative and the Challenge 2030, the first dedicated to ecological education, in Rome, Italy, a small group of researchers, consisting of Franca Bossalino, Rosalba Belibani and Anna Gadola decided to build the <http://www.diarambiente.it> website, a virtual ecological literacy site for a change in education. The site primarily aimed at supporting the architects in designing with care and art to reconnect humanity with nature and places. The imperative urged a change in education by 2010, "*Ecological literacy must become a central principle of education: an important transformation of the academic community responsible for planning must start today*" (Mazria 2007). The aim pursued was to give students and architects all the information they needed to design for justice in an overcrowded world, to design a world powered by natural energy, to design in order to eliminate waste, or rather to reuse and integrate it into life's cycle. In short, to build prosperity on a durable basis.

The response to Edward Mazria's appeal, engaging the group concretely and publicly in the international community initiative and respecting the Imperative 2010, has found its roots in the critical reflection on the need to make substantive changes in the architect's resume and, above all, in his education.

The challenge involved and involves the activation of a new awareness to liberate the way of thinking from the ideologies and dogmas of the past in order to place the ideas on which to build the necessary architectural knowledge of today: a holistic / ecological knowledge that would help finding the lost meaning and value of a profession at the service of humanity, responding with a new project to the goals of the future, to new aims and new needs, with creativity, competence and, above all, with a new awareness.

In the 21st century, the architect's profession will be pursued with a view to protect, preserve and rationalize natural resources, to leave future generations of all living species a healthy Earth in which there is freedom, equality and the right for all to decent living conditions. However, first we must know and love our Earth, because "*We will not be able to save the species and the planet unless we develop an emotional relationship between us and Nature because we will not save what we do not love*" (Stephen Jay Gould).

Mazria's second challenge was to change the design at all stages in order to reduce by 50% the levels of CO2 emissions produced by construction by the year 2030.

This is a new meaning for design, a new mission, that of proposing *'solving for patterns'* (Wendell Berry), namely finding solutions to multiple problems, minimizing the creation of new problems and addressing how the project recovers energy, materials, housing, transportation, food, water and the way we recycle waste.

2 The ecoliteracy design

"Armed with the security of tenure and the time to study the world with care, professors would appear to have a unique opportunity to act as society's scouts to signal impending problems. […] Yet rarely have members of the academy succeeded in discovering emerging issues and bringing them vividly to the attention of the public." (Orr 2011)

The challenge is to mainstream sustainability and drive the planning process for good architecture. These good behavioural practices have now become concrete applications in many different cities, but in Italy, while the projects are many, the achievements are very limited.

Moreover, in order to make a good ecological architectural project, one must not forget the lesson on the ethics of doing.

Figure 1: A sustainable project developed within Design Studio, by student S. Calabresi

"If we understand that design leads to the manifestation of human intention and if what we make with our hands is to be sacred and honor the earth that gives us life, then the things we make must not only rise from the ground but return to it, soil to soil, water to water, so everything that is received from the earth can be freely given back without causing harm to any living system. This is ecology. This is good design. It is of this we must now speak.
If we use the study of architecture to inform this discourse, and we go back in history, we will see that architects are always working with two elements, mass and membrane. We have the walls of Jericho, mass, and we have tents, membranes. Ancient peoples practiced the art and wisdom of building with mass, such as an adobe-walled hut, to anticipate the scope and direction of sunshine. They knew how thick a wall needed to be to transfer the heat of the day into the winter night, and how thick it had to be to transfer the coolness into the interior in the summer. They worked well with what we call "capacity" in the walls in terms of storage and thermal lags. They worked with resistance, straw, in the roof to protect from heat loss in the winter and to shield the heat gain in summer from the high sun. These were very sensible buildings within the climate in which they are located." (Mc Donough 1993)

In this holistic approach to sustainability it is important to understand what in Ecology is relevant to the design of architecture.
Ecology began as a scientific discipline in 1866, when Ernst Haeckel first defined it as "the body of knowledge that pertains to the economy of nature". In fact, ecological thinking originated much earlier when Haeckel's contemporaries, from Thoreau and Olmstead to Marsh intertwined ecological thinking in their lives and in their writings (Ricklefs 1976). Yet, while ecology was moving forward in the twentieth century, technology that changed the world turned society away from ecological thinking and led it to a different economy, intended as home science (the original meaning of economics). A limited ecological thinking in major public debates has left decadent living systems and this decline threatens the well-being of humanity, and failure to understand or work with the economy of nature has produced the environmental challenges we face today.
Many of these challenges are important to the designers' work, and to infuse ecological thinking into the disciplines of the project is crucial. Designers work in the interface of them, as for the nature of their discipline they are generalists and integrators. From the

building's design, growth management and landscape design, ecological aspects impose limits, but also serve as inspiration (Karr 2002).
Recently, there are many promoters of sustainability themes in the architectural design education. However designers and technologists sometimes use the term sustainability as a quality assurance indicator, and pass under its name projects that only partially face the environmental issues but can hardly be globally considered as sustainable products. We have to recognise that even though the consciences are sensitive to this, the products are still partially sustainable and the knowledge on the subject and related issues is still superficial.

3 Sustainable design

In order to achieve a sustainable intervention, it is necessary to identify, evaluate and formulate some of the design phases required to define the new form of the ecological project.
The stages of a sustainable process provide for careful reflection on the following topics:

1. Relationship between ecological thinking and design inspiration
2. Definition of good sustainable project
3. Relationship between energy and shape of the project
4. Study of design themes

Figure 2: A sustainable project developed within Design Studio, by student M. Ippoliti

3.1 Relationship between Ecological Thinking and Design Inspiration

The discipline of Ecology should be more effective in communicating the connections between the needs of human society and the understanding of ecological principles, models and processes, and should also support the creative inspiration that is central to the project, from the landscape to architecture and engineering.
As David Orr notes: *"Industrial civilization, of course, was not designed at all. It was primarily imposed by certain individuals, armed with any doctrine of progress that required a homogenization of nature and society".*
Knowledge of living systems was not a key component of the conceptual structure of design practice.
The good ecological project should focus on correct spatial and temporal scales, simplicity, efficient use of resources, adaptation between means and goals, durability, repetition and elasticity. The project must also be specific to the site and for the site. The

project should focus on more than one problem at a time to avoid undesirable side effects.
Good architectural design requires ecological thinking, that is, a conscious effort to avoid unexpected biological consequences.
The most important attribute of all members of a true interdisciplinary group is the acknowledgment that no individual is sufficiently prepared and that no discipline is wide enough to grasp the many dimensions of the complexity of ecological issues facing modern society.
Designers who are proud of being generalists can and should play a key role in bringing together the various disciplines. But their success depends far more than on a superficial familiarity with the three fundamentals: aesthetics, economics, ecology.
Success in protecting the environment and people's quality of life requires interdisciplinary synthesis and communication that makes the real challenge and the viable solution clear (Karr).

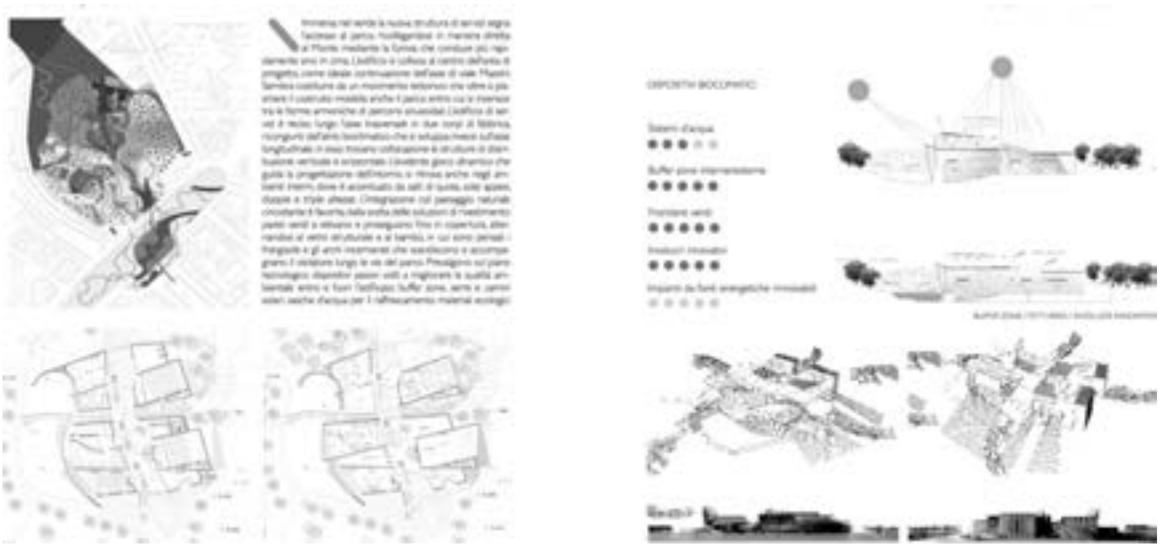

Figure 3: A sustainable project developed within Design Studio, by student M. Lumare

3.2 Definition of good sustainable project

At the beginning of the 21st century we need a new science and a new art of home care (the original meaning of economics) to help us understand and interpret the consequences of human-induced changes.
We need a new vision of the project and its purpose. We must find a balance between our modern industrial economy - and the project that supports it - and the natural economies of the territories in which we live. Even the beauty of plants and animals, of extensive landscapes, inspires people. But these systems are collapsing to a great extent due to human activity, the main force of change that exists on Earth's surface.
As individuals and as a society we must understand the consequences of our actions in the present and in the future; Ecological Thinking is and will continue to be central to achieving this goal.
The efficiency of ecological systems is unmatched. The good project provides the basis for recycling because the standard in closed systems is that there is no waste. Air and water are not polluted so as not to cause ecological collapse.
Designers will have a fundamental role in a new vision of home care. Their artistic tradition - finding solutions to unique and aesthetically pleasing design problems - has always been shaped by the functional and economic limits.

They now have to add to their thinking and their formation the ecological thinking with its limits and inspiration.
Although their relative importance may vary somewhat in various projects, aesthetics, economics and ecology are crucial in any project.
Good design requires ecological intelligence, intimate familiarity with the ways in which nature works (Karr 2002).

3.3 Relationship between energy and shape of the project

Contemporary buildings can be considered, in general, as isolated systems because they need energy to work but do not necessarily interact with their environment to continue to operate. Like all isolated systems these buildings will work in accordance with the Second Law of Thermodynamics. They import energy in the form of electricity, propane and / or natural gas, transform it into heating, cooling, ventilation and lighting systems, and then dissipate it as wasted heat. These buildings require uninterrupted supply of imported energy. Otherwise, after all the energy has been consumed, they become uninhabitable, too hot, too cold, without light, etc. They isolate themselves against the environment to preserve internal conditions for as long as possible.
Live organisms, on the other hand, work in a completely different way. They are open systems, which means that to stay alive they must maintain a continuous flow and exchange of energy and materials with their environment.
Through the process known as metabolism, they absorb substance to get the energy and nutrients needed for vital functions such as heartbeat, muscle contraction, or organic molecule production (Karr 2002).
At the same time, open systems have a high degree of stability and elasticity, which consist in maintaining the overall structure despite changes in the environment. This ability to adapt and self-preserve in a constantly changing environment is an essential quality of open systems. Fluctuations play a key role in the elasticity of these systems. A system fluctuates within certain limits in order to maintain its flexibility in a continuous state of equilibrium. The movement of one will be compensated by the others who will move within their own field, to keep the system stable. This is how open systems, as a whole, adapt to environmental change.
A living organism also creates its own border that defines it as a distinct open system. This border, or membrane, is a filter required by the elements of the environment to support the body. The border also contains a specific series of internal relations and an order that distinguishes the existence of one organism from that of another. Order is then a particular configuration, or pattern of relationships, which defines a specific open system and gives the system its shape.
To understand and view the form, you can map the patterns of relationships that make up the system. The shape is therefore both the casing and the content that constitutes the system. It is the visual nature of that System (Mazria, Riskin).
The neoclassical economy has strengthened man's arbitrary domination over the free wealth of nature and has brought unprecedented gains to social well-being in some places, but it also appears to have been the cause of the divorce of the human economy from the natural economy. The environmental challenges faced by modern society are a direct result of the widespread failure of mankind to understand the risks associated with the degradation of living systems.

3.4 Study of design themes

Design themes, expressed in the freedom of their own language, are analyzed in advance.

- Choosing the right place. It is necessary to evaluate the resilience of the site and to estimate the adaptation strategies. It is necessary to maintain the character of the site and also to define in advance the construction and maintenance costs.
- The objective of the sensitive project. The project must re-propose natural rhythms in the search for physical and environmental comfort. Attributing a spatial conception that links the rhythms of nature to the rituals of life can bring a new life to the project.
- Elastic buffer zone. Define the real limits of construction and allow for its growth or modification, always contained and controlled in buffer zones, taking into account all seasons and ages of the project.
- Solar politics and dynamic design. The relationship between the sun, dynamic, and the static architectural design impels the concept of architecture in anything but static, but to predict, if and when possible, moving elements that allow it to relate to the sun and to the environment.
- Solar casing and energy saving. Applied as a zoning tool, the solar envelope will not only enable growth, but will open new aesthetic possibilities for architecture and urban design.
- Solar aesthetics and its shape. The interest in a new architectural aesthetic, also in relation to the widespread need to conserve energy, now assumes a new meaning for a design research not just for the building's casing but its shape.

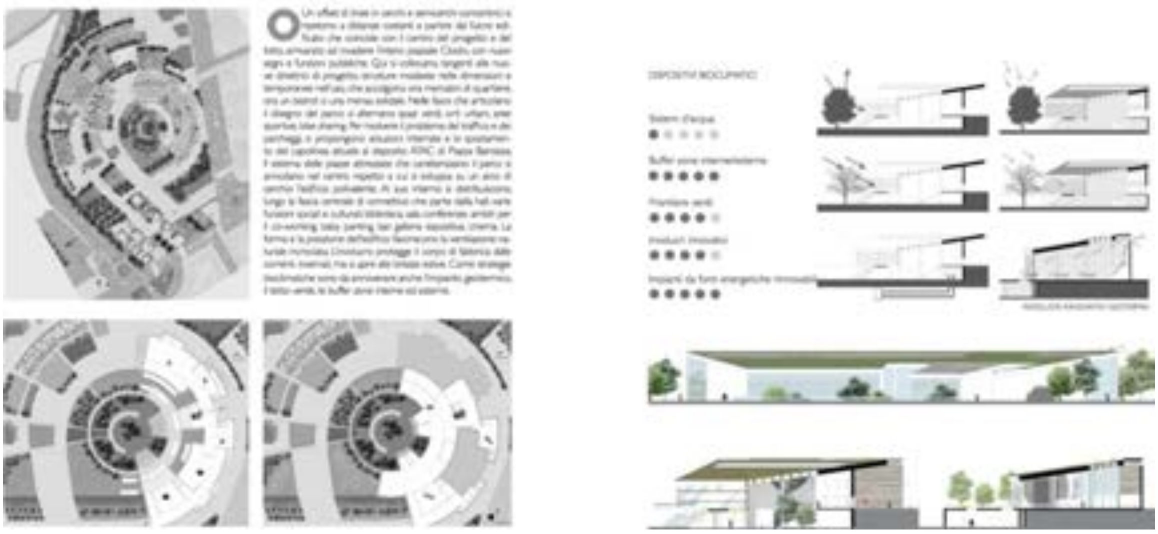

Figure 4: A sustainable project developed within Design Studio, by student F. Ficcadenti

4 The Design Strategies

Among the interpretive strategies that need to be followed for a good project, it is important to first define some *Qualities*, the irreducible characters of the settlement.

1. Recognition.
2. The value of the site and the plant is given by its identity.
3. Value of the Perception that allows value assignment by the user.
4. Urban Dimension, if present.
5. Project and Control of Green and Open Space.
6. Project with Social significance.
7. The awareness of the inhabitants for the value of the place.

Design Strategies intervene in the various phases under multiple aspects of intervention and must always ensure that they respond to a social demand and do not only implement aesthetic strategies.
Urban agglomeration strategies are defined for the following areas:
Services and New Features. Entering new services that offer new features and attract new users. Enclosure of buildings and façade solutions for improving energy behavior.
Design of open spaces and connections. A new landscape design is proposed in which green spaces predominate, to maximize the permeability of the site. Within the project a new system of streams, for cars, pedestrians and cycles is proposed. New functional spaces, destinations and various activities are identified, and especially the green is differentiated according to use: urban gardens, accessible spaces, multiple use spaces.
Partition of the landscape. Inclusion of materials for new spaces (playgrounds, spaces for events) and ground movements to make small height differences. Provision of devices for environmental sustainability (rainwater collection, geothermal plants).
Shared space. Privatization of Common Spaces. Attribution of new ways to use spaces, favoring in the project the proposal of personal cultivation of urban gardens and also providing for a form of dedicated privatisation.
Mobility. Project of viability, with regards to public transport, especially in the area. Parking facilities, even protected and underground, but not totally on the surface.
Green and Open Space. Defining existing green spaces and integrating them into a single green system through a coherent design with the general plan: a sustainable project that reconstructs the landscape of the area. The use of vegetation in urban spaces has always had many functions: symbolic, aesthetic, productive and of microclimate regulation. The thermoregulatory function of vegetation in the summer period has been known since the earliest times throughout the Mediterranean. Building green walls or green roofs can also improve the microclimate, soundproof or mask blind walls of the buildings. Planting new tree species (sempervirens to the north, deciding south) for an optimal relationship with the winter and summer winds.
Services. Placing new neighborhood services, focusing on the most sensitive categories, children and the elderly (e.g. a nursery and an elderly center). The nursery project must be backed up and protected from the roadside. The kindergarten can be conceived as a space around a central nucleus, dedicated to outdoor play, around which are the different sections, the entrance hall and the direction, kitchens and dining area. The elderly center can propose organic forms and compositional solutions that follow the land design, it should be developed as a continuation of external pathways that invite indoor access where there are areas dedicated to free activities, projections, fitness and a cafeteria.
Among the Operating Modes for the implementation and management of the building program, it is planned to experiment with new forms of Consultation and Welfare through participatory practices.

The initial plan presents site analysis from a sustainable point of view and assesses climatic and environmental factors such as sunshine and shadow study, summer and winter ventilation, as well as the study of existing tree species and their more or less efficient location on site. A preliminary assessment is made of the objectives, strategies and technological devices planned and applied with a general reference to LEED certification, presented as a percentage in the six categories. Finally, in the project specific layouts, the devices adopted aim to improve the sustainability of the intervention.
Among the strategies outlined in the project are:

- The insertion of tree species (sempervirens to the north, deciding to the south) to improve the quality of the air and to act as a barrier against wind and noise.

- The diversified treatment of common green. Areas dedicated to urban gardens, roof gardens, green walls and green systems as a link between different heights.
- Rainwater recycling for irrigation of gardens and local green. Wastewater recovery, also used for hygienic services, must be carried out through dedicated façade-based descendants that convey the water into special tanks. The presence of water tanks for summer cooling can ensure the right degree of humidity on the façades exposed to summer winds.
- Different type of façades based on their exposure, with ventilated walls. The new wall / façade will be finished with alveolar polycarbonate panels, green walls and brise-soleil, eventually with photovoltaic film on the south side. It can create new open areas, functioning as mini buffer zones to mediate between internal and external temperature and for thermal control, supported by the presence of new types of sealed windows with double opening to improve indoor ventilation.

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Figure 5: A sustainable project developed within Design Studio, by student F. Cavaterra

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IMPACT OF FOURTH INDUSTRIAL REVOLUTION IN ARCHITECTURE UNDERGRADUATE COURSE

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Abstract: *Advances in Information and Communication Technologies (ICT) have led to changes in different sectors. Discussions around this theme were intensified after the World Economic Forum in Davos, which called this era as "the Fourth Industrial Revolution." According to the report released, the impacts on architecture and construction range from changes in employment, definition of skills and work strategies, to green energy production and construction management. With regard to methodologies aimed at assisting design management for buildings with high environmental quality, the potential of digital modeling must be highlighted. The possibility to anticipate the performance of building, allows adjustments in the beginning of the design process. But alternatives offered through new technologies to architectural management go beyond digital modeling. Building Information Modeling (BIM), Augmented Reality (AR), Rapid Prototyping (RP) and Virtual Reality (VR) are some of the new technologies that can strongly contribute to construction industry. However, the potential offered by new digital technologies will require professionals properly trained in order to contribute for the improvement of civil construction industry. In this sense, this paper discusses the impact of the fourth industrial revolution on architecture training, emphasizing the changes that can occur during undergraduate course. A case study has been carried out in order to identify opportunities to incorporate the new technologies on didactics practices adopted by professors. Case study demonstrated the great potential for insertion of ICT (BIM, AR, VR and RP) in teaching construction technology.*

Keywords: *Building Information Modeling, Information and Communication Technologies, Architecture Management, Architecture Teaching, Construction Technology*

1 Introduction

Advances in information and communication technologies have led to changes in different sectors of the economy. The subject has raised interest by the speed in how it is processed, and by the urgency in which the main impacts should be considered. Discussions around this theme were intensified after the World Economic Forum in Davos, which called this new era as "*the Fourth Industrial Revolution*". The report released from that event highlights the impacts in different areas but, particularly in what refers to architecture and construction, changes are ranging from employment and the definition of skills and work strategies, to green energy production and construction management.

According to the report, the modernization of buildings and cities is one of the consequences of this revolution, as a result of innovations provided by new technologies. The following technological drivers of change can be highlighted (World Economic Forum 2016):

- Mobile internet and cloud technology;
- Advances in computing power and Big Data;
- New energy supplies and technologies;
- The Internet of Things;
- Crowdsourcing, the sharing economy and peer-to-peer platforms;
- Advanced robotics and autonomous transport;
- Artificial intelligence and machine learning;
- Advanced manufacturing and 3D printing;
- Advanced materials, biotechnology and genomics, among others.

Among the innovations related more specifically to architecture and construction, the dissemination of BIM Platform (Building Information Modeling) has encouraged changes in project management. However, even in relation to BIM, there are still doubts among professionals, who resist adopting the new technology and - particularly in Brazil – are insisting on developing projects using the CAD platform.

Previous research (Salgado et al. 2015) has revealed the timid use of the BIM platform, even in projects with non-traditional forms. This resistance can be attributed to the low dissemination of new technologies during the undergraduate courses. In this sense, this paper discusses the impacts of new technologies on architecture education, particularly considering the benefits in construction teaching aiming environmental performance of buildings.

The research methodology adopted is divided in four parts. The first part presents an overview about the digital technologies arisen through the 3rd and 4th Industrial Revolution. The second part summarizes the Brazilian legislation of undergraduate courses in architecture, and highlights the areas of 'construction technology' and 'structural systems' which is addressed in the paper. Then possibilities of adopting digital technologies in the teaching of these areas are evidenced. The third part presents the case study obtained through the observation of traditional teaching practices of 'construction technology' of a renowned Brazilian undergraduate architecture course. The last part presents some strategies that can ally teaching construction technology through digital technologies.

2 From the 3rd to the 4th Industrial Revolution

The 1st Industrial revolution (1784-1869) represented a transition from the artisanal to the industrial economy and was marked by the use of steam, coal and iron. Lately those innovations have led to the 2nd Industrial Revolution (1784-1869), which includes electricity, oil and steel. (Cohen 2013). During the 2nd revolution, there was the development of researches that have led to the 3rd Industrial Revolution, characterized by the beginning of Information Technology with the first computers.

According to Mitchell & McCullough (1994 apud Righi 2009), the 3rd Industrial Revolution was characterized by the use of electronics and Information Technology (IT) to automate production. Braz (2016:7) adds that this revolution was also marked by the invention of the computer in World War II, and the internet and wireless system in the 1990s, integrating the world through networks. According to Righi & Celani (2007), the computer has advanced as a design tool, becoming part of the creative process.

As an unfolding of the use of the Internet in everyday activities of society and with the increase of its speed (data exchange) in a smaller space of time, the processes carried out in the digital world have an increasing impact in the physical world. That is probably the reason why the end of the 3rd Industrial Revolution overlaps the beginning of the 4th Industrial Revolution.

The 4th Industrial Revolution is based on the cyber-physical systems concept that deals with a deep interaction of the real and virtual worlds (Ferracane 2015). According to this author, one of the key technological advances for the rise of the 4th Industrial Revolution is 3D printing (also known as Rapid Prototyping - PR), which allows to print physical objects from virtual models. In architecture, RP can be used at different stages of the design process. According to Andrade (2016) in the conceptual stage, the technology can help understanding the relation between the building and the environment, testing a constructive feature, visualizing the design solutions, and also combining the study of complex forms. Savignon et al (2012) highlights the possibility of creating innovative proposals supported by tests and simulations in the prototype, with the guarantee the final product constructability.

BIM platform has also been identified as one of the technologies that are transforming civil construction industry. Eastman et al (2014) report that BIM is a design process, based on a parameterized 3D model that contains specifications of the components of all the projects involved in the building. The same author adds that this platform manages and produces construction data throughout its entire life cycle, allowing a better performance of the building. It is worth mentioning that the concept of BIM "presupposes the existence of a set of integrated and complementary tools capable of performing different types of operation on the single model of the building ..." (Freire et al 2012:3414).

Another technology that deserves attention, due to the possibilities offered to the architecture and construction sector, is the Augmented Reality (AR). This technology, according to Cuperschmid (2016), consists of superimposing virtual images or information in the real world through a camera device. The same author (2016:168) points out that the interaction in the AR environment occurs in a real environment with the addition of virtual data, generating a composite view in real time. Compositing is a combination of a real scene seen by the user and a virtual scene generated by a computer system (Cuperschmid et al 2011).

Also considering the possibilities offered to the universe of architecture, it is important to mention Virtual Reality (VR) that allows immersion in the completely virtual world through glasses, or helmet, data gloves, among others (Cuperschmid 2016, Paraizo 2016). Immersive experiences have been in constant development since the 1990s. A trend in the segment of interactive visualization for Architecture is its development in more accessible platforms, through the use of virtual reality glasses present in the market, generating almost photorealistic models (depending on the equipment used), connected to computers or coupled to cell phones (Canuto et al 2016:256). This technology promises to expand the notion of reality. More and more gadgets such as Google CardBoard (Fig.1), Samsung GearVR, and Oculus Rift, among others, are on the market.

Figure 1: Google cardboard with cell phone coupled

By highlighting some emerging technologies from the revolution of the digital age, there is clear the need to rethink the didactics methods adopted to teach architecture and engineering in order to take full advantage of the possibilities offered. However, this potential can be underutilized if professionals do not have the mastery of those technologies.

3 The use of digital technology in teaching architecture and construction

The curriculum of Brazilian Architecture and Urbanism undergraduate course is determined by the Ministry of Education (MEC) through National Curriculum Guidelines (DCN), which establishes how the course should be organized and also defines the curricular contents required in all Brazilian courses (MEC 2010).

According to MEC-DCN (2010), the core of professional knowledge during Architecture and Urbanism undergraduate course is formed by the following areas: theory and history of architecture, urbanism and landscaping; architecture, urbanism and landscaping project; urban and regional planning; construction technology; structural systems; environmental comfort; retrospective techniques; informatics applied to architecture and urbanism; and topography (MEC 2010: Article 6, § 2).

The areas chosen to be addressed in this article are 'construction technology' and 'structural systems'. These areas will be referred to in this article as **'construction'** areas. In this sense, this paper tries to demonstrate the possibilities that can be adopted during the teaching of construction, particularly considering the architecture

undergraduate course. It is understood that through digital technologies, professors can motivate students to search creative solutions.

Following the above definitions, the possibilities of using ICTs (BIM, RA, RV and PR) in the teaching of 'construction' for the course of architecture and urbanism were searched in the literature.

Kubicki et al. (2012) discuss the application of 4D simulation to assist in teaching structural principles and construction processes in order to confront the student with the analysis of the characteristics of existing projects and problems of construction management. This study was carried out at the University of Liège, Belgium, and the software used in the course was SkethUp™ for 3D modeling and 4D Virtual Builder© (SketchUp™ plug-in) for 4D modeling and simulation. In this experiment, students used the technology to model and test structural solutions and components of the constructive system of constructed buildings. However, teachers could also have used the 4D simulation to explain the theoretical contents of the course and thus optimize the students' in the classroom, such as structural principles and construction processes.

Kuo et al (2004) reports on the application of AR to teach the operational system of the ecological garden at its university. The students practically visualized the system of reutilization of water by means of a tablet. 2D, 3D, and text information overlapped the real scene, helping students understand the campus mechanism. In addition, students could cycle with the tablet on a particular axis to acquire information from surrounding buildings. Therefore, it is concluded that the AR allows the inclusion of post-construction information that will enable an adequate maintenance of the building.

Behzadan, et al (2016) developed and tested the AR Magic Book where the technology has been used to increase the content of textbooks. The pictures, tables, and diagrams of the book worked as a marker. When web-enabled portable devices captured these markers, virtual information (videos, sounds, images) overlapped the book. With this, the AR can be used to enhance learning with the didactic material.

Another possibility of ICTs refers to the use of VR for training on a construction site or with students in the classroom in order to explain the construction process sequence, such as the study carried out by Stange & Scheer (2012). The authors have developed a non-immersive VR prototype where the user performs a virtual training of assembly of a mold to form a concrete pillar. The activity is performed on a laptop and uses the mouse to navigate and assemble the formwork.

Kieferle & Woessner (2015) propose the combination of the BIM platform with VR through the communication of the Revit (BIM) and COVISE and OpenCOVER (RV) softwares. In this approach, information is exchanged between these systems and changes made in Revit are automatically changed in RV and vice versa. Therefore, it is possible, in real time, to interact with the model, such as moving elements, changing texture, interacting with simulations, and accessing a panel with information about the room visited (room name, square footage, floor number, etc.). Users can change parameters by tablet or mobile phone while working in the virtual environment. In this way, projects can be visited on a 1: 1 scale in a Cave Automatic Virtual Environment (CAVE) by project teams and changed during the meeting. The immersive experience plus the possibility of interaction with the model, allows users to evaluate the quality of design solutions in addition to testing new solutions and without the need for rework to update the BIM model. This study opens doors to several possibilities of interaction of the technology with the civil construction and with the teaching.

Behzadan et al (2016) proposed the integrated use of BIM platform with AR through an application called Skope. This application provides access to a location-sensitive BIM model allowing the overlay of this model in a real-world building. With this, students can interact with different parameters of the model such as orientation, environment, direction of prevailing winds, construction processes, structural systems, connection details, heating, cooling and ventilation systems during the class and were able to analyze and Understand the operation of the building.

Similarly, to the other ICTs pointed out, RP can also be explored in teaching construction technology and structural systems. In their research, Savignon et al (2012) highlights advantages of using prototypes to integrate constructive technique with architectural design. Physical models have always played an important role in architectural representation. The model constructed by Gaudi can be cited as a known example of this practice to recognize the architectural form intended in the famous Basilica and Expiatory Church of the Holy Family, as shown in Fig.2 and Fig.3.

Figure 2: Gaudi's model for the domes of the Church of the Holy Family in Barcelona

Figure 3: Domes of the Church of the Holy Family in Barcelona

According to the authors, the prototype assists in communicating ideas about materials, connections, textures, shapes, sizes and proportions among other aspects; reduces the time of understanding the design details; dribbles the problem of representation in design with constructive solutions; provides instant access to the study object; assists in the early evaluation of the product and elimination of possible failures; and help in the detection of execution problems not observed during the design process.

4 Teaching of Construction Technology in Architecture undergraduate course: case study

Successful didactic practices previously reported were used as a basis for a theoretical study of ICT implementation in the teaching of 'construction' contents. The theoretical study was done through the case study of the course ‘Constructive Processes II’ offered to third year of the undergraduate course of Faculty of Architecture and Urbanism at Federal University of Rio de Janeiro – Brazil (FAU-UFRJ).

4.1 Case study

Through the observation of traditional teaching practices, this case study was used to analyze how technologies can be used in a 'construction' course that hasn't appropriated it to teach the contents of their subject matter yet.

This case has been chosen because it stimulated the practical experience in the laboratory and experimental site, besides the traditional theoretical teaching of materials and building systems. In the course, teams are organized and each one is responsible for designing and producing different equipment such as: lightweight concrete luminaire, children's toy in colored concrete, water cooler in high performance concrete, among others. Throughout the semester, the groups deliver the projects to execute the equipment (projects, material quantity and execution schedule) and, at the end, execute. Fig.4 presents examples of student projects.

Figure 4: (A) luminaire in lightweight concrete, (B) child's toy in colored concrete, (C) high-performance concrete drinking fountain

Products presented on Fig.4 are success cases developed during the classroom experience using physical modeling at the construction site. However, the use of digital technologies should be considered in this course.

Based on the didactic experiences and the literature review, alternatives are presented aiming at the adoption of the digital tools to teach construction technology. In addition to the benefits during the teaching process, gains in relation to the environmental performance of the solutions can also be achieved

4.2 Incorporating digital technologies in construction education: case study

Through BIM platform, professor can demonstrate and analyze the result of a structural simulation, associating physical, thermal and mechanical properties of materials. It would be also possible to verify building performance, searching for the best constructive method. Students can take advantage of the BIM model to obtain the quantitative survey of materials prior to the execution at the experimental site.

One example that should be highlighted is the Architecture Undergraduate Final Project developed by a student at his final year. In this experiment, the student has developed a BIM Model of an important Brazilian modern building: the Environment Protection Center of Balbina at Amazonas – Brazil (EPC Balbina). Unfortunately, the building is abandoned with evident signs of looting, vandalism and pathologies in the structures. It has been detected that some parts of the roof have been destroyed and most of the windows are broken.

EPC Balbina has been digitally reconstructed through Revit in order to create the BIM Model of the building, digitally preserving the built heritage. Fig.5 and Fig.6 presents photos of EPC Balbina and Fig.7 and Fig.8 presents part of website contents.

Figure 5: EPC Balbina – general view

Figure 6: EPC Balbina – general view

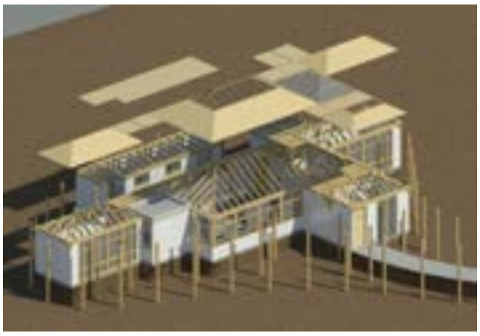

Figure 7: EPC Balbina - BIM model of Laboratory. Source: Cunha, et al 2015

Figure 8: EPC Balbina website and virtual reality visit. Source: Cunha 2017

The final model is available through website (Cunha 2017), and allows the opportunity to carry out the virtual visit to the building, and access to the information of the constructive details. It is worth mentioning that only half of EPC Balbina project has been built. But the model built digitally allows the virtual visit to the complete project, and the possibility of visualizing the complexity of its execution (Fig.9).

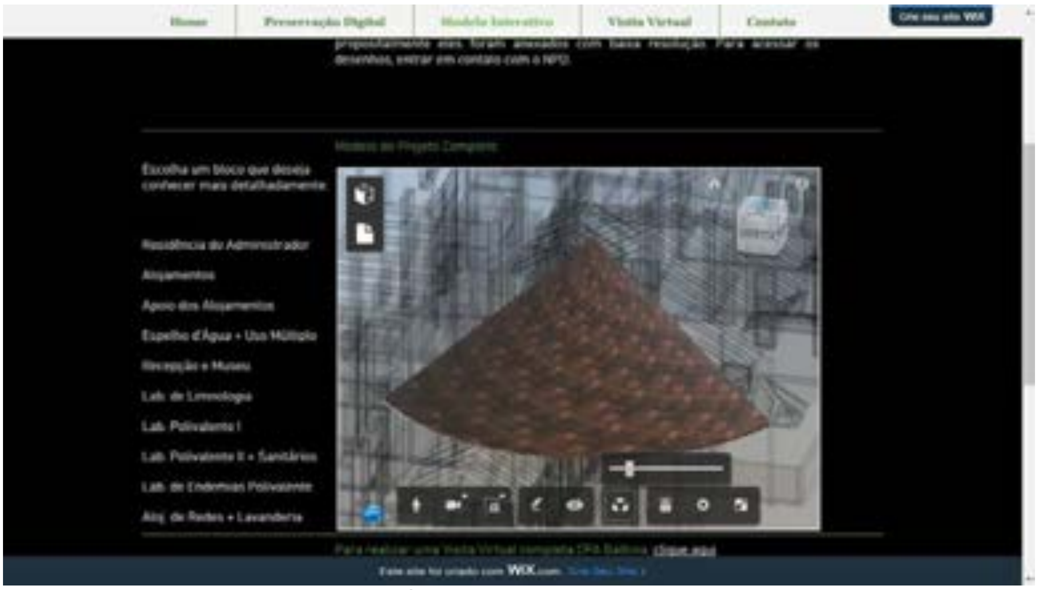

Figure 9: EPC Balbina – roof detail
Source: Cunha 2017

This example demonstrates some possibilities offered by the adoption of digital tools in architecture teaching, since, through the construction of the model, this student had the opportunity to:

- apprehend the constructive details of the project studied with greater precision (indicating the potential in the teaching of construction technology);
- identify the potential of digital tools in the preservation of built heritage;
- participate to the architect's design process - particularly in the part that has not been executed.

It is worth mentioning that the student used existing information in drawings produced at AUTOCAD.

4.3 Impacts on environmental sustainability and heritage preservation

The possibility to create a database that can help during the operation and maintenance phase of building is another possibility offered by BIM Model. In this sense, research developed by Canuto & Salgado (2016) revealed the possibilities offered by BIM Platform through the digital reconstruction of Palacio Gustavo Capanema – icon of modern architecture of the city of Rio de Janeiro.

From the document with the building design it was possible to create its three-dimensional model in ArchiCAD 19 software using the GDL language (Figura 8). […] Once the geometry was ready, it was possible to add historical information fields that can contribute to the conservation of the building (Canuto & Salgado 2016:4873).

BIM methodology allowed the unification of historic and research data, providing orientation for the preservation of this modernist heritage and also contributing for the operation and maintenance of the building. Moreover, the model also allows the analysis of energy efficiency and carbon emission, combining digital preservation and environmental quality in building operation and maintenance phase (Fig.10).

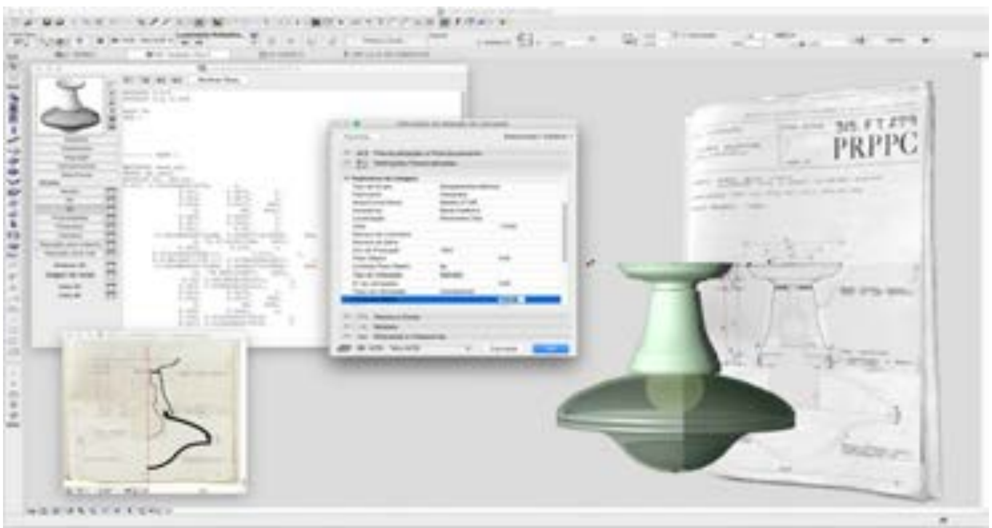

Figure 10: BIM model of a luminaire with the technical and historical information of the model. Source: Canuto & Salgado 2016.

5 Conclusions

Through the study of industrial revolutions, it was possible to identify the ICTs that stand out in the scenario of transition from the 3rd to the 4th industrial revolution. This theoretical study demonstrated the great potential for insertion of ICT (BIM, AR, VR and PR) in teaching 'construction' with the adoption of adequate technological resources. In addition, the suggested proposals for the course don't require major changes, but specifically the proper qualification of professor in order to incorporate the possibilities offered by the new technologies in their didactic practices. Examples presented illustrates some possibilities that has already been explored by architecture undergraduate and master students at FAU-UFRJ, but professors should also incorporate those innovations in their didactics practices.

The use of BIM model could enable the evaluation of interfaces at the construction site, making easier the comprehension of construction phases. The students could also print to prototype previously, in order to test the assembly of parts, predicting possible execution failures.

Regarding the adoption of the Augmented Reality (AR) feature in teaching construction technology, the professor could use an application similar to Skope to visit a building and explain the functioning mechanisms of the building and also the structural systems from the overlap of information of a model on the building in the real world. Another possibility is to use the AR Magic Book to increase learning in teaching materials.

The immersive experience through virtual reality can be very positive, as allows the evaluation of the quality of the constructive solutions adopted. Likewise, the professor can use VR as a play activity, so that students learn constructive processes in a scenario simulating the reality of the construction site.

Moreover, BIM platform applications such as BIMx or A360 can be used in the classroom to facilitate understanding of projects due to their ease of migration from a plant or cut to the 3D model. Videos produced in 4D and 5D planning software can also be used to explain the assembly phases of construction, budget evolution over time, and also to demonstrate the stages of experimental bedding. It is worth highlighting the possibilities that those software offer to the rationalization of the construction and, consequently, environmental sustainability in the choice of the most economic solutions and with rapid execution.

The case study demonstrated the great potential for insertion of ICT (BIM, AR, VR and PR) in teaching construction technology, with the adoption of adequate technological resources. In addition, the suggested proposals for the course do not require major changes, but specifically the proper qualification of professor in order to incorporate the possibilities offered by the new technologies in their didactic practices. Examples presented illustrates some possibilities that has already been explored by architecture undergraduate and master students at FAU UFRJ, but professors should also incorporate those innovations in their didactics practices.

It is worth highlighting the possibilities that those software offers to the rationalization of the construction and, consequently, environmental sustainability in the choice of the most economic solutions and with rapid execution. One of the intentions to stimulate the use of digital technologies by the professor in the classroom, is to bring benefits to the students who are able to understand the contents taught more easily. But it also instils interest in students to learn these technologies that are part of everyday life of society. In

this way, the adoption of didactic practices by professors exploring digital technologies possibilities in classroom is the best strategy to disseminate innovation among future architects. Therefore, the digital technologies can be of great value in the didactic process in the classroom and also as a way to encourage students to use them.

However, despite the possibilities offered by the technologies, a professor today is mobilized by false paradigms regarding technology and its practical application; a teacher who still has difficulty using ICT in everyday practice and, above all, appropriating them for teaching didactic use. (ROSA, 2013).

It is important to emphasize that it takes more than a single domain instrumental, it becomes necessary a knowledge of the potentialities provided by each type of technology according to each teaching method to be applied. The teacher needs to be reflective and ask himself: How can this technology favor my teaching work? How can it transform my activity, creating new goals, new work processes, new ways of interacting with my students? (ROSA, 2013:222-223)

Finally, this study provides a theoretical contribution to the works that seek to dialogue between teaching and technology of construction, teaching and ICT, and construction technology and ICTs.

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SUSTAINABLE ZERO-ENERGY HEATING OR COOLING AND VENTILATION OF AFFORDABLE HOUSING

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Abstract: *This paper updates a study to use only onsite renewables to heat or cool water for low temperature (23±3°C) radiators (LTRs) and run water pumps and fans for comfortable, affordable housing. This research is by simulations and experimental houses in Melbourne, Australia which has an annual average temperature of 15°C and tropical Kuching Malaysia. In South East Melbourne, a thermistor at the bottom of a 50m-deep borehole and an Emerson™ recorder recorded the temperature as 17°C. Simulation shows that circulating the water in the U-tube of this vertical ground heat exchanger (VGHE) to floor-LTR, and water heated by solar collector and stored in a 2m^3 indoor tank at 50°C by the end of summer to wall-LTR, a 30m^2 house could be heated to the 20°C daytime and 15°C midnight-to-7am heating thermostats in the Australian Nationwide House Energy Rating Scheme (NatHERS). A linear projection of this measured 2°C increase at 50m depth, gives 23°C as the average ground temperature for a 400m-deep VGHE. Simulation shows that circulating the water in the U-tube of this 23°C-VGHE to wall-LTRs, a similar 30m^2 house is also heated to NatHERS thermostats. Ground heat extracted in winter can be replenished by circulating solar-heated water back to the U-tube in summer. In Kuching, Malaysia, radiation to the night sky can cool water in a 0.3m^3 insulated tank to 25°C by morning and simulation shows that circulating it to a wall-LTR can keep the hottest west-end unit of a row of single-storey houses to below the thermally-comfortable-with-fan 30.5°C. Thermal comfort being subjective, the water temperature can be lowered with the cooling coil of a solar-powered chiller. The low power to circulate water and run fans can be provided by onsite photovoltaic thermal (PVT) and battery. In winter, outdoor air that cools the PVT will be preheated as it is drawn through the indoors for ventilation and will also remove latent heat. Since LTRs can be used for both heating and cooling, it is viable to integrate LTR into one side of mass-manufactured structural insulated panels (SIPs) to become affordable building materials for easily-constructed housing. Experimental houses would enable subjective evaluation of comfort by the local community and the validation of EnergyPlus™ simulated results.*

Keywords: *Renewably-heated/cooled Water; Low-temperature Radiator; Affordable Zero-energy Houses, Air-cooled-photovoltaic-thermal*

1 Introduction

In winter, the heating thermostat (temperature at which heating begins) is 20°C during daytime and is 15°C at night. Low temperature (23±3°C) radiators (LTRs) on inside surfaces can provide these 15-20°C indoor operative temperatures and the water can be heated or cooled by renewable sources. The mean skin temperature with normal clothing in a 15-20°C room is 32-35°C (Freitas Jr., R.A 1999), so the sensible portion of the occupants' metabolic heat could be transferred to 20-25°C wall-LTR (Stefan-Boltzmann constant of 5.67 x 10^{-8} watt/m^2/K^4 gives the radiative heat transfer from 1m^2 of the human body surface parallel to a wall as 43-92W). For summer or tropical houses, with fans the indoor could be comfortable with temperatures of up to 31°C (Fountain, M. and Arens, E. A., 1993)

Low power is required to circulate waters and run fans and could be provided by onsite photovoltaic thermal (PVT) and batteries. In winter, outdoor air can be preheated as it is drawn through the indoors to remove latent heat and for ventilation. Measurements are made in experimental buildings in Melbourne, which is the capital city of Victoria, the state that uses more energy to heat houses than the rest of Australia (Department of Environment, Water Heritage and the Arts, 2008). The LTR can be water ways between two metallic plates, like the flat plate heat exchanger, integrated into a surface of mass-manufactured structural insulated panels (SIPs) to become affordable building materials for quickly constructible housing.

2 Background

Ooi, K., et al 2015 reported that a thermistor to the bottom of a 50m-deep U-tube and an Emerson™ recorder measured the temperature at the bottom of the borehole as 17°C at an experimental house in South-East Melbourne. Simulation showed that the circulation of water from this U-tube to floor-LTR and water heated by 30 evacuated tubes, stored in 2m^3 indoor tank to wall-LTRs, a 30m^2 house could be heated to the heating thermostats of 20°C daytime and 15°C nighttime in the Australian Nationwide House Energy Rating Scheme (NatHERS, 2016). Ooi K., and Noguchi M., 2016 reported the findings of the May 2016 experiment. Melbourne has an annual average temperature of 15°C, so there is a 2°C increase at 50m depth. The Intergovernmental Panel on Climate Change (IPCC 2008) gives a more conservative but nevertheless linear 25-30°C increase per kilometer depth. Using a linear projection of the 2°C increase measured at 50m, a 400m-deep VGHE would be surrounded by ground with an average temperature of 23°C. Koon Beng Ooi and Masa Noguchi, 2017 showed by simulations that circulating the water in this U-tube surrounded by 23ºC ground to LTRs on opposite long walls, a rectangular 60m^2 Melbourne Australia house, is heated to NatHERS settings and, in the hot half of the year, circulation of water heated by a 3.4m^2 flat plate collector back to the VGHE could replenish the heat extracted in the cold half for family-size houses. Therefore, the ground source heat pump may be obviated.

Typical metrological year weather supplied by the US Department of Energy (2016) showed that for Kuching, Malaysia, the temperature of the sky would drop to 25°C at night. Baharun A., et al (2011) showed by simulations that 25°C night-cooled water stored in a 0.3m^3 indoor tank, circulated to bottom wall-LTR could cool the hottest west end unit of a row of single-storey houses to less than the thermally comfortable-with-fan 31°C. Over the past two years measurements showed that water cooled by radiation to the night sky is, by morning, not over 25°C. Experiments with a wall-LTR in the hot June

month of 2017 revealed that it would be better to lower the temperature of night-cooled water using a small solar-powered chiller.

3 Literature Review

3.1 Problematic Interseasonal Storage: VGHE is possible solution.

Arnould, M. (1985), Oliveti G.& Arcuri N (1995), Oliveti G. et. al. (1998) and Kroll, J.A. & Ziegler, F. (2011) studied inter-seasonal storage of solar-heated water. Kroll & Ziegler concluded that for small residential buildings, the ground could be used for inter-seasonal storage, and stated that. "The loss of heat is acceptable if the ground storage is cuboidal shape and must be heat-insulated and damp-proof". This implies that after 3 decades of research, storing summer heat for winter is still problematic. The thermal capacitance of the ground is large and thus a VGHE can serve as a source and store of renewable heat.

3.2 EnergyPlus™ simulation objects.

The LTR is modelled by the EnergyPlus LowTemperatureRadiant:VariableFlow object. (object names cannot have spaces) 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". Therefore, in experimental buildings, some of the insulation thicknesses and hydronic tubing lengths are adjustable. In simulations to heat indoors, water is circulated from the VGHE directly to the LTRs. The long and short time response factors (g-functions) of borehole temperature responses was 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. EnergyPlus™ provides 35 pairs of non-dimensionalized times and g-functions that can predict the sub-hourly responses of variable time steps, and explicit equations to calculate the outlet fluid temperature of the VGHE. PVT research has been conducted for the past 30 years and several reviews of PVT developments. show that there are no standards or rating systems such as for thermal-only, hot-water collectors. EnergyPlus currently has one simple model based on user-defined efficiencies, which will be obtained from PVT to be installed in Melbourne's experimental houses.

3.3 Use of water on inside faces

Trancossi M. et al.(2016) presented 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".

4 Methods and Results for Heating

4.1 First Experimental house with a 50m deep VGHE.

Figure 1 Left shows a print of the DXF of a model of the present 30m^2 experimental house in Melbourne, Australia. Figure 1 Right shows a photo of the 3-meter-wide x 6-meter-long extension under construction next to the metallic garage. Part of the garage is used as a kitchen, zoned as part of the living area in the northern half of the extension. The southern half of the extension is zoned as the bedroom. The white curve in the middle of the six posts in Figure 1 Right shows the insulated top of one end of the U-tube in the 50m deep. 17°C bottom-temperature VGHE.

Figure 1: Left: 30m^2 2.4mH experimental house next to 2mH metallic garage, Right: Top of 50m-VGHE

4.2 Passive Feature

Figure 2 Left shows the double-glazed windows at the top of the 150mm thick NW wall and the 200mm thick ceiling/roof. The floor is 100mm thick polystyrene covered with 45mm thick wood, shown in Figure 2 Right. This 30m^2 experimental house is rated by the FirstRate5™ house energy rating software at the mandatory 6 stars.

Figure 2: Left: Double glazed window at top of NW wall. Right: Floor for 13mm tubing of floor-LTR

4.3 4.3 Active Features:

4.3.1 Floor-LTR.
The 90mmW 45mmT wood strips shown in Figure 2 Right will sandwich 13mm dia poly tubing for the floor-LTR, which will be circulated with 15-17°C water from the 50m deep U-tube of the VGHE in December 2017. ***Wall-LTR***. By the end of summer of 2017/2018, glazed flat plate solar collectors on top of 2.44mW x 6mL, 10 degree sloping North-West facing roof of the adjacent garage will heat water in a 2m^3 indoor tank to 50°C for wall-LTRs. This tank buffers the lower solar radiations in winter. From simulations, the minimum temperature of this solar-heated water should around 25°C. The highest heating thermostat in the Nationwide House Energy Rating Scheme is 20°C.

4.4 Air-cooled PVT on roof

There is 200mmT insulation under the 2% sloping metallic roof. In the middle 1.2m span of this 6mL insulated ceiling is a SIP lowered by 30mm to enable air under the 30mm-high ridges that forms about 20% of the roof area, for the outdoor air to be drawn indoors.

4.5 Simulated results. 15-17°C VGHE water to floor-LTR and solar heated water to wall-LTR

Figure 3 shows the simulated heating rates and living and bedroom temperatures for a coldest week. Solar radiation through the NW double-glazed windows cause the indoor temperatures to peak as high as 24°C before noon of July 1st and 6th. The spikes in the heating rates are because the NatHERS night time heating thermostats are set-backed from of the 20°C waking hours (8am to midnight in this case) setting for the living area and 18°C from 7am to 9 am and 4 pm to midnight for the bedroom.

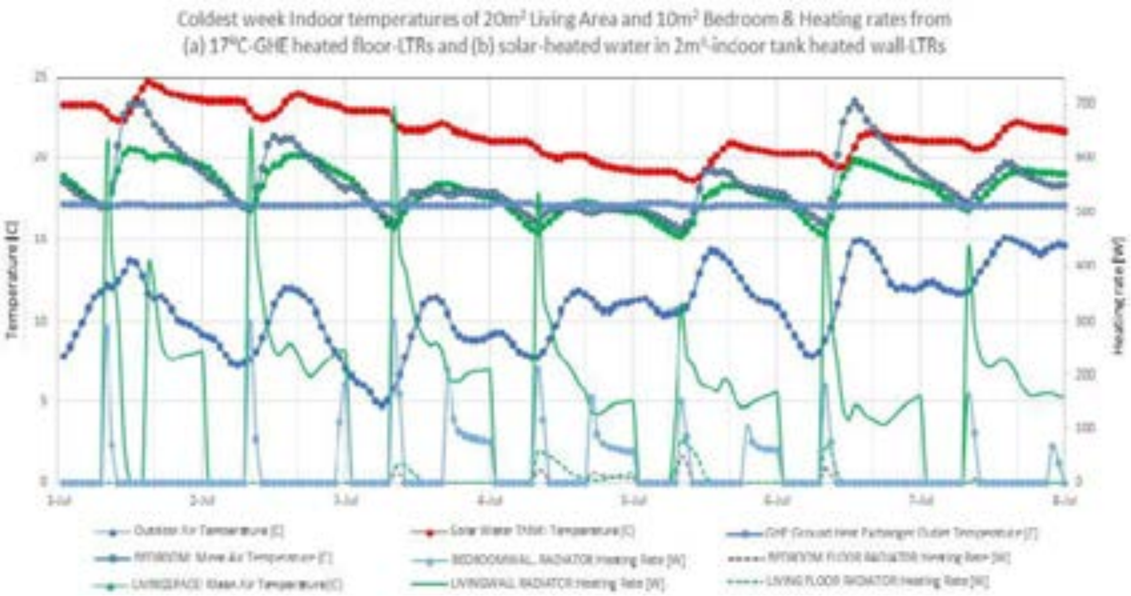

Figure 3: Temperature of 20m^2 Living Area, 10m^2 Bedroom and solar-heated water –Coldest week

4.6 4.6 Second Experimental house. – heated by 23°C average-temperature VGHE

The state of Victoria in Australia accounts for a 59% share of the national space heating energy consumption. (Department of the Environment, Water, Heritage and the Arts DEWHA, 2008). The Melbourne University's Burnley campus in Victoria's capital city has approved a site for the construction of a new experimental house with north facing double-glazed windows for both living area and bedroom shown in Figure 4, and a VGHE surrounded with ground of average temperature 23°C. The living area is situated on the hotter west side as its heating thermostat is 2°C hotter.

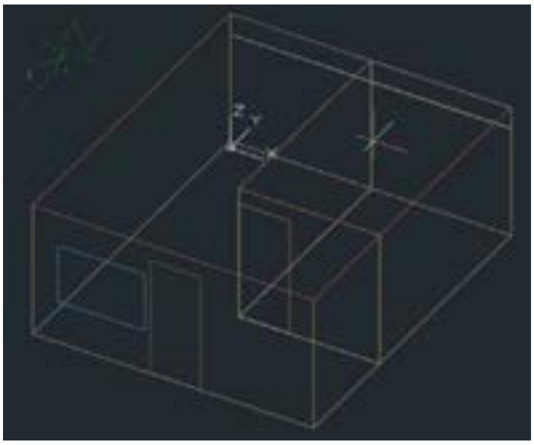

Figure 4: 30m² experimental house with north facing windows

Figure 5 shows the simulated operative temperatures for the living area and bedroom when water from VGHE surrounded by ground with an average temperature of 23°C is circulated directly to LTR on opposite 6-meter long walls of this proposed experimental house, with 0.4mH double glaze windows at the top of the north walls could heat indoors above NatHERS heating thermostats.

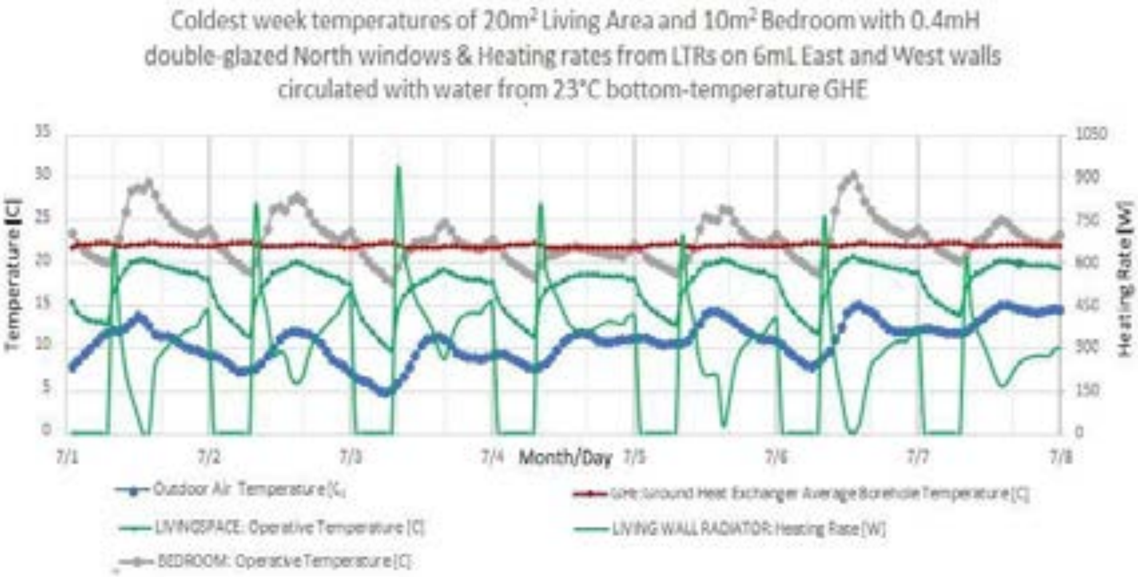

Figure 5: Temperatures of 20m² Living area, 10m² Bedroom and heating rates by LTR-Coldest week

5 Method and Results for Cooling

5.1 Simulated Results

Figure 6 shows that when the outdoor temperature in Kuching Malaysia is exceeded on average for 0.4% of the year, the circulation of 25°C night-cooled water, stored in a 0.3m^3 insulated tank, to wall-LTR on the partition of the hottest west-end unit of a row of single-storey houses, the indoors could be cooled to below 30.5°C, thermally comfortable with fans.

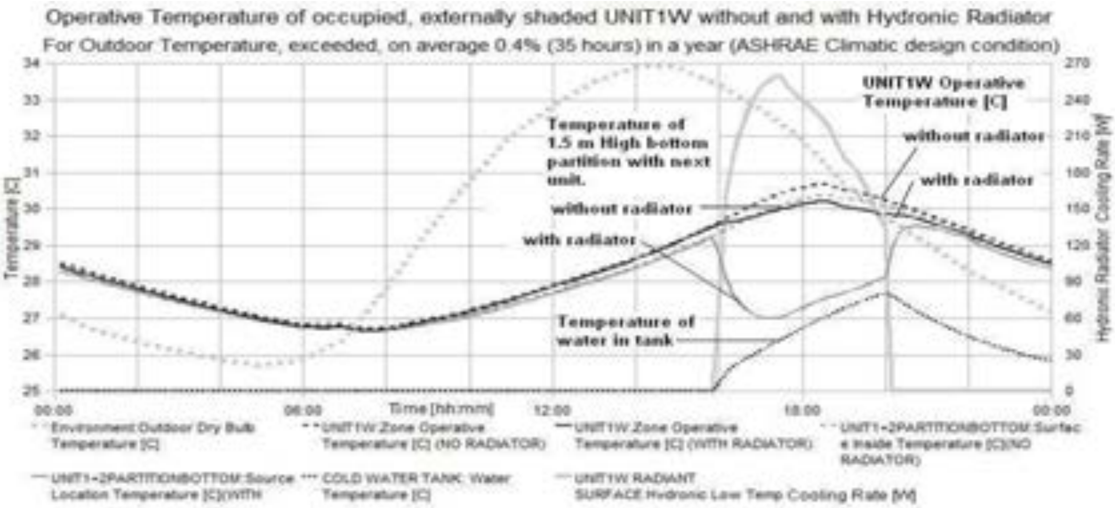

Figure 6: Simulated temperatures for thermally stored 25°C water in LTR of hottest west-end unit

Figure 7 Left shows the sloping surface at a forest monastery in Kuching, Malaysia that during the nights, cools about 200mL of water in the insulated tank to not more than 25°C by morning for hot afternoons i.e., indoor temperatures above the thermally-comfortable-with-fan 30.5°C. Figure 7 Right shows 45m-long 13mm-diameter black polyethylene tubing spaced out into eight slinky coils on 800mmH 50mm thick metallic-clad polystyrene on the bottom wall of the adjoining room.

Figure 7: Left: Radiation to night sky and thermal storage. Right: LTR on bottom wall -Kuching

Measurements were carried out in July 2017. Night radiation could indeed cool the 200mL water in the drum to less than 25°C by morning. By afternoon, the water at the top of this insulated drum has increased to about 26°C while that at the bottom is still 25°C. The water in the 1m tall drum has stratified. The water pump is placed at the bottom of the tank.

In the afternoon, the water was made to flow into the 13mm diameter tubing shown Figure 7 Right. The flowrate was measured at 0.0375L/sec. The surface of the tubing at the entrance to the room was wet, there was condensation of the indoor air, the relative humidity of which was measured recorded at about 80% from June 22 to July 10. However, the indoor air temperature never exceeded 30°C, and with ceiling fans, the radiator was not fully tested.

The experiment will continue in June/July 2018. Meanwhile preparations are being made to include the cooling coil of a solar powered refrigerator to add coolness to the night cooled water. Also, the radiator may be changed to a commercially available mat-type with more exposed cooling area.

6 Summary of Simulation and Experimentation for Heating and Cooling

Table 1 shows a summary of heating or cooling and ventilation by renewable sources and the equipment used or proposed for dwellings in seasonal or tropical climates. Footnotes elaborate on each item. Table 2 lists the three phases of this research, i.e., simulated verification of concepts, validation experiment and subjective evaluation of comfort by local community. The following figures show pictures of the experimental equipment. Table 3 shows a list of the three measuring instruments.

Table 1: Summary of heating or cooling and ventilation by renewable sources and the equipment

Climate	Seasonal Climates		Equatorial
Weather	Cold (Winter)	Hot (Summer)	Hot tropical
Heating or Cooling	Heating	Cooling	
Primary method	LTRs[1]	Air movement from fans[2]	
Alternative/Secondary cooling		Alternative cooling: Evaporative Cooler[3]	Secondary cooling: LTR[1]
Renewable Heat/coolth source	VGHE[4]	---	Night cooling[5]

[1] **LTR**: Low Temperature Hydronic Radiators, circulated with around 20-25°C water on inside surfaces. For heating, wall-LTRs is preferred as walls have better view factors for radiative heat transfers than floors. Floor-LTR is used when VGHE is not deep enough to give 22-24°C water. In this case, solar-heated water is circulated to wall-LTR. For cooling in humid tropical climates, wall-LTR is used because of possible condensation that would make floor-LTR slippery

[2] **Fans** create a cooling sensation of up to 4°C and can be used also for ventilation in summer. In tropical countries, thermally-comfortable-with-fan temperature is up to 30.5°C

[3] Evaporative cooling is used in many existing houses in seasonal climates which have lower humidity.

[4] **VGHE**: Vertical Ground Heat Exchanger: Water from 50m and 100m deep VGHE in south eastern Melbourne has been measured at 15-17°C and 22-24°C respectively. These depths are about half those calculated for Melbourne's annual average temperature of 15°C using IPCC 2008 data of 25-30°C/km depth. Most of habitable places have annual average temperature of above 0°C, and the VGHE depth would thus be less than 1km.

Heat Replenished by	---	Solar-heated water[6]	---
Booster source when VGHE is insufficiently hot or night-cool water insufficiently cold.	Indoor tank with water heated by solar collectors to 50°C by end of summer.[7]		Chiller run by photovoltaic[8] for hot sunny days
Fresh air for Ventilation	Outdoor air that cools PVT[9]	Air movement from Fans & Openable windows	
Onsite power from	Air-cooled photovoltaic thermal (PVT)		Photovoltaic (PV)
Development of LTR integrated into structural insulated panels (SIPs) is supported by large Australian SIP manufacturer. This could lead to commercially manufactured affordable building material for affordable housing.			

Table 2: Three phases of this research

Three Phases of Research	**Status**		
	Seasonal Climates		**Tropical Climates**
(1) EnergyPlus™ simulations	Simulated results presented in this paper		
Location of experiment	Cool (annual average temperature of 15°C.) Melbourne, Australia		Hot tropical Kuching, Malaysia
Annual Average Outdoor	15°C		About 30°C
Latitude, Longitude	-31.82°N, 144.97°E		1.52°N,110.35°E
(2) experiment house - 1st (existing)	Water from 17°C-VGHE to floor LTR Solar-heated water in tank to wall-LTR		Night-cool water measured at <25°C.
2nd experiment house (proposed, seeking funds) /next experiment	23°C-VGHE to heat water for only wall-LTR		Add solar powered cooling coil in June/July 2018
(3) Survey of Comfort	Future	Future	Future
SIP integrated with LTR/PVT	Manufacturers of structural insulated panel (SIP) are invited to fund this research and manufacture affordable building integrated LTR/PVT		

[5] Typical Meteorological year (TMY) weather data for Kuching shows night sky temperature is not more than 25°C. This is measured in water cooled by radiation to the night sky in June/July of 2015 to 2017

[6] **Sustainability**: Simulations show that during summer in Melbourne, 30 evacuated tubes could collect 1.2MWH of heat. This solar-heated water can replace the heat extracted from VGHE for family-sized ($144m^2$) houses.

[7] **50m-deep VGHE in Melbourne** is heating water to only 15-17°C. So, it is used in floor-LTR and solar collectors are used to make solar-heated water for wall-LTR. Simulations show that when a $2m^3$ indoor tank is used as buffer storage for less solar radiation in winter. At end winter, water in tank is still about 25°C

[8] June/July 2017 experiments in Kuching show that It is difficult to maintain 25°C in night-cooled water by afternoons, and cooler water is desirable. Therefore, the cooling coil of a solar-powered chiller will be used to boost the coldness in this water for experiments in June/July 2018. This extra coldness can be expected to match the indoor heat as hot days are usually sunny, thus more power to cool the cooling coil.

[9] **Photovoltaic thermal** (PVT) cooled by air is used. Outdoor air that cools the PVT will be heated and can be drawn indoors as preheated ventilation air in winter.

Table 3. Available measuring equipment and accuracy

Make	Model	Accuracy
Fluid in glass tube thermometer	Range 0 to 50°C	By eye of about 0.5°C 2mm division per °C
Elitech RC-4HC	1, Temperature measuring range: -30℃~+60℃; external sensor (cable length 1.1m), -40℃~+85℃ 2.Humidity measuring range: 0~99%RH	Temperature accuracy: ±0.5℃/0.9℉ (-20℃~40℃); 2.Humidity accuracy: around 3%RH(25℃,20~90%RH)
TPI Digital Thermometer	343 with Type K thermocouple,	+/- 0.56°C system (tester & probe) accuracy within -1°C to 48.88°C temperature range
Fluke 62 Mini Infrared thermometer	Fluke 62 IR Thermometer	

7 Discussion

7.1 7.1 Heating in cool/cold climates

Many ground source heat pumps in cool Melbourne Australia operate intermittently causing cyclic loads in the ground heat exchanger (GHE). Fang Z. et al 2002 concluded that "GHE operate better with a constant load than with cyclic loads with large variations in the heating load to keep its temperature rise restrained within a certain limit". Therefore, GHE would perform better without the heat pump, as can be done by VGHE with bottom temperatures of 23°C.

Simulations verify that circulating water, heated by VGHE surrounded by ground with an average temperature of 23°C in cool i.e. annual average temperature of 15°C, Melbourne, Australia, to LTRs on the inside surfaces of opposite walls could heat the indoors to thermal comfort. Modern houses are well insulated, thus houses in colder climates, LTRs circulated with water in the U-tube of similar VGHE could also provide thermal comfort

The Intergovernmental Panel on Climate Change (IPCC 2008) gives a ground temperature increase of 25-30°C/km and the British Geological Survey (2011) estimates a 2.6°C increase in temperature for a 100m increase in depth. These data indicate that for places with an average annual temperature of 0°C (between light blue and green in Figure 8), the depth of the VGHE would be about 1km.

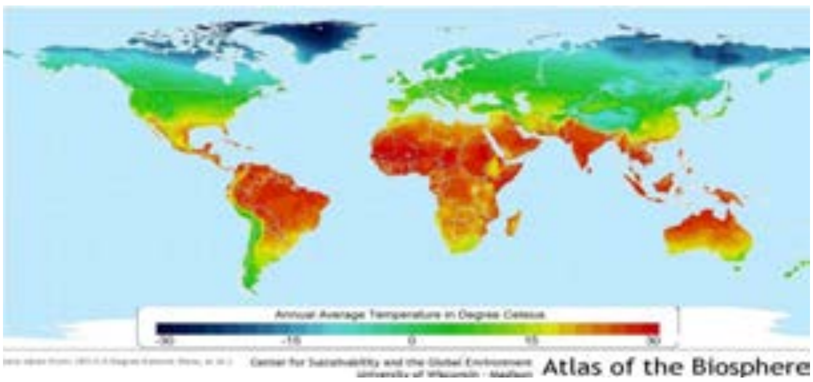

Figure 8: Average Annual Outdoor Air Temperature

Heat extracted from the ground can be replenished by circulating solar-heated water to the U-tube of spare VGHEs. Without the ground source heat pump, the cost of VGHE-LTR could be comparable to the cost of horizontal GHE with ground source heat pump and high-temperature floor radiators.

7.2 Cooling in hot tropical climates

Simulations with typical meteorological year weather data show that the hottest west-end unit of a row of single-storey Malaysian houses, insulated at the ceiling to MS1525:2007 could make indoors above the thermally-comfortable-with-fan temperature of 30.5°C for 0.4% of the year. Though radiation to the night sky in Kuching, Malaysia can cool water to 25°C by morning, June/July 2017 experiments show that by afternoon, the water will hotter by 1-2°C. This makes the temperature of 26-27°C too close to the thermally-comfortable-with-fan 30.5°C. Therefore, in the next experiment in the hot months of June/July 2018, a photovoltaic shall be used to power a chiller. The cooler coil will increase the coldness of the water in the storage tank. The water will be colder during the hotter days when, in tropical places, would have more solar radiation to run the chiller.

7.3 Ventilation

Kumar., R, & M. A. Rosen (2011) determined that “the photovoltaic–thermal (PVT) air heater is or may in the future be practicable for preheating air for many applications, including space heating and drying, and that integrated PVT collectors deliver more useful energy per unit collector area than separate PV and thermal systems. Although PVT collectors are promising, it is evident that further research is required to improve efficiency, reduce costs and resolve several technical design issues related to the collectors”. PVT will be tested in experimental buildings in Melbourne.

7.4 Affordability

The water-conditioned LTR could be integrated to the inside faces of structural insulated panels (SIPs) for walls. Similarly, the air-cooled PVT could be integrated into roof SIPs. Mass-manufacturing of such wall or roof SIPs is very likely to lower costs of building materials to make dwellings more affordable.

8 Conclusion

Low temperature hydronic radiators (LTRs) are fitted to experimental buildings in cool Melbourne Australia and hot tropical Kuching Malaysia. These are used to validate the simulated results that circulates water conditioned by renewable sources i.e., the vertical ground heat exchanger (VGHE), and if necessary solar radiation for houses in cool/cold climates, and radiation to night sky and if necessary solar powered chiller for houses in hot tropical places. In cool/cold climates, operating power can be from onsite photovoltaic thermal (PVT) that will, with the help of batteries, operate the pumps for the LTRs, cooling fans in summer and exhaust fans to draw outdoor air that cools the PVT and ventilate the indoors in winter.

Availability of experimental houses would enable the local communities'These LTR, and maybe PVT, could be integrated into the inside faces of metallic-clad structural insulated panels. This innovative building material can be mass-manufactured, and housing would be affordable. Since rooftop PVT and batteries can operate the water pumps and fans, operational cost will also be low.

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DESIGN OF A PREFABRICATED ROOFTOP EXTENSION WITH LOW ENVIRONMENTAL IMPACT

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Abstract: *Urban sprawl, a growing population and a decreasing household size are some key challenges Flanders is currently facing. Densification of the current residential areas by means of extending (vertically) existing houses offers a solution to address the additional housing needs and to avoid further fragmentation of open space. This paper is part of an ongoing research which focuses on designing and evaluating prefabricated timber frame systems for low-energy rooftop extensions of existing residential buildings. A minimum disturbance of the inhabitants and a lightweight structure are key requirements to allow for a widespread implementation. In a preliminary research step a Belgian rooftop extension in timber frame has been analysed over a lifespan of 60 year. The wood-based parts in the timber frame walls were identified as an important source of environmental loads. This paper builds further on the findings of this preliminary research step and focuses on designing a prefabricated timber frame system for a rooftop extension with a low environmental impact. A timber frame system is developed, including the elaboration of the technical details. Moreover, a possible solution to connect the developed timber frame system with the existing residential building is analysed and discussed. More generally, guidelines to deal with the consequences of various building characteristics of the original building are provided.*

Keywords: *Life Cycle Assessment (LCA), Prefabrication, Timber Frame Systems, Rooftop Extensions*

1 Introduction

A growing population and a decreasing household size in Flanders (Belgium) results in an extra housing need (Ryckewaert et al., 2011). Urban sprawl is moreover one of the key challenges Flanders is facing (i.e. very low density of the residential area of Flanders compared to other European countries) (Eurostat, 2012). Densification of the current residential areas by means of vertically extending existing houses offers a solution to address the additional housing needs and to avoid further fragmentation of open space. This paper is part of an ongoing research which deals with these densification issues and focuses on designing and evaluating prefabricated timber frame systems for rooftop extensions on residential buildings. Minimal disturbance for the neighbourhood and inhabitants and not overloading the existing structure including foundations (i.e. need for a lightweight structure) are decisive factors in the choice for prefabricated timber frame systems.

Fully prefabricated systems are often used for renovation in various countries, e.g. the Netherlands and Switzerland. These systems are however rather rarely used in Belgium. A review of recent rooftop extensions in Belgium showed however that semi-prefabricated building systems are more and more used. Semi-prefabricated systems consist of the load-bearing structure and a structural sheeting. The insulation and finishing layers are placed on site. The main reasons for using semi-prefabricated systems instead of fully prefabricated systems are the fixation possibilities, they are easier adjustable to deviations in the dimensions of the underlying structure and modifications to the structure can still be made on-site.

Compared to on-site construction, prefabricated building systems have several advantages. Prefabricated systems are assembled off-site, the work on-site is hence limited to the mounting of the prefabricated elements, attaching these elements on the existing structure and some finishing works. These aspects reduce the construction time to few days, which leads to less disturbance for the inhabitants of the renovated houses and the neighbourhood. The elements are fabricated in a controlled environment and the construction on-site is less exposed to weather conditions and less susceptible to moisture and insects due to a faster construction on-site. In addition, manufacturing plans are available and the structure is clear for any necessary adjustments or damage repairs later on. Despite a lower labour cost, prefabricated building systems require a higher cost for the necessary crane and prefabrication study compared to on-site construction.

Some innovative European demonstration projects (TES EnergyFacade, n.d.) (IEA ECBCS Annex 50, n.d.) (E2ReBuild, n.d.) have been set-up in the past decades which investigate the feasibility and potential of prefabricated building systems. These projects show among others that a high quality renovation can be reached by the use of prefabricated elements while inhabitants can remain in their houses during the renovation works. The TES Energy façade project shows furthermore the many possibilities of prefabricated elements for renovation with volume expansion (Cronhjort et al., 2014).

2 Methodology

2.1 Review of Belgian building typologies

The Belgian building stock is characterized by mainly private home ownership and a high design variety. Renovation interventions are hence ad hoc solutions for ad hoc renovation questions. In case of a rooftop extension, the various wall and roof/upper

floor structure are the main boundary conditions to deal with. As the prefabricated system developed should be widely useable and hence easily adjustable to these boundary conditions, a review of the Belgian building stock has been made based on the TABULA (Cyx et al., 2011) project. In the TABULA project, reference buildings have been defined which represent the housing stock in Belgium. For these reference buildings, a distinction is made in construction period based on variations in characteristic set-ups of construction elements over time. The different technical characteristics for the external walls per construction period are listed in Table 1. In existing buildings, variant structural constructions for the upper floor are present: reinforced concrete, wooden beams or composed floors such as concrete beam and pot floors or hollow core slabs.

Table 1: Technical wall characteristics per construction period (Cyx et al., 2011)

Construction period	Technical wall characteristics
<1945	Solid masonry wall
1945 - 1970	Cavity wall - no insulation
1971 - 1990	Cavity wall - 2 cm insulation
1991 - 2005	Cavity wall - 6 cm insulation
2006 - 2011	Cavity wall - 8 cm insulation
2012 - …….	Cavity wall - 15 cm insulation

The composition of the Belgian housing stock in terms of building types is shown in Figure 1. The scope in this research is on single family houses, apartment buildings are therefore excluded in the graph. As detached buildings represent around 40% of the single family houses (Belgian Federal Government, 2014), a detached house is used as reference building in this study. The system being developed will however also be useable for the front and back facades of semi-detached and terraced houses, but further research is needed for the common walls. The technical details of the prefabricated system elaborated in this paper are for a reference building with a flat roof and a cavity wall of 2.5 cm insulation. The system is however adjustable to other cavity compositions. The consequences of different characteristics of the original house on the prefabricated system are discussed in section 2.3. It concerns a different insulation thickness in the cavity wall, pitched roof instead of flat roof and various floor finishes. The consequences of other floor structures are not yet discussed and will be investigated in a next step of the research. Besides, the presence of asbestos in old buildings might be an issue of concern when extending buildings. Although this might influence the environmental impact of the rooftop extension, this paper does not focus on the demolition of the roof in terms of asbestos or other hazardous substances.

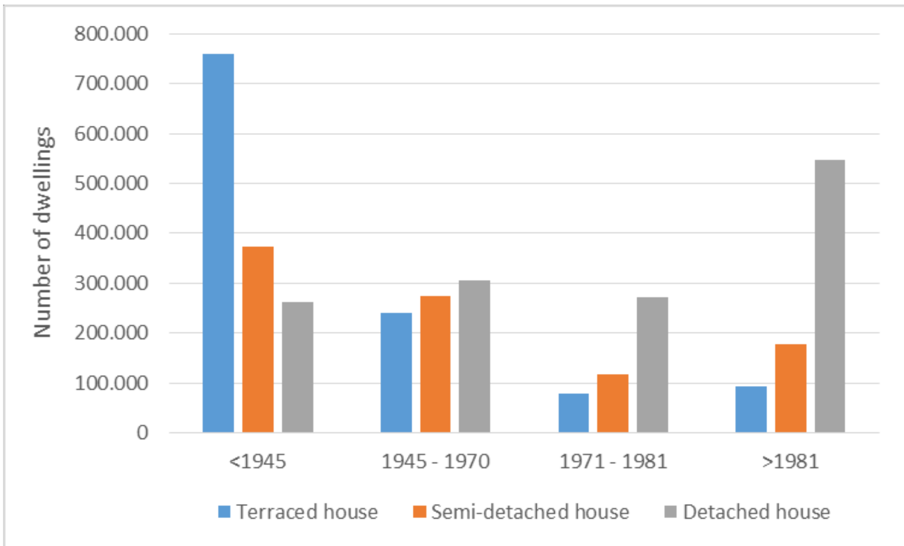


Figure 1: Graphical representation of the number of dwellings per building typology (terraced, semi-detached and detached) and per building period (Belgian Federal Government 2014)

2.2 Environmental review of Belgian rooftop extensions

In preliminary research (Wijnants et al., 2016), the life cycle environmental impact of a current Belgian timber frame system for rooftop extensions was assessed. The assessment was performed both at the element and building level. The life cycle assessment revealed the wooden based parts of the timber frame as environmental hotspots. In a next step it was studied how the environmental impact of the structural wooden parts in the timber frame walls could be reduced. More specifically, the impact of I-joists (consisting of laminated veneer lumber flanges and a web with a thickness of 10 mm in OSB) instead of solid studs was studied (Wijnants et al., 2017). It was furthermore investigated how the heat resistance of the walls can be increased aiming at a low life cycle environmental impact. A comparison was made between adding an insulation layer without changing the solid studs and enlarging the solid studs and the insulation in between the studs. The study concluded that changing the type and dimensions of a timber frame wall could reduce its environmental impact up to 10%. Despite an equal material impact, I-joist are in general preferable compared to solid studs due to a higher insulation level and thus lower operational energy use for heating the building. From all alternatives considered, a timber frame wall composed of I-joists of 24 cm was the preferred solution from an environmental perspective. The study moreover revealed that a thinner timber frame structure combined with an extra insulation layer has a higher environmental reduction potential than enlarging the dimensions of the studs (with insulation in between). Seen the positive effect on the thermal resistance and environmental impact of the wall, I-joist will be used instead of solid studs in the prefabricated system developed. The system developed consist of I-joist of 16 cm combined with an extra insulation layer of 6 cm at the outside. An additional advantage of this extra insulation layer is that the impact of thermally weaker points of the wall, namely the wooden studs or I-joists, are reduced. The dimensions of the I-joists can vary according to stability requirements.

2.3 Design requirements

Prefabricated timber frame systems have to meet several requirements in Flanders which were taken into account during the design of the prefabricated system. The

requirements are summarised in the subsequent paragraphs and the solution proposed in the prefabricated system are described.

2.3.1 Thermal and acoustic insulation

To fulfil the current energy performance of buildings in Flanders a U-value of 0.24 W/m²K is required for walls and roofs (Vlaams Energieagentschap, 2016). This requirement is taken into account for the prefabricated system. The walls have a U-value of 0.16 W/m²K and the roofs a U-value of 0.17 W/m²K. There are no extra requirements for acoustic insulation in the building envelop of detached single-family houses.

2.3.2 Air, vapour and water tightness

In order to limit the heating demand, the rooftop extension should be air-tight. This can be achieved by using air-tight foils or air-tight wood derivate boards. Any joints in this layer must be sealed with adhesive tape. In case an air-tight foil is used, this foil is attached to the underlying structure with staples and a 10 cm overlap between two foils is foreseen and sealed with a universal adhesive tape. Furthermore, special attention must be paid to the air-tight connection between the various building elements and to avoid any perforations of the air-tight screen. For the connection of two building elements, it is important that the air-tight screen can deal with possible movements of these elements. (WTCB, 2013) (Van Leemput and Hilderson, 2010) In the prefabricated wall system developed, air-tight OSB boards are used and the joints are sealed with an adhesive tape. Perforations that could be generated by electrical ducts are avoided by using a cavity at the inside between the air-tight screen and the internal finishing layer. The air-tight foils of adjacent roof elements are on site attached to each other.
The air-tight screen (at the warmer side of the construction) moreover serves as a vapour barrier. This vapour barrier is required to ensure the thermal performance of the insulation material and to prevent mould and bacteria formation. At the colder side of the construction, a vapour open, water- and wind-tight foil or board should be added to prevent air flow and water infiltration in the insulation and wooden structure. To connect this screen between the different building elements, also a 10 cm overlap should be provided. (WTCB, 2013) In the prefabricated wall system developed, a vapour open, water- and wind-tight foil is fixed at the extra insulation layer. An overlap of at least 10 cm is foreseen at the connection between different wall elements. The roofing membrane of the roof elements is placed on site.

2.3.3 Stability and safety

Before adding a rooftop extension to an existing building, the existing structure needs to be inspected. The general condition of the structure should be analysed, i.e. are there any structural problems, moisture problems, etc. Furthermore, it should be examined if the load-bearing capacity of the existing floor, wall and foundation is sufficient to bear the extra load of an extra storey. This extra load is mainly determined by the weight of the rooftop extension, safety (Ultimate Limit State) and serviceability (Service Limit State). The prefabricated wall system developed has a weight of 0.65 kN/m^2, the roof system has a weight of 0.51 kN/m^2. In Belgium, the bearing capacity of the masonry is often sufficient, the condition and bearing capacity of the foundations are mostly decisive. The condition and bearing capacity of the existing structure should always be checked by an architect or engineer. Although these are important aspects in a refurbishment project, it is beyond the scope of this paper and is not further discussed.

2.3.4 Fire safety

There are no requirements regarding fire safety for detached single-family houses. Nevertheless, by designing timber frame constructions, special attention must be paid to fire and smoke flashover. Fire and smoke can easily spread through cavities in walls, floors and roofs. It is therefore important to choose plate materials with a high fire resistance and to carefully perform good connections between these plates. In case of perforations for ducts, these perforations should also be carefully sealed according to the manufacturer's instructions. To prevent a rapid spread of fire, there must be fire stops between the roof, the outer walls and the floors. Possible fire stops are non-combustible insulation plates, plates with a good fire resistance or mineral wool or rock wool strips. (WTCB, 2013)

2.3.5 Size, transportation and mounting

Larger sized prefabricated building systems have important benefits, although it is harder to hoist the elements into place. A major advantage of larger elements is the more limited number of joints that need to be sealed on site. This requires less construction time on-site and reduces the risks of internal condensation or bad air-tightness. The maximum size of the prefabricated elements is defined by the maximum dimensions allowed for a construction truck. General regulations for transport within the EU are defined in the Directive 96/53/EC and allow a height of 4 m, a width of 2.55 m and a length of 12 m. To avoid too much stress on the window fixtures, the best position to transport the prefabricated system is upright. Besides, an upright position of the elements on the transportation trucks makes the hoisting of the elements into place at the construction site easier. For the final hoisting of the elements at the rooftop, temporary attachment points should be added to the prefabricated elements. Furthermore, a carefully planned transportation process is required. It is also necessary to provide the necessary cranes for mounting the elements on the construction site. The necessary type of lifting equipment is dependent on the heaviest weight and largest dimensions of the elements and the highest location to reach (Dubois et al., 2016).
Seen the large possible dimensions of prefabricated elements, in the system proposed, every wall is designed as one prefabricated element. For a rooftop extension of one storey this is possible for most Belgian single-family houses. The roof elements are case specific and made as large as possible in order to limit the number of seals that need to be sealed on-site. Generally, the length of the element is the width of the rooftop extension (i.e. shortest span) and the width of the standard elements is fixed at 4 m. The width of the last roof element is adjusted to add up to the depth of the rooftop extension.

2.3.6 Guidelines

As aforementioned, the Belgian building stock is characterized by a high variety of buildings, both in terms of typology, size and build-ups. In order to fit the prefabricated system in many situations, it should be easily adjustable to specific boundary conditions. Therefore, guidelines to deal with the consequences of different insulation thicknesses in the original wall and a pitched roof instead of a flat roof in the original building are provided in Table 2.

Table 2: Overview of consequences of various building characteristics

	Flat roof	Pitched roof
Existing wall	Possible difference in base level between inner and outer leaf after demolition, the non-bearing part of the developped system should be adjustable to this possible level difference.	
	Other insulation levels of the original construction results in an adjustment of the water profile dimension.	
	The walls are not always perpendicular to each other, the system must be able to deal with this.	
Existing floor/ roof	Removing membranes, insulation and sloping screed	Removing all floor coverings and screed layer.
		If wall plate is directly connected to concrete floor slab, wall plate can be used as leveling layer.

3 Results

3.1 Description of prefabricated system developed

The composition of the prefabricated wall and roof systems are described in Table 3. The roof is attached to the wall according to the balloon method, i.e. there is no interruption in the wall element. The roof is fixed between the walls. The main advantage of this method is that there are no additional joints to be sealed in the wall.

Table 3: Overview of the composition of the roof. The work sections indicated in italic are prefabricated. *The dimensions and spacing between the studs should be controlled on stability

Timber frame wall
External finishes - cladding - ventilated cavity
External finishes - support structure for claddings - wood Belgian mix - 38 x 38 mm
External finishes - vapour open, water-and wind-tight foil
External finishes - insulation - 60 mm
External finishes - wood fibre board - 18 mm
Thermal insulation between timber frame
Timber frame - I-joists 160 mm*
Internal finishes - OSB board - 15 mm
Internal finishes - support structure for boards - wood Belgian mix - 22 x 47 mm
Internal finishes - gypsum board – 12.5 mm - screwed - width 600 mm
Internal finishes - painting on gypsum board - acrylic paint

Timber frame roof
External finishes - EPDM (thickness 1.2 mm) - width 1200 mm
Thermal insulation - 140 mm
External finishes - vapour-tight foil
External finishes - roof plate - OSB board - 18 mm
Sloping layer
Timber frame - I-joists 300 mm*
Internal finishes - support structure for boards - wood Belgian mix - 22 x 47 mm
Internal finishes - gypsum board – 12.5 mm - screwed - width 1200 mm
Internal finishes - painting on gypsum board - acrylic paint

As mentioned before, the walls of the rooftop extension designed consist of four prefabricated wall elements. The connection between these elements is a key issue to solve. In existing buildings, walls are not always perpendicular and hence the prefabricated system designed should also fit on non-perpendicular walls. A horizontal section of a non-perpendicular corner connection between two prefabricated wall elements is shown in Figure 2.

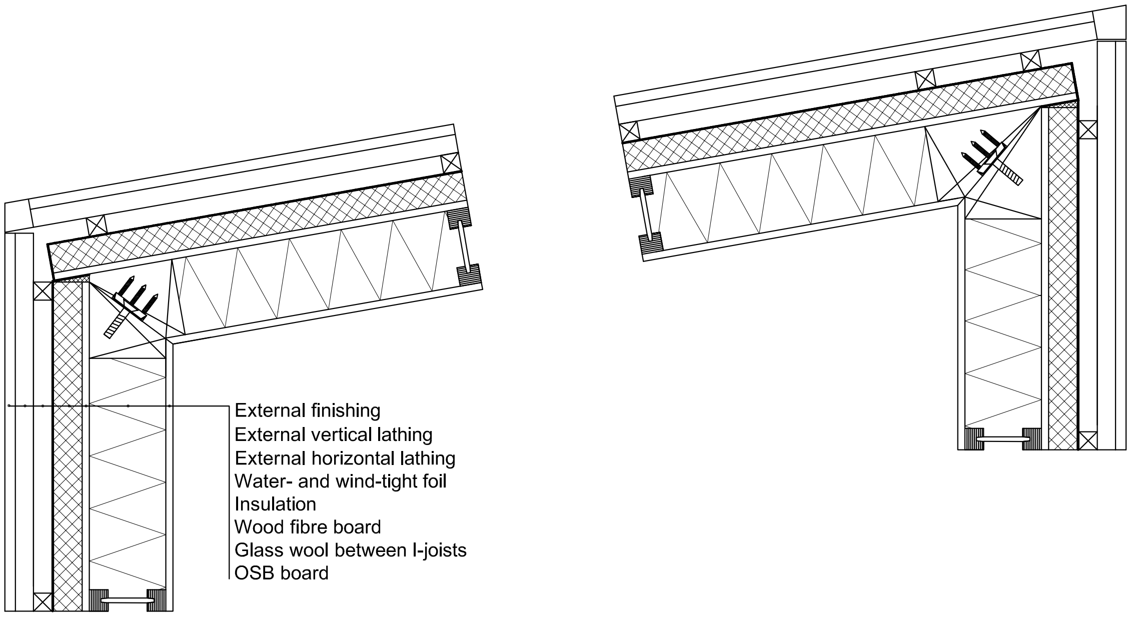


Figure 2: Horizontal section of corner connections between two prefabricated wall elements (non-perpendicular walls of existing building assumed). Connector systems for prefab walls are used (e.g. Knapp Walco®V).

The production of the prefabricated building system can be more or less automated. A possible production process is sketched based on some site visits in building systems factories in Flanders. This production process is briefly described for the wall as well as the roof systems in the subsequent chronological steps.

The production process of prefabricated wall system:

1. 2D assembly plans of the prefabricated building system are generated.
2. The beams, joist, I-joists and sheeting are cut in the right dimensions by an automated machine.
3. The timber frame structure is positioned and assembled on the production line by an automated machine.
4. The outer sheeting is nailed on the timber frame structure. The joints are manually sealed with adhesive tape.
5. The water profile is fixed on the outer side of the construction.
6. The extra insulation layer is fixed on the outer sheeting.
7. The vapour open, water- and wind-tight foil is fixed on the extra insulation layer.
8. The external lathing and external finishing are fixed at the prefabricated system.
9. The timber frame structure is tilted to a vertical position, transferred to another production line and laid back down horizontally on its external facing.
10. The insulation is placed between the timber frame.
11. The vapour-tight inner sheeting is nailed on the timber frame. The joints are sealed with adhesive tape.
12. A vapour- and air-tight foil is fixed at the place where the wall beam will be fixed (for the connection with the roof element).
13. The wall beam is fixed at the prefabricated wall system.
14. A beam support is fixed at the wall beam at the place where the I-joists of the roof connect to the wall.

The production process of prefabricated roof system:

1. 2D assembly plans of the prefabricated building system are generated.
2. The beams, joist, I-joists and sheeting are cut in the right dimensions by an automated machine.
3. The timber frame structure is positioned and assembled on the production line by an automated machine.
4. The sloping battens are assembled on the timber frame structure by an automated machine.
5. The structural sheeting is nailed on the top of the sloping battens.
6. A vapour-tight foil is fixed on the structural sheeting.

3.2 Description of mounting process

A chronological action plan for mounting and fixing the rooftop extension on the existing building is provided in the subsequent list and is illustrated in the subsequent detail drawings. As mentioned before, the technical details of the prefabricated system are elaborated for a reference building with a flat roof and a cavity wall of 2,5 cm insulation, but can be easily adjusted to fit other cavity compositions.

The mounting process of the prefabricated rooftop extension:

Step 1: Demolition of the cavity wall and roof finishing until the concrete floor slab level.

Step 2: Sill plates should be placed to adjust the floor level horizontally. The sill plates are fixed with anchor bolts. Furthermore, a sealing is fixed between the sill plates and the original concrete floor slab.

Step 3: The prefabricated wall system is mounted on top of the sill plates and fixed with slant nailing from the interior side.

Step 4: If required, an extra fixation could be placed to attach the timber structure in the existing slab.

Step 5: The prefabricated roof elements are placed in and fixed at the beam supports.

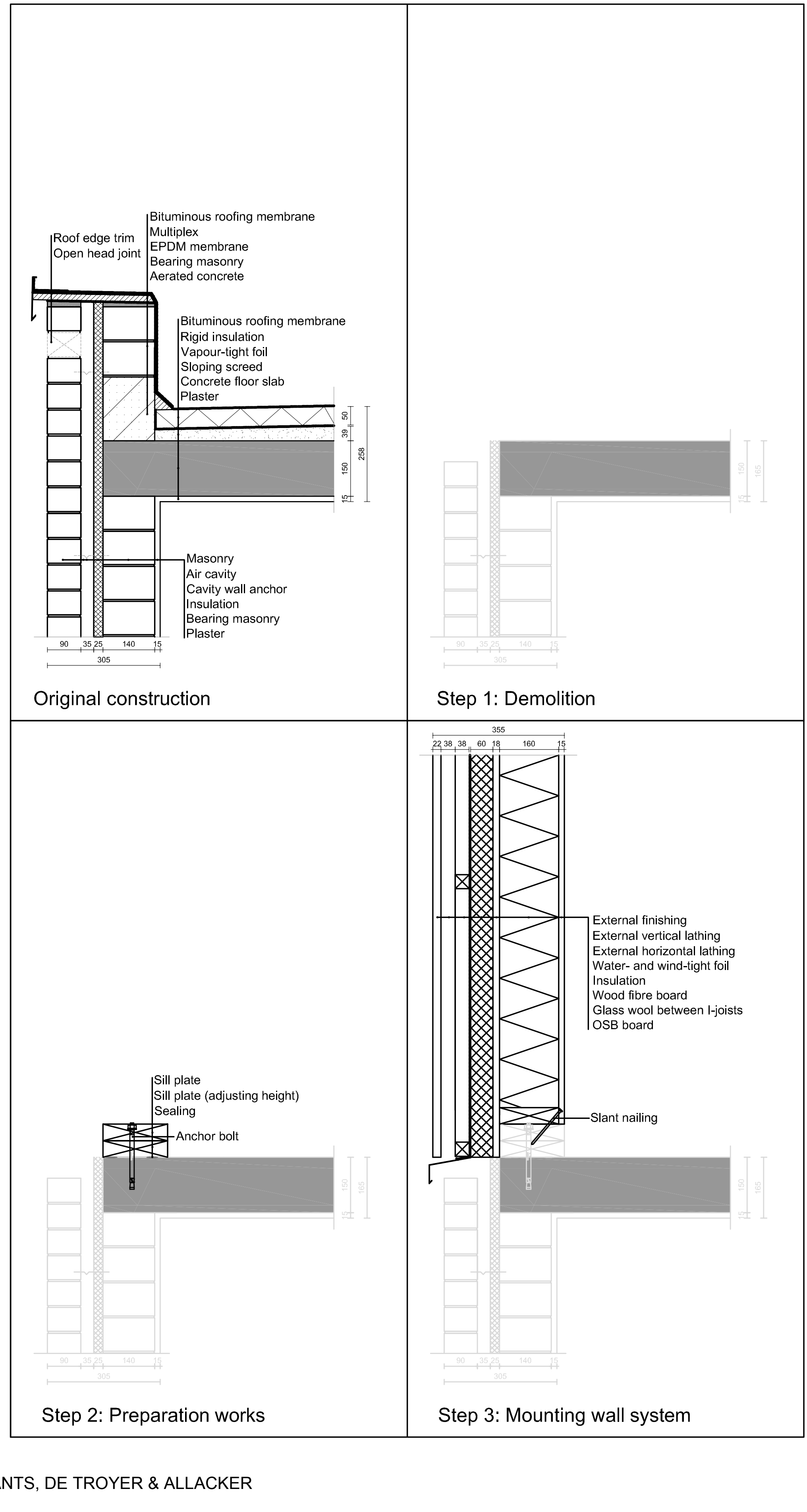
Step 6: The vapour-tight foil of the adjacent prefabricated roof elements is fixed and sealed to each other. The roof insulation is placed, followed by the roofing membranes and the multiplex sealing plate and the roof edge trim on top of the prefabricated walls.

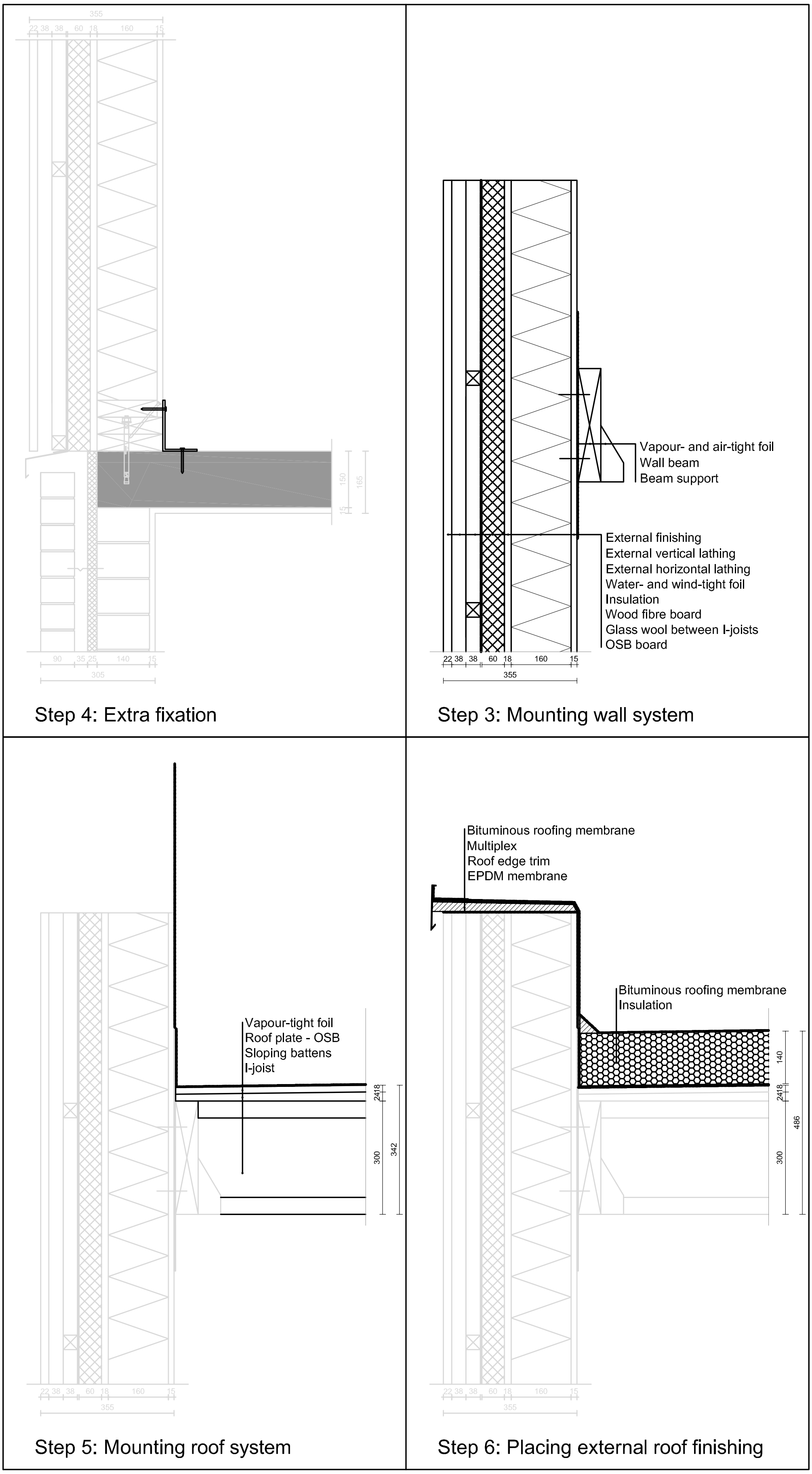
Step 7: A vapour- and air-tight connection between the two prefabricated wall elements in the corner and the roof of the rooftop extension is made. The joints between the different building elements are sealed with adhesive tape.

Step 8: The internal floor is placed on top of the concrete roof slab (Screed layer, acoustic layer, water membrane and screed layer).

Step 9: The internal wall and roof finishing is placed.

Step10: The internal floor finishing is placed.


Roof edge trim
Open head joint
Bituminous roofing membrane
Multiplex
EPDM membrane
Bearing masonry
Aerated concrete
Bituminous roofing membrane
Rigid insulation
Vapour-tight foil
Sloping screed
Concrete floor slab
Plaster
Masonry
Air cavity
Cavity wall anchor
Insulation
Bearing masonry
Plaster
Original construction
Step 1: Demolition
Sill plate
Sill plate (adjusting height)
Sealing
Anchor bolt
Step 2: Preparation works
External finishing
External vertical lathing
External horizontal lathing
Water- and wind-tight foil
Insulation
Wood fibre board
Glass wool between I-joists
OSB board
Slant nailing
Step 3: Mounting wall system

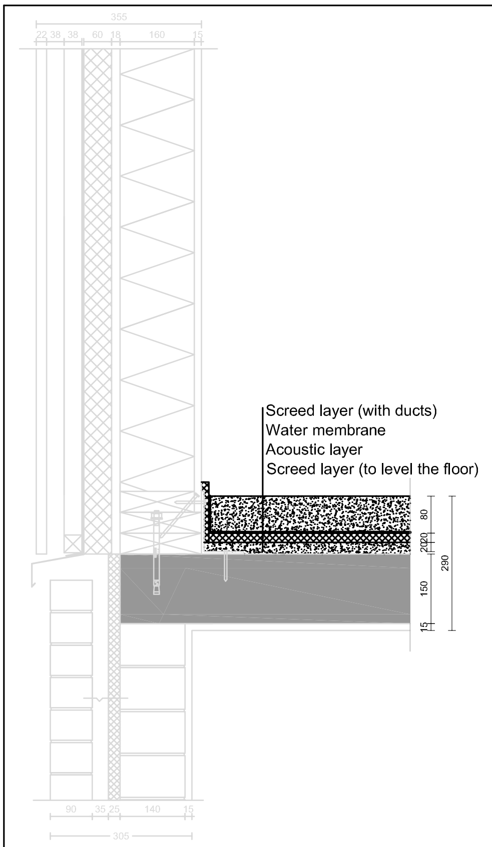


Step 4: Extra fixation

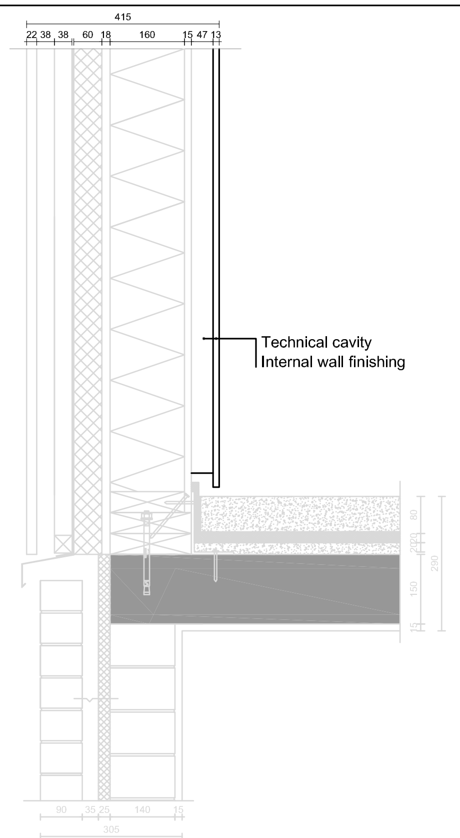
Step 3: Mounting wall system

Step 5: Mounting roof system

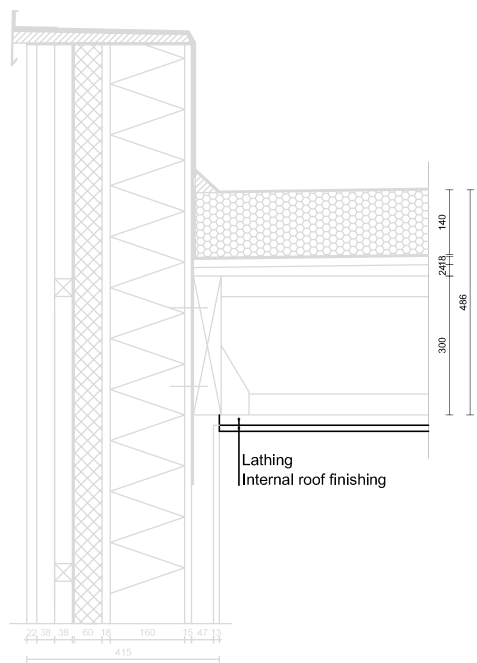
Step 6: Placing external roof finishing



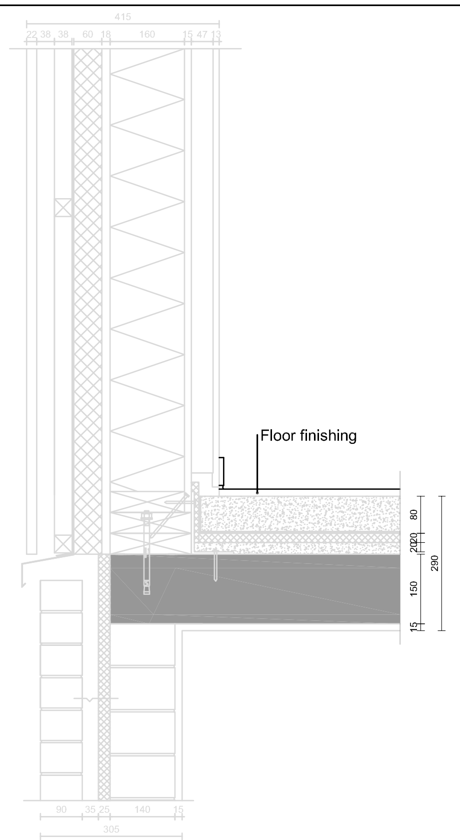
Step 8: Placing internal floor



Step 9: Placing internal wall finishing



Step 9: Placing internal roof finishing



Step 10: Placing internal floor finishing

3.3 Environmental impact calculations

The environmental life cycle cost of the prefabricated timber frame wall system developed is analysed and compared with a commonly used semi-prefabricated wall system for rooftop extensions in the Belgian context, as described in Wijnants et al. (2016). Both walls have been analysed over a life span of 60 year to assess the potential environmental impact reduction by optimizing its structure. The environmental life cycle assessment is based on the Belgian MMG LCA method (Allacker et al., 2013). The results are expressed in external environmental costs; the environmental impact calculations are based on the generic database Ecoinvent v3.2 (Ecoinvent, 2014). In a first step the operational energy use is calculated using the equivalent Degree Days (EDD) method, assuming 1200 equivalent degree days. This value has been determined as an appropriate value for well-insulated residential buildings in Belgium (Allacker, 2010). The environmental life cycle cost of both walls is shown in Figure 3. Both walls have an equal life cycle cost regarding material use. However, despite this similar material use impact, the prefabricated system developed has a lower thermal conductivity (i.e. 0.16 W/m^{2}K compared to 0.20 W/m^{2}K in the commonly used semi-prefabricated system). This results in a 26 % lower environmental life cycle cost regarding energy use. The prefabricated wall system has an 11 % lower environmental cost when considering the total life cycle of the wall.

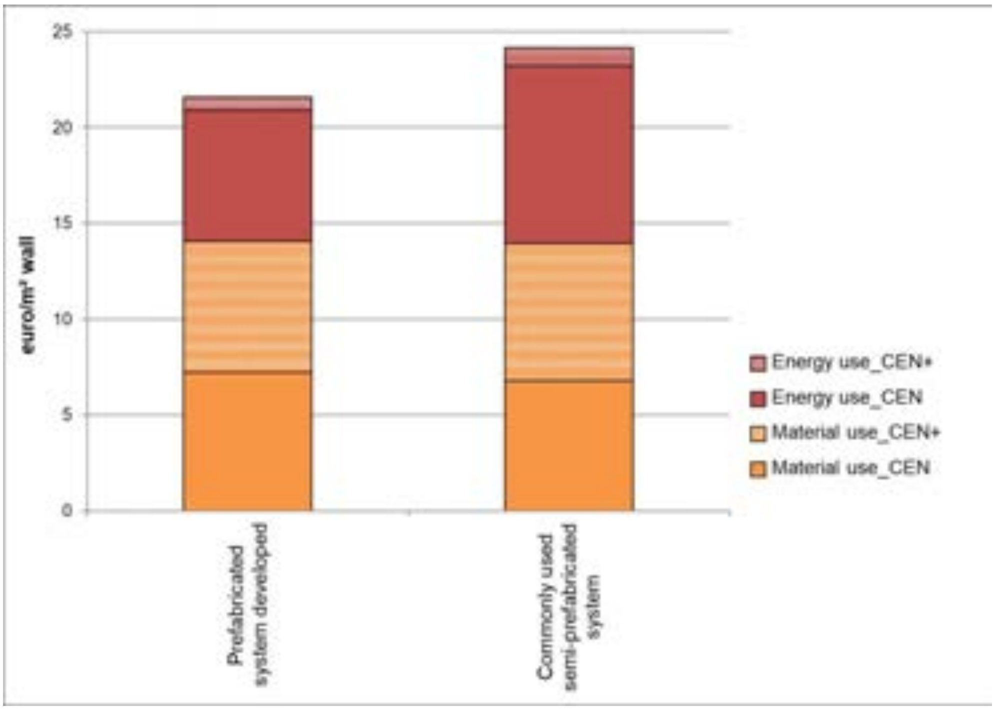


Figure 3: Environmental life cycle cost, subdivided in material use and energy use and expressed in euro/m^2 wall

Furthermore, the environmental life cycle impact of the entire rooftop extension has been analysed and compared with a commonly used semi-prefabricated rooftop extension as described in Wijnants et al. (2016). It concerns a rooftop extension of 97 m^2 built on a detached residential building. The composition of the wall differs in both rooftop extension, as described above; the roof composition (Table 3) and windows are similar in both cases. The window frames are made of PVC and the total window has a U-value of 1.50 W/m^{2}K. The total roof area of the rooftop extension is 97 m^2, the wall area equals 78 m^2 and the window area equals 32 m^2.

Wijnants et al. (2016) compared two methods for estimating the operational energy use of a rooftop extension. The static Equivalent Degree Days (EDD) method is compared with a semi-dynamic Equivalent Degree Days method, which takes solar gain and shading conditions into account. It is concluded that the static EDD method (1200 eq°d) seems to be a good approximation for the energy use calculations of a typical rooftop extension in the Belgian context. However, for specific situations with high shading conditions and/or low insulation level, the semi-dynamic EDD method is recommended. Therefore, the operational energy use is calculated in three ways, based on: (1) static EDD (1200 eq°d), (2) semi-dynamic EDD assuming there are similar detached houses surrounding the building with the rooftop extension (D.eq°d) and (3) semi-dynamic EDD assuming there are apartment blocks of five floors surrounding the building with the rooftop extension (D.eq°d). Figure 4 shows the environmental life cycle cost of both rooftop extensions. Depending on the energy calculation method used, the prefabricated rooftop extension has a 2 % (1200 eq°d) to 4 % (D.eq°d apartment) lower total environmental life cycle cost.

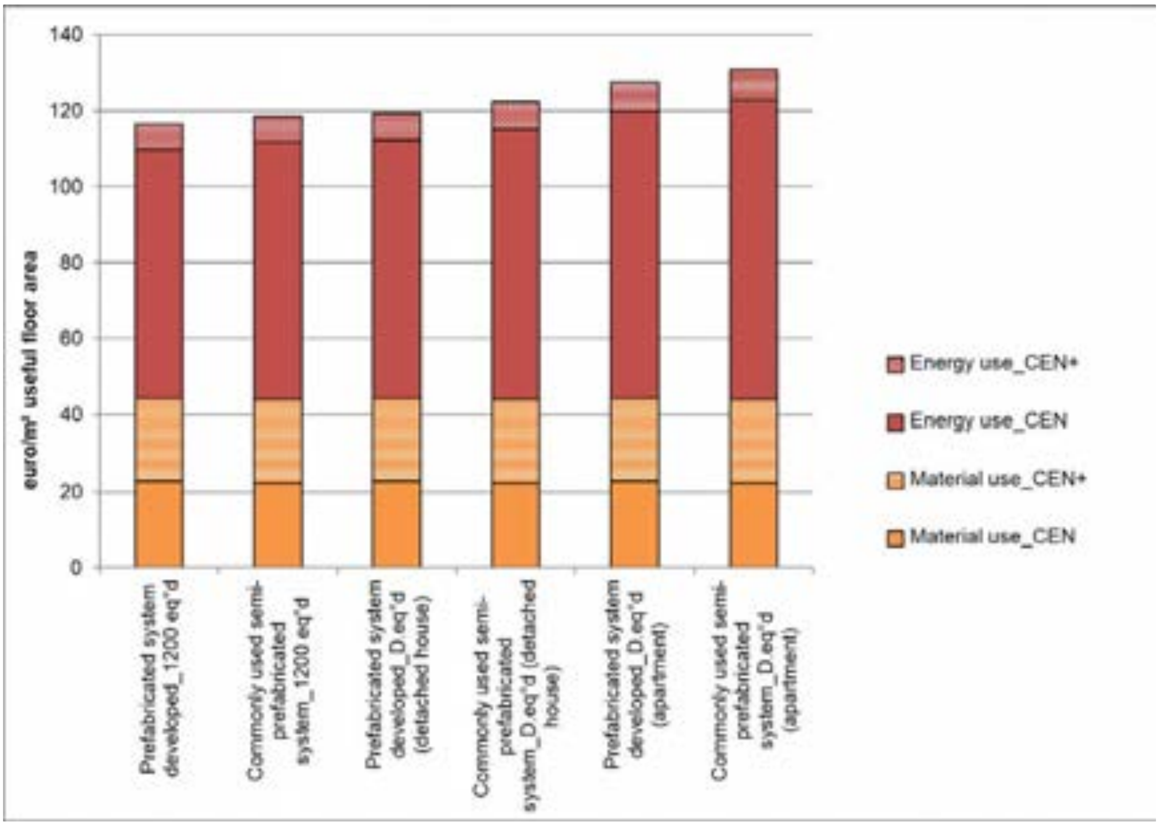


Figure 4: Environmental life cycle cost of the rooftop extension, subdivided in material use and energy use and expressed in euro/m² floor area

4 Conclusions and future research

This paper describes the first step in the development of a prefabricated timber frame system with a low environmental impact for rooftop extensions on a typical detached house in Belgium. Besides a description of the design requirements, technical details of the system are elaborated. The paper includes a solution to connect the developed timber frame system to the existing residential building. Furthermore, guidelines are provided to deal with the consequences of various building characteristics of the original building.

In the next steps of the research, the prefabricated system proposed in this paper is further analysed, revised and adjusted based on feedback from various stakeholders (prefab companies, architects, engineers, constructors). The future development focuses on checking building physics and stability issues concerning the fixation of the elements. Moreover, the environmental impact of various insulation options and building materials is currently further assessed. The possibilities concerning integrating building techniques will also be studied.

Acknowledgements

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TOWARDS SUSTAINABLE QUALITY MANAGEMENT – EXPLORING UNDERLYING MECHANISMS

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Abstract: *Although large amounts of research have been carried out into different sustainability issues, the research into sustainable quality management is very limited. The purpose of this study is to explore underlying mechanism of an award-winning company's successful work with sustainability and quality. The ambition is to contribute to the development of sustainable quality management. A case study has been carried out at Tower Companies, an award winning, LEED certified real estate company and green pioneer, in order to identify and probe deeper into their principles and best practices. In-depth interviews with top-managers have been conducted aimed at exploring their way of working and their attitudes regarding quality and sustainability. The data collection also included document studies and observation. The research was inductive, based on the Grounded Theory methodology and the data was analysed with the constant comparative technique. Four categories in the form of dimensions resulted from the analysis: (1) commitment, (2) partnership, (3) customer focus and (4) continuous improvement. The company has commitment to sustainability as its core including commitment to philanthropy, people, leadership and quality. This explains much of their success. Based on the dimensions a framework for sustainable quality management is proposed. The main limitation is that the study only concerned one company, which may limit the possibilities for generalisation. Nevertheless, the findings and the proposed framework could constitute a vantage point for further research.*

Keywords: *Sustainable Quality Management, Commitment, Customer Focus, Continuous Improvement, Grounded Theory*

1 Introduction

Sustainability has become an area of significant research activity. Organizations that lead the way for a change to a sustainable society create advantages for themselves (Global Commission on the Economy and Climate, 2014).

In the report 'Our common future', often referred to as the Brundtland report, sustainable development is broadened to also include social and economic concerns in addition to environmental issues (Brundtland, 1987). In the report sustainable development is defined as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs.' At the Rio Summit in 1992, the United Nation (U.N.) broadened that definition and agreed on a set of principles to guide future sustainable development (Tsai & Chou, 2009). The 17 sustainability goals were set by the U.N. in September 2015 in order to transform the world by, among other things, combating the climate change and ensuring prosperity for all.

According to the U.S. Building Council, buildings count for 38% of all CO2 emissions and 73% of U.S. electricity consumption (U.S. Green Building Council, 2017). Benefits of sustainable (also called green) buildings have been recognized regarding environment and human health as well as for being economically viable (Azhar, Carlton, Olsen, & Ahmad, 2011). Ammenberg (2003) concludes that the effects of standardized environmental systems (EMSs) depends to a very large extent on how companies choose to use them and that some of these voluntary standards were influenced by Quality Management (QM). Nevertheless, limited amounts of research has been carried out regarding sustainable quality management. The need for more empirical research in the field has recently been raised (Siva et al., 2016). Much remains unclear and this field is therefore worth further exploration (Zairi, 2002).

The purpose of this study is to explore underlying mechanism of an award-winning company's successful work with sustainability and quality. The company was chosen due to its recognition in the real estate industry for being a leader in sustainability. Over a long time the company has received several prestigious awards.

The rest of the paper is structured as follows. First, relevant theories and literature in the field of quality management and its connection with sustainability are briefly explored. Thereafter, the company is presented along with the results from the qualitative case study and a framework is proposed. A discussion and conclusion concludes the paper.

2 Quality management

Quality management is a well-established practice in industry as well as in the public sector and the theory in the field has reached certain maturity. Utilising quality management has been shown to be related to high performance as well as profitability, customer satisfaction and employee health (Easton & Jarrell, 1998; Hansson & Eriksson, 2002; Hendricks & Singhal, 1997; Hirtz, Murray, & Riordan, 2007; Lagrosen, 2001; Lagrosen, 2006; Westlund & Löthgren, 2001).

Quality management has been described as a system consisting of values, techniques and tools (Hellsten and Klefsjö, 2000). The parts of the quality management system can also be seen as existing on different levels of profundity (Lagrosen and Lagrosen, 2005) (Figure 1).

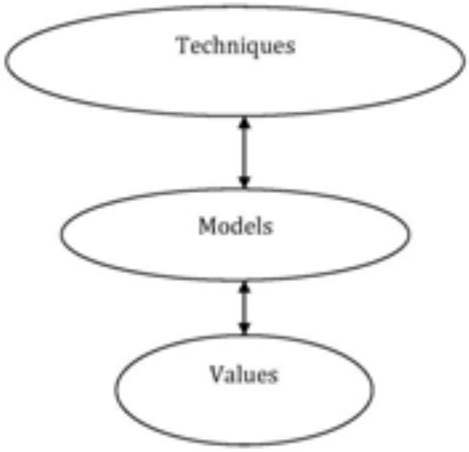

Figure 1. The levels of quality management

The most superficial level consists of an array of practical techniques for improvements, such as decision-making aides or statistical tools. The second level contains comprehensive models, systems and ways of working. This level is also called practices (J.W. & Bowen, 1994). Adopting them creates a larger impact on the entire organization.

At the third level there are certain phenomena labelled values (Hardjono, ten Have, & ten Have, 1997), principles (Dale, van der Viele, & van Iwaarden, 2007) or cornerstones (Bergman & Klefsjö, 2010) that are seen as especially fundamental. The most often used set of such values are ‘participation of everybody’, ‘leadership commitment’, ‘customer orientation’, ‘continuous improvements’ and ‘base decisions on fact’ (Sila and Ebrahimpour, 2002; Lagrosen and Lagrosen, 2005). The more profound the level is, the more it impacts the whole organization.

Customer focus is not sufficient for delighting the customers, in order to provide real quality for customers, *customer understanding* is necessary (Lagrosen, 2001). A recent stream of research has identified associations between quality management and workplace health (Lagrosen, 2006) as well as with work environment (Taveira, James, Karsh, & Sainfort, 2003) and work environment has been found to be an underestimated concept in successful quality management (Denton & Maatgi, 2016).

3 Quality management and sustainability

An attempt to explore the relationship between sustainability and quality management is made by Gorman and Krehbiel (1997). The authors argue that quality management is only one important part of the concept of sustainability since the boundaries of quality management systems seldom extend to communities and ecosystems affected by the actions of their particular organizations.

Quality management has been found to lead to sustainability of advantage (Flynn, Schroeder, & Sakakibara, 1995; Reed, Lemak, & Mero, 2000). In addition, since continuous improvement over time is a prerequisite for quality management to be successful, sustainability becomes a crucial factor (Bergman & Klefsjö, 2010; Curry & Kadash, 2002).

An attempt to include quality management principles in value co-creation processes towards sustainability has been undertaken by Aquilani et al. (2016). Customer focus and continuous improvement are both included in their model. Kanji and Yui (1997) argue that 'total quality management is the culture of an organization committed to customer satisfaction through continuous improvement'.

The systems perspective in sustainability includes the ecological (or environmental), economic and social systems of companies and their stakeholders. Both quality management and sustainability movements can be improved by mutual awareness of each other (Aquilani et al., 2016).

Key issues of sustainable quality management, derived from 20 quality management award winners, have been highlighted by Zairi (2002) and the author conclude that much remains unclear and is therefore worth further exploration. Seven critical factors were found which can create a sustainable advantage when working in harmony (Zairi, 2002):

- Leadership and top management commitment
- Strategic planning and policies
- Information analysis
- Customer resources
- Partnership and resources
- People management
- Process management

4 Environmental standards

For buildings there is a range of voluntary environmental certification systems available including Green Star (Australia), ENERGY STAR (US), LEED (Leadership in Energy and Environmental Design, US) and BREEM (Building Research Establishment Environmental, UK) (Fuerst & McAllister, 2011).

The LEED rating system is the most widely utilised certification in the United States. It was developed by the U.S. Green Building Council (USGBC) in 1998 and it focuses on six major categories related to sustainability of sites (SS), water efficiency (WE), energy and atmosphere (EA), materials and resources (MR), indoor environmental quality (EQ) and innovation (IN). There are four levels of LEED certification determined by the number of points the building is awarded (USGBC, 2017).

Compared to buildings in the same submarkets, eco-certified buildings have been shown to have both rental and sale price premium, with a 5% rental and 25 % sale price premium for LEED certifications (Fuerst & McAllister, 2011).

5 The Case Company

The Tower Companies develops, owns and manages commercial, retail and multi-family residential properties in the Washington DC metropolitan area. Their mission is to build, own and manage buildings which are among the most sustainable in the world, blending design, smart growth principles, amenities and service in a way that transforms expectations about real estate and improve the way people live, work and play.

The company has been recognized and awarded for its on-going commitment to sustainability and energy independence (e.g. reducing GHG emissions, electricity and water usage) by several national organizations and federal agencies such as US Department of Energy, US Green Building Council and US Environmental Protection Agency (EPA).

In 2004, the company certified the first LEED multi-family apartments in the U.S. and nowadays 90% of all their commercial and multi-family residential properties are LEED certified and 85% are ENERGY STAR certified. In 2008, their goal to a achieve net-zero GHG emissions becoming 'carbon neutral' was met and they were the only real estate company in America to make such a commitment.

The company has 67 employees and their executive team consist of 7 managers. The owners want to help create environments were business and people can excel. Some main features characterising their design are LEED, EPA, ENERGY STAR and Vedic Architecture. Their latest office building built in 2009, comprising nine floors of 23,000 rentable square feet (RSF), has an efficient design reducing energy use by 28% and water consumption by 41%; a three-stage outside air filtration system removing 95 % of airborne pollutants, the capability to re-supply the whole building with 100% outside air every 51 minutes and the ability to maintain a steady, comfortable temperature. It was the first LEED Platinum office building in the Mid-Atlantic Region. The underlying rationale for the building is that healthier environments boost productivity, attitudes, attendance and learning as well as increasing sales in retail stores. Documentation on critical on-the-ground issues involved with this innovative real estate development was carried out by Macomber and Griffin (2010).

In a study on three of Tower Companies' large, multi-tenant office buildings in Washington D.C., Henderson and Waltner (2013) focused on operational improvements - measures that do not require construction, disruption to an occupied office building or substantial capital investment. The results for the first year was a 13.2 % reduction in electricity use in the three buildings, showing that substantial gains are possible when building owners operate their buildings with attention to reducing the amount of energy waste.

The owners consider the environment to be everyone´s responsibility and that to be a change agent you have to think outside the collective thinking of the world around you. Buildings should be designed to enhance the creativity of the work force occupying it. Therefore they have started to incorporate principles of Maharishi Vastu into their design. These are not principles of style but use orientation, placement and proportion as ways of influencing the productivity (Henderson & Waltner, 2013; Travis et al., 2003; Wah, 1998).

6 Methodology

Methodologically, the study has been characterised by case study research (Yin, 1994). This research approach is especially appropriate in new research areas for which existing theory seems inadequate (Eisenhart, 1998). The study was inductive, based on Grounded Theory methodology (Glaser & Strauss, 1967). This means that the empirical material was collected first and then analysed before it was related to research and theory in quality management and sustainability. In-depth interviews (Patton, 1990) with several managers at the studied company were carried out. In addition, internal and

external documents were studied and the buildings and activities were observed. The empirical data were then interpreted and analysed with the constant comparative method from the grounded theory approach (Glaser, 1992; Glaser & Strauss, 1967).

Using open-ended questions is particularly suitable for research in new areas (Bryman, 2001). The following open questions were used in the in-depth interviews.

- How do you work with sustainability?
- What is quality for you and for the company?
- How do you work with quality in your organization?

Follow-up questions were asked, depending on what came up during the interviews. Five people from the management team were interviewed (see Table 1). The vice President of property management was not available at the office during the visit so this interview was carried out by telephone while the others consisted of personal meetings.

Table 1 – the respondents in the study

Role in company	Duration
Owner and partner	62 min
Chief Operating Officer (COO) and vice president of development	76 min
Vice President of strategy and sustainability	52 min
Vice President of property management	65 min
Accounting manager	57 min

7 Results and Analysis

In the following section the findings from the analyses of the data is presented. Utilising the constant comparative technique from the grounded theory methodology (Glaser & Strauss, 1967), categories in the data were identified. Since the aim was to find the underlying mechanisms for sustainable quality management at the Tower Companies, the categories with their properties could be viewed as the dimensions of sustainable quality management that the company expresses. Four dimensions were extracted: (1) commitment, (2) partnership, (3) customer focus and (4) continuous improvement. The categories with their dimensions are presented below.

7.1 Commitment

Overall, the company has sustainability as a core value and sustainability practices are a critical part of their mission. The commitment category includes following properties:

- ***Philanthropy*** – They believe in volunteerism, going from caring to taking responsibility. They support the broader community by giving for charity purposes including their time and engagement. For instance they educate their community in sustainable practices and work for free with practical things like planting trees in a school in their surroundings. They also offer some scholarships in order to empower women and girls in Africa through partnership with NGO's.

- ***People*** – Time and money are invested in people. Some examples are their life-style program, fitness centres, individual funds for health development, courses in the Transcendental Meditation (TM) technique etc. They strive for a culture characterized by high performance where people also are healthy and happy. They argue that it makes business sense to invest in their employees by helping them to stay healthy. In consequence, they have loyal employees and low employee turnover.

- ***Leadership*** – They want to be a good example of sustainability and a sustainable leader in the field. They are committed to do things right and to lead by example. In addition, they challenge their suppliers and vendors to be greener and more socially responsible. They have a visionary leadership with the company´s values as their guide. The owners are available and personally present in day-to day activity. Their executive leadership encourages the entire team to put their clients first. Time spent in their building should be enriching, healthy and productive.

- ***Standards*** – The company is known for setting standards how buildings should be renovated in a sustainable way. They are also committed to high standards for the maintenance of their properties. They follow the LEED standard, reaching the two highest levels – LEED gold and LEED platinum.

- ***Innovation*** – They are aware of the need to think outside the collective thinking of the world around them – to think out of the box.

- ***Quality*** – They strive for perfection in all aspects. This extends to creating a quality environment, having facilities with lots of daylight, good air quality, health programmes, and wellness benefits.

7.2 Partnership

They try to co-create with stakeholders by building fruitful relationships. Their stakeholders seem to appreciate their ambition to improve the environment and make people healthier. They build partnerships with clients and tenants in the following ways:

- **Lifestyle Programmes -** The lifestyle programmes include organizing walking tours as well as clubs for biking, cooking and knitting. Walking and biking clubs are also organized for tenants' employees.
- **Green teams** – At office buildings they build green teams which discuss ideas for sustainable practices such as recycling, reducing energy and healthy cooking practices. They also involve residents in some of their green initiatives, like making compost.
- **Networking and evening events** – Managers share what they have learnt so that industry colleagues also can improve. In addition they challenge their suppliers and vendors to be greener and more socially responsible. They join seminars frequently and arrange seminars regarding e.g. solar energy.
- **Close relationships -** Managers meet tenants face-to-face, for instance having lunch with them to find out how their business is doing and if they are comfortable in their space.

- **Careful recruitment** - Vendors and contractors are carefully selected since they are treated as partners, and are an extension of the company´s practices and vision.

In summary, their partnership concerns sharing and educating clients by providing resources, programmes and amenities to live more sustainable and healthy lives.

7.3 Customer focus

They aim to delight the customers by going beyond their expectations. The company received the 'Real Estate Customer Service Award for Excellence' three years in a row, 2011-2013. Customers are viewed as clients instead of tenants and residents. Characteristics of this dimension are:

- **Responsiveness and excellence** – They try to respond to customers´ needs and concern beyond their expectations. They aim at giving same experiences and service that you can expect at a five-star hotel. This includes kindness and trust.
- **Empathy** – With their annual satisfaction survey, they receive input from their office clients including ideas and suggestions, which they try to implement as promptly as possible. For instance, they installed a garment steamer in a fitness centre one week after receiving the suggestion. Employees in their office are told to come and look at their facilities in order to understand the challenges people have in the field. However, they have still no employee-survey regarding satisfaction etc.
- **Access –** The owners of the company are usually available to clients. In addition, the owners sometimes randomly call a tenant just to ask how things are going. They also offer online rent payment and communication systems

7.3 Continuous improvement

They have an ambition to progress continuously. Characteristics of this dimension are:

- **Benchmarking** – Setting their own benchmark helps them maintain a high-quality brand that is also environmentally responsible. They constantly watch business trends and to some degree benchmark top hotels. They benchmark energy and water data, set goals, track progress and measure utilising EPA's ENERGY STAR programmes.
- **Innovation** - continuous innovation has resulted in awards and all employees are encouraged to come up with ideas. They support employee initiatives. They try to continuously implement innovative strategies, tools and resources to meet their sustainability goals.

- **Training** – They continuously provide sustainability training to their on-site teams for instance regarding going towards paperless, fewer servers etc. Staying current with technology helps them to become more efficient with smart use of technology.
- **Rewarding system** – Teams are rewarded rather than individuals.

8 A proposed framework of sustainable quality management

Based on the findings of the study, we propose the conceptual model of sustainable quality management depicted in Figure 2. In accordance with the model of quality management presented in Figure 1.,this model also consists of different levels of profundity.

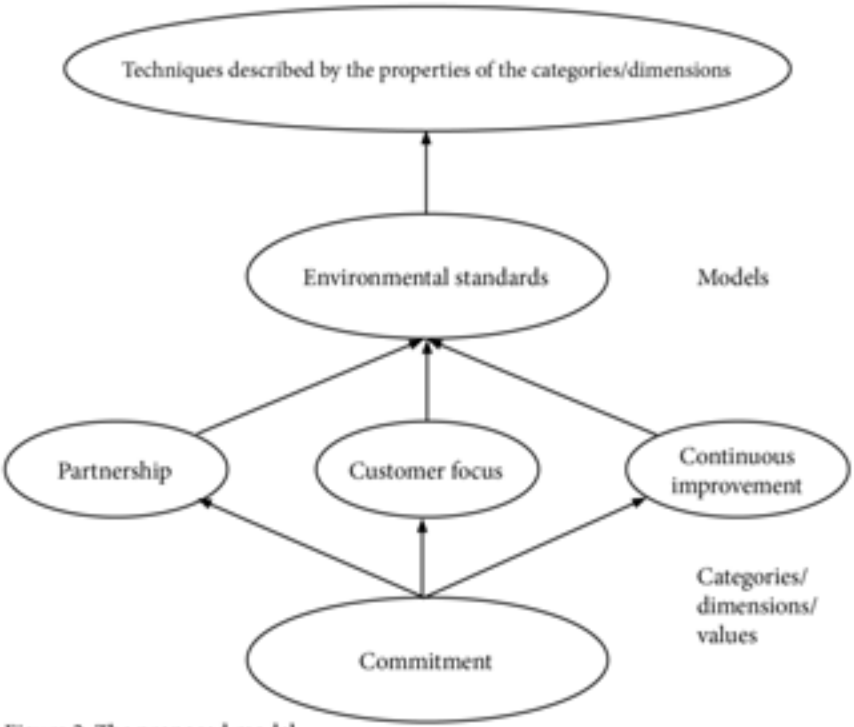

Figure 2. The proposed model

The basis is constituted of the four categories or dimensions that emerged in the study. Thus, they fulfil the same function as the values in quality management. However, the ultimate foundation that the sustainable quality management of the company rests upon is their *commitmen*t. In this case, this means commitment to sustainability as described in the properties of the dimension presented above. The commitment is then translated into the other three dimensions*, partnership, customer focus* and *continuous improvement*, which expresses the commitment according to their properties. The next level consists of the environmental standards that the company adheres to. They are used to structure, document and organize the processes and products in a way that resembles the way the models are used in quality management. Finally, just as in quality management, the most superficial level contains the concrete techniques by which the dimensions are manifested into practical activities and the criteria of the standards are fulfilled.

9 Discussion

Tower Companies is a small family company which has evolved organically. They both own and manage properties which is unusual in this industry. This means that they have more control over their assets and properties. Their independence also allows them to have a global perspective and develop their company according to their beliefs and the commitment that they have towards sustainability.

Managers at the company are concerned about how people will feel when they are in their buildings and what their needs are. This is in line with Buchholtz et al. (1999) who found that managerial discretion and values affect philanthropic decisions and that more attention to executive values should be given. The crucial importance of management commitment is also in line with previous research (Zairi, 2002).
Policies for increasing energy efficiency requires a co-ordinated portfolio of energy policies and are in themselves insufficient to generate environmental improvements (Hanley, McGregor, Swales, & Turner, 2009). In the same way, we saw in this case that the commitment of the owners and managers is what really drives the sustainable quality management.

This case shows an example of an organization which seems to have reached the most ambitious level of integration according to Jorgensen (2008) meaning that a culture of learning has been created where there is a focus on stakeholders, continuous improvements and synergies between them. The company considers the whole life cycle perspective, which is of importance for innovating more energy efficient systems and building according to the highest environmental standards (Jorgensen, 2008). The altruistic motivation with philanthropic outcomes is in line with CSR-activities in other award-winning companies (Virakul, Koonmee, & McLean, 2009)

10 Conclusions

Four dimensions were extracted from the empirical data. These were commitment, partnership, customer focus and continuous improvement. Commitment concerned a wide range of areas such as philanthropism, people management, leadership, standards, innovation and quality. Along with their properties they were formed into a model that depicts sustainable quality management at the company. The conclusions of the study reside very much in this model. It shows that commitment and other values constitute a necessary foundation for sustainable quality management. They can then be translated into practices, procedures and techniques on a concrete level with the help of environmental standards that need to be fulfilled.

10.1 Limitations

A single company, which was not randomly selected was studied, thus generalisability cannot be ascertained. An appropriate way of discussing the extent of generalisation could be 'transferability' (Lincoln & Guba, 1985). If a rich and 'thick' description of the case is made, it may be applicable to transfer the results to other cases. However, Lincoln and Guba (1985) state that it is up to the readers to judge '*…the degree of congruence between the sending and receiving contexts*'.

For further research, studying other award-winning companies in other countries as well as in other industries should be fruitful. The proposed framework that this study resulted in can be a vantage point in these endeavours. It could also be a basis for broader studies involving large numbers of companies, quantitative methodology and statistical analysis.

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ZEMCH— ZERO ENERGY MASS CUSTOM HOUSES: DEFINITIONS AND CORRELATION

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Abstract: *This paper presents clear definitions of Zero Energy and Mass Customisation. It concludes by proposing a ZEMCH definition to respond to the increasing interest in the term and practice. "Zero Energy Mass Custom Homes" was first utilised as a single expression to name the 2010 technical-tour to Japanese housing factories, and first used as an acronym for the 'ZEMCH International Conference' in 2012. Since then, a diverse range of publications, technical tours, academic activities and networks have used it. However, ZEMCH is not currently defined in any dictionary or encyclopaedia. Therefore, this paper intends to develop a 'systematic review' to identify and synthesise significant research evidence and present a linked collection of texts that describe Mass Customisation and Zero Energy and its potential correlation. This study defines Zero Energy from a pragmatic perspective based on thermodynamic theories rather than presenting how it has been ambiguously defined by government or agencies. This paper also clarifies why Zero Energy should be seen as a threshold rather than a restriction or strict balance of energy. The Mass Customisation concept is defined as a theoretical concept, revisiting the thoughts of Stanley Davies, Alvin Toffler, Joseph Pine, Frank Piller and Walter Gropius. The study is structured as a response to the ZEMCH definition implied on the ZEMCH Network organisation website, in complement/contrast to Masa Noguchi's texts and information gathered from a personal interview. In conclusion, this paper aims to found the basis of any research that aims to explore the topics of Mass Customisation and Zero Energy. This study forms part of a wider research on ZEMCH applicability in contexts where other processes predominate.*

Keywords: *ZEMCH, Zero Energy, Mass Customisation, Systematic Review, Semantics.*

1 Introduction

ZEMCH is the acronym for 'Zero Energy Mass Custom Home' (ZEMCH Network, 2017). These five different words were combined by a group of academics in 2010[1] to refer to industrial collaboration in the *delivery* of zero energy mass-custom *homes* around the globe (Noguchi 2016a, ZEMCH Network, 2017, Noguchi, 2016b: v-vii). Mass customisation (MC) and zero energy (ZE) buildings are known concepts and existing practices; thus, the significance of ZEMCH relies on the declared relationship between **MC** and **ZE** dwellings; or framed more straightforwardly as the production of zero energy dwellings by a process of mass customisation.

Today, ZEMCH is not defined in any dictionary or encyclopaedia. The ZEMCH Network implies a definition on their website, which does not directly reflect the tangible meaning of either Zero Energy or Mass Customisation (ZEMCH Network, 2017).

[1] During the 2010's edition of the technical tour visits to Japanese housing factories, Masa Noguchi and Hasim Altan decided to abbreviate the name of the tour from 'Zero Energy Mass Custom Homes Mission to Japan' To 'ZEMCH Mission to Japan'.

This paper aims to define ZEMCH precisely. A legible definition is needed to respond to increasing interest in the term and its practices. This paper will complement what has been established by the ZEMCH Network, but subtracting from their ideologies and ambitions.
ZEMCH is described through an anthology of key references and literature. The narrative is intended to be a continuous enquiry from one concept to the other (from ZE to MC) as a way of emphasising their interdependence. The study is a response to the book, 'ZEMCH: Towards the Delivery of Zero Energy Mass Custom Homes' (2016b) and Noguchi's editorial text of the 'open house international' magazine (2013)[2]. The references presented on these texts were studied forward to *extract* the roots of the term.

In addition, the concept of 'Home' is presented, but not fully addressed, as it seems to play only a framing and symbolic role. However, the ZEMCH Network's selection of 'Home' over similar terms such as 'dwelling' or 'housing', is explained. Also, a brief selection of literature about the topic is suggested for those interested.

2 Definition

'ZEMCH', as a term, has been employed to badge conferences, technical tours, workshops, networks and postgraduate programmes. The ZEMCH Network (2017) defines it as follows:

> *'[Concept that aims] 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.'*

Those familiar with the constructions of the term 'sustainable development' will note the definition is certainly influenced by *spirit* of 'Our Common Future'— the foundational document developed by the World Commission on Environment and Development (WCED, 1987). However, the specific terms, 'zero energy' and 'mass customisation' appear overlooked.

In a personal interview (2016), Noguchi explains how both terms are holistically immersed as follows:

> *'... energy is energy, is the same everywhere, a KW is a KW. So zero energy is simple, zero energy needs to be a standard. While zero energy needs to be a standard, mass customisation is a social need. Thus, ZEMCH is social, economic and environmental sustainability; not only environmental sustainability. All things come together as ZEMCH.'*

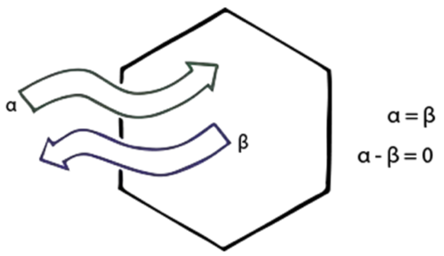
In contrast with the ZEMCH Network definition, Noguchi assertively recalls the term 'energy', pointing out its *simplicity* and measurability.

Figuratively, energy simply refers to the capacity of a system to work. However, energy can be referred to various settings: the kinetic moving of an object, the potentiality stored by an object's position in a force field (gravitational, electric or magnetic), the elasticity of stretching solid objects, the chemical energy released when a fuel burns, the radiant energy carried by light, and the thermal energy due to an object's temperature.
Conversely, referring to the built environment, energy is specifically considered as electricity (*'KW'*) for practical reasons. In this context, energy have been tagged as *positive* or *negative* depending on the environmental impact of its provenance.

[2] The 2013 Open House magazine was entitled ZERO ENERGY MASS CUSTOM HOME RESEARCH PARADIGMS where mainly members of the ZEMCH Network present their studies.

2.1 Zero Energy

Therefore, there is a misunderstanding on looking at ZE as a minimum or limitation for energy, because if ‘zero energy’ is taken literally, we would be referring to the absence of energy. But, different to a lightbulb, a house is a system where energy can flow from it, as well as it flows into it. Thus, it is more accurately defined as an equilibrium of energy flowing in (α) and out (β) a system (Fig.1). Same rule applies when more than 2 energy flows are involved; the energy equilibrium is referred to the sum of energies transferred into (∑α) a system with to the ones emitted (∑β) from it (Fig.2).



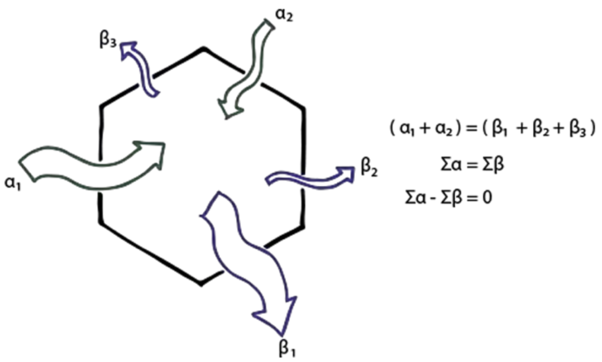


Figure 1: (left) ZE on a system with a single energy entity flowing in and an equal flowing out.
Figure 2: (right) ZE on a system with multiple energy entities flowing in and out.

As previously stated, the energy used in the operation[3] of built environments is generally conceptualised as electric (gas) energy (Srinivasan and Moe, 2015). It is usually measured in watts, which correspond to the rate of *consumption* of energy. It means the energy calculations overlook those energies that are not implied in an electric (gas) circuit.
In a house, there are appliances (γ) that *consume* and could be others that *generate* (δ) energy (Fig.3). Considering that ***energy can neither be created nor destroyed***; *consumption* refers to the transformation of electric energy into mechanical, electric or electronic energies, while *generation* to the transformation of other energies (solar radiation, wind kinetics) into electric ones.

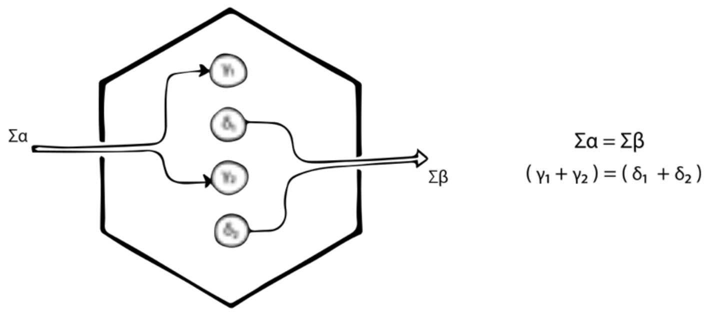


Figure 3: ZE expressed over the consumption and generation of energy through appliances.

This way, energy flows through electric conduits and usually cross the system boundary in a single specific point (ε), where it can only flow in or out at a time (Fig.4). The energy flowing into the system is consider *positive energy,* while the one coming out from it is *negative energy.* The ‘positive’ connotation is given assuming that the energy generated in the house is produced through renewables; while the ‘negative’ energy is taken from the electric grid, which source is unknown. Therefore, ZE refers to the equilibrium observed over a certain period of time (ζ) (Fig.4). The following diagram present separately the two possible flows of energy that occur in a single system during a fixed period of time.

[3] Operational energy refers to the amount of energy consumed during the building’s life, independent of the energy used in processes associated with the production/construction of it (Australian Government, 2017).

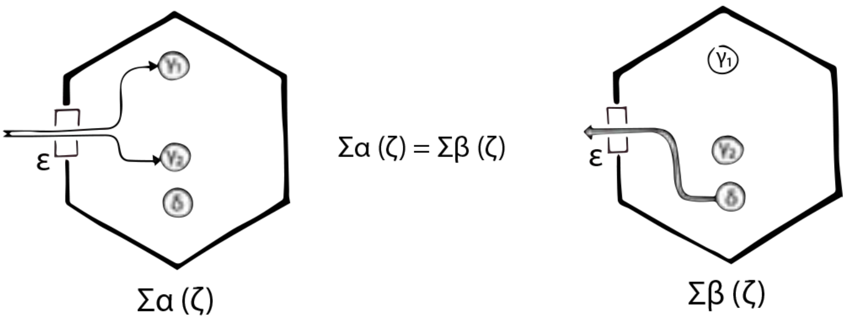


Figure 4: ZE equilibrium over a period of time— positive/consumed energy (left) and negative/generation energy (right).

However in practice, an exact equilibrium (even over a fixed period of time) is rare to happen[4], buildings like all objects are defined by dynamic, so a point of true 'zero energy' flow is highly elusive and is what might be called a false equilibrium.
The ZE concept has been brought-up as a strategy to reduce energy consumption, not as an *obsession* with the zero; but, if it is not delimited it would have no pragmatic function. Therefore, 'zero' has been considered as a threshold where the 'negative' energy is equal or higher that the 'positive' one.

ZE has been considered by nations and agencies as a 'standard' to determine levels of quality or attainment that merge with political or commercial ambitions. Moreover, ZE 'standards' depend and varies on each context; e.g. the 'MINERGIE-P in Switzerland and the 'Energy Efficiency Rating' in Europe'. In other words, the term is nuanced, not only by the specific of context and measurement, but also by social and cultural contexts in which they operate. Because of this, it is important to clarify what does ZE means for ZEMCH to ensure that its effectiveness as a concept is clearly communicated to interested audiences.

We identify the following definitions as precise, politically neutral and with global applicability; which differ depending on the metric[5] selected to measure the energy flow and on how a building's thermodynamic boundary[6] is defined (Sartori et al, 2012: 10; Voos and Musall, 2013: 12; Torcellini et al., 2006: 4-5, 11; Aelenei et al., 2015: 277, 293; Marszal et al., 2011: 972):

- *Zero Site Energy*— the building produces at least as much energy as it uses, when audited at the grid interaction at the boundary of the building site giving a net value of import energy of either zero or less than zero. This interpretation is conceptually easy to comprehend as it ignores primary sources. It can be verified through on-site measurements.

- *Zero Source Energy*— the building produces at least as much energy as it uses, when accounted by the primary energy used to generate and deliver[7] the energy to the site and set against that generated on site. It is a more sensible depiction of the *real* energetic balance; however, the calculation of the source energy is complicated and usually imprecise. Energy source calculations should be specific to each site location.

[4] A ZE equilibrium could be easily achieved if the period of time adapts to the energy flow by stopping calculations whenever the equilibrium is fulfilled, but this calculation will lack to demonstrate the real energy efficiencies of a building.
[5] The metric refers to the way the energy is defined. These can be: delivered, end-use, primary energy, CO_2 equivalents, exergy or other parameters (Marszal et al., 2011: 2).
[6] The energy boundary refers to the point where energy is considered to flow in or out the system (Sartori et al., 2012: 2).
[7] It refers to the energy primary source—power plants. Transmission and distribution lead to some energy losses (EPA, 2017).

- *Zero Energy Costs*— the energy charges for the operational use of a building are equal or less than the amount of money the utility pays the owner for renewable energy the building feeds into the grid. Using currency as a metric makes this interpretation attractive to implement and easy to grasp by agencies not related with energy units. However, it is highly volatile and dependant to each context and does not reflect an energy balance as price may not be a direct measure of consumption.

- *Zero Energy Emissions*— building that produces at least as much renewable energy as it uses from emissions-producing energy sources. Contemplate renewable energy from primary sources in the balance. Percentage of renewable energy on the grids is volatile. Calculation is complicated and imprecise.

These definitions consider the energy balance on an annual period and imply a connection to electrical grids, reason why ZE is usually known as **'net**[8] zero energy' (Hernandez and Kenny, 2010: 817; Sartori et al, 2012: 1; Marszal and Heiselberg, 2009: 6). Therefore, it would more convincingly refer to 'net' flows being zero or negative in terms of exchange. In this case the acronym ZEMCH does not include but should imply the term 'net' in an accepted definition.

'Off-grid' houses were not considered because they achieve ZE *by nature*, as they depend on their own energy production and storing (Laustsen, 2008: 71). However, energy storage (batteries) involve a high amount of emergy[9] and special disposal management. Therefore, they are not recommended unless it is unpractical to connect to any existing electric grid.

2.2 Mass Customisation

In relation to 'mass customisation', the ZEMCH Network (2017) refers to it as *"…a paradigm case of a systems approach to identifying the … wants and needs that should be incorporated into the design of end-user products (or homes)"* (Noguchi, 2012: iii). Then, Noguchi *brings-up* MC as a strategy to ensure *social needs.* But, before adventuring to define the social *wants* and *needs,* it is important to understand what MC is and how it works, to finally conclude, on why is it useful in the conception of ZE houses.

From a theoretical perspective, MC emerged as a business model proposal. The term was coined in 1987 by Stanley Davis (1987: 169), who inspired on Alvin Toffler's (1970: 233-238) envisions in diversity and technology, referred to MC when large number of individuals can be reached as in the mass markets of industrial economy, but treated individually as in the customised markets of pre-industrial economies*.* Joseph Pine (1993) popularised the concept with the publication of his book entitled 'Mass Customization' by considering MC a sophistication of industrial production models. Later, Tseng and Jiao (2001: 685) redefined MC more pragmatically as: those technologies and systems used to produce goods and services that meet individual customers' needs with near mass production efficiency*.* In recent years, many experts have written about its applicability, where Frank Piller's scrutiny texts stand out because of the clear description of MC elements and processes.
Framed into housing, Walter Gropius is one of the visionaries of MC. On the early 20th century, Gropius visualised the production of full houses through mass production of interchangeable elements of standard dimensions, which could be assembled different to obtain diverse outcomes, or as what he referred as *Variabilität*[10] (Herbert 1984, 35-36; Gropius, 1910; Gropius, 1956: 149; Noguchi, 2013: 5). There exist a range of architectural examples that stress the same concept, but this paper do not have the intention to present a

[8] *Net* is the adjective that refers to final/total after deductions.
[9] Emergy is a type of energy that is consumed in direct and indirect transformations needed to make a product or service.
[10] In Gilbert Herbert's book entitled "The Dream Factory-Made House" — which focus on Gropius and Wachsmann's Industrialised housing projects — the author keep the word in its original language, as for him perception 'Variabilität' specifically referred to the capacity to adapt to individual needs.

chronology of projects and rather focus on describing the logic behind and over an architectural perspective.

In essence, MC is the synthesis of *mass production* with *crafting (tailor-made)* production (Noguchi; Davis, 1987: 169). An apparent paradox, but in reality, an oxymoron with practical implications that has been successfully implemented in some business and markets; e.g. automobile, shoe and computer industry (Davis, 1987: 140, Piroozfar and Piller, 2013: 4-5).

Mass production is characterised by the manufacture of large quantities of standardised products (Noguchi et al., 2016b: 102). Mass manufacturers innately produce homogenised products that are then commercialised in an open market. In mass markets, users select a product from the market by comparing the different models offered by different manufacturers (Fig.5). The creation of mass products is independent to the customer; and it is only once the products are finished that they are put to sale in the market. Its manufacturing process are efficient and stable because they are based on assembly lines that work with specialised machines and labour routines (Pine, 1993: 15).

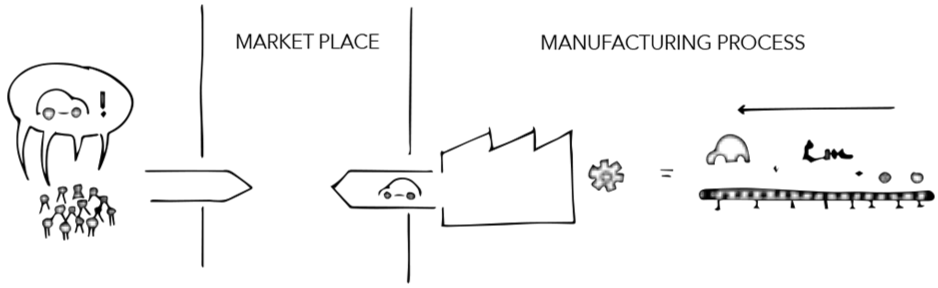


Figure 5: Mass production and market traditional system.

In contrast, craftsmen offer a service rather than a product. Customers explain directly what they want and then the craftsman decide how to produce it. The market space is practically *skipped* and transactions are made directly with uncertain prices and production times (Fig.6).

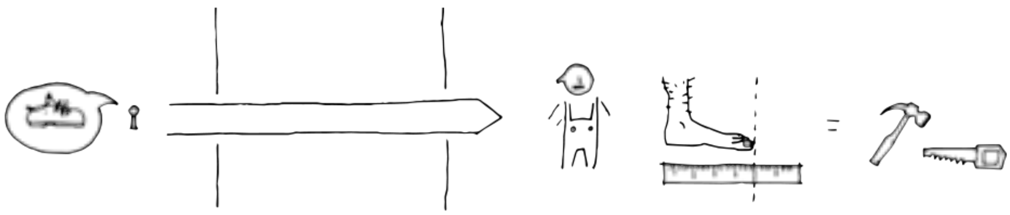


Figure 6: Craftsman traditional production and market system.

Both systems have clear limitations and advantages. MC has been proposed as a *set of organisation capabilities that supplement and enrich an existing system*, looking to reduce the system limitations, while keeping its advantages as much as possible (Piller and Tseng, 2010: 4). Therefore, it is a business strategy that manufacturers can use to sophisticate their processes by adopting principles from the opposite system.

However simple as an idea it is pragmatically complex and sometimes complicated. MC is a paradox, not only in its semantic composition, but in logistics. It presents an apparent *chicken and egg* situation[11] where it is ostensibly tough to determine which element of the supply chain have to be modified in order to successfully implement it.

[11] A situation where it is impossible to decide which of two things existed first, or which caused the other.

In reality, MC mainly relies on the ability to manage parallel processes, where manufacture processes have determine the design variability limits, but should only be selected as a consequence of market analysis, and *vice versa*.

The following diagram represents the assumed rationale of a product provider that opt for MC strategies to *improve* the established market, which is dominated by providers that utilise mass production systems, but where the customers are demanding more and more variability (Fig.7).
First, the mass customizer (1) select observe a specific market (shoe, automobile, etc.) identifying the minorities' demands. Then (2) register the different products offered in that market and (3) *figure-out* their production and marketing processes. Then, (4) select or design a *flexible* supply chain capable of producing a variety of products that resemble the observed market desires; and (5) offer a service where customers can interactively select and personalise a product (Piller, 2004: 318; Hippel, 2001: 249). Finally, (6) produce the customer's specific product and deliver it directly to them.

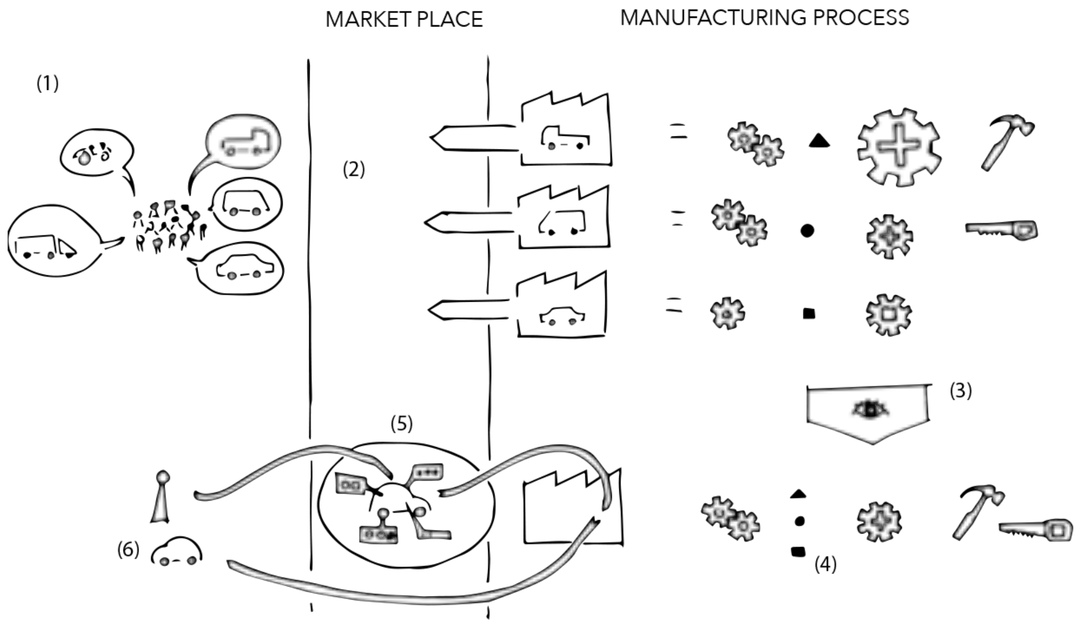


Figure 7: MC application as a sophistication of Mass Production systems.

Concretely, MC is a subcategory of *co-design* that refers to the management of *marketing, design* and *manufacturing* systems capable of producing a controlled variety of products preselected by individuals, without sacrificing the production efficiency, effectiveness and relative cost (Noguchi et al., 2016: 95; Piller, 2004: 315).

It is considered part of *Co-design,* because is an approach based on collective creation and MC can be seen as the product's design agreement between customer and provider (Thallmaier, 2015: 11).
The interaction between a customer and provider strictly happens during the selling process. Customers are bridged with the production decision-making process, which they can *manipulate* in order to produce what they want to purchase.

This customer's apparent control is in reality circumscribed on a set of parameters pre-established by the provider. These parameters can be referred as the ***solution space***[12],

[12] In mathematics the solution space refers to the space of all possible solutions for a problem.

which represent *'the pre-existing capability and degrees of freedom built into a given manufacturer's production system'* (Piller, 2004: 316; Von Hippel, 2001: 251).
The solution space is a key concept in MC systems. It is usually materialised on an interface display (*menu*-like toolkit) where customers can visualise the provider's portfolio, which can be named as the 'choice navigation tool'. In it, customers decide on a product by *navigating* through a series of pre-established options. Those decisions are translated to manufacturing processes and, once the final design has been taken, the order is sent to manufacture for its later assembly and delivery (Fig.8).

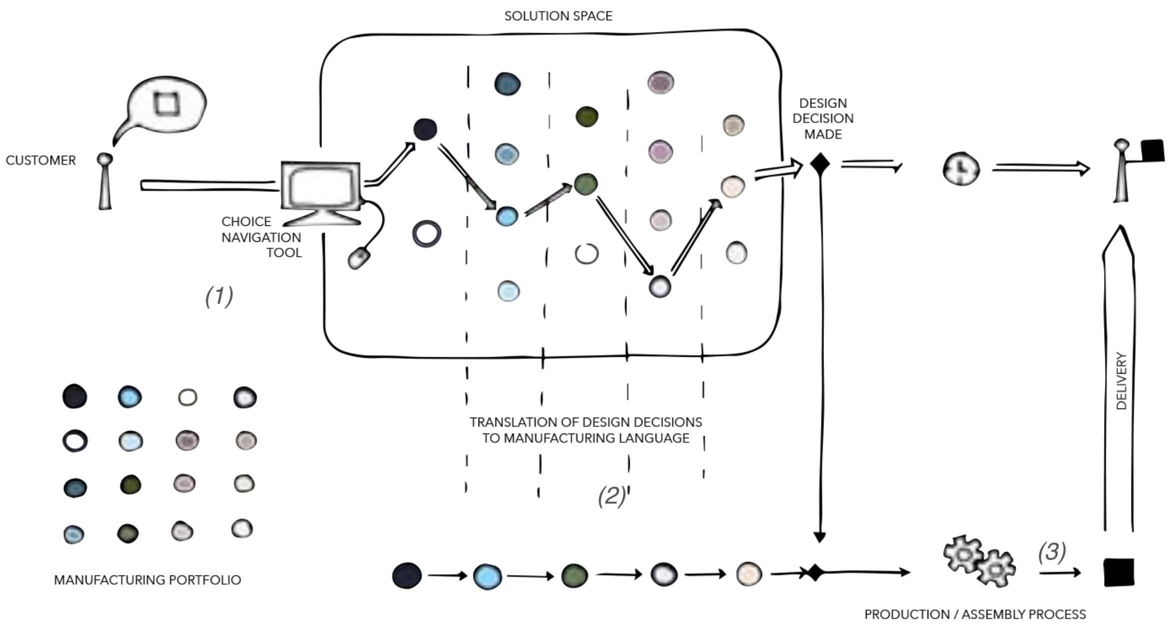


Figure 8: Solution space in a MC supply chain.

The implementation of MC systems need of special *'enablers'* to achieve the flexibility and efficiency envisioned. The enablers are those processes, methodologies and technologies that allow the conception of customisable products through similar supply chains used for mass production (Silveira et al., 2001: 5; Fogliatto et al., 2012: 17). There are three moments during the supply chain where these enablers are critical (Indicated in fig. 8):

(1) *Creation of a choice navigation tool*— configurators, menus, design systems or co-design platforms (usually addressed as software tools) that allow the customers to visualise and choose a product from the provider's manufacturing portfolio.

(2) *Translation of design decisions to manufacturing language*— process of deciphering and decoding the design decisions into outcomes that machines and/or builders understand and can transform into manufacturing; e.g. 'Building Information Models' (BIMs) as a complement of 'Computer-Aided Design' (CAD) tools.

(3) *Manufacturing flexibility*— manufacturing strategies, tools and/or machines to produce different outcomes and tasks, accompanied with assembly logistics capable of assembling complex modular arrangements.

In short, these enablers are the tools that assist in the managing of parallel processes in the supply chain. Digital technologies, as a communication sophistication, can accelerate the information flow among the supply chain, but the enablers are not exclusive to computerised technology.

One of the main advantages of 'mass production' over the tailored market is that consumers and providers have certainty over the cost and quality of the products. To differentiate of the crafting market, MC suppliers need to provide immediate information of the products.
Therefore, MC systems are more dependent to assertive management than production capacity or flexibility. Providers might opt to outsource the manufacturing, assembling or delivery, but have to ensure efficient communication among them to conceive a product that reflects the customer choice and budget.

The customisation of a product can happen at any stage of the supply chain and depending on that, the level and type of customisation varies (Silveira et al., 2001: 2-3; Duray et al., 2000: 610). This *trade-off* point between standardised production and customer's design decision-making is called 'Customer Order Decoupling Point' (CODP), which refers to the point that separates decisions made under uncertainty from decisions made under certainty (Rudberg and Wikner, 2004: 447). In short, customizers strategically decide where to locate their CODP in their supply chain in order to increase the variability or to control production costs.

As seen, MC refers to the production and marketing of products. The *Property* market is where houses are purchased and sold. A 'house' is a tangible object; therefore, can be marketed as a product. But, a 'home' implies immaterial aspects that might be difficult to grasp in a product or service.

3 H is for [ ]

Noguchi (2016a) explained that the decision of selecting the term 'home', in the ZEMCH acronym, over other similar terms, like *housing* or *living unit*, was to emphasize the subjective interpretations a dwelling can have, declaring that '*Home is … where family gets together, people come back and children grow'.*
The ZEMCH Network (2017) have stressed that achieving social sustainability is one of their primordial ambitions. 'The family' is usually referred as the nucleus of society; therefore, from their perspective, it makes sense to promote the term using 'home'.

However, this study propose to consider the word 'houses' to define ZEMCH whenever the term wants to be used objectively.
Moreover, not in every language do we find correspondents for the term 'home' as an arguably different concept from 'house' as in English, which can cause misinterpretations.

For those interested on the 'home' concept, Blunt and Dowling (2006) book simply entitled 'Home', provides an essential guide to studying home and domesticity; while Miller's (2001) book 'Home Possessions: Material Culture Behind Closed Doors', will be interesting for those interested on seeing 'Home' as a process.

4 Benefits of using MC systems in the conception of sustainable houses

MC systems are only present within those markets that require customised products, imposing it to markets without this need will be meaningless (Piller, 2004: 323; Silveira et al., 2001: 4; Fogliatto et al., 2012: 17). The main difference between housing and other markets (automobile, shoes, etc.) is that a dwelling is fixed to a unique place and environment. Actually, the housing market do not have a physical exchanging place, customers buy a house that is already placed in situ. Hence, housing design, despite a discussable social desire for individuality, needs to respond to a specific location, orientation and context. Standardised dwellings fail to consider these specifications.

MC systems can be applied as a strategy to consider contextual and environmental aspects during the design decision-making process, which should merge to the customer's needs and financial capacities.
The conception of ZE houses mainly relies in the effective application of the following fundamental strategies— *Passive design*, *Selection of energy efficient mechanical systems* and *Generation of energy through renewables*. The ZE threshold can be achieved by applying these strategies in different ways corresponding to each context, which will result in variations in the production and its cost.

MC systems can allow the selection of different housing options (programme, size or form), but restricting the choices only to those options that achieve ZE. Customers receive instant pricing or, failing that, limit their options to a budget. Either ways, the outcome will ensure a ZE house.
An alternative scenario could be one where the customer decide the house's energy capabilities based on the information provided; in terms of cost, added economic value over time and environmental impact (energy usage, carbon emissions). The house sustainability characteristics will be decided by the customer values and financial capacity. This model is closer to what can be observed in an open market.

In addition, MC production models work on demand contributing to reduction of waste and are based on industrialised processes, which benefits are well known: controlled environment and precision over the production, associated with higher levels of airtightness, and as a consequence, more energy efficient buildings.

5 Conclusion and ZEMCH definition

This study has demonstrated that even though ZE and MC are complex terms, they can be defined in an objective and measurable way encouraging their precise use. Future studies and practices could benefit through direct citation of the terms ZE, MC, and ZEMCH.

ZE was defined based on thermodynamic principles revealing the impossibility of a 'zero' energy equilibrium as energy flows and is measured in that sense. Therefore, ZE have to be seen as a threshold obtained over a period of time rather than a restriction of energy. Therefore, ZE refer to the 'net' flows being zero or negative in terms of energy exchange.

On the other hand, MC was defined as the management of supply chains capable of producing controlled variety of products preselected by individuals, without sacrificing the production efficiency, effectiveness and relative cost. MC systems depend on the development of solution spaces that evince their manufacture portfolio with the use of appropriate 'choice navigation tools'. Enablers can be used, not only to increase the manufacturing flexibility, but to allow customers to select a design a design and to translate it to manufacturing language.

MC correlates with ZE as MC systems can be applied to housing supply chains to allow the selection of different housing arrangements keeping its ZE characteristics. Effective 'choice navigation tools' can guide customers to opt for a design option that reflects their sustainable values and adapts to their financial capacity.

Therefore, this study defines ZEMCH as follows:

> ZEMCH is the acronym of 'Zero Energy Mass Custom Houses', which refers to those zero energy houses conceived through supply chains that utilise mass customisation systems to ensure they reach a designated zero energy threshold.

It is implied that only houses that reach a ZE threshold can be named ZEMCH; however, it does not mean MC systems are conditional to ZE. On the contrary, this study highlight that MC systems can contribute to the increase of sustainable houses options in the current housing market.
Lastly, this study suggests the selection of the 'net zero site energy' interpretation because its simpler calculation could be more precisely applied in the development of effective solutions spaces. The use of the other three zero energy interpretations might be considered if identified as market demands, but due to its volatility, providers could only compromise to achieve ZE on the delivery day.

6 Further studies

This study forms part of a wider research on ZEMCH applicability. Further research around the successful conception of 'solution spaces' is intended to understand how (and which) enablers can be used to develop efficient 'choice navigation tools' for the production of ZE dwellings with available manufacturing process. Duray et al. (2000), Joann Daaboul et al. (2011) and MacCarthy et al. (2003) have been identified as relevant studies in terms of operation approaches in MC systems; while Kuo (2012), Boër et al. (2013), Drizo and Pegna (2006), and Sakao and Fargnoli (2010) will be considered as references for the design of sustainable MC systems.

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BARRIERS TO INNOVATIVE HOUSING IN SCOTLAND: NRGSTYLE'S 'ZEMCH 109' CASE STUDY

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Abstract: *This paper presents a detailed description of the 'ZEMCH 109' project— a case study for the delivery of 'Zero Energy Mass Custom Homes (ZEMCH)' in the UK by NRGStyle, a Scottish entrepreneurial organisation. The paper aims to identify the processes, possibilities, barriers and limitations that industries may confront when applying ZEMCH theories in practice. Moreover, this paper describes the particulars of this project and recapitulates the academic studies referenced/developed around it. NRGStyle intend to attach new sustainable houses to existing post-war houses with generous plots. As a result, the owners could move to a super insulated house capable of generating clean energy, while the existing dwellings could be retrofitted and used for rental purposes. Mass customisation manufacturing processes are intended not only to ensure energy and resource efficiency through off-site construction, but also to achieve design flexibility that follows the principles of 'multi-generational homes' and to accommodate users' wants and needs. ZEMCH 109 began with the ambition to eradicate fuel poverty in Scotland by means of constructing "eco-houses". In 2009, the Mackintosh School of Architecture collaborated by collecting data from an existing property in Prestwick, Scotland, to generate the initial designs. A feasibility study was then funded by "CIC Start", Glasgow Caledonian University, whereby cost-effectiveness, energy efficiency and waste reduction aspects of the designs were analysed. After which, the Building Environments Analysis Unit (BEAU) of Sheffield University monitored the energy usage of the selected case study. Presently, NRGStyle is applying for the construction licence to erect a prototype show house. Ongoing research with the University of Edinburgh is focusing on how mass custom manufacture and marketing processes are linked to the delivery of zero energy houses. Finally, this paper also covers ongoing research into resource efficient materials and Circular Economic business models.*

Keywords: *Planning Applications, Housing, ZEMCH, NRG Style, Theory Application*

1 Introduction

When Norrie Smith developed the idea of constructing eco-houses in 2005 and later incorporating the NRGStyle company in 2011* to host the project, he could not have imagined the long and complicated journey he was about to embark upon (Companies House, Department for Business, Energy and Industrial Strategy). This was mainly due to the fact that the ambitions of his project not only relied on dwelling, but in the search of achieving social *justices* through the construction of houses. Houses that aid in abolishing fuel poverty, reuniting families and promoting mental, physical, and social health. Back then, an 'Eco House' was the closest term he could find to encompass his idea.

The development of the project has involved continuous research and development, as well as multiple learning processes. The decision to incorporate academia resulted in the adoption of the ZEMCH term— Zero Energy Mass Custom Home— where the project found a frame correlating with its ambitions. The project prototype will be constructed in Prestwick, Scotland, at 109 Adamton Road South. Therefore, the project has been named 'ZEMCH 109'.

This document provides insights and explanations into the bureaucratic processes crucial for building in Scotland. It narrates the 'ZEMCH 109' journey from NRGStyle's perspective, from its conception to current state. This study was developed following a rigorous examination of the NRGStyle's archive. The author's aim was to identify the moments where the project confront barriers for its completion, looking for the gaps where scientific (academic) conjectures conflict with the practice.

2 Definition of the project

The 'ZEMCH 109' project aims to construct 'net zero site energy houses', which means that the houses constructed will produce at least as much energy through renewables as they consume, when accounted on the grid interaction at the boundary of the building site (Sartori et al, 2012: 10; Voos and Musall, 2013: 12; Torcellini et al., 2006: 4-5, 11; Aelenei et al., 2015: 277, 293; Marszal et al., 2011: 972).

The Prestwick prototype will work as a show-house and example for its replication in similar plots around the UK. The proposed houses will be attached to existing end-of-terrace houses with generous plots; as a result, the owners will be able to move into a new super-insulated house equipped with energy-efficient mechanical systems, while the existing dwellings are able to be retrofitted and used for rental purposes (NRGStyle).

The intended houses can be produced following a standardised construction system, but the outcome (house) has to adapt to each specific context– plot size, latitude, orientation and customer financial capacity– therefore, mass customisation strategies will be utilised to mediate these factors without modifying its procurement system. NRGStyle is the agency that will manage the marketing, production and delivery of the zero energy houses.

3 The Journey

In 2005, Norrie Smith started running a 'Neighbourhood Watch' scheme as a response to the unsafe social conditions (Scottish Crime Prevention Council). The scheme successfully brought the community together and consequently evolved into a 'Regeneration Project' that worked to improve the local built-environment. The 'Raploch

Regeneration Project' and the 'Home zone'[1] principle were used as conceptual references to start shaping the project (Robertson; Kaiya, 2016).

It was observed that the construction of the built environments, in particular those financed by individuals, require high investments that people in poor areas are not capable of funding. It was also noted that a significant percentage of their income was utilised to pay for energy bills, to the extent that increasing cases of 'fuel poverty'[2] were becoming evident (fig. 1). Therefore, the generation of energy through renewables was considered as a logical solution.


MILLIONS PAY £270 TOO MUCH ON BILLS

DAILY EXPRESS

Our brilliant astrologer Lori Reid reveals how your life is going to change NOW

£434 EXTRA ON ENERGY BILLS

Electric bill shock for eco-home residents

Figure 1: Media (newspaper) coverage of the 'fuel poverty' situation in the area (NRGStyle archive)

The approach to energy efficiency has been the most significant learning curve for the project and the central driver thus far. Research at that time consisted of attending energy fairs and training as wind turbine technicians. It was quickly understood that renewables do not represent a significant economic and environmental value if they are not merged with passive design strategies– airtightness and thermality. The initial idea was to retrofit existing dwellings, but retrofitting was considered a complicated process with uncertain impact. On the other hand, the construction of new 'eco-houses' is measurable and straightforward.

Through intuitive surveys in the area, a large number of end-of-terrace houses with room for the construction of new houses were identified. Given that it followed the desired characteristics, the house located on 109 Adamton Road South was bought in January 2007 with the construction of a prototype in mind. Several months later, an 'Outline Planning Application' was submitted for its construction, however the construction license application was refused some months after.

Actions towards social regeneration and sustainability are usually encouraged by politicians and governments; however, the 'ZEMCH 109' project has encountered obstacles in policies that have delayed its completion. The paper proceeds by presenting the execution of the project, planning application processes, its refusal and actions taken by NRGStyle in order to counteract them.

[1] A 'home zone' is defined as the residential street where people come before vehicles (CIHT-4).

[2] A fuel-poor household is defined as one which spend more than 10% of its income on energy to heat its house to an adequate standard of warmth (Energy UK).

4 The Planning Applications

4.1 Outline Planning Application

The first planning application process lasted from March 2007 to June 2008. An 'Outline Planning Permission for the erection of dwellinghouse'[3] was submitted through a local Architect[4] (NRGStyle (a), 2007). Statutory basic information was supplied including location and block plan. No architectural plans, design statement nor reference to Eco House guidelines were required at this stage.

In May 2007, a letter from a council planning officer[5] notified that the policies H6 & H7 of the Local Development Plan (LDP)[6] were *'material to the consideration of [the] application'* (NRGStyle (b), 2007). A material consideration, in Scotland, is a process in planning law which the decision must consider during the assessment of an application for development when deciding the application's outcome. Policies H6 and H7, which were later 'Refusal Reasons' stated in 2007, are the following:

- *H6— 'the layout, density, plot ratio, scale, form and materials of any proposed development not detracting from the character of the surrounding buildings and the locality; and… The* ***provision of an acceptable residential environment****/ amenity being provided'*

- *H7— 'Within areas predominantly in residential use as identified on the Proposals Map,* ***the Council will seek to protect the character and amenity of the area*** *concerned, especially from non-residential development with potentially adverse effects on local amenity.'* (emphasis added)

It was advised to revise these policies on the council's website. However, they were not available online at the time of writing; they have most likely been superseded by the most recent LDP.

It was also stated that *"… the proposed development would interrupt the rhythm of the street…, unduly compromise the established character of the area and… would have an adverse impact on the visual and residential amenity of both the existing and proposed properties."* Finally, it was suggested to submit a **written** statement to attempt to justify the proposal (NRGStyle (c), 2007).

Therefore, in June 2007, a response supporting the application was submitted arguing that (from NRGStyle's perspective) the application submitted complies with the mentioned policies; backing up the argument by referring to existing extensions approved in the area, including the one located on the site.

It was also expressed that the arguments and policies were subjective and lacked measurability, e.g. it was doubtful to state the proposal would *interrupt the rhythm* of the street compromising the *character* of the area, when it is composed by an eclectic combination of housing types (detached, semi-detached, terraced and flats) and styles dating from different eras (NRGStyle (d), 2007).

[3] At 109 Adamton Road South, Prestwick, with the following reference number: 07/00380/OUT.
[4] David Campbell from 'Architecture Design and Development Solutions'.
[5] South Ayrshire Council Planning Officer, David Clark.
[6] The South Ayrshire Local Plan (SALP) is the land use plan that sets out strategic spatial priorities and policies for specified uses (South Ayrshire Council).

At this point, construction details or design representations couldn't be submitted; therefore, it was compromised that the quality and design styles would conform to the mentioned policies.

4.1.1 Outline Planning Application Refusal

The Outline application was refused in August 2007 stating that it was contrary to the above mentioned policies H6 and H7.

The hired architect advised to appeal at National Government level, as there was no objective reasons for the refusal. Therefore, in September 2007, an appeal was submitted to Scottish Ministers at the Scottish Government Inquiry Reporters Unit in Falkirk. The appeal contained all the information submitted in the Outline Planning Application and a supporting letter from the neighbours.

4.1.2 Outline Planning Application Refusal Appeal

As part of the appeal procedures, a Scottish Government Reporter[7], accompanied by the council planning officer in charge, visited the site in April 2008. The applicants were permitted to attend but not to speak to nor approach the Reporter.

The appeal decision was **dismissed** in May 2008, which meant that planning permission was refused under the appeal process. The reasons stated for the dismissal followed the Planning Application Refusal, arguing again that the proposal runs contrary to the already mentioned policies H6 and H7. The objecting points remained subjective declaring that *"…the development …would be unsympathetic in relation to the planned form of the area [sacrificing] the symmetry of the terrace, and appear[ing] out of place…"* Moreover, the mentioned similar existing examples were not considered comparable to the proposed site. The community supportive letter was noted, however, the council's concern was that by allowing the proposal, this would set a negative precedent.

The Reporter's decision was *final*[8]. Consequently, a new planning application could not be submitted for another two years from the date of the Reporter's decision.

A senior planning manager and an elected councillor visited the site and commented,

> *"if it [the application] had landed on a different planner's desk on a different day, then planning permission would have been granted".*

This statement, not only reinforces that the planning process loses subjectivity when justified with unmeasurable policies, it also suggests a matter of *luck,* which refers to the criteria, capability and efficiency of the planning officer determined.

In June 2008, a supportive Councillor[9] attended a meeting with the Head of Planning and a Senior Planner to discuss the proposal and its outcome. It was informed then that planning history would be taken into account in further procedures even in applications resubmitted after the two year's time gap. Advised by diverse councillors it was decided not to appeal and invest (the time and money) on preparing a new planning application.

[7] Ms Allison Coard.
[8] Could only be reconsidered if any person was *aggravated* in the process, conferred in Sections 237 and 239 of the Town and Country Planning (Scotland) Act 1997.
9 Hugh Hunter

4.2 Planning Application Interim Period

In January 2009, the original architect was discarded and an Independent Planning Consultant[10] was commissioned to prepare a report over the planning decision. It was not until this date, that the applicants were able to see the council notifications and previous consultant reports. The new consultant noted that 'green credentials', although laudable, would NOT overcome the Council and the Reporter's decisions. She finally suggested to meet the council's Planning Manager[11] before "*…getting more detailed plans drawn up to demonstrate what you would like to do."*

In February 2009, the applicants met the Planning Manager and Officer, the latter who refused the previous planning permission. The Planning Manager explained her officers' point of view and gave the applicants the same courtesy. The Planning Manager could not see any apparent issue and asked the Planning Officer if planning permission could be given to an alternative proposal on the same plot. He refused and was visibly uncomfortable at the suggestion, insisting that *'South Ayrshire Council could not be seen to be doing a U turn!'*. The manager herself drew some diagrams on paper and suggested the applicants elaborate with architectural drawings and arranging another meeting.

At the time of writing, the advises given by diverse consultants opposed to each other and, only two years after starting the first planning application process, it was finally advised to elaborate an architectural design. The council planner's ironic contradiction emphasised the subjectivity of their decisions; and demonstrate that 'planning applications' are linear bureaucratic processes, where planners resist to modifications as they might imply re-work.

On the coming months, efforts were focused on consolidating a political network that could *back-up* the project, getting the support of Mr Chic Brodie who went on to become the Scottish Government MSP[12] for the area and who continues to be a strong supporter of the project to this day; while searching for the adequate person to elaborate the design.

An academic was selected over an architect[13], in order to capture the ideas of sustainability and replicability. Dr Masa Noguchi, Lecturer in Architectural Technology and Code for Sustainable Homes Assessor, had a portfolio on 'Mass Customisation', which was considered more suitable for the project.

5 The Academia Approach

In February 2010, the collaboration with Dr Noguchi was initiated, who at that point was conveniently based on the Glasgow School of Art, working with the Mackintosh Environmental Architecture Research Unit (MEARU). Dr Noguchi suggested that one of his Masters Students14 become involved, who later visited the site and eventually produce a series of architectural designs.

The project was utilised as a case study for the design and test of architectural integration of Hybrid Solar Thermal Mass (HSTM) and heat waste management

10 Greta Roberts– MA Dip TP Town Planning Consultant.
11 Catherine Parish– Lead Conservation Planner, Planning Service, South Ayrshire.
12 MSP stands for Member of the Scottish Parliament.
13 Architect Paul Barham from John Gilbert Architects, Glasgow.
14 Audrius Ringaila

(NRGStyle and ZEMCH Network, 2012: 24). An environmental analysis of the site was developed, including sun and wind analysis, a thermal survey of the house envelope and equipment, and measurement of internal temperature, humidity and CO2 (NRGStyle and ZEMCH Network, 2012: 26-31). Then, a design was developed in response to the negative aspects observed, which consisted of an adaptation of a model used in their previous studies. The proposal demonstrated an increase of heat efficiency obtained by maximising solar gains and with a smart use of the heat extracted from mechanical systems (boiler and kitchen extractor) and water used in utilities (washing machine, shower and sinks). The heat recovered, plus the obtained from PV/T panels, was proposed to be introduced through a mass concrete wall and parts of the flooring (NRGStyle, 2012: 35-36). This design, in conjunction with supportive studies, shaped the document submitted for the further planning application.

5.1 Application for Full Planning Permission

After careful deliberations and multiple meetings between NRGStyle, the planning consultant, academics and construction engineers from an industrial company[15]; a Full Planning Application was finally submitted in March, 2012. The application consisted of: location plan, ownership plan, block plan, architectural plans (floor, roof, sections and elevations), a design statement and an illustrative video (fig. 2 and 3).


Figure 2: (left) Perspective of ZEMCH 109 proposal, south view
Figure 3: (right) ZEMCH 109 proposal with wind turbine, frontal view

In addition, the application had an appendix, which consist of a series of academic documents that justify the dwelling's design, in terms of sustainability, which include: a 'Standard Assessment Procedure' (SAP) that demonstrate that the design was capable of achieving 'net' zero site energy capabilities. A PV/T assessment (fig. 4). Technical information of the construction system provided by the construction engineers. A socio-demographic survey of Prestwick, Scotland and the UK, which demonstrated that Prestwick had the lowest social housing stock in the region, where more than 20% of the dwellings in Scotland are terraced (NRGStyle, 2012: 90-96). An academic paper that presented how the knowledge obtained from technical visits to Japanese Housing factories was transferred to the prototype (Noguchi et al., 2011). And 9 different designs alternatives (fig. 5).

15 Designers and Construction Engineers from Powerwall– Frame System Company based in Glasgow. Currently under an Administration status.

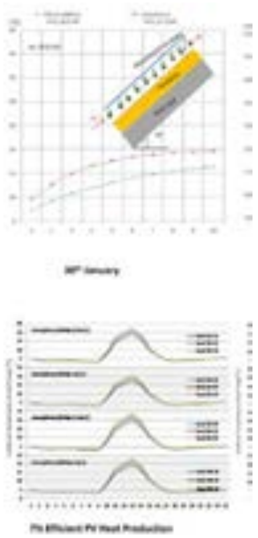

Figure 4: (left) Outcomes of analysis over the efficiency of PV in the proposed site.
Figure 5: (right) ZEMCH 109 alternative design proposals

In short, it was a solid and well referenced document. However, it might be considered overwhelming, extent or out of normality. The council had troubles uploading and reproducing the video, which was a crucial part of the submission; and there were no comments on the academic papers or technical information, which suggests the authorities might overlook them or did not comprehend them.

In May 2012, the application for Full Planning Permission was refused. The reasons remain on the same line as the previous refusal. It was stated again *that the proposed dwelling house does not respect the scale, form and density of its surroundings and does not enhance the character or amenity of the locality.* The policies H6 and H7 were referenced once more.

On August of 2012, the first ZEMCH International Conference took place in Glasgow (fig. 6). NRGStyle had a pivotal position, not only on assisting in the organisation of the event, but with the 'ZEMCH 109' project taken as a case study of several of the papers presented. All the delegates were taken to visit the site, where Dr Avi Friedman highlighted the virtues of the project.

Simultaneously, an application was made to South Ayrshire Council to appeal the refusal decision (NRGStyle (b), 2012). An appeal at this stage is held by the Local Review Board (LRB), which is a Board of Elected members of the Council. A site visit was requested so that all members of the local review board could visit the site in person. The site visit did not take place.

The LRB meeting[16] was held in October 2012 and they upheld to the refusal (NRGStyle (c), 2012). As there were divided opinions, the decision went to vote, where councillors' arguments were stated in personal voice, e.g. *"I would not have a problem living next door to it"* or *"I wouldn't like to see that building when I'm out walking my dog"*. A councillor[17] who had previously assured interest in the project, left the proceedings before voting. The LRB decision was taken without the advice of any expertise on sustainability and was driven by personal judgements.

[16] A 'court room' style discussion where the applicants could only watch from the viewing gallery.
[17] Mr Hugh Hunter

There was the possibility to select another plot in another Local Authority for the construction of the prototype; however, NRGStyle decided to insist over the same site to understand all the adversities that the project could confront in the future. Since then, the Planning Process has been on hold and the project was developed form other angles.

5.2 Parallel work

'ZEMCH 109' continued being used for academic studies. In 2012, monitoring systems were installed in the existing house to promote energy conscious behaviours (Han et al., 2012: 168). It demonstrated that the energy patterns have a correlation with the occupants' lifestyle (Han et al., 2012: 175). The same data was utilised by additional studies that assess the cost-effective relevance that passive design techniques and use of Photovoltaic Thermal (PV/T) systems and Mechanical Ventilation Heat Recovery (MHVR) (Rohatgi et al., 2012: 223; Dhamne et al., 2012: 613). These studies highlighted the significant effects of building orientation and thermal properties on reduction of energy demand. In 2013, Dr Noguchi extended the research of MVHR and PV/T systems. The study evaluated 19 different scenarios in order to identify their economic value over 10 years (Noguchi, 2013: 1256). Moreover, in 2013, the NRGStyle team attend to the 'ZEMCH International Conference' in Miami, USA, where another study developed around the project was presented (fig. 7) (Jimenez-Moreno and Noguchi, 2013: 85-100).

Figure 6: (left) 'ZEMCH 2012 International Conference' reception and *official* photo: Dr Masa Noguchi, Chic Brodie, Norrie Smith, Alison Quinn and Paul Heron
Figure 7: (right) NRGStyle team in the ZEMCH 2013 International conference in Miami, USA: (from left to right) John Onyango, Hasim Altan, Dr Masa Noguchi, Alison Quinn and Pablo Jimenez-Moreno

In September 2013, NRGStyle members, accompanied by a selected group of experts in sustainability[18], were invited to a Scottish Government Meeting at Holyrood in Edinburgh to present their project and to discuss their experience, which helped that in 2014, the Scottish Government introduced Material Consideration in sustainable development (Scottish Government, 2014). Later that year, NRGStyle was referenced by the 'Home Renaissance Foundation' in a publication that promoted multi-generational Living (Housing LIN, 2015: 6-7). In 2015, Norrie was invited as a Speaker in the House of Lords at Westminster, London, to present the 'ZEMCH 109' multigenerational living qualities.
In 2015, Norrie introduced plans to build a housing factory in Scotland at the "ZEMCH International Conference" at the University of Salento in Italy. In 2016, part of the NRGStyle team attended the 'ZEMCH Mission to Japan' to visit the state-of-the-art facilities of leading housing manufacturers (ZEMCH Network). The knowledge gathered from the visit is being analysed for its successful application in the UK context. In

[18] Prof Tim Sharpe from MEARU, Gareth Feeney and David Fotheringham from the Scottish Government Sustainability Group.

parallel, complementary site works initiated in 2008 and completed in 2016, to adjust the site to some notes and advices observed in the application refusals. The prototype design has been modified during these years.

6 Future actions and targets

Foremost, NRGStyle will apply for construction permission for the ZEMCH 109 prototype. A new planning application will be placed in the coming months considering the same site, but a modified design proposal. It follows the outcomes obtained from the academic studies, but is shaped in a layout, form and style sympathetic to the surrounding urban context (fig. 8)

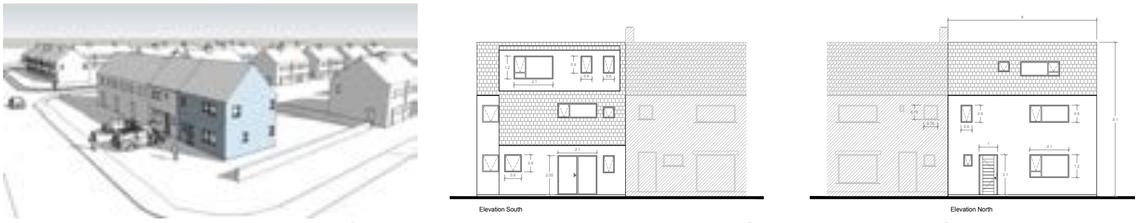

Figure 6: ZEMCH 109 design response to refusal (work in progress)

The new proposal considers the use of Scottish Cross Laminated Timber (CLT) for the structural shell. CLT envelopes have demonstrated to be highly airtight where insulation material can be easily attached. Moreover, its production process allows high customisation, in terms of where to *cut-out* openings. CLT boards can be outsourced until the company is capable of producing their own.

The company will follow Circular Economy principles to ensure sustainability, not only on their operational life, but also during their construction and demolition. Circular economy refers to the economic model in which resources are reutilised instead of being disposed, maximising their value and regenerating products and materials at the end of each service life (Wrap).

ZEMCH 109 provides an excellent platform for introducing circularity in terms of resource recovery and multigenerational utility. Prefabrication and modular production allows the easy disassembly of the material so as to maximize recovery and regeneration at the end of its service life. Circular business models promote the selling of performance of certain goods than the good itself. However, the enterprise benefits, in terms of profit and reputation remain uncertain. Primarily because there is a direct competition with the traditional approach of ownership of tangible goods, in this case a 'house' (Planning, 2015).

Moreover, NRGStyle propose the retrofitting of houses as part of the project and is exploring the viability of adopting innovative circular business model regarding to: product recycling transformation and customisation possibilities in material recycled from construction.

Research will remain as the main drive for continuous improvement, which has been spotted as a key element of the project. Innovation and efficient application of new technologies is essential for the conception of zero energy dwellings. This study, not only demonstrates the barriers of implementing ZEMCH theories in practice, but will be utilised to promote the project in the academic and political circles. NRGStyle will develop an expert planning questionnaire to investigate whether these barriers to innovation are common place throughout. This questionnaire will be presented to all

local planning authorities in the UK. The data will be collated and presented to ZEMCH 2019 for review.

7 Conclusions

The complexity of housing, as practice and concept, could not only be addressed only from a social stand point. The 'ZEMCH 109' journey demonstrated that planning permission can be refused even with the guidance of qualified consultants and academics. Despite being sceptical about the capability, efficiency and objectivity of the existing policies and governmental authorities; it has been understood that the success of a housing project relies on holding an adequate interdisciplinary team that work around architectural principles.

This paper presents the ZEMCH 109 project, describing its transformations to adapt to the limits and obstructions presented in its progress. ZEMCH 109— is a feasibility study for the development of zero energy houses through mass customisation systems— initiated as a 'scheme' to promote community security, which has evolved into a housing project. Its ambition consists of providing 'zero energy houses' to families that currently live in dwellings that do not accommodate their needs, in terms of energy efficiency, spatial flexibility and adaptability to family change.

The project was originated to overcome social necessities. Academics got involved to concretise the ideals into a prototype. Their approach resulted in the adoption of mass customisation strategies and zero energy theories and technology. However, even backed with scientific arguments, the prototype was not guaranteed with construction permission.

This study demonstrates that the application of innovative housing– energy efficiency–is highly dependent on modifying/adjusting to construction policies despite the high levels of scientific and academically engineering research made on during the design process.

Planning policies are focused on conserving homogeneous "traditional" urban appearances that conflict with innovative proposals. These policies do not reflect governmental ambitions towards carbon reduction and energy efficiency. Their modification process is slow and dependant to the efficiency and judgement of local authorities. NRGStyle have taken actions towards the modification of these policies. However, policies (new or old) are open to interpretation; therefore, the approval of new policies still do not ensure success on future planning applications. Moreover, planning applications are long and linear bureaucratic processes where previous refusals are carried, like stigmas, regardless whether or not there have been modifications in the law.

To guarantee planning permission, diverse entities were involved in the conception of the project: applicants (users), technical expertise (scientists), planning consultants, politicians and designers (architects). Ironically, it is unclear when the architectural or engineering expertise have to be included in a sustainable housing project. Housing planning applications can be initiated without architectural designs, fostering misinterpretations and premature verdicts over incomplete projects. The architectural practice, which is supposedly the expert entity in terms of sustainable housing, is not at the centre (or top) of the decision processes, empowering other entities that lack judgement on sustainable design, e.g. planners and consultants.

It has also been recognised that political support is crucial for a positive affect on the policy decision making process. NRGStyle has developed a significant effective and

varied network, not with the intention of inducing politicians; but, due to the complexity of the project (sustainability), to certify a full understanding of it. It has been observed that decisions made by planners and local governmental committees could be taken precociously if they have to rush their decisions due to established bureaucratic timings and formats.

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ZEMCH NETWORK

BUILT HERITAGE CONSERVATION AND SOCIAL SUSTAINABILITY IN HONG KONG

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Abstract: *Social sustainability is a process of creating places where provide good quality of life for people to live and work[1] according to a UK-based social enterprise specialising in place-based innovation. In community level, socially sustainable communities concerns the development of interconnected healthy and liveable communities which is able to provide nutrient for the future generations to grow into the same (or similar) state according to Western Australia Council of Social Services. Community involvement in decision making for matters related to welfare and development is one the keys to developing a more sustainable society. Community involvement in heritage conservation is not new to many countries such as Australia, UK, North America and many other European countries. However, in Hong Kong, a city in the heart of Asia, it is rather a new idea. In Hong Kong, majority of built conservation projects are favouring a top-down conservation approach mainly led by government officials and social elite in the past and even in the present time. Although a true bottom-up approach involved community involvement in conservation process has not yet emerged in Hong Kong, conservation projects have been slightly increased to involve people-centred themes and programs which will bring about a more sustainable social and community development in long term. Conservation of Blue House Cluster (in urban area) the first conservation project conserving both the built heritage and the associated community, and Lai Chi Wo Village (in rural area) the first rural village conservation project in Hong Kong will be studied in details on this paper to illustrate how local community are involved during and after the course of conservation and how they contribute to develop a more sustainable social and community development.*

Keywords: *Built Heritage Conservation, Community Involvement, Social Sustainability, Blue House Cluster and Lai Chi Wo Village*

[1] See: <http://www.social-life.co/> (accessed 18 Aug 2017)

1 Introduction and Research Framework

Heritage values change over times. In the past, heritage values relating to history, architecture and aesthetics governed most heritage conservation projects worldwide. However, in recent decades, intangible values related to more present time and people related values such as society, community and identity are emerging as an important attribute in heritage conservation. In this regard, local community involving in conservation process in determining what the heritage values and their future of the heritage are (English Heritage 2008:19-20) becomes increasingly important to bring about a successful heritage conservation project. Nevertheless, this contemporary and people-valued driven conservation approach is yet to be popular in a lot of places, like Hong Kong. Most conservation projects are still heavily governed by a traditional top-down conservation process that involves limited community involvement.

1.1 Issue of Research

Historic environment is a collective effort of past human activities (English Heritage 2008: 19-20) and it provides links from the past through the present and into the future. Therefore it is considered it often contributes to a better social cohesion and a stronger sense of identity for people belonged to the same historic environment. They tend to viewing they are having similar interests and perspectives on many aspects. In built heritage conservation, because local community are more closely related to the historic environment, they are having the best knowledge and skills about the subject heritage. However, currently, built heritage conservation in Hong Kong are heavily anchored by a top-down conservation process mainly involved decision making made by government officials, professionals and other related experts. Therefore, there is not enough room for local community whom are more closely related to the heritage or simply the general public to express their views or contribute their knowledge about heritage values because their views are often considered insignificant. Particularly in matter like whether a place is qualified as a heritage place or not. When in the case of demolition of a historic place, local community and/or the public and the authority having disagreeing views, tension and conflicts between them become apparent.

1.2 Focus and Scope

This paper is to explore a more sustainable heritage conservation approach with a focus on how conservation projects are incorporated people-centred themes and how local community take part in shaping a more sustainable conservation project as well as community and society. Two conservation projects, one in urban (Blue House Cluster) and another rural area (Lai Chi Wo Village) of Hong Kong will be studied in details. The two projects represent the recent development in built heritage conservation. The Blue House Cluster is chosen since it is the very first built heritage conservation project that conserves both the hardware (the heritage building) and the software (the attached community). And Lai Chi Wo is selected as it is the first last scale rural heritage conservation project supported by the Government in Hong Kong history. For a better understanding what governs heritage conservation, discussion also involves examination of broader statutory and non-statutory frameworks and policies of heritage conservation and a general background of current urban-rural redevelopment pattern in Hong Kong.

1.3 Theoretical Basis

Historic environment belongs to every member in society because it is a shared social, economic and learning resource (English Heritage 2008:19-20). Disregarding ownership, heritage is a unique and physical record of past human activity embodying the aspirations and skills for current and the successive generations. It is a representation of public interest in place reflecting the knowledge, beliefs, cultures and traditions of different communities. As historic environment is a shared resource, everyone in society should be given equal opportunity to contribute his or her knowledge about the values of places, and take part in sustaining it. The role of experts, government high officials and or other elite in the society whom have special knowledge, skills and resources should only be acting as facilitators for the community and the public to establish, sustain and refine the values of places (English Heritage 2008:19-20).

2 Development of Heritage Conservation in Hong Kong

2.1 An Overview of Conservation Policy and Legislation Framework

There are two levels in institutional framework in built heritage conservation in Hong Kong, one concerning policy and the other legislation. The former is conservation directions that the Government intends to follow and the later statutory or lawful measures taken to achieve the policy. In Hong Kong, there was no official conservation policy existed until an overwhelming public concern against the demolition of Queen's Pier in Central to give way for construction of the Central Bypass in 2006. The overwhelming public concern putting Hong Kong's cultural heritage at risk of lost had forced the Government formulate the first conservation policy and written in the 2007-08 Policy Address. This Policy firstly set out the Government's intention to support and promote conservation of cultural heritage through protecting, conserving and revitalising historical and heritage sites, and buildings[2]. In the Policy, the Government also firstly established the Commissioner Heritage's Office under the Development Bureau to take charge of heritage matters.

Statutory designation of heritage buildings in Hong Kong is that Declared Monuments or Proposed Monuments is protected under the Antiques and Monuments Ordinance. This Ordinance also establishes administrative and advisory arms - Antiquities Advisory Board (AAB) and Antiquities and Monuments Office (AMO) to ensure appropriate protection to Hong Kong's heritage. The Ordinance also gives AAB the power to declare a place as a "Declared Monument" or a "Proposed Monument". The Government then has the power to prevent or place conditions on altering the protected heritage buildings.[3] AAB also is empowered to classify historic buildings into different grading – grade I, II or III depending on their heritage values according to a set of preset criteria. At present, there are 114 numbers of Declared Monuments[4] and 1444 numbers of graded historic buildings in the city wide.[5]

2.2 Conservation Policy and Legislative Framework

The current conservation policy and legislative framework is criticised of not promoting a more sustainable approach in heritage conservation in Hong Kong. Heritage

[2] See: <http://www.policyaddress.gov.hk/07-08/eng/policy.html> (accessed 30 Aug 2017)
[3] See: < https://www.elegislation.gov.hk/> (accessed 19 Aug 2017)
[4] See: <http://www.amo.gov.hk/en/monuments.php> (accessed 20 Aug 2017)
[5] See: <http://www.amo.gov.hk/en/built2.php> (accessed 20 Aug 2017)

conservation most time mainly involves conservation and protection of individual heritage building scattered over Hong Kong. At present, individual historic building is recognised as heritage and listed as Declared Monument, Proposed Monument or graded building. Antiquities and Advisory Board (AAB) is empowered to advise on heritage matters, declare a building as a Declared Monument or a Proposed Monument as well as make decision on grading of historic buildings. However statutory protection is not offered to graded of historic buildings made by AAB. The grading has no binding effect between the Government and building owners. Further, AAB is empowered to decide what buildings can be qualified as heritage and what their grading are according to a set of preset criteria. However, the process of declaring and grading of historic buildings is criticised of heavily relying on a typical top-down approach involving very limited community or public involvement in the entire process. The background and knowledge of the appointed board members (mostly government officials and elites in society) of AAB whom also have been criticised of having insufficient connection and conservation knowledge of the concerned heritage and therefore they may have tendency to judge heritage heavily on the basis of economic value[6].

2.3 Urban-rural Redevelopment Pattern

The current conservation policy and statutory frameworks have not stressed on social and community values in the preset criteria while determining grading of historic buildings. Instead, a large area of historic environment is demolished and rebuilt from time to time through series of top-down redevelopment projects with very limited consideration of protecting the existing local culture and old community anchored in the historic environment. Redevelopment pattern in Hong Kong is typically represented by urban redevelopment projects implemented by the Urban Renewal Authority (URA) a quasi-government body which has been playing a very important role in speeding urban redevelopment process of Hong Kong since 1999.[7] The URA's projects are typically criticised of favoring wholesale demolition[8] and large commercial and residential redevelopments targeting middle class buyers while undermining local community and grassroot culture attached to the historic fabric in the redevelopment process.

2.4 Demolition and Redevelopment of Lee Tung Street in Wan Chai

Redevelopment of Lee Tung Street in Wan Chai is a typical example of URA's urban redevelopment project concerning a wholesale demolition and redevelopment of historic environment took place in 2007 with little community and public opinion incorporated in redevelopment process. Lei Tong Street is known as the "Wedding Card Street" with a large numbers of shops doing wedding card printing and related business for the past few decades before the redevelopment took place. The street is also known as the motherland of publishing business in Hong Kong. Although URA theme the new shops with "Wedding-city"[9] on the redevelopment site to response to an overwhelmed public calling for keeping the existing "wedding themed" spirit of the place, existing community, social and business networks no longer sustain because most former shop owners, tenants and residents could no longer afford to resume their businesses and way of life in new shops and residential units after redevelopment simply due to high rent.[10] The

[6] See: <https://www.hongkongfp.com/2016/06/11/are-politicians-and-the-hong-kong-government-becoming-less-transparent/> (accessed 20 Aug 2017)
[7] See: <http://www.legco.gov.hk/yr00-01/english/panels/plw/papers/a711e06.pdf> (accessed 19 Aug 2017)
[8] See: <http://www.scmp.com/article/630733/letters> (accessed 20 Aug 2017)
[9] See: <http://www.scmp.com/article/620669/residents-reject-wedding-city-partial-preservation-market> (accessed 20 Aug 2017)
[10] ditto

redevelopment site has now become homes for international and exclusive brands and living quarter for middle class people. It has also become a popular destination for local people and tourists. However the spirit of place and the old community of old Lei Tong Street no longer exist.

Fig.1: Happening Lei Tong Street before demolition. (Source: https://zh.wikipedia.org/wiki/)

Fig.2: Lei Tong Street after the redevelopment. (Source: http://topick.hket.com/)

2.5 Demolition and development of Nga Tsin Wai Village in Kowloon City

The residential redevelopment project in Nga Tsin Wai Village is another typical top-down URA-led redevelopment project. The village, a 650-year-old and the last urban-rural walled village with rich historic and local cultural values located in the densely populated Kowloon City was demolished in 2016 to make way for a new residential and commercial redevelopment project carried out by URA. The village contains large numbers of simple one-to-two-storey high village houses, shops, street markets, a Mother-god Temple and series of intersecting alley ways. Although the redevelopment plan has given some rooms for conserving the temple and three sets of relics including the memorial plaques of the names of the village[11], it has destroyed the attached local culture and the entire old community. No existing resident and business owner will be resettled on the same site after redevelopment.

Fig.3: A bird view of the Nga Tsien Wai Tsuen in the densely populated Kowloon City before demolition.
(Source: http://www.ura.org.hk)

[11] See: <http://www.ura.org.hk/en/projects/redevelopment/wong-tai-sin/nga-tsin-wai-village-project.aspx> (accessed 30 Aug 2017)

3 Towards a more People-centred Heritage Conservation

3.1 Why community involvement?

Community involvement in the conservation process would lead to a more sustainable heritage conservation. Historic environment belongs to local people who have the best knowledge and skills about the place both physically and intellectually. Taking this further, local community is more familiar with the historic environment and therefore can better identify and develop more relevant initiatives and solutions to address unique problems of their own place (LOW 1997:13). This suggests that community involvement in the conservation process would produce a better conservation project.

3.2 Conservation of the Blue House Cluster in Wan Chai

The Blue House Cluster conservation project is funded under the Government's Revitalising Historic Buildings through Partnership Scheme with physical conservation works commenced in 2011. The project, the first of its kind in Hong Kong adopts a more sustainable conservation process stressing on preserving both the historic fabric as well as the attached community and social networks. In this regards, existing tenants are given a choice of staying or leaving with compensation packages. The staying tenants then become one of the key players in the conservation process. Their views on how their residential units to be conserved and renovated are incorporated in the conservation process. A non-profit organisation is further assigned to operate and manage the heritage place during and after completion of the conservation works.[12] To date, the conservation process is still undergoing.

Fig.4: Blue House cluster in Wan Chai with the Blue House on the left and the Yellow House on the right.
(Source: https://www.heritage.gov.hk)

[12] See: < https://www.heritage.gov.hk/en/doc/rhbtp/ResourceKit_BlueHouseCluster.pdf > (accessed 18 Aug 2017)

3.3 Historical Background

The Blue House cluster comprises three numbers of government-owned buildings painted in three distinctive colour- blue, yellow and orange in Wan Chai District of Hong Kong Island. Wan Chai is a hybrid district having a good mixture of old and new buildings. To its immediate surroundings, there are historic buildings such as Hung Shing Temple, Wan Chai Market, Old Wan Chai Post Office and Pak Tai Temple and so on. The first generation of chief landlords was wealthy Chinese merchants - Pangs and Chans who developed the land into Chinese style shophouses. The building cluster is a representation of typical composited building (shops on ground floor and residential units on upper floors) occupied by Chinese immigrants in the early 20th Century of Hong Kong. The building cluster was also once homes for licensed brothels.[13]

3.4 Conservation Works

Historically, The Blue House Cluster is a very good example of typical Chinese shophouses with ground floor shops and upper floor residential quarters offering affordable and basic housing for poor Chinese immigrants. The historic use of the buildings is also a good record of the co-living style and social practices of traditional Chinese medical practitioners, herbal tea sellers and low income class in the early last century.[14] The distinctive colour of the Blue House has become a major landmark in Wan Chai.

The original use, key character-defining-elements (CDEs) and architectural features are maintained and intrusive modern interventions are minimised in the conservation plan. The predominant use of Chinese shophouse – shops of ground floor and residential units on upper floors is critically maintained while at the same time introducing new uses such as restaurant, areas for exhibition, classroom, workshop, recreation, ancillary office and public open space. The use mix has given a reasonable balance between existing and new uses such as restaurant (for generating revenue), classroom and exhibition area (for education), ancillary office (for administration) and the Hong Kong House Stories and public open space (for community development). Except for preserving all key character-defining-elements (CDEs) and distinctive architectural features, existing timber roofs, timber staircases, timber floors, reinforced cantilevered balconies and their metal balustrades are repaired and restored.[15] In order to meet the requirements of modern building codes, the buildings are genuinely upgraded to meet current statutory standards in health, safety, environmental hygiene and sustainable development.

[13] See: < https://www.heritage.gov.hk/en/doc/rhbtp/ResourceKit_BlueHouseCluster.pdf > (accessed 18 Aug 2017)
[14] ditto
[15] See: <http://www.amo.gov.hk/form/Blue%20House%20Cluster-HIA.pdf> (accessed 18 Aug 2017)

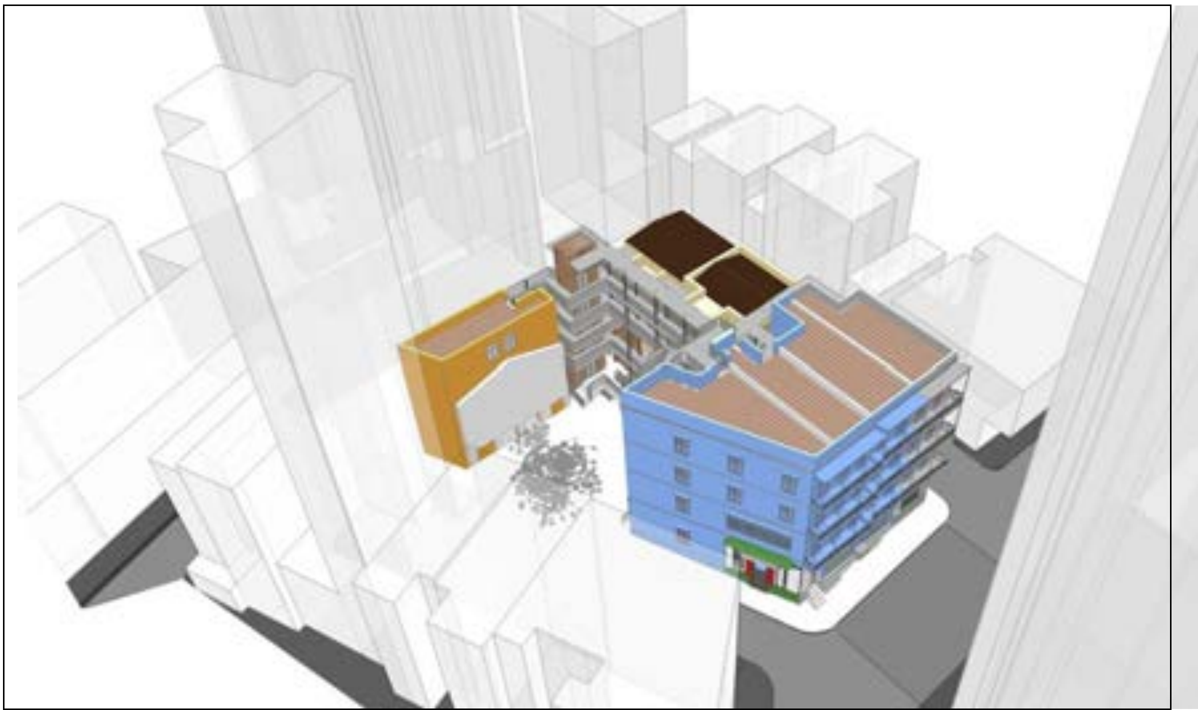

Fig.5: The conservation proposal of Blue House cluster in a densely populated Wan Chai . (Source: https://www.heritage.gov.hk)

3.5 Community-centred Conservation Approach

Community involvement forming parts of the conservation process is a very distinctive feature in conservation project in history. Views and opinions of the existing tenants are incorporated when conserving the residential units they continue to occupy upon completion of the conservation work.[16] The project also dedicates a range of community-centred features and programs to strengthen social networks for both existing and new tenants. The programs include dedicating a new social space – Hong Kong House Stories and introducing a brand new socially innovation scheme - Viva Blue House – Good Neighbour Scheme to strengthen community development and social connections.

3.6 Hong Kong House Stories

In order to sustain the existing community network and in the same time build new social connection between existing and new tenants as well as wider Wan Chai community, The Hong Kong House Stories located on the ground floor of Blue House is dedicated purposely to encourage social interaction and good neighbourhood practice. Simply speaking, The Hong Kong House Stories (originally a shop space) is an informal gathering space for many community activities for tenants and non-tenants. The space can be freely used by tenants and the public to do causal talks and hangouts. There is also an exhibition area inside this social space displaying history and development of the Blue House cluster and the wider Wan Chai District.[17]

[16] See: <https://www.heritage.gov.hk/en/doc/rhbtp/ResourceKit_BlueHouseCluster.pdf > (accessed 18 Aug 2017)
[17] See: < http://houseofstories.sjs.org.hk/> (accessed 25 Aug 2017)

3.7 Viva Blue House – Good Neighbour Scheme

A socially innovation scheme - Viva Blue House – Good Neighbour Scheme is introduced (the first of its kind in Hong Kong history) to strengthen community development and social network. There are dedicated programs to encourage existing and new tenants to actively and interactively making out a co-living life style and practice friendly neighbourhood culture which were commonly found in old Hong Kong. The program is initiated and operated by St James' Settlement, a non-profit social enterprise. In order to encourage existing tenants to stay after revitalisation, the scheme only requires the staying tenants to pay their inexpensive old rent while new tenants to pay at new market rent. There are twelve numbers of newly conserved residential units with six of them in the Blue House and the remaining in the Yellow House. The selection criteria of new tenants is brand new to Hong Kong as perspective tenants are required to attend workshops and interviews to show their willingness to jointly practise a co-living life style and practise friendly neighbourhood culture.[18]

Fig.6: A commercial of the Viva Blue House – Good Neighbor Scheme showing how the co-living style works. (Source: https://www.facebook.com/vivabluehouse/)

3.8 Conservation of Lai Chi Wo Village in Sha Tau Kok

Conservation of Lai Chi Wo Village is the first rural village in Hong Kong intending to developing a more sustainable conservation project through re-establishing an inter-relationship between built heritage, nature, traditional rural culture, local economy and farming activities in rural area of Hong Kong. The project in fact aligns the government's policy to promote sustainability of rural area and community in recent years (LAM 2017).

[18] See: <http://society.sjs.org.hk/GNS/> (accessed 20 Aug 2017)

Fig.7: A bird view of Lai Chi Wo Village. (Source: http://www.globalgeopark.org)

3.9 Historical Background

Lai Chi Wo is a 300-year-old traditional Hakkal village located in the north-eastern of Hong Kong. The Tsangs and the Wongs originally from China resettled in Lai Chi Wo and cultivated the hilly land into fengshui woodland and rice terrace about 300 years ago. At its peak, there were about 1000 inhabitants in the village (LAM 2017). The ancestors of the Tsangs and the Wongs built traditional closely spaced Hakka walled houses accordingly to Hakka traditions (LAM 2017). Longitudinal elevations of the walled houses are typically built facing south and south-east to catch the summer cooling and blocking the north-western prevailing winds in the winter in the sub-tropical climate. Villagers also practised traditional Hakka clansmanship, rituals, religions, fengshui principles, language, food, costumes and so on. However, the village had been declining since 1970s making abandoned built features and farmlands commonly found. The village has been completely vacant since 2000s (LAM 2017). The causes of declining is believed generally due to its remote geographical location, difficult topography, lacking job opportunities and basic civic services and educational facilities. .

3.10 Conservation of Lai Chi Wo's Natural and Historic Environment

The first batch of conservation works of Lai Chi Wo's built and natural heritage was commenced in 2014 and completed in 2015. The reason for Lai Chi Wo was selected as a pioneer rural conservation project is due to its rich biodiversity and generally intact built features. The program was initiated by a retired civil servant and an academia in 2010 aiming to revitalise the abandoned farmlands for growing of wild habitants and crops. The project team further worked in collaboration with local experts, professionals and

volunteers from The University of Hong Kong and non-government organisations such as Produce Green Foundation and Conservancy Association. Funded by Hong Kong Bank Foundation, the project “Living Water & Community” was formally launched in 2013 to enhance biodiversity and habitat, regenerate rural village life, and promote community and public participation.[19]

Alongside the same program, four traditional villages were revitalised in 2015. The program was largely supported and engaged by Lai Chi Wo villagers, volunteers and heritage and natural conservation professionals. In the course of conservation process, traditional Chinese vernacular building techniques and locally available building materials (sand, mud, rice straw and oyster shells) were employed. The revitalised village houses are used for communal gathering and public education. With the success in revitalising the four numbers of village houses, further twenty five numbers of Hakka village houses will be revitalised starting in the end of 2017. Funded by Hong Kong Jockey Club Charity Trust, the second batch of the revitalisation work is led by Hong Kong Countryside Foundation with a strong support by local villagers. The project program is to convert the twenty five numbers of village houses into short stay accommodations and activity centre for enjoyment of the public (LAM 2017).

3.11 Community Involvement in the Course of Conservation Process

Local community taking part in the conservation process makes conservation of Lai Chi Wo Village possible. The local community involve in establishing the heritage values in the conservation process and form part of the voluntary work force in collecting information and carrying out physical conservation works.

3.12 Establishment of Puishingtong Community Trust

The villagers well understand the importance of establishing a steering committee to take charge of all community matters. Except for being a passive receiver of various helps from society, in 2015 villagers proactively established a community base steering committee - the Puishingtong to look after welfare of villagers and potential impact induced by cultural tourism, coordinate with various stakeholders during the course of conservation process, organise and manage communal activities such as Hing Chun Yeuk (a community Spring feast), Chingming Festival and Farmer’s Market etc. [20]

3.13 Hing Chun Yeuk (a community Spring feast)

Since 2014, the feast has been organising annually in Lai Chi Wo Village and jointly attending by six other neighbouring villages (including Sanyam Village, Meizi Lin Village, Xiaotan Village, Ngau Chi Lake Village, Clam Village and Locked Pan Village) in the eighth day of the Lunar New Year to celebrate and signify a new chapter of the new year. The importance of the feast lies to that it enables social network building and passing traditional Hakka food culture and social practice from the older generations to successive generations.

[19] See: <http://www.socsc.hku.hk/psl/laichiwo/> (accessed 30 Aug 2017)

[20] See: <https://www.facebook.com/LaiChiWoVillageliZhiWoCun/> (accessed 30 Aug 2017)

Fig.8: 600 people attended the Spring fest to celebrate Chinese New Year in Lai Chi Wo Village in 2017 (Source: http://www.hkcd.com).

3.14 Farmer's Market

A farmer's market has been established by local villagers in Lai Chi Wo Village. The market is run on weekends and public holiday basis to promote eco-farming and sustainable living style.[21] Local organic farming products include ginger, chilly, Chinese radish, carrot, pokchoy, choysim, spring onion, papaya, Japanese ginseng, candied fruit and so on are sold in the market. Although the amount of farming products is far from sufficient to meet local food demand, it carries an important message to the community and the public that Lai Chi Wo Village is able to grow its own food in eco-friendly manner as well as live in an eco-friendly living style.

[21] <https://www.facebook.com/LaiChiWoFarmersMarket/> (accessed 25 Aug 2017)

Fig.9: local farmers selling her locally planted farming products in the Lai Chi Wo Farmer's Market. (Source: https://www.facebook.com/LaiChiWoFarmersMarket/)

4 Conclusion

Interconnected healthy and liveable communities contribute to a more sustainable society. Community involvement in decision making process helps to bring about interconnected, healthy and happier communities in long term. Community participation increasingly plays an important role in heritage conservation worldwide. Although a true community led conservation process in heritage conservation has not yet emerged in Hong Kong, conservation projects have been increasing involving community-centred themes and programs benefiting local community and future social and community development. Conservation of the Blue House Cluster and Lai Chi Wo Village are very good examples of conservation projects showcasing local community participating during and after the conservation process making heritage places and the attached community more sustainable in long run.

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ZEMCH SUSTAINABLE DESIGN WORKSHOP: AN INTERACTIVE MODEL FOR SUSTAINABILITY EDUCATION

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Abstract: *The term 'sustainable development' has been widely used after the Brundtland Commission report published in 1987. Education for sustainable development was promoted by the UNESCO and four key learning processes were identified covering collaboration and dialogue, engagement with the whole system, innovative curriculum, as well as active and participatory learning. Due to the complex nature of sustainability, it is very important to prepare students to respond to the interconnected social, economic and environmental aspects of sustainability. In this paper, the ZEMCH Sustainable Design Workshop delivered at the University of Melbourne in 2016 was used as a case study to examine whether it could fulfil the four key learning processes of education for sustainable development promoted by the UNESCO. The course outline of this workshop was firstly introduced, followed by an analysis illustrating how the four key learning processes were implemented. The results indicated that ZEMCH teaching approach was in line with the key learning processes proposed by UNESCO. The pedagogy of the ZEMCH Design Workshop was evaluated, potential improvements were discussed and further guidance for replicating similar course at other institution was given.*

Keywords: *Education for Sustainable Development, ZEMCH Sustainable Design Workshop, Mass Customisation, Experiential Pedagogy*

1 Introduction

Since the Declaration of the United Nations Conference on the Human Environment at Stockhom in 1972, education has been formally recognised on an international level for playing an essential role for fostering environmental protection and conservation (UNEP, 1972). This led to the development of environmental education (ED) at various universities in the 1970s and 1980s (Wu & Shen, 2016: 633). In 1987, the Brundtland Commission in *Our Common Future* report clearly defined sustainability as 'satisfying the needs of present without compromising the ability of future generations to meet their own needs' (Brundtland Commission, 1987). Apart from the previous concern for environmental protection, the Brundtland Commission highlighted the importance of the other two pillars of sustainability: social equity and economic development. After the release of *Our Common Future* report, the concept of sustainable development (SD) and its principles have been adopted by some higher education institutions, which responded to various declarations, such as the Talloires Declaration in 1990 (Lozano, 2006; 2013), and the implementation of campus greening and other sustainable and ecological initiatives in universities (Wood & Cornforth, 2016: 344). However, those non-binding declarations might not lead to a significant change in university's sustainability practices (Bekessy et al., 2007). Therefore, Wals and Blewitt (2010) called for the third-wave sustainability in higher education, requiring for a re-orientation of the curriculum and pedagogy for sustainability as well as an integration of sustainability within and across tertiary curricula.

Although the term SD has been widely used after the Brundtland Commission report published in 1987, sustainability education may merely be perceived from the environmental sustainability aspect (Lozano, 2006: 787). Due to the complex nature of sustainability, it is still an issue to overcome the dominance of traditional single-discipline based teaching approach (Howelett & Ferreira, 2016: 310). How to transform the pedagogy for enabling students to respond to the interconnected social, economic and environmental sustainability through an interdisciplinary model is a challenge. Such challenge is also valid for teaching sustainability in the built environment, involving the social practice of the users, economic viability and the impact to the natural environment. Facing the challenges of global warming and the staggering increase in energy prices, developing a net zero energy and greenhouse gas (GHG) emission sustainable houses has become a pressing issue.

The United Nations Educational, Scientific and Cultural Organisation (UNESCO) promoted Education for sustainable development (ESD) through the United Nations Decade of Education for Sustainable Development (DESD) from 2005 to 2014 (UNESCO, 2005). A key document for DESD is *Education for Sustainable Development: An Expert Review of Processes and Learning*, which identifies the following four key learning processes for the education for sustainable development (UNESCO, 2011):

Processes of collaboration and dialogue: Sustainability issues cannot be adequately addressed or understood without a primary recognition of interdisciplinary collaboration among multi-stakeholders (Jones et al., 2010: 20). Complex problems have to be tackled beyond the scope of any discipline (Klein, 1990: 11). However, if multiple perspectives are merely presented without any integration of disciplinary knowledge, this will only lead to multidisciplinarity rather than real interdisciplinarity (Spelt et al., 2009: 366). Therefore, during group collaboration, students from diverse background are encouraged to share their respective cultural knowledge and personal experiences, which can contribute to a

better understanding of the integrative nature of sustainability through intercultural dialogue (Ivanitskaya et al., 2002).

Processes which engage 'the whole system': The term 'whole system' was used by UNESCO to highlight the importance of engagment with a complex web of relationship through systems thinking (Johnston, 2012: 220). Therefore, real-world learning experiences are very important in sustainability education (Brundiers et al., 2010). Bringing real-world issues into the classroom can draw students' awareness of the complexity of the whole system and equip themselves the capabilities to formulate corresponding strategies, which can enable them to respond to the ever faster changing professional environment (Barth, 2014: 118). The learning-by-doing approach encourages students to tackle the respective issues on their own through problem-solving rather than the absorption of content knowledge (Steinemann, 2003).

Processes which innovate curriculum as well as teaching and learning experiences: In addition to integrate real-world learning opportunities into the sustainability program, experiential pedagogy is promoted as a crucial component of an innovative curriculum (Sipos, 2008). Two-way communication is highly recommended to counteract the risk of tutors taking an authoritarian role in the learning process (Cotton, 2010: 46).

Processes of active and participatory learning: The learning process should be problem driven and project oriented, so students have freedom to identify which key issues and objectives they want to address, which trigger their motivations to be actively involved (Barth, 2014: 95). Applying knowledge to address sustainability problems requires students to ask critical questions (Brundiers et al., 2010: 312). Critical thinking skills is essential for understanding the complexity of sustainability and stimulates students for self-reflection and evaluation of assumed norms (Scott and Gough, 2003).

In this paper, the ZEMCH Sustainable Design Workshop delivered at the University of Melbourne in 2016 was used as a case study to examine whether it could fulfil the above-mentioned four key learning processes of education for sustainable development promoted by the UNESCO.

2 ZEMCH Sustainable Design Workshop

ZEMCH stands for 'zero energy mass custom home' which emphasises the idea of mass customisation by combining the notions of mass production and customisation together. The aim of ZEMCH is to raise the level of social sustainability for accommodating users' individual needs, and at the same time, reiterates the importance of affordability in view of economic sustainability, and zero energy or net carbon neutral towards environmental sustainability (Noguchi, 2016: v-vi).

The ZEMCH Workshop was initially held in Brazil in 2014 as a pilot project, followed by two subsequent workshops in 2015 and 2016 respectively. All of them focused on social housing development in Brazil (Yokota et al., 2016). After gaining the experience of delivering the workshops in Brazil in three consecutive years (2014-2016), the ZEMCH Sustainable Design Workshop was firstly taught at the University of Melbourne in 2016 and the theme of the workshop was related to private housing development in Melbourne. Melbourne has been ranked as the world's most liveable city by the Economist Intelligence Unit since 2011 and has been increasingly attracting people from all over the world to come for living, working and studying (The Economist Intelligence

Unit, 2016). Under the influx of immigrants and the impact of population growth, there is a significant housing demand in Melbourne. According to the statistics, Greater Melbourne's population grew by 182,538 people over the two years (2014-2015) requiring a total of 70,207 dwellings or 35,103 dwellings per annum (Pressley, 2016). However, there are some housing issues to be overcome, including affordability, diversity of choices and environmental performance (City of Melbourne, 2013:7). Therefore, the provision of customised quality housing at reasonable prices to suit the diverse needs of end users is critical.

The ZEMCH Sustainable Design Workshop was a five-day intensive workshop coursework offered for postgraduate students from architectural, engineering and construction disciplines at The University of Melbourne. This intensive workshop took place during the non-teaching period to avoid potential time clash and to serve as a complement to other postgraduate subjects.

A total of sixteen postgraduate students attended the workshop and they were divided into four groups: Groups A, B, C and D. The workshop activities were allocated into three categories: pre-workshop period, workshop and post workshop period.

During the pre-workshop period, students were recommended to study the textbook, *ZEMCH: Toward the Delivery of Zero Energy Mass Custom Homes* (2016) before attending the intensive workshop. The required pre-reading helped students to obtain basic knowledge regarding the ZEMCH principles.

The scope of the five-day intensive workshop was divided into five main phases: 1) theoretical basis, 2) industry engagement and site visit, 3) function analysis and evaluation criteria scoring matrix, 4) housing prototype development, as well as 5) final presentation. On the first day of the workshop, the subject coordinators and tutors delivered introductory lectures for students and provided software trainings on energy and environmental design simulation. For enhancing industry engagement, housing manufacturers were invited to deliver lectures about current industry practice and site visit was arranged for students. After site visit, the function analysis and evaluation criteria scoring matrix were explained. After that, students in each group started to use the knowledge gained and digital skills learnt to develop housing prototypes. On Day Five, students presented their final work in groups which marked the end of the intensive workshop.

At the end of the semester, students were required to participate in a two-hour written examination as a post-workshop requirement. Figure 1 illustrates the intensive workshop framework.

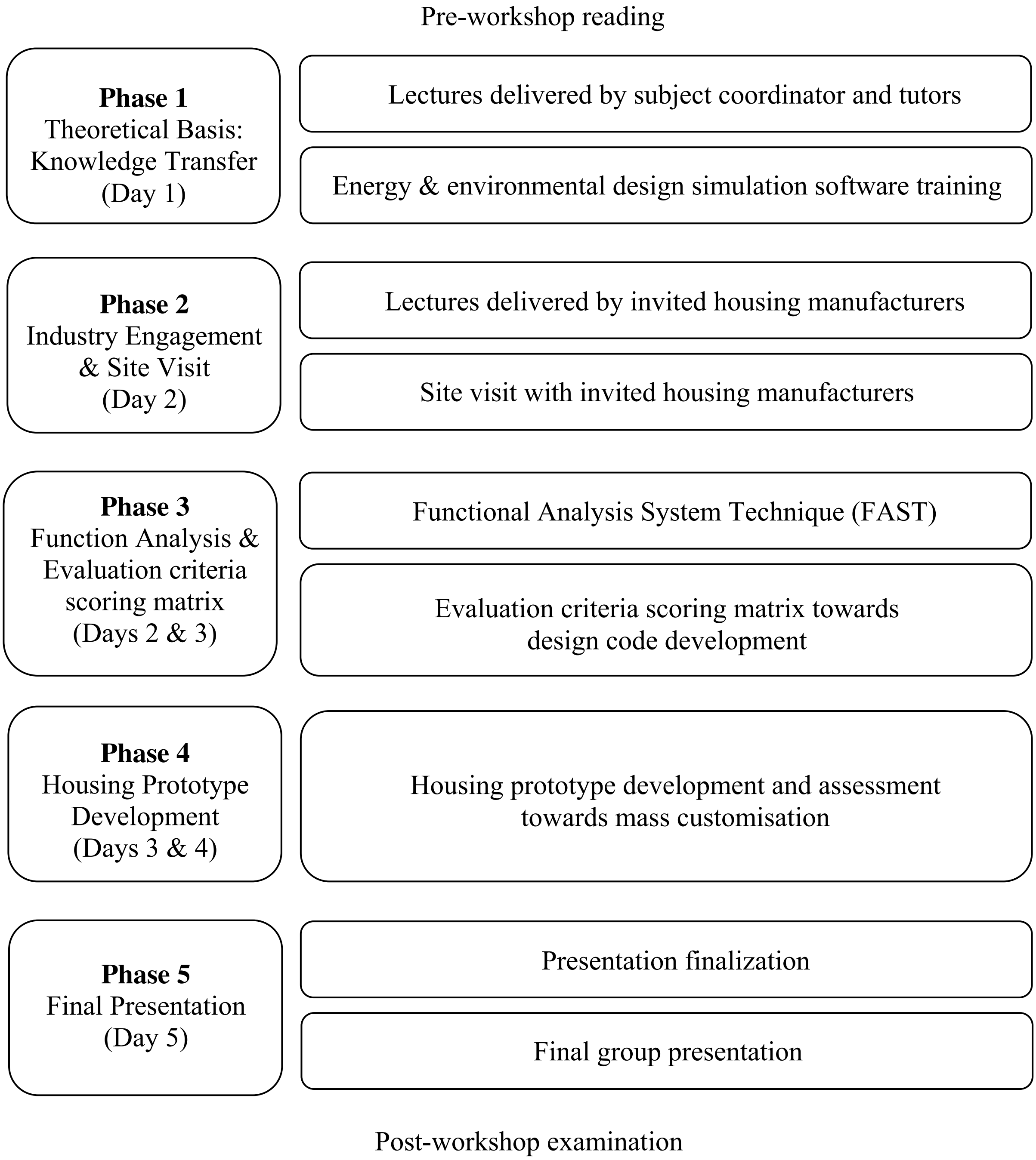


Figure 1: Phases and activities of the ZEMCH Sustainable Design Workshop

In Phase One, technical design knowledge required for the delivery of zero energy mass custom homes was transferred. The ZEMCH concept was introduced and design stimulation training for software, such as HOT 2000, RETScreen, Ecotect and Groundhog was provided to equip students the relevant digital skills for analysing environmental and energy implications.

Two industry partners, MARA Studio and Misawa Homes Australia, were invited to share their practical experiences in mass customised house design and production with students in Phase Two. They further engaged with students during the site visit and subsequent dialogue sessions. The south lawn, located within the campus of the University of Melbourne, was selected as the site for exploration and design development during the workshop. Students were encouraged to carefully observe existing site conditions for preparing subsequent site analysis. After the site visit, students were divided into four groups (Groups A to D) with four students in each group. In each group, there was a mix of domestic and international students.

At the beginning of Phase Three, students brainstormed with their groupmates the main objectives they would like to handle and how the objectives might be accomplished. Using the Function Analysis Systems Technique (FAST), different functions were properly described, identified and categorised (Wixson, 1999). Firstly, each function was written on a small post-it pad for sticking it onto a large piece of paper for developing the FAST Diagram. The FAST Diagram is basically a graphical representation showing the logical relationships between various functions based on the questions of “why” and “how”, illustrating the reasons behind and the ways of implementation (Figure 3). The main objective was written on the far left of the diagram followed by various dependant functions. Secondly, through the evaluation of the values of different functions, the positions of post-it pads would be re-arranged in terms of their importance. Functions with higher order were located near the left, whereas functions with lower order were located to the right. Finally, during the re-arrangement process, two main questions to be considered were: “why is such function necessary?” and “how is the function performed?” (Figures 2 & 3). Therefore, some functions identified on the FAST Diagram were then selected for preparing the Evaluation Criteria Scoring Matrix. Each evaluation criterion was compared with each other in pairs and three levels of importance were defined as weighting criteria: 1) high, 2) average, 3) low. The total scores in terms of points and equivalent weight in terms of percentage were then calculated. The weighting proportion of different criteria was useful for the subsequent development of the design code, which defined the hierarchy of the functions according to its order of importance (Figure 4). The FAST Diagram and the Evaluation Criteria Scoring Matrix were crucial elements of the workshop highlighting the underlying principle of mass customisation.

In Phase Four, students referred to their priorities according to the FAST diagram and the Evaluation Criteria Scoring Matrix results to develop housing prototypes towards their defined objectives. Previous site visit and analysis were highly relevant for understanding the site configuration, generating the master plans and exploring design solutions. Students also applied software stimulations for environmental and energy analysis.

At the final phase of the workshop, students completed their designs and prepared for final presentations. Each group was required to prepare and deliver a poster (Figure 5) and an oral presentation to summarise their analysis and design outcomes. Industry partners and other external critics were invited to attend the final presentation session for providing feedback and assessing students’ performance.

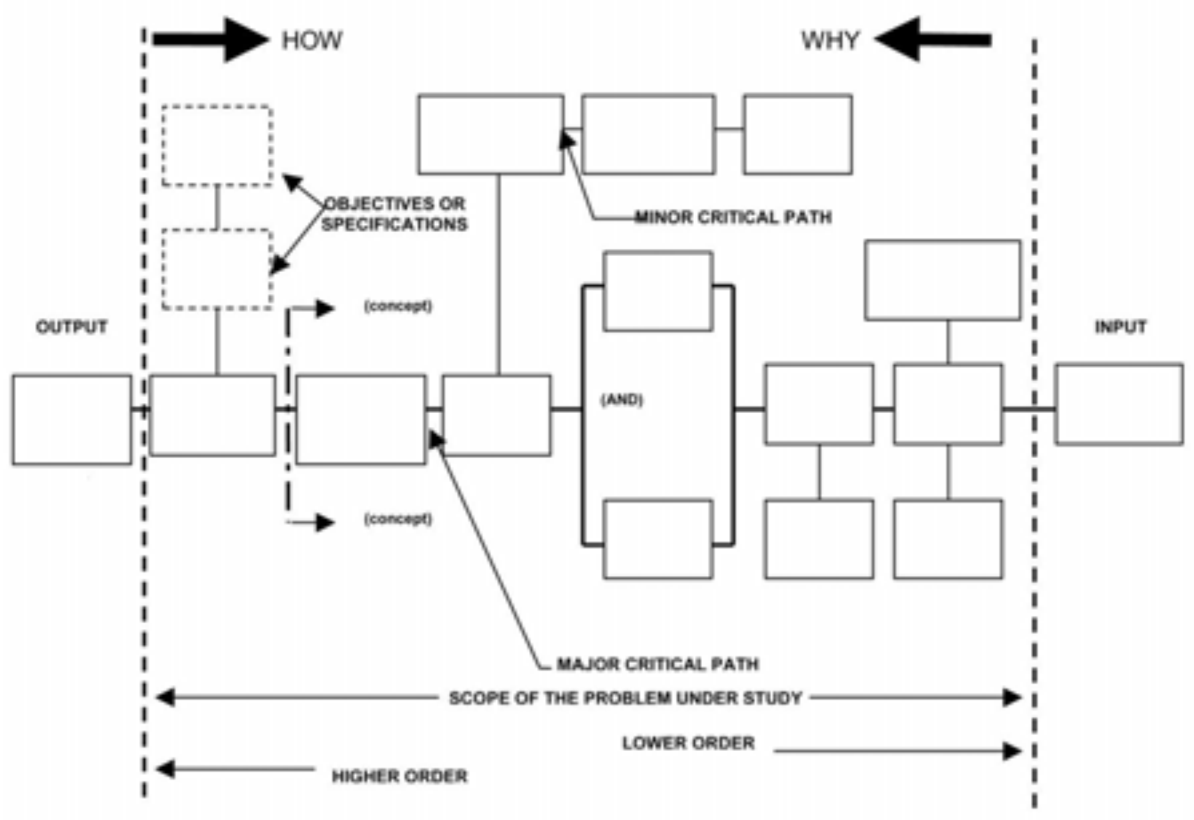


Figure 2: The schematic FAST Diagram (Wixson, 1999)

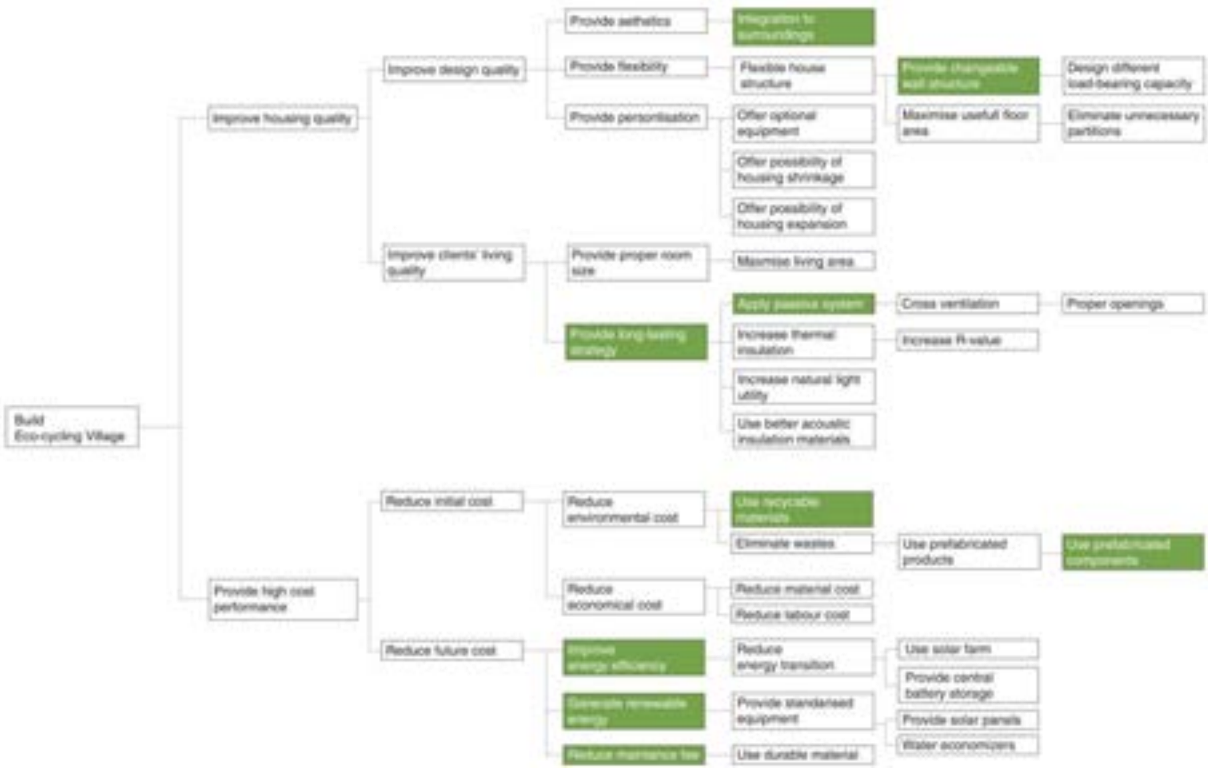
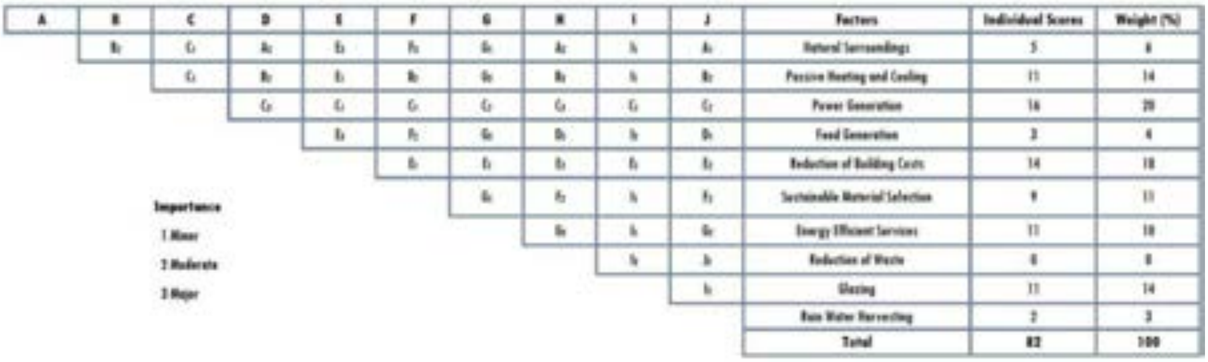


Figure 3: FAST Diagram prepared by Group A



A	B	C	D	E	F	G	H	I	J	Factors	Individual Scores	Weight (%)
	B	C	A	E	F	G	A	I	A	Natural Surroundings	5	6
		C	B	E	B	G	B	I	B	Passive Heating and Cooling	11	14
			C	C	C	C	C	C	C	Power Generation	16	20
				E	F	G	D	I	D	Food Generation	3	4
					E	E	E	F	E	Reduction of Building Costs	14	18
						G	F	I	F	Sustainable Material Selection	9	11
							G	I	G	Energy Efficient Services	11	10
								I	J	Reduction of Waste	6	8
									I	Glazing	11	14
										Rain Water Harvesting	2	3
										Total	82	100

Importance
1 Minor
2 Moderate
3 Major

Figure 4: Evaluation Criteria Scoring Matrix prepared by Group B

Figure 5: Presentation posters prepared by Group C (left) and Group D (right)

3 Results and Discussions: The four key learning processes for the education for sustainable development

The four key learning processes for the education for sustainable development listed in UNESCO's document, *Education for Sustainable Development: An Expert Review of Processes and Learning* were covered in the ZEMCH Sustainable Design Workshop as explained below:

3.1 Collaboration and Dialogue

Collaborative learning approach was emphasised in the ZEMCH Sustainable Design Workshop. Through a series of group discussions, students could freely share their opinions and listen to others' views. Different ideas and thoughts were not simply tolerated but in fact appreciated. This process was valuable for students to develop their interpersonal skills and learn how to implement a collaborative process and work in teams. As the Design Workshop lasted only for five days, how to bring different opinions together and work effectively within the limited time frame became challenges for students to ensure timely delivery of design outcomes. On the basis of collaborative experiences, a range of perspectives among students were encouraged to be expressed towards a consensus of having a shared group understanding towards sustainable development. Interdisciplinary collaboration was further enriched by cross-cultural dialogues due to the significant proportion of international students coming from various countries at the University of Melbourne.

3.2 Engaging the Whole System

Students were required to develop strategies to address the issues of social, economic and environmental sustainability holistically. In the ZEMCH Sustainable Design Workshop, the FAST Diagram could facilitate students to identify their main objectives and to propose possible solutions to tackle identified issues in a systematic manner. The inter-relationship between causes and actions could be visually represented by the FAST Diagram. The Evaluation Criteria Scoring Matrix was also helpful for students to handle complex issues and compare the level of importance of various factors.

The challenges of the ZEMCH Sustainable Design Workshop were to accommodate users' individual housing needs at reasonable prices with zero energy consumption. For students to have a better understanding of the real-world situation, industry partners outside academia were involved in the learning process for sharing their hands-on experiences and current practices. Interaction with industry partners could enable students to have a more comprehensive understanding of the issues at stake from various perspectives and learn how to engage with different stakeholders. Through the exposure to realistic contexts, students could learn how to link theory to action and how to apply their knowledge to develop practical but innovative solutions to cope with society's challenging and pressing problems.

3.3 Innovative Curriculum

The innovative curriculum learning process was achieved through site visits which provided students with first-hand experience to perceive the characteristics of site conditions in person. Subject coordinator, tutors and industry partners were also involved in the site visit for having more interaction with students. Besides collecting physical environmental parameters, students could have a variety of spatial experiences, including the atmosphere of the place, scale and proportion, materiality and colour, as well as subjective visual and tactile perception. During the site visit, students recorded their personal observations by drawing sketches, taking photos and even videos. Those findings were important to inform their subsequent group design strategies.

Through the workshop, students were encouraged to think big and project sustainability visions. Alternative options could be explored against mainstream conventions towards a sustainable and desirable future. For achieving the desired outcomes, students were required to unfold an open-ended exploration for alternative possibilities and to formulate practical strategies to implement sustainability ideas to deal with the changing needs of our society.

A series of peer review activities were organised throughout the whole learning process. Students were required to present their work in teams and encourage to raise queries to other groups' presentations. Tutors actively participated in providing feedback to students after presentations for setting up the discussion atmosphere in the classroom, which could enable students to experience the dynamics of communication and gain confidence in expressing their ideas.

3.4 Active and Participatory Learning

Active and participatory learning was reinforced in the ZEMCH Sustainable Design Workshop through problem-solving approach. Under an inquiry-based model, students were expected to intensively participate in the workshop and take the initiative to find relevant information. Apart from collecting data, students were required to negotiate and reach consensus among their group members, especially with different personalities and conflicting positions. During the process, students could examine their underpinning beliefs and clarify their own values. After defining their objectives, students were required to share the workload among themselves. Since the number of students in each group was caped at the maximum of four, so each student had the responsibility to contribute his or her effort as a key player and tackle identified issues collectively. Such participatory learning approach could cultivate students self-directed learning interests and stimulate students' motivation towards lifelong study interest on sustainability development.

4 Conclusion

This paper demonstrates that the ZEMCH Sustainable Design Workshop delivered at the University of Melbourne is in line with the four key learning processes established by the United Nations Decade of Education for Sustainable Development and shows how the four key learning processes were implemented in the workshop.

Students' feedback about this workshop was collected through Subject Experience Survey (SES) at the end of the semester. Over 80% of students agreed or strongly agreed that the workshop was intellectually stimulating and the assessment tasks were useful in guiding their studies. Having said that, some students raised the areas of improvement, such as the time dedicated to software training could be longer and more practical exercises could be provided to enable them to master the skills before applying the skills to the group work.

After delivering the ZEMCH Sustainable Design Workshops in Brazil and Melbourne, such pedagogy can be applicable elsewhere and the program can be replicable at other institutions within the ZEMCH Network worldwide and beyond.

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PROCUREMENT, SUSTAINABILITY & ADAPTIVE REUSE PROJECTS IN SYDNEY

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ABSTRACT: *With large scale projects like Baragaroo about to flood the market with a large supply of office space, the city of Sydney is poised to undergo a change whereby existing office stock will be made available for adaptive reuse projects. Some 102,000m2 of office space is earmarked for residential conversion in Sydney due to the growing demand for centrally located residential properties and to help house a population that is expected to increase by 4% by 2031. Adaptive reuse projects have an inherent bent towards sustainability in that they make use of existing structures, which reduces economic, environmental, and societal impacts associated with demolishing existing structures to make way for new ones. This paper investigates how project owners can best select designers and builders for their adaptive reuse projects. Using case studies from completed adaptive reuse projects and literature review, this paper makes recommendations as to the best practices for the procurement of design and construction services for adaptive reuse projects in the Sydney market.*

Keywords: *Adaptive Reuse, Sustainable Procurement, Sydney, Office Space*

Introduction

The City of Sydney, Australia is currently experiencing a significant development of commercial office space projects within the city's central business district (CBD). Approximately 229,000m^2 of new build and refurbished office space is due for completion in 2015 and a further 611,000m^2 is currently in the development pipeline (Research and Forecast 2015, City of Sydney 2010). The rapid addition of office has stock has created a situation whereby vacancy is expected to increase in lower grade office stock, which is considered to be suffering from obsolescence, and as a consequence, will be made available for adaptive reuse projects. Some 102,000m^2 of this obsolete office space is earmarked for residential conversion in Sydney due to the growing demand for centrally located residential properties and, to help house a population that is expected to increase by 4% by 2031 (Remøy and Wilkinson 2015)

With such a large area of obsolete office space being made available for adaptive reuse, there are excellent opportunities to deliver sustainable housing that makes use of existing structures. Adaptive reuse projects have an inherent bent towards sustainability in that they make use of existing structures, which reduces economic, environmental, and societal impacts associated with demolishing existing structures to make way for new ones or simply abandoning structures in place. Adaptive reuse reduces the amount of waste that is deposited in landfill sites. Additionally, the amount of greenhouse gasses that are emitted during the transport of old materials to landfill sites and the harvesting, manufacturing, and delivery of new materials is reduced. Furthermore the overall embodied carbon in adaptive reuse projects is lower than new build projects. In order to maximise the potential for adaptive reuse projects to be sustainable, appropriate procurement methodologies need to put in place. The procurement of the 'right' designers and contractors allows for sustainability measures to be capitalized upon. These measures include reusing materials, minimising emissions and water consumption, maximising energy efficiencies, and creating positive social outcomes throughout the buildings lifecycle. This paper investigates the issues related sustainable procurement as it pertains to project participants.

Adaptive Reuse

Adaptive reuse in the form of conversion of existing building stock is a practice has that been utilized in Europe for centuries. An example of adaptive reuse is the canal-houses in Amsterdam. Since their initial construction in the 17th century, the use of the buildings has undergone numerous changes. Over the past 400+ years, the Amsterdam canal houses have been used for housing, offices, retail, and warehousing at various different stages, with each change in use imparting some changes to the buildings (Leupen 2006, Remøy 2010).

Recent examples of places that have experienced adaptive reuse include Toronto and London, where reuse in the form residential conversions was used as means towards inner city redevelopment and revitalisation (Heath 2001). In New York City the government established a subsidy program as part of the Lower Manhattan Revitalization Plan in order to encourage the conversion of obsolete office spaces into residential apartments. The plan resulted in the residential conversion of more than 60 buildings (Beauregard 2005). A collapse of the Tokyo market for office space in 2002-2003, caused by oversupply, led to older offices becoming obsolete. The obsolete offices were then converted to residential housing (Ogawa, et al. 2007).

Adaptive reuse in Sydney, Australia

While adaptive reuse is commonplace in Europe, it is a relatively novel concept in Australia due to several barriers that face these projects. Wilkinson and Remøy (2015) categorized the barriers for conversion adaptation as either political, economic, environmental, social, technological/physical or legal. Further stating that one of the obstacles to residential conversion is the specialized nature of the work and competence of the actors. Identifying experts and outsourcing the decision making to those experts will help project owners to identify potential risks up front, as well as providing value added alternatives. Within residential conversion projects some of the technical areas and barriers that require expert attention include:

- Structural alterations may be required by regulations, causing exorbitant costs or potentially rendering a project infeasible (Bullen and Love 2010).
- As built construction drawings are not always available or accurate, which causes thorough inspections and opening up works to be necessary (Remøy and Van der Voordt 2007).
- Residential spaces require more vertical shafts for plumbing, electrical, and heating, ventilation and air conditioning necessary (Remøy and Van der Voordt 2007).
- Local infrastructure might not be in place to support the social needs of a residential conversion (i.e. healthcare, schools, shops, etc.) (Heath 2001).
- Removal and remediation of dangerous materials such as asbestos may cause a project to incur high costs (Remøy and Van der Voordt 2007).
- In the Sydney market the key drivers for residential conversions are economic, and the social and environmental benefits are only realized coincidentally (Wilkinson and Remøy 2015).
- The Sydney housing market does not put great value on sustainability in the home buying decision, and thus developers have little need to market sustainability attributes to attract buyers (Wilkinson and Remøy 2015).

Even with these barriers in place, adaptive reuse is becoming an increasing popular idea within the Sydney real estate market and is fueled by increasing demand for housing close to or in the city centre (Wilkinson and Remøy 2015).

Research Aims and Objectives

Past studies on residential conversions via the adaptive reuse of office space have shown the potential for enhancing sustainability in urban areas in various different parts of the globe (Heath 2001, Remøy and Van der Voordt 2007, Bullen and Love 2010, Koppels, et al. 2011, Wilkinson and Remøy 2015). However, none have focused on the procurement of the design and construction teams tasked with actually designing and constructing these residential conversion projects. In addition to past case studies and research undertaken on adaptive reuse, there is a field of research focused on procuring the best value design and construction teams for construction projects. Using literature from both the field of adaptive reuse and the field of designer and contractor procurement, this study makes suggestions as to a theoretical framework to employ best practices for the procurement of design and construction services for adaptive reuse projects in the Sydney market.

Procurement of professional services for design and construction of residential conversions

Literature in the field of the procurement and management of architectural, engineering, and construction services has identified the need for the use of performance information when

selecting professional service providers. The International Council for Research and Innovation in Building and Construction (CIB) commissioned a report that identifies the worldwide use and impact of performance information in the construction industry that advocates the need for greater use of performance information when procuring professional services (Egbu, et al. 2008). Performance information is the set of metrics used to quantify both the efficiency and effectiveness of actions (Neely, et al. 1995). When used correctly, performance information is used not only for selection of service providers, but also for benchmarking. Benchmarking can be used as reference points to measure change and improve future outcomes (Martin 2004). Research conducted into the use of performance information in procurement has yielded many successful methods or systems. These systems have been used to increase performance in terms of quality, budget, schedule, performance, and customer satisfaction (Carey 2009) and include: The Fort Worth ESD system, the Hong Kong Housing Authority's PASS system, and the Best Value Business Model (BVM) that was formerly known as the Performance Information Procurement System (Sullivan, et al. 2008)

While the PASS system and the Fort Worth ESD systems have found success in improving the performance of their contractors, both are highly specialised and configured to meet very specific program needs. BVM as presented by Kashiwagi (2012) is a formal structure that allows for considerations of both price and performance factors when selecting contractors and is flexible enough to be used in virtually any procurement scenario. Even though BVM involves a formal structure it is easily adaptable to meet any user's needs, this is evidenced by the breadth of different organizations that have achieved successful outcomes (i.e. on time and on budget) by employing BVM in the procurement and management of more than 1750 projects totaling $US6.3 billion in professional services. Organizations that have successfully employed BVM to procure construction and design services include, but are not limited to, the United States General Services Administration, the State of Oklahoma, the State of Idaho, the City of Peoria, the University of Minnesota, the University of Alberta, and the Rijkswaterstaat (highway agency in the Netherlands) (Performance Based Studies Research Group 2015)

In developing a successful methodology for the procurement of designers and contractors for residential conversion projects in Sydney, the research finds that the success and applicability of BVM across different countries and markets means that it provides a solid platform from which to start. The BVM approach follows three phases (Kashiwagi 2012, Smithwick, et al. 2013)

- Phase 1- Identification: Identification of the best value vendor using a weighted model based on the vendors proposed price, risk plan, value added plan, interviews and Past Performance Information surveys provided by the vendor's previous clients.
- Phase 2- Preplanning: The documentation of project expectations occurs in this phase, whereby the expectations of both parties (owner and vendor) are documented. Clarification of expectations is a structured process to help the owner fully understand the potential best value firm's offer. The potential best value firm or firms (in cases where both design and construction services are procured) must clearly explain their offer, and how they know their plan will be successful, how they will minimize risk and manage risks that come to fruition, and establish how success will be measured.
- Phase 3 – Project Management: After preplanning is complete to the owner's satisfaction, the contract is awarded and the project begins. In this phase the vendors complete and submit a weekly risk report. Should any previously identified risk come to fruition, it is managed in accordance with the risk plan created in Phase 2. Any unforeseen risks that are encountered are entered into the weekly report, along with the vendor's solution and submitted to the owner for their rating of the risk. At the end

of the project, the owner rates the vendor using the same criteria from the Past Performance Information surveys and this rating then impacts the vendor's future ability to secure work with said owner.

The proposed system will utilize a similar three phase framework to BVM. Due to the fact that sustainability is a point of emphasis in residential conversions in the form adaptive reuse projects, the research proposes a procurement system that differs from BVM in that it would monitor and rate designers and contractors beyond project completion, by collecting performance information throughout the lifecycle of the building and. This is necessary in order to see if sustainability goals and building performance are met throughout the building's lifecycle, and to use in the procurement of design and construction services on subsequent projects.

Sustainable Adaptive Reuse Procurement

The proposed Sustainable Adaptive Reuse Procurement (SARP) and project management system takes pieces of other successful procurement and project management systems and modifies them to best suit the Sydney market. On such best practice that should be incorporated is Early Contractor Involvement (ECI). Having the project contractor onboard during the design stage has long been shown to positively affect project outcomes via (Song, et al. 2009)

- specialized training and field expertise allows contractors to provide feasibility analysis;
- ability to provide an in-depth knowledge of construction materials, methods, and local practice;
- contractors are in the best position to provide project and contractor specific information on the availability and limitations of resources in terms of cost, performance, access, and site conditions to support design; and
- contractors' inputs to design have a direct impact on their own construction performance.

ECI is particularly important for sustainability oriented adaptive reuse projects due to the highly specialized nature of the projects. When paired early on in the design phase, contractors can provide the designers with accurate feasibility and cost information in relation to the reuse of materials and structural elements on the project. Additionally, contractors are able to provide feedback as to the performance of the systems they will be installing. Thus, EVI will be used in SARP and designers and contractors will be tasked with teaming together on their proposals.

SARP will utilize a small set of performance specifications rather than filling a request for proposals (RFP) with owner generated specifications that designers and contractors are required to follow. The RFP will make use of performance specifications that will be used to guide designers and contractors in their proposals, while allowing them to leverage their expertise in creating and implementing solutions to the owner's needs. Kashiwagi's BVM method has shown that a reduction in an owners prescription specifications leads to higher performance, and that when project owners defer to the experts that they are hiring to tell them what is achievable that customer satisfaction increases (Kashiwagi 2003, Kashiwagi 2012) Hence performance specification is suitable to SARP.

SARP Framework

The SARP will use a four stage framework as outlined in Figure 2, and is based on Kashiwagi's BVM. The phases are designed to address each of the barriers to residential conversion projects in the Sydney marketplace.

Stage One will consist of an owner identifying their needs and desires for their adaptive reuse project. This will be used to create the RFP by where the desired performance and characteristics of the residential conversions will be conveyed to proposing teams of partnered designers and contractors. Performance specifications will need to include: material reuse, landfill diversions (tonnage), embodied energy of new materials, water efficiency of constructed facility, energy efficiency of constructed facility, operational costs for tenants of constructed facility, as well social wellbeing indicators such as open space and community connectivity. Proposers will be required to submit proposals consisting of the following (consistent with BVM):

- Simple past performance surveys from past clients, used to show that the experts have successfully performed in the past
- Risk analysis plans detailing the major risks that could prevent them from achieving the sustainability, cost, and schedule performance specifications, and how the team will minimize those risks. The risks will be only the risks that are beyond the proposing team's control, for any true expert should already have minimized the risks they are in control of.
- Value Added Sustainability measures that are beyond the scope owner's original requirements that can be included for an extra price should the owner choose to do so.
- Price to carry out the proposal to meet the owner's needs.

After the proposals are submitted, there will be a short listing of the top proposals followed by interviews where the major participants (i.e. project manager, design manager, construction superintendent) of shortlisted teams are allowed to present their solutions to the owners and/or owner's representatives. From there, one team will be advanced to Stage Two, where in depth project preplanning can begin

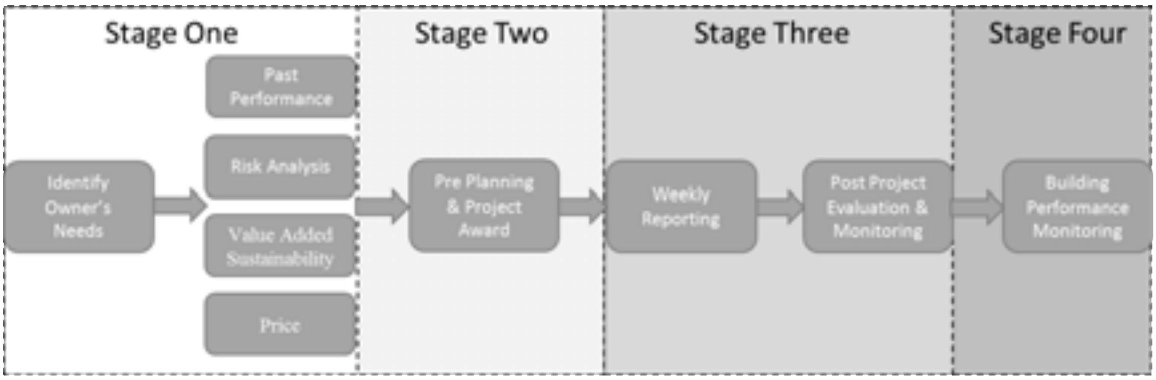

Fig. 1 SARP Framework based on Kashiwagi's BVM (Kashiwagi 2012)

Stage Two will consist of the preplanning of the project where the team that is selected will work to solidify the project plan and satisfy the owner's concerns prior to contract award. The metrics by which the design and construction team will be measured will be agreed upon during this stage. This stage will follow the outline of BVM Phase Two described above in Section 3 of this paper [for in depth overview see Kashiwagi 2003 and Kashiwagi 2012], and the stage will end with a signed contract.

The third phase will include weekly reporting and measuring against the expectations established during preplanning through till project completion, as in (Smithwick, et al. 2013) At the end of BVM project projects are assessed by owners in terms of budget performance, schedule performance, and customer satisfaction.

Stage Four will be where the primary difference between SARP and BVM occur. In SARP, the team of designers and contractors will be measured against expectations beyond project completion. For SARP projects, the building will be measured at the end of a project and throughout its lifecycle to see if it achieved its intended goals. As proffered by Love et al. (2015) it is important that projects take a life-cycle approach to their evaluation. A lifecycle approach is needed to 'future proof' building performance and ensure the value and sustainability characteristics of an asset, while also providing key decision makers with the ability to make informed decisions across a project's life-cycle (Love, et al. 2015).

Taking a lifecycle approach to the measurement of the success an adaptive reuse project and annually updating the evaluation of the project team allows for owners to make better decisions when procuring design and construction teams on future projects. Rather than only utilizing information specific to the project phase like budget and schedule performance, actual lifecycle performance (energy, water, operational costs, social wellbeing indicators, etc.) can be fed back into the selected teams past performance information and used in Stage One when selecting a potential best value vendor for future projects.

Conclusions

The SARP framework was presented for the procurement of design and construction services for sustainable residential conversion projects in the Sydney market. There are many sustainability related benefits to adaptive reuse projects that make use of obsolete office space for residential conversions including:

- Materials can be reused and diverted from landfill
- Embodied carbon is lower than new build
- Emissions can be reduced in the form of reduced transportation and harvesting of materials
- Costs can be kept down by reusing existing structural elements and a faster build time
- Social benefits in the form of neighborhood revitalizations or transformation.

In order to ensure that these sustainability related benefits are achieved, owners need to select the correct designers and contractors and defer to their expertise in completing these projects at the best value. The barriers to realising these benefits are many and can be categorized as political, economic, environmental, social, technological/physical or legal [9]. While political barriers cannot entirely be addressed by the procurement of the best value vendor, a best value vendor can ensure that economic, environmental, social, technological/physical and legal barriers are all minimized.

In the SARP framework presented, the economic, environmental, social, technological/physical barriers to sustainable adaptive reuse in the form of residential conversions are addressed systematically during the first three stages of the SARP process and the fourth stage ensures that accurate performance information as to building performance is used for future procurements. SARP capitalises on designer and contractor expertise by allowing them to team together and develop sustainable solutions to the challenges that face adaptive reuse projects and then monitor those solutions over the lifecycle of the building in order to prove their performance and use that performance in the evaluation of future proposals. The next phase of this research is to test the framework with Sydney developers specialising in adaptive reuse projects.

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THE RELATIONSHIP BETWEEN RETROFITTED DOUBLE GLAZED WINDOWS AND OCCUPANT WELLBEING

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Abstract: *Around a third of heat loss in residential buildings in the northern hemisphere, and cooler climates occurs through windows. Conversely in hotter climates excessive heat gain through windows adds to energy use. As window costs have reduced, buildings have been designed with ever greater areas of glass; and ever greater amounts of energy consumption and greenhouse gas emissions. In Australia, this situation is compounded further as the average size of residential buildings has also grown. One answer is to retrofit thermally efficient double glazed windows; another might be to reduce window size. Either option is a very tangible change to an existing building to reduce environmental impact. However, windows provide views, which can have a positive impact on human health and wellbeing through exposure to nature and sunlight. The question is how do we balance these conflicts; and further could the retrofit of double glazed units have other positive impacts on occupant behaviour? This conceptual paper presents a theoretical model, which attempts to explain how retrofit double-glazed windows can impact occupant wellbeing*.

Keywords: *Green Windows, Double-glazed Windows, Occupant Behaviour, Occupant Wellbeing, Energy Efficiency*

1 Introduction

In centuries past, windows were an expensive product and therefore, large glazed window areas were seen as a visible indicator of homeowner wealth and status (Bahaj, James et al. 2008). The industrial revolution made the mass production of glass possible. The economies of scale resulted in lowering of the price of glass, thus making it more affordable to be used in construction projects. However, this change was accompanied by issues related to the heating and cooling of these monumental glass structures; namely heat loss and heat gain. A single pane of glass can lose almost ten times as much heat as the same area of insulated wall (Sustainability Victoria 2017).

In the past 60 years, this is compounded as Australian homes have more than doubled in size; from an average of around 100 square metres in 1950 to approximately 240 square metres in 2016 (Stephan and Crawford 2016). Furthermore, the amount of electrical equipment used in buildings has increased and perceptions of indoor comfort have also changed. In view of the ever-increasing energy bills and size of houses, it is not surprising that different window systems (Hee, Alghoul et al. 2015) are being considered to provide cost-savings. However, the type of windows a building has is not just related to occupants' energy consumption. Scientific literature now supports the conventional wisdom on the role windows can play in boosting occupant-health (Boubekri, Cheung et al. 2014) by providing exposure to sunlight and nature.

This conceptual paper presents a theoretical model, which attempts to explain how retrofitted double-glazed windows can impact occupant wellbeing. Such a window system is a simpler option than replacing the entire glass, as it uses windows which are already fitted in the building. While double-glazed windows have long been a popular choice across Europe and the US, the same is not the case in Australia. According to an estimate, double-glazed windows account for over 55 per cent of all new and replacement windows in the US. In Australia, it is estimated that the double-glazed window market is less than five per cent, even though we have a climate which is similar to some parts of the US (MacMillan 2015). The market acceptance of retrofit double-glazing in Europe and the US is not embedded in Australia, and the questions arise such as; are we missing an opportunity to reduce energy consumption and make our houses more comfortable?

This paper is organised as follows: the next section provides an explanation of the proposed theoretical model. It also justifies the three hypothesised links between our focal concepts: occupant comfort, occupants' behavioural change and occupant-wellbeing. Then, we have a discussion on the model and finally conclude by providing a summary of the main model.

2 Theoretical Model

Figure 1 below outlines the theoretical model which is proposed as part of our research study.

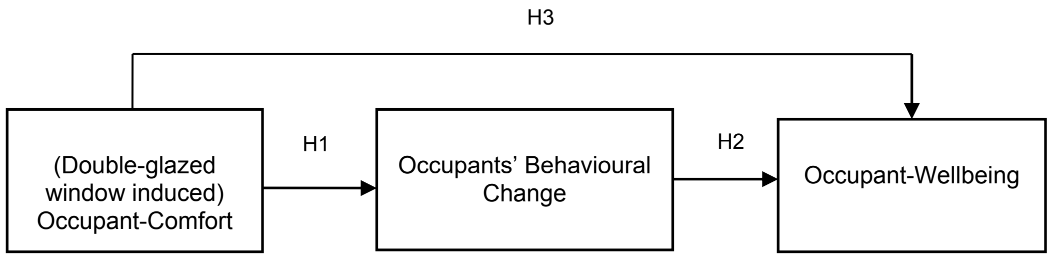

Figure 1: Theoretical Model demonstrating the link between comfort, behaviour and wellbeing

In line with the comfort theory (Kolcaba 2003), it is proposed that as a result of occupants' perceptions of comfort (which occur due to the installation of double-glazed windows), a change in occupants' behaviour will take place. The word, 'comfort' is derived from the Latin word 'confortare' which means to strengthen (Morse, Bottorff et al. 1995). According to the comfort theory, enhanced comfort strengthens recipients (i.e. building occupants and residents) to engage in activities which are synonymous to positive behaviours. Researchers have explained this phenomenon by referring to Maslow's Theory of Hierarchy of Needs (Maslow 1967). As proposed by Maslow, an individual's needs are arranged in a hierarchy from lower-level physiological needs to higher-level needs for esteem and self-actualisation. The physiological needs are of highest priority because until these are reasonably satisfied, the individual will not be motivated enough to undertake behaviour to meet higher level needs. Comfort has been categorised as a basic-level need, which needs to be met before other needs can be satisfied.

Hence, it is argued that ensuring comfort to building occupants comes with a practical rationale. Once occupants feel comfortable they will be motivated to undertake positive actions. Our explanation below argues how these actions ultimately result in an increased wellbeing for the building-occupants. Due to the similarity in concepts of comfort and wellbeing, it is also proposed that even if there is no behavioural change amongst occupants, perceptions of comfort would be directly associated with wellbeing (Ali, Chua et al. 2015). The hypothesized links in the model are explained below.

H1 Occupant-comfort linked to behavioural change

Individuals desire for comfort has been addressed across a number of disciplines such as marketing (Spake, Beatty et al. 2003), tourism (Balcombe, Fraser et al. 2009), building and environment (Han, Zhang et al. 2007) and health-care (Kolcaba and DiMarco 2005). Comfort-seeking is a basic human need, with individuals striving for comfort throughout their lives. Individuals undertake an active role in making decisions to increase or protect their levels of comfort.

A review (Spake, Beatty et al. 2003) shows that the 'comfort' construct has been termed as a positive emotion, which has been also explained as being the opposite of anxiety. Comfort is associated with feelings of being at ease, or experiencing a relief from mental discomfort. In view of the range of explanations provided, it is not surprising that comfort

is regarded as a multi-dimensional construct, which is based on dimensions such as physical comfort, physiological comfort and psychological comfort (Slater 1985).

Occupant comfort is a widely researched topic in the area of urban living, with researchers acknowledging the role of double-glazed windows in boosting occupant-comfort (Barlow and Fiala 2007). The environment of an individual directly impacts his/her physical and physiological comfort, the two dimensions which are discussed in this section. As suggested by Kolcaba and DiMarco (2005), it is proposed that once occupants are more comfortable in their building environment, they will be able to bring about positive changes to their behavioural patterns.

It is not surprising to find a focus on thermal comfort since windows are a major factor contributing towards the control of a building's indoor temperature. Thermal comfort refers to an individual's satisfaction with the air temperature within a built environment. The in-door air temperature contributes to individuals' physical comfort. Double-glazed windows provide an opportunity to better regulate the internal temperature of a building. A single pane of glass provides poor insulation as glass is a good conductor of heat. According to one estimate, such a window can lose almost 10 times as much heat as the same area of insulated wall (Sustainability Victoria 2017). Double glazing of windows consists of two panels of glass set together with a spacer in between. The spacer is sealed and contains trapped air inside. The air inside the spacer greatly reduces the amount of hot or cold air that transfers from either side of the panel. Such a window system halves the amount of heat loss through the window. As a result of this, occupants experience 'thermal comfort' (Lyons, Arasteh et al. 2000). This performance can be enhanced further when the cavity is filled with Argon gas and low emissivity glazing is specified (Arasteh et al, 1989)

Double-glazed windows also provide protection from UV and infrared rays of sunlight. While earlier studies have highlighted the health benefits associated with sunlight, the ultraviolet (UV) component of natural light is now recognised as a serious risk to human beings. Besides contributing to sunburn and skin cancer, prolonged exposure to UV rays is also linked to erythema, photo carcinogenesis and ocular diseases such as cataract and macular degeneration (Reichow, Citek et al. 2006). More importantly, the risk of UV rays is not just limited to outdoors. The indoor built environment is of critical interest to researchers as a growing number of buildings now consist of a larger proportion of glass façade. Some initial studies have shown that double-glazed windows can impact occupants by providing UV protection (Kim and Kim 2010).

Noise, an environmental pollutant is a major issue in buildings situated in busy areas. Researchers have linked noise with health problems such as hearing loss, blood pressure, depression, agitation and fatigue (Mishra, Parida et al. 2010). Moreover, the impact of noise on human performance has also received researchers' attention (Smith 1989). Single pane windows do not offer adequate protection to occupants from outdoor noise. Double-glazed windows are increasingly seen as a solution as they provide good noise insulation (Kaiser, Pietrzko et al. 2003) and therefore add to occupants' physiological comfort.

Due to its design, it is more difficult for external temperatures to transfer through to the inside window panel of a double-glazed window. Therefore, many industry sources claim that double-glazed windows reduce the amount of condensation which, in turn, helps to reduce the risk of mould (Magnetite 2017). Mould-growth and other indoor pollutants can have negative impact on an individual's health through inhalation. Therefore, it can be

argued that double-panels provide long-term physiological comfort by reducing the chances of mould-growth.

It is proposed in our model (see Figure 1) that when occupants' levels of comfort increase, they would undertake 'adaptive actions' (Nikolopoulou, Baker et al. 2001) or initiate a change in their behaviours. While a major portion of the literature looks at the adaptive actions undertaken to restore comfort, we argue that when an environment becomes more comfortable, it could result in a positive change in overall household-behaviours.

As residents are more comfortable with the thermal environment, it should lower their energy-usage. It is also felt that there might be changes in the nature of clothing being worn indoors. More comfortable environments may also positively contribute to occupants' consumption behaviours with reference to food and drink in-take. Similarly, a reduction in noise pollution could boost occupants' productivity (Errett, Bowden et al. 2006) as well as positively contribute to a better quality sleep (Miedema and Vos 2007). Double-glazed windows, theoretically lead to fewer chances of mould growth. In such a situation, building occupants not only prevent health-related issues but may also save precious time and energy in trying to get rid of the fungi. Therefore, we propose:

H1: Occupant-comfort will lead to positive changes in occupant behaviour

H2 Occupants' behavioural change linked to wellbeing

It is generally recognised that Australians spend 90 per cent or more of their time indoors (Department of the Environment and Energy 2017). While not all these hours are spent at home, it is easy to understand why examining occupants' indoor behaviours are of great significance. Behaviour has been defined as 'observable actions or reactions of a person in response to external or internal stimuli, or actions or reactions of a person to adapt to ambient environmental conditions such as temperature or indoor air quality or sunlight (Chen, Yang et al. 2015; p 2). While much of the research focuses on occupant-behaviour from the perspective of energy consumption, for our proposed model we conceptualise the concept as including all those household behaviours which get impacted due to the retrofitting of double-glazed windows.

The model in Figure 1 proposes a link between occupants' behavioural change and their overall, wellbeing. As double-glazed windows add to the comfort of the building residents, we predict certain behavioural changes. We anticipate these changes to be of a positive nature. With ever increasing energy prices (Cormack 2017), residents would positively evaluate any reduction in their energy usage. On a similar note, residents should have a positive experience through noise reduction. Exposure to reduced levels of noise (due to the installation of double-glazed windows) should result in both auditory and non-auditory effects on health (Basner, Babisch et al. 2014). It is also anticipated that occupants can be more productive and focused at their tasks, if they do not face health issues related to mould growth and UV rays. The type of clothing occupants wear is determined by the indoor temperature conditions. When building temperatures are engineered to be maintained, occupants may find it easy to wear the type of clothing they find more comfortable (Morgan and de Dear 2003). All these changes in behaviour will be linked to the occupants' overall wellbeing.

The 'wellbeing' construct has been defined in a number of ways across different disciplines. While the business researchers focus on the overall satisfaction of

customers with experiences in the marketplace (Sirgy and Lee 2006), others have advocated its conceptualisation as consisting of both health and happiness (Steemers and Manchanda 2010). Following a similar line of thinking, much of the building environment literature examines occupant wellbeing from the perspective of both physical and psychological wellbeing (Thatcher and Milner 2012). Social scientists refer the Social Production Function (SPF) theory (Lindenberg 1996), which asserts that people produce their own wellbeing by trying to optimize achievement of universal goals, within the set of resources and constraints faced by them. The two universal goals identified in the SFP theory are physical and social wellbeing. It is proposed by SPF theory, that when individuals undertake 'stimulating' activities, their overall wellbeing can be impacted. Stimulating activities include all those tasks that produce arousal including mental and sensory stimulation, physical effort and sports which can help in achieving physical wellbeing (Orme;, Lindenberg et al. 1999).

Just as health behaviour change has been linked to patient wellbeing (Dennison, Morrison et al. 2013), similarly it is anticipated that positive changes in residential-living behaviour, will also lead to occupants' wellbeing. Due to changes in behaviour patterns, residential occupants will not only physically feel good – in fact, their psychological health will also get positively impacted.

Therefore, it is proposed that:

H2: Modified occupant behaviour will be positively linked to occupant-wellbeing

H3 Occupant-comfort associated with wellbeing

The model in Figure 1 suggests a direct link between comfort and wellbeing. According to the Social Production Function (SPF) theory individuals wish to achieve the overall goals of physical and social wellbeing. These two goals together formulate the subjective wellbeing of an individual. In line with the proposition put forth via the theory, individuals will achieve overall universal goal of physical wellbeing through the fulfilment of the instrumental goal – comfort. Comfort is a somatic and psychological state based on absence of thirst, hunger, pain, fatigue, fear, etc. (Orme;, Lindenberg et al. 1999). Empirical evidence also demonstrates that being comfortable in one's physical environment is strongly related to occupants' health and productivity (Ali, Chua et al. 2015).

When individuals are healthy and engaged in productive activities, their overall wellbeing will be positively impacted. However, even if there are no adaptive behaviours or activities undertaken, it is possible that comfort alone will lead to a positive evaluation for subjective wellbeing.

Therefore, it is proposed:

H3: Occupant-comfort will be positively linked to occupants' wellbeing

3 Discussion and Future Research

This conceptual paper presented a theoretical model which links occupant wellbeing to double-glazed windows. The effect of windows on building-occupants has been studied across a number of disciplines include psychology, education, lighting, architecture, engineering, medicine and city planning (Farley and Veitch 2001). Over the past couple

of decades, the focus has been on examining the impact of windows on residents' health and satisfaction (Bone, Murray et al. 2010). We extend this line of research by proposing the effect of double-glazed windows on occupant wellbeing. While some researchers have explored the concept of wellbeing with reference to windows, hardly any work has been undertaken which proposes a direct and indirect link from window-induced occupant comfort to wellbeing.

Currently, Australia has one of the highest levels of household debt (Janda 2017), with a debt-income ratio as high as 190 per cent. This unusual debt-to-income ratio concerns many experts because – historically - it has frequently coincided with financial crises. It is believed that by installing a measure which helps to reduce energy costs for Australian households, will contribute positively towards helping Australian borrowers to be more resilient towards any future increases in lending rates.

In this study, we have only conceptualised one characteristic – that is, the effect of double-glazed windows on energy consumption and occupant wellbeing. It is well-recognised how 'good orientation' of windows can help in reducing the need for auxiliary heating and cooling. North facing windows receive more solar radiation in winter than in summer, which can lead to significant cost savings due to reduced energy use(Australian Government 2017). Future research should also factor in the impact of window direction on energy consumption as well as occupant-comfort and wellbeing.

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IS THE SUSTAINABILITY MESSAGE COMING HOME?

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Abstract: *Sustainability elements of homes in Australia are not typically captured within traditional considerations of housing and value. Neo-classical economics states if consumers are educated about sustainable housing they will chose more sustainable housing. However, this scenario is not manifesting due to market failures. This paper explores what messages about the sustainability of a house are being provided to consumers, and how consumers consider sustainability within their decision-making hierarchy of priorities. The analysis involved a content analysis of 155,780 real estate advertisements from Melbourne between July 2008–March 2015. Interviews with 19 households were also conducted to understand the decision-making process of how they ended up in their current home. The analysis found that 10-15% of advertisements mentioned something to do with sustainability, however there was limited engagement with the specific sustainability features, other than solar panels. There is evidence that more recent advertisements were gradually highlighting sustainability elements. This was supported by the interviews which highlighted that the historic priorities of location, affordability and number of bedrooms/bathrooms are the main considerations, with sustainability elements seldom discussed. In the absence of state or national requirement for point of sale or lease sustainability information there is an opportunity that real estate agents to act as intermediaries and increase knowledge and awareness of sustainable housing amongst consumers. There is significant progress required if information and education of sustainable housing is to drive the market towards sustainable housing outcomes.*

Keywords: *Sustainable Housing, Decision Making, Advertising, Priorities*

1 Introduction

The residential sector is a significant contributor of greenhouse gas emissions (BZE 2013). However, it is a sector which has been identified as having significant opportunity for cost-effective sustainability improvements, such as using energy-efficiency and renewable energy technologies (IPCC 2014). In this regard, the sector has a key role to play in a transition to a low carbon urban future (Moore 2014).

Improved sustainability of housing results in a myriad of benefits; not only for the environment (e.g. lower greenhouse gas emissions) but also for occupants (e.g. lower operating costs, improved thermal comfort and health) and broader society (e.g. lower fuel poverty rates) (Berry, Whaley et al. 2014, Willand, Ridley et al. 2015). Furthermore, many of these benefits can be achieved for little, or no, additional capital costs compared to standard housing (Sustainability House 2012). Despite such findings the sustainability and performance of housing in many developed countries, including Australia, falls significantly short of what is required for a transition to a low carbon future (Horne and Hayles 2008, Moore 2014).

In Australia, the current mechanism of improving the sustainability of housing has primarily been through the setting of minimum performance standards (BZE 2013). These standards have focussed on improving the thermal performance of the building envelope and have been found to have improved the energy performance of new and renovated housing; although outcomes have been tempered through the increase of floor area of new homes and increased numbers of appliances (Ambrose, James et al. 2013).

To close the performance gap to what is required for a low carbon future (e.g. zero energy homes), these standards will need to increase their energy efficiency requirements and include elements such as renewable energy generation. Some building industry stakeholders have argued against the increase of minimum standards, saying that the market will determine the appropriate outcome for sustainability and performance (HIA 2009). This argument fits within the neo-classical economics belief that if consumers are educated about sustainable housing they will chose a more sustainable house and therefore drive the market to provide such housing (Cato 2011). However, sustainability elements of homes in Australia, as in other countries, struggle to be captured within traditional considerations of housing and value, both within policy but also by consumers.

Consumers tend to prioritise elements such as affordability, location, quality, function and aesthetics when looking at purchasing (or renting) a property (Kelly 2011, Ridley, Moore et al. 2014). For example, research from the Grattan Institute found that many of the elements people were seeking for their ideal house were about larger houses with more space in good locations (Huang, Barnett et al. 2013). Figure 1 shows the results from the Grattan Institute report which asked people to consider 57 variables for housing preferences (Kelly 2011). However, it is telling that there were no variables relating to smaller houses, or sustainability features such as double-glazed windows or solar panels.

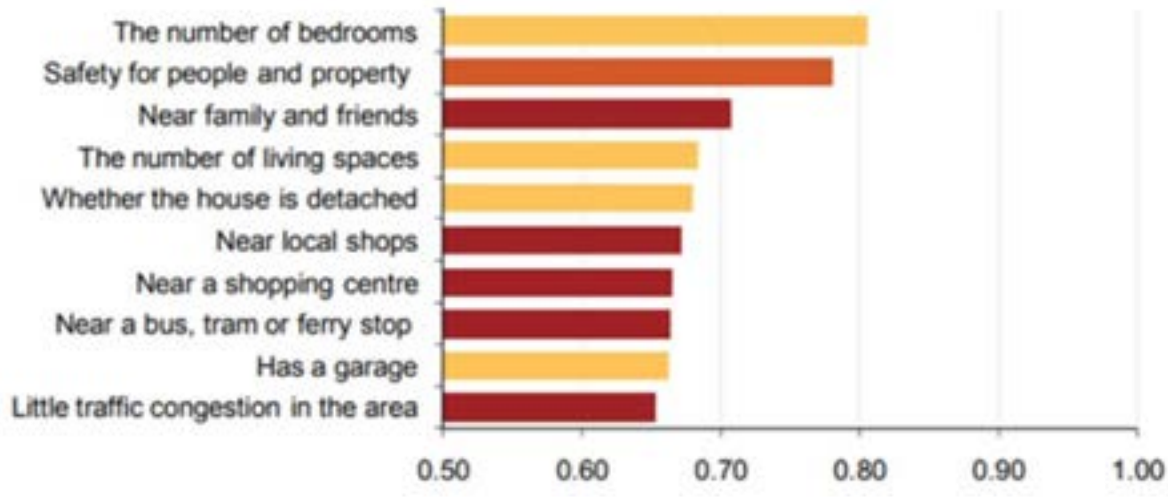

Figure 1: Outcomes from what people wanted in their housing from research by the Grattan Institute (Kelly, 2011:12).

While there is limited research looking at where sustainability outcomes fit within the decision-making process for potential home buyers, there is increasing research which is analysing the economic value which is being placed on such outcomes. A report found that for every one-star Nationwide House Energy Rating Scheme (NatHERS) improvement to a house in the Australian Capital Territory, an added economic resale value of almost $9,000 was achieved (DEWHA 2008). In the U.S., Bloom *et al* (2011) compared energy star certified homes and standard homes in Colorado and found that the certified houses attracted an additional sale premium of $8.66 per square foot. In terms of specific sustainability technologies, Hoen *et al* (2011) found an added resale value for houses with solar photovoltaics, up to $17,000 for a 3.1kW system. There are also tangible benefits for occupant health and wellbeing outcomes (Maller and Strengers 2011, Huang, Barnett et al. 2013).

There is clearly economic, social and environment value in sustainability housing. However, this value is not yet translating to the general housing purchaser. The scenario of educated consumers demanding more sustainable housing is not manifesting in Australia and other countries. This is not surprising as the decision to purchase, and what to purchase, is an extremely complex process, where purchasing decisions are not always rational and are made within constraints of what is available in the market and the purchasers current life situation (Levy, Murphy et al. 2008). The provision of information about potential houses to purchase is just one element which informs this process.

It has been identified in previous research that real estate agents play a critical role in the provision of information and guiding purchasers through their purchasing journey (Levy, Murphy et al. 2008). Advertisements are useful to understand social trends and have been used previously to interpret societal movements in housing (Pryce and Oates 2008). Information imbedded within real estate advertisements reflects how real estate agents are interpreting buyer trends, including what is not desirable, and ultimately trying to identify elements which will unlock financial value. Despite this, there has been limited research into what information is being provided to consumers about their housing choices and how this relates to their decision making. This paper explores what messages about the sustainability of a house are being provided to consumers, and how consumers consider sustainability within their decision-making hierarchy of priorities.

2 Methods

To address the aim of this paper, two approaches were applied to collect and analyse data. The first step was a content analysis of real estate advertisements of detached housing in Melbourne, Australia. This data is part of a larger PhD project that is examining real estate agent engagement with energy efficient housing. The second step was to locate these outcomes in the context of the decision-making processes as found in interviews with 19 households.

2.1 Advertisement analysis

The Real Estate Institute of Victoria provided a data base of more than 352,560 land and property sales for Melbourne for the period of 2008 – 2015 for analysis. The data set included basic transaction information such as sale price and date, postcode and suburb and the advertisement used to market the property. The data set was cleaned to remove land, apartment and other non-detached residential sales leaving 155,780 sales used in this research. Detached housing was the focus of this research as it remains the most common form of housing in Melbourne (ABS 2012). A content analysis was then undertaken on the advertisements to identify trends and patterns in textual data (Krippendorff 2004). Keywords to conduct the content analysis were identified through a literature review. Based upon this literature, two primary categories for analysis were established. The first category relates to personal attitudes that influence housing choice and the second category relates to houses attributes. Both categories then had several sub categories to refine the key words further into common themes. To focus on sustainability technologies and elements that influence buyer choice, the aim of this paper, language referring to house attributes is the subject of interest in this paper. The full analysis will be presented in forthcoming publications.

Under the housing attributes there were several sub categories based upon logical groupings of key words. These sub categories were Altruistic, Parsimonious, Technology and Design. Of these, two are of interest for this paper; Technology and Design as they relate to sustainability elements which are visual and can be easily identified. Technology keywords were devised based on technologies that can be retrofitted into a house post construction such as solar photovoltaic systems. Design attributes are attributes of a house that must be designed into or are typically too expensive to install post construction such as passive design. Table 1 details words and phrases that were captured within these two keyword sub categories.

Table 1: Technology and design key words applied for content analysis.

Technology key words	Design key words
Solar electric	E glass
Solar energy	Smart glass
Solar enhanced	Double glaze
Solar heated hot water	Miglas
Solar heating	Grey water
Solar hot water	Recycled water
Solar HWS	Insulation
Solar power	North aspect
Solar system	Energy rated
Solar (where not one of the above)	Energy rating
Photovoltaic	Energy passive

Watertank	Sustainable energy
Solar boosted	Sustainable design
LED light	Solar design
Low volt light	Solar home
	Solar passive
	Solar principals
	Recycled material
	Hydronic
	Passive energy
	Passive design
	Low energy design

SPSS was used to analyse the advertisements for the key words which coded as 0- not found in advertisement and 1- found in advertisement. SPSS analysis included identifying the frequency of appearances of each keyword and creating histograms to investigate the word/phrase location. This information is important for understanding the emphasis that real estate agents place upon sustainable housing technologies or design elements when advertising a house for sale.

Psychology has relevance to marketing and primacy-recency theory, resident in this body of knowledge, posits that a receiver of a message, whether verbal or textual, is more likely to recall the information that was provided either at the beginning of the message string or at the end (Ohanian and Cunningham 1987, Li 2010). Information located within the middle is more likely to be lost. Therefore, as part of a robust analysis, it is important to consider where real estate agents are locating the keywords within the textual string that is the advertisement. To this end histograms were considered useful.

2.2 Interviews with home owners

The above data is supplemented with analysis from interviews with 19 Melbourne owner-occupier households conducted in 2014-2016. The interviews were conducted as part of a larger set of 80[1] household interviews for an Australian Research Council funded project *Lifetime Affordable Tenable City Housing*.

The interview questions related to their housing histories, the circumstances surrounding leaving their last dwelling and the process of finding their current residence, including what the key priorities were for them, the availability of such properties and any trade-offs that might have been made. Participants were also asked about their expectations of living in the dwelling and how these expectations were being met (or not), how their recent lived experience might inform future moves and included questions relating to sustainability elements within their homes. The interviews were undertaken at the participants home or a nearby café and took about an hour to complete. Participants were given an $80 Coles-Myer gift card as a thank you for their time. NVivo was used to analyse the data and identify key themes and trends. This paper does not link the specific households to the real estate advertisements, which will be explored in a future publication.

[1] The remaining households from the larger study were either rental housing or apartments.

3 Analysis and discussion

3.1 Advertisements

Table 2 presents both the total number of Design and Technology keywords that appeared in advertisements over each calendar quarter of the research period. The number of Design keywords was found to be between 8.3% - 12.5% across the period. While relatively consistent when compared to the Technology keywords, the frequency of Design mentions declined slightly in Quarter 3 2009 until Quarter 3 2011 where appearances increased again. The reason for this is not apparent from the dataset and requires further investigation.

The Technology keywords show a more consistent pattern of increasing frequency of mentions. In Quarter 3 2008 the percentage of advertising with Technology keywords was 4.7%. This grows steadily throughout the period to 14.5% in Quarter 1 2015. Several of the keywords in the Technology relate to solar photovoltaics. The period of analysis coincides with a significant increase in the installation of residential solar photovoltaic systems (APVI 2017). Driven in part by government rebates and falling costs of the technology, the number of households with solar photovoltaics rose from a few hundred to almost 25% of houses in Australia now having a solar photovoltaics system installed (Vorrath 2017). The data shows that real estate agents are increasingly highlighting this technology. This might be the result of broader community normalisation of solar photovoltaics in recent years and that agents will highlight features most attractive to buyers (Robertson and Doig 2010). The question remains however how such technologies influence buyer decision processes, or if the sustainability elements are just the bi-product of other decision making.

Table 2: Appearance of keywords over research period.

Sale – Year_ Quarter	Number of advertisements with Design keyword	Number of advertisements with Technology keyword	Total number of advertisements analysed	% of total which mention Design keyword	% of total which mention Technology keyword
2008_03	357	138	2947	12.1%	4.7%
2008_04	473	274	4695	10.1%	5.8%
2009_01	436	312	4611	9.5%	6.8%
2009_02	640	440	6112	10.5%	7.2%
2009_03	564	494	6227	9.1%	7.9%
2009_04	659	585	6999	9.4%	8.4%
2010_01	483	437	5308	9.1%	8.2%
2010_02	579	550	6226	9.3%	8.8%
2010_03	488	541	5556	8.8%	9.7%
2010_04	581	583	6032	9.6%	9.7%
2011_01	428	516	4843	8.8%	10.7%
2011_02	408	461	4355	9.4%	10.6%
2011_03	305	352	3638	8.4%	9.7%
2011_04	395	381	3740	10.6%	10.2%
2012_01	362	386	3668	9.9%	10.5%
2012_02	397	361	3811	10.4%	9.5%
2012_03	336	350	3658	9.2%	9.6%
2012_04	410	440	4627	8.9%	9.5%
2013_01	321	430	3874	8.3%	11.1%

2013_02	391	423	4199	9.3%	10.1%
2013_03	887	1026	9164	9.7%	11.2%
2013_04	1141	1209	10163	11.2%	11.9%
2014_01	768	967	7264	10.6%	13.3%
2014_02	999	1148	8847	11.3%	13.0%
2014_03	881	982	7744	11.4%	12.7%
2014_04	1290	1413	10357	12.5%	13.6%
2015_01	798	1030	7115	11.2%	14.5%

For keywords relating to Design, appearances in advertisements remained reasonably consistent over the research period. While there is some slight decline during the middle of the research period, the trend line however reveals a slight positive trend overall (Figure 2). This is interesting from an environmental and policy perspective. The data set includes all sales of established housing within the period. Houses built after to the introduction of minimum energy performance standards 2005 (and revised in 2011) would be included in this data where the property has been sold. However, with an average 'hold' time of detached housing of 11 years in Melbourne (Winter 2015), it is likely that there will only be a small percentage of newer houses in the data set, and therefore a small percentage that should have been designed and built to higher sustainability standards. That is not to say that the older houses did not have Design characteristics relevant to sustainability; they may well have, but they were not being identified by real estate agents. This reflects a challenge for policy makers if they hope to use the turnover of housing ownership to drive improved sustainability across the residential sector. In contrast to the Design analysis, the Technology analysis found a strong positive upward trend throughout the analysis period.

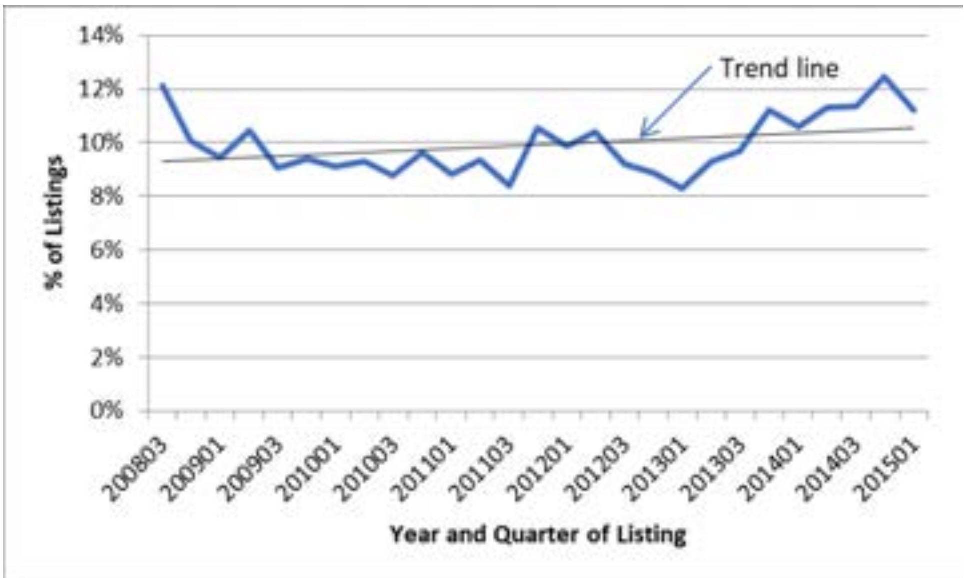

Figure 2: Appearance of Design keywords over research period.

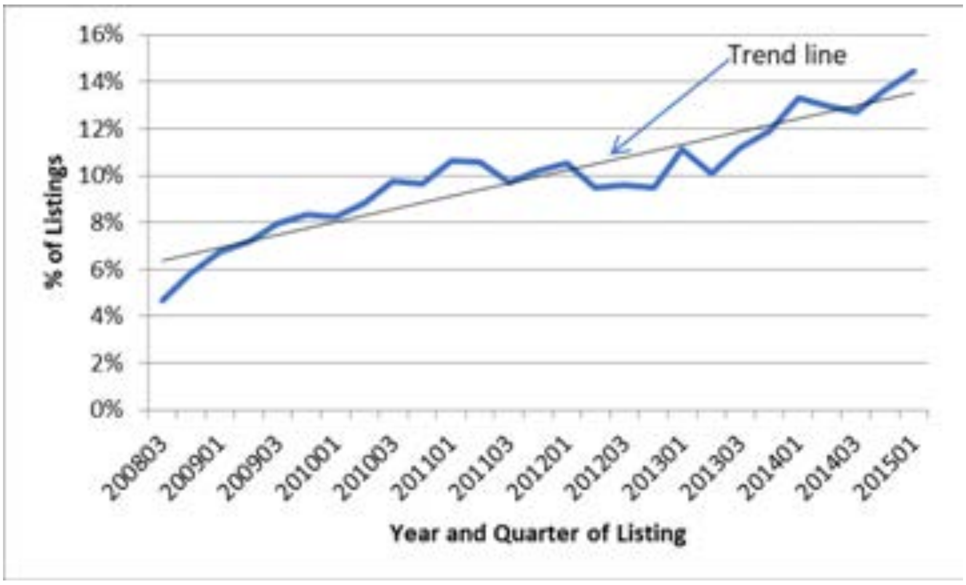

Figure 3: Appearance of Technology Keywords over research period.

The above analysis demonstrates an increasing propensity to mention technology elements relating to sustainability does not talk to the context of which that occurs. Figures 4 and 5 present two histograms showing the location of the language within the body of the text. These are presented in relation to the percentage location into the advertisement. This format was necessary to account for the fact advertisements vary in length and therefore words and phrases appearing in smaller advertisements, for example, would seem to appear early thereby creating a distorted understanding.

It is clear that inclusion of words relating to environmentally friendly technologies are located in later portion of the advertisement but not at end. In the case of the Design keywords, the frequency of relevant words peaked around 70% into the advertisement. For the Technology keywords, there was a much clearer peak at around 80%. This means that the keywords examined here are less likely to be remembered based upon primacy-recency theory, and therefore less likely to be a serious consideration in the house buying decision process. From an environmental perspective, this is of concern, especially as many of these sustainability elements have longer term liveability and affordability impacts of a housing decision (Moore, 2014).

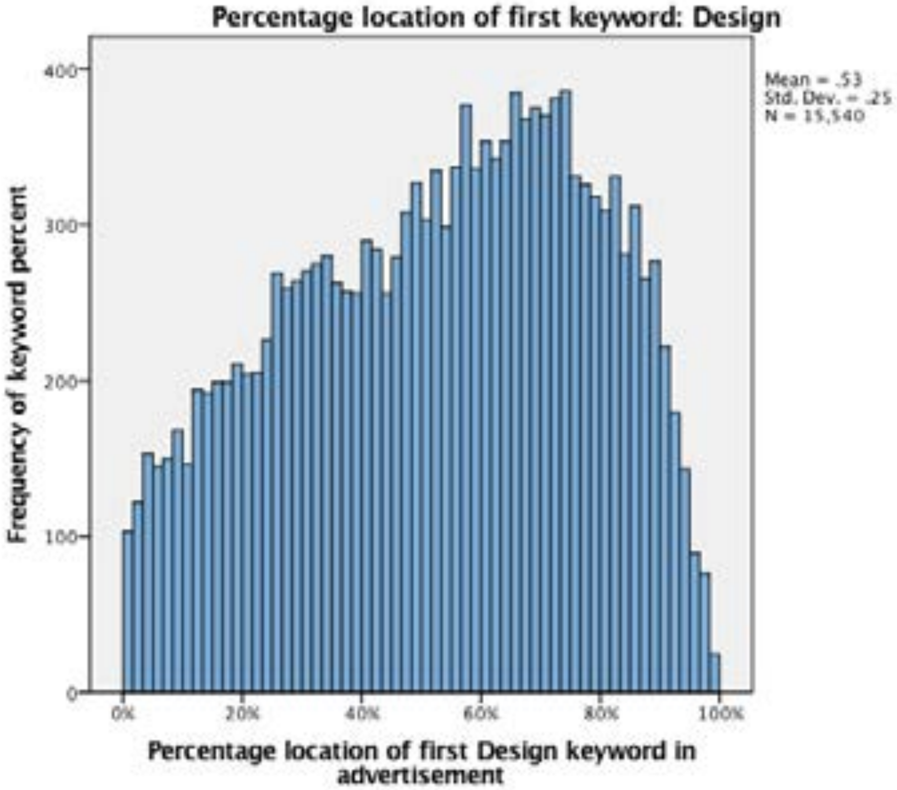

Figure 4: Relative location of first Design keyword within advertisement.

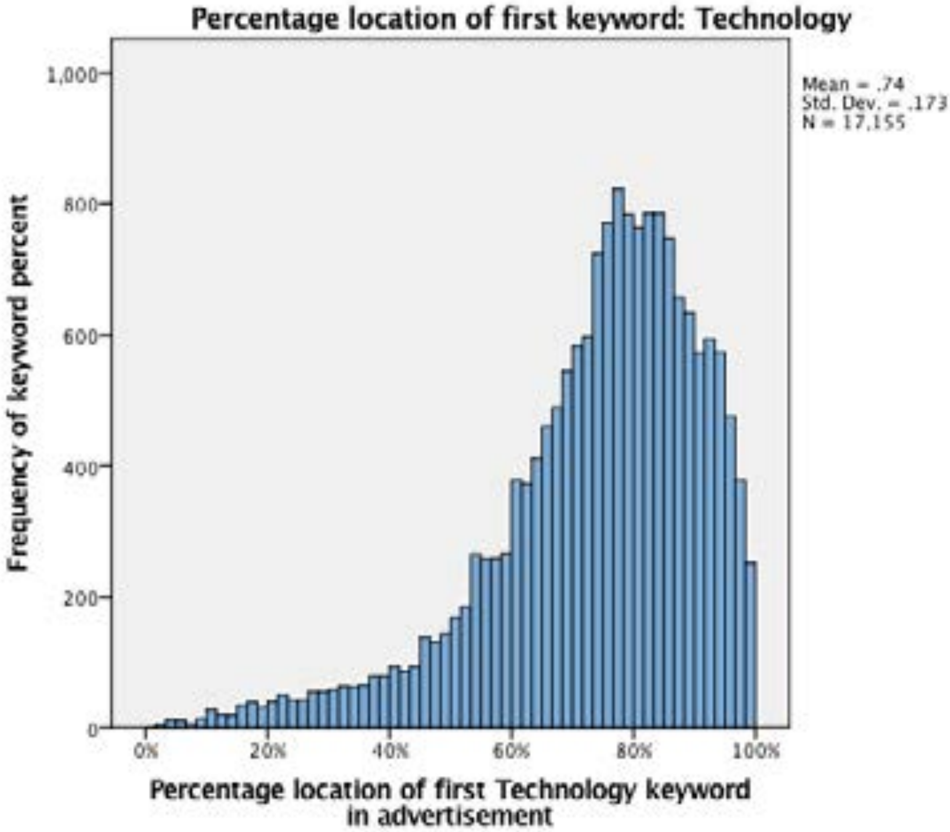

Figure 5: Relative location of first Technology keyword within advertisement.

3.2 Household interviews

The broad characteristics of the 19 households interviewed are presented in Table 3. The participants had been in their dwellings for an average of 12.1 years, with ten having moved into their dwellings during the period which correlates with the advertisement analysis.

Table 3: Household characteristics and dwelling location.

Participant Reference	Participant Gender	Participant Age	Number of occupants in dwelling	Year moved into current dwelling	Dwelling location
Household 1	Male	42	1	2012	Mill Park
Household 2	Female	59	3	2009	South Morang
Household 3	Female	55	5	1982	Thornbury
Household 4	Female	50	4	1999	Yarraville
Household 5	Female	54	2	2014	Brunswick
Household 6	Female	41	2	2011	North Brunswick
Household 7	Female	36	4	2011	Richmond
Household 8	Female	52	2	2006	Lalor
Household 9	Female	63	4	2010	King Lake
Household 10	Female	45	4	2016	South Morange
Household 11	Female	50	4	1997	North Fitzroy
Household 12	Female	52	2	2005	Glen Waverley
Household 13	Male	83	3	2013	Edithvale
Household 14	Female	62	1	1978	Northcote
Household 15	Female	68	3	2011	North Fitzroy
Household 16	Male	67	5	1980	Brunswick
Household 17	Male	49	3	1998	East Malvern
Household 18	Female	30	2	2010	Eaglemont
Household 19	Male	31	2	2011	Lower Plenty

Participants were asked to explain what their key priorities were when looking for their current house. Figure 6 presents the first priority mentioned by the households. There is a clear bias towards the traditional framings around values and desires: location, affordability and specific design requirements (e.g. number of bedrooms/bathrooms), with no initial responses relating to sustainability elements. These have also been found in previous research (Kelly 2011).

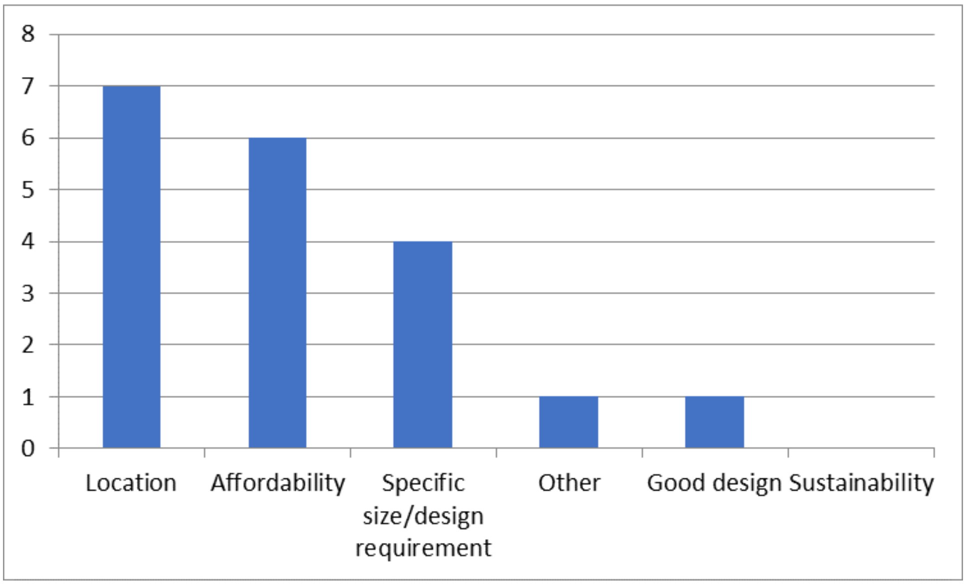

Figure 6: First priority mentioned by households when asked about previous move.

As the participants were not asked to rank in order of importance the priorities, Figure 7 presents all the priorities (N=113) they mentioned during the interview. There was an average of 6 priorities per household, with a minimum of one priority and a maximum of 12. Again, the data shows a bias towards the traditional framings of value and desires within housing. There were also multiple mentions by many participants about these key priorities such as location being important for work as well as being close to family/friends. Only four times clear sustainability priorities were stated, and this was only by one household who had bought a block of land to build a house on and had previous experience of living in a low-energy home. Specifically, it was the inclusion of double glazed windows, the requirement for smaller windows and a requirement for solar passive design which was identified as being part of their priorities, although this came after their priority of location and affordability. This household also identified it as a priority to have 'big bedrooms' so their desire for improved sustainability was a fluid concept to meet their broader housing 'requirements'. Interestingly the sustainability priorities mentioned by the household were more about design requirements than technology, which was the opposite to what was found in the real estate advertisement analysis.

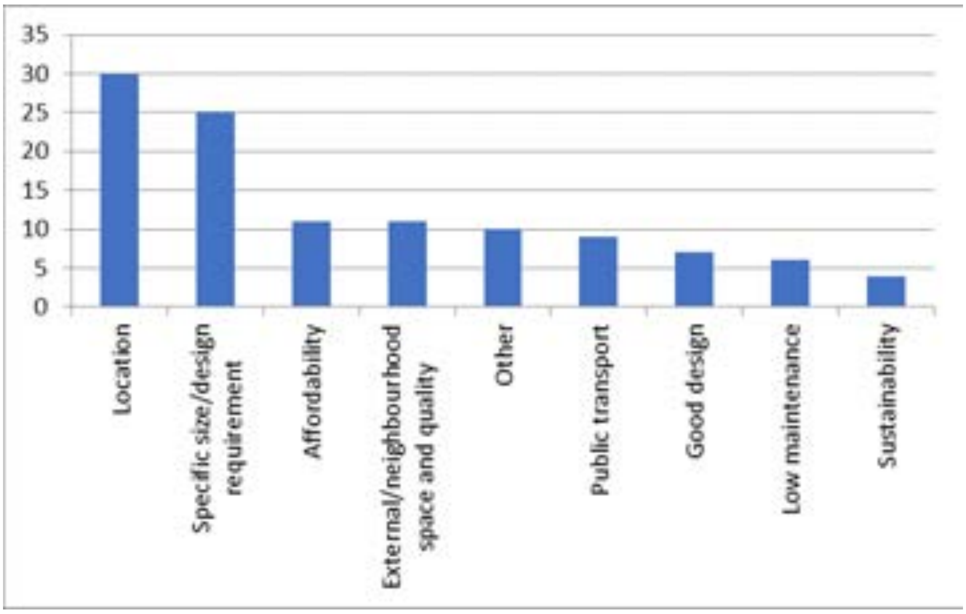

Figure 7: All priorities identified by households in relation to their last move.

When households were asked about how the lived experience was in their current house, many made comments which related to the sustainability or performance of the dwelling without overtly realising it. For example, several commented that their houses became too hot during heatwaves in summer, or spoke of the rising cost of utilities. They were not making the connection between these liveability challenges and the decisions they made about priorities. This is reflected in their responses to what they would be looking for next time they moved. Only four clearly desired sustainability elements (such as technology or design), with most still focused on the elements such as location, affordability and number of rooms. The limitation of these interviews is clearly that only a few had moved into their house in recent years, which was when the boom in residential solar photovoltaics was happening, and being picked up more frequently in the real estate advertisements. It is therefore hard to make clear conclusions although the message is similar to the advertisement analysis – that sustainability is still not a key consideration when looking to buy a property in Australia.

3.3 Implications

The question clearly remains about how to leverage sustainability to become a more pressing priority for households. While there is evidence from the advertisements that sustainability features are being identified as part of the sales information at an increasing rate, there is still improvement in terms of making it more prominent in the advertisement. As primacy-recency theory states, it is not just the inclusion of the word, but its location and context which is important. While real estate agents have a challenging role, having to identify what will bring in their client (i.e. the seller) the highest price, they also have a role to play as an intermediary in delivering information about housing performance and liveability (Levy, Murphy et al. 2008).

Information provision about sustainable housing is not translating to consumer's broader concerns about the environment and liveability (e.g. energy prices). However, part of this may be the historical lack of sustainability elements in housing by all stakeholders. This has started to change as minimum building regulations have set increasing requirements and the innovation of technologies, both in terms of design and cost, have proliferated the market. For example, solar photovoltaics in Australia has gone from being installed on very few properties, to having almost a quarter of all houses in Australia now having a

solar system within a decade (Vorrath 2017). There was clear evidence that more recent advertisements were gradually highlighting sustainability elements such as solar which may mean such information is included more often as consumers and the real estate industry recognise the value in these outcomes.

In the absence of state or national requirement for point of sale or lease sustainability information there is an opportunity that real estate agents to act as intermediaries and increase knowledge and awareness of sustainable housing amongst consumers. While there is some education of the real estate industry occurring in Australia (e.g. https://liveability.com.au/), there is more that can be done. However, it should not just be left to real estate agents to drive consumer demand for sustainable housing. The benefits of such housing need to be communicated to the public so that sustainable housing is no longer seen as 'different' or an 'add on', but becomes normalised.

Furthermore, the Australian federal government should also explore other ways in which is can further direct the sustainable housing market. The Victorian government has just release a voluntary Residential Energy Scorecard for housing which aims to address this gap.

4 Conclusion

When looking to purchase housing in Australia, consumers are still typically focused on historical housing priorities such as affordability, location, number of bedrooms and size. Sustainability technology and design elements are typically overlooked. Real estate agents play an important role in the provision of information about housing. There has been limited research to date looking at how their advertising material treats sustainability elements and how this relates to consumer decision making processes. This paper explored more than 155,780 real estate advertisements for Melbourne, Australia between 2008-2015. This was supplemented with interviews with 19 households about their decision-making processes. The evidence shows that there is increasing frequency of real estate advertisements making mention of sustainability technology or design elements. However, even those advertisements, which engage with sustainability, the message is located in the middle part – where information is often forgotten according to primacy-recency theory. The lack of engagement with sustainability in the decision-making process was confirmed by the household interviews who still placed traditional considerations of housing such as affordability, location and number of bedrooms as their key priorities.

Overall it appears that neither market facilitators nor house buyers are prioritising energy efficiency in the house purchase and traditional attributes remain the focus. Therefore, there is an opportunity for the Australian government to play a more direct role to enable the housing market to imbue such important attributes into the house purchase decision.

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HYBRID GEOTHERMAL-GAS AND GEOTHERMAL-SOLAR-GAS HEATING SYSTEMS FOR POULTRY SHEDS

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Abstract: *Poultry sheds have unique indoor air temperature requirements to raise poultries (chickens: broilers & layers, turkeys, ducks), which determine their unique heating and cooling demand cycles. In this paper, heating options of a typical chicken shed for broilers in Peats Ridge, NSW are investigated. The farming operation of this shed involves six heating and cooling cycles in one year, each cycle lasting for seven weeks. The thermal load for the first three weeks of the cycle is heating dominated, while the load for the rest of the cycle is cooling dominated. The chicken shed typically utilises evaporative coolers and liquefied petroleum gas (LPG) heaters to maintain required indoor air temperature. To reduce the cost of heating the shed, hybrid geothermal-gas and geothermal-solar-gas heating systems are proposed. In these systems, the baseload heating capacity is supplied by ground source heat pumps (GSHPs) that use the ground as a heat source. It should be noted that a continuous operation of the heat pump may decrease the ground temperature over time and thus reduce the energy efficiency of the system; therefore, flat plate solar collectors are proposed to be coupled with the GSHPs to thermally recharge the ground and increase energy efficiency of the heating system. Moreover, gas boilers are proposed to be integrated with the GSHPs to reduce the overall installation costs of the heating system. This paper discusses the sizing of various components of these hybrid systems. Preliminary results revealed that, if hybrid systems are used for heating, significant savings of annual heating costs can be expected.*

Keywords: *Geothermal Energy, Rural Industries, Hybrid Systems, Energy Efficiency, Heat Pump*

1 Introduction

In Australia, agriculture and related food processing industry contribute 12% to the national Gross Domestic Product (GDP) (NFF 2016; NFF 2012). Annually, about 600 million chickens are raised nationwide (Australian Bureau of Statistics 2016). Chicken sheds consume a significant amount of energy, which is mainly used for heating and cooling. An estimation by Zhou et al. (2017) suggested that about A$ 80 million is spent annually for this purpose. To reduce operational costs of chicken sheds, their energy bills could be reduced. Since existing cooling systems for chicken sheds can be very cost-effective to operate (for example, if evaporative cooling systems are used), the primary focus should be on the reduction of heating costs.

In Australia, the primary energy sources for heating are network piped natural gas and bottled liquefied petroleum gas (LPG) (Allison Ball et al. 2016). These fuels are not only expensive to utilise but also produce significant amount of greenhouse gas (GHG) emissions (Australian Government. Dept. of the Enviroment 2015). Through the partial replacement of current gas heating systems with high-performance equipment that uses renewable and more sustainable energy sources, both operational cost savings and GHG emission reductions could be potentially achieved.

A Ground Couple Heat Pump (GCHP) system extracts thermal energy from the ground during heating mode and rejects heat into the ground during cooling mode. By utilising the ground as a heat source and heat sink, GCHP systems provide low-carbon thermal energy for heating and cooling (Johnston, Narsilio & Colls 2011). If the systems are applied for heating only utilising ground as a source they are termed Ground Source Heat Hump (GSHP) systems. In the previous few decades, GSHP systems have been installed worldwide for different applications and such systems are especially popular in the United States, Canada, Sweden and China (Lund & Boyd 2016). GSHP systems have also been introduced for the heating of poultry sheds (Kharseh & Nordell 2011).

Despite the relatively high energy efficiency of the GSHP systems, they require considerable capital investments. It has been demonstrated that hybrid systems where GSHPs are coupled with other types of systems can be more economical for heating (Eslami-Nejad & Bernier 2011; Kjellsson, Hellström & Perers 2010). For example, gas boilers and gas burners have relatively low installation costs and can be integrated with GSHP systems to reduce installation costs of these systems. To boost heating efficiency of GSHP systems, renewable solar thermal systems can also be coupled to form solar assisted GSHP systems. By combining these three sources of thermal energy, lower operational heating costs as well as lower installation costs of heating systems can be potentially achieved.

This study investigates financial benefits of a geothermal-solar-gas hybrid heating system for poultry sheds in Australia. In particular, the paper discusses optimisation of a hybrid geothermal-solar-gas heating system for a typical chicken shed in Peats Ridge, NSW, Australia. A building energy simulation model of the shed was developed using EnergyPlus and verified against current energy consumptions. By using this verified energy model, an optimisation of the installed capacities of different components of the geothermal-gas-solar hybrid heating system was performed to minimise the operational cost of the hybrid as well as the 40-year lifetime cost of heating. The 40-year lifetime is considered in this study because the lifetime for ground heat exchangers is at least 40 years and the shed are also expected to be used for the next 40 years. Based on the optimisation study, the proposed design of the hybrid system for the shed is discussed.

2 Heating Cycles of Chicken Shed

In this case study, a chicken shed located in Peats Ridge, NSW, Australia was examined to exemplify the study for temperate climate regions. The main parameters of the shed are presented in Table 1. An EnergyPlus building energy simulation model was developed for the shed. The energy model simulates the heating and cooling loads for the shed using 'ideal air flow' option in EnergyPlus. The performance data of components (GSHP, FPSC, Solar PV) were based on the equipment currently available on the market in Australia.

Table 1 Chicken Shed Parameters

Location	Peats Ridge, NSW, Australia (33°23'49"S, 150°24'09"E)
Dimensions	Width:18.3 m, Length:138.7 m, Height: 2.7 to 4.3 m
Wall/Roof Material	No windows; Insulation with thin layers of metal cladding. Insulation thickness: 0.075 m, thermal conductivity: 0.039 $Wm^{-1}K^{-1}$, density: 16 $kg\,m^{-3}$, specific heat: 340 $Jkg^{-1}K^{-1}$
Climate Data	Typical Meteorological Year (TMY) data (Remund et al. 2016)

Zhou et al. (2017) demostrated that the operational schedule significantly influences the heating energy consumption of chicken sheds. They estimated that up to 20% variation in the annual energy consumption can be expected for different starting dates of batches (growing cycles for young chicks grow up fully to the market which usually last seven to eight weeks in Australia). For this study, the first batch is assumed to start on 1st of January and that the shed is used for six batches per year. Each batch is assumed to last seven weeks with two weeks break time in between batches.

Similar to the normal operation of the case study shed, 50,000 chickens are assumed at the beginning of each batch. Three harvests are expected in one batch, happening in the mid-night of the end of the fifth, sixth and seventh weeks of the cycle. The first harvest is assumed to depopulate 15,000 chickens while the second one 10,000 chickens and the last harvest remaining 25,000 chickens. Mortality of chicken during growing cycles is not considered as no detailed reliable mortality data is available.

The chicken weight gain and metabolic heat generation data applied in each cycle are presented in Table 2. This data is in accordance with the chicken growing recommendations provided by the shed owner and operator.

Table 2 Chicken growth and metabolic heat generation

Day of growing cycle	Mass per chicken (kg)	Heat generation per chicken (W)	Number of chicken (-)	Indoor setpoint temperature (°C)
1	0.054	0.82	50,000	31.0
7	0.180	2.02	50,000	28.6
14	0.438	3.93	50,000	26.1
21	0.829	6.34	50,000	23.7
28	1.337	9.08	50,000	21.2
35	1.897	11.80	50,000	19.0
42	2.444	14.27	35,000	19.0
49	2.873	16.11	25,000	19.0

Currently, the case study shed has been heated by LPG burners. The energy consumption model developed was calibrated and verified with the two-year LPG bills provided by the farm owner. To match the actual LPG consumption, we adjusted the ventilation rate (air exchange rate with the outdoor environment). The calibrated

ventilation rate of $1.04\times10^{-4}\text{m}^3\,\text{s}^{-1}\text{kg}^{-1}$ (Vest & Tyson 1991) was applied to closely match the actual and calculated annual heating costs.

Fig. 1 shows the simulated heating power demand of the shed based on the verified energy consumption model developed. It was estimated that the annual heating energy of the shed is 143,811 kWh_h* with a peak heating power demand of 195 kW_h. During each heating cycle, the heating demand is at its maximum at the start of each cycle when the least metabolic heat is generated by chickens and, at the same time, the required indoor temperature is at maximum (Table 1). The heating demand decreases later in each cycle due to the increase in metabolic heat generated by chickens and lower indoor temperature requirement corresponding to the age of the batch (Table 1).

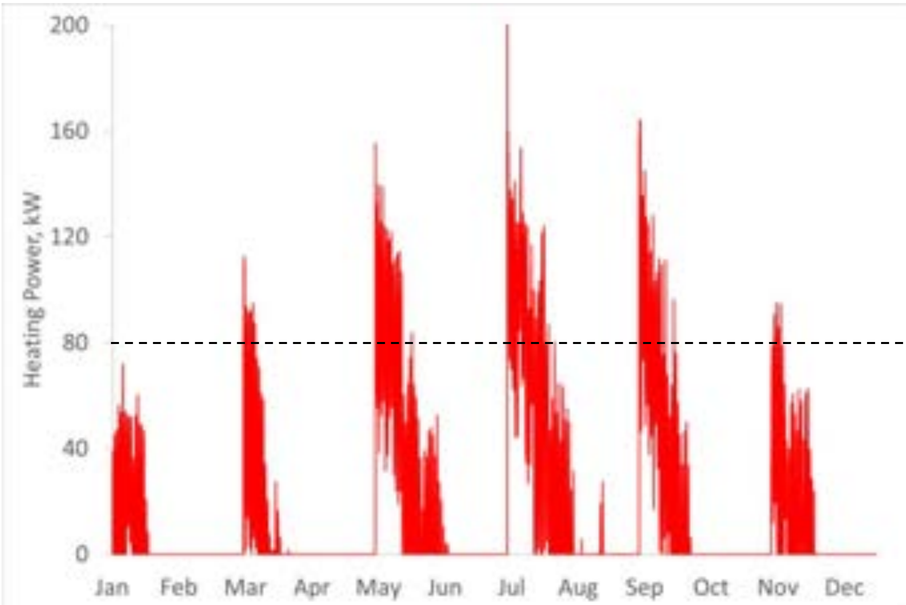

Figure 1 Hourly heating demand of the chicken shed

It should be noted that most of the time, the heating demand of the shed is lower than 80 kW_h (Fig. 1). This means that if a hybrid heating system with an installed GSHP capacity of about 40% (~80 kW_h) of the peak heating power demand is used for heating, more than 86% of the annual heating energy can still be satisfied by the GSHP. This illustrates the advantage of a hybrid heating system as it could satisfy most heating requirement with cost-effective, renewable energy resources with a relatively lower initial capital cost. The next section of the paper discusses such potential operational cost savings of hybrid systems in detail.

3 Annual Heating Cost Analysis of Different Hybrid systems

This section discusses operational costs of different sizing combinations of the hybrid geothermal-gas and geothermal-solar-gas heating systems for the chicken shed presented in previous sections. To describe the capacity portion of the GSHP in the hybrid system, '*shave factor*' is used. It is defined as the ratio of the installed capacity of the GSHP system to the peak heating demand of the load to be satisfied (Eq. 1) by the hybrid system (Alavy et al. 2013; Mikhaylova et al. 2016).

*subscript $_h$ represents heating, while subscript $_e$ represents electricity.

$$S = \frac{\text{Installed capacity of GSHP}}{\text{Peak heating load}} \times 100\,\% \qquad (1)$$

As an example, a shave factor of 40% in a geothermal-gas hybrid (195 kW_h peak load) means that the installed capacity of a GSHP system within a hybrid system is $195\,kW_h \times 40\% = 78\,kW_h$, and the installed capacity of a boiler will be 117 kW_h.

Table 2 presents the system component efficiencies and assumptions used in the analyses. The energy prices used in this study were obtained from the current gas and electricity contracts of the farm owner in NSW (note that gas and electricity prices can be differ for farm to farm depending on the contracts with the suppliers). System energy efficiency of each equipment was assumed based on the equipment currently available on the market in Australia. Annual operational costs of shed heating using a LPG boiler and a GSHP system as well as two types of hybrids with different shave factors were calculated using the annual heating demand presented in Fig. 1 and the assumptions shown in Table 2. It is important to note that for GSHP systems, the energy efficiency is usually expressed in Coefficient of Performance (COP), which is defined as the ratio of output heat power to the input electric power. To be consistent with the LPG system, the performance of GSHP systems are expressed in energy efficiency, where, 300% of energy efficiency means the COP of 3.0. The employments of flat plate solar collector (FPSC) and solar PV will reduce the electricity consumption by improving the efficiency as well as the electricity offset. The results of these calculations are discussed in the following section.

Table 2 Energy Efficiency and Prices of Gas and Electricity for the Systems Investigated

	LPG Boiler	GSHP	Hybrid GSHP+FPSC	Hybrid GSHP+FPSC and Solar PV
System energy efficiency, %	85	300	320	320
Energy source price, c/kWh	7	10	10	10
Solar offset, %	Nil	Nil	Nil	100

3.1 Hybrid Geothermal-Gas Heating System

Fig. 2 shows the annual operational cost of the hybrid geothermal-gas heating system with different shave factors as well as the portions of the heating energy provided by the GSHP system in each sizing combination of the hybrid system. It is apparent from the figure that the maximum and the minimum annual heating costs are expected when the gas-only and the GSHP-only heating systems are used for the shed, respectively. In addition, as the shave factor increases, the annual heating cost decreases. These observations are explained by the higher energy efficiency of the GSHP compare to the LPG boiler (Table 1). At the same time, the increase in the shave factor to more than 50% does not seem to have any significant reduction of the annual operational cost (Fig. 2).

The maximum 60% reduction in operational cost in comparison with the original gas-only system can be achieved when the shave factor of the hybrid geothermal-gas system is 100%. However, with a shave factor of 40%, about 87% of the annual required heating energy can be delivered by the GSHP and the operational cost can be reduced by about 50% compared to the gas-only system. This observation implies that a significant reduction in operation costs may be still achieved with a GSHP system that is half the size of that corresponding to the maximum possible reduction, which in only marginally better.

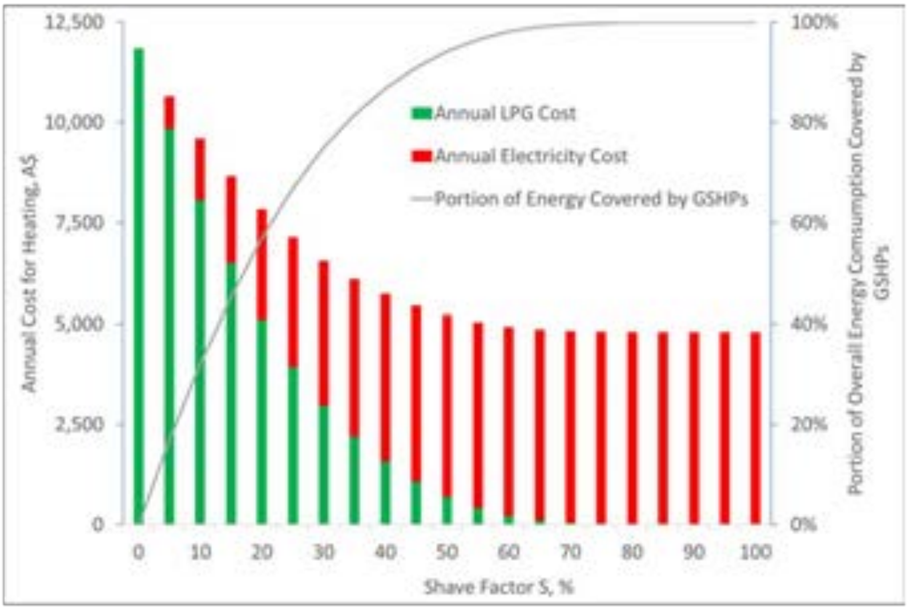

Figure 2 Annual Heating Cost of a Hybrid Geothermal-Gas System

3.2 Hybrid Geothermal-Solar-Gas Heating system

"Solar" may refer to *solar thermal* or *solar photovoltaic* (PV) systems. FPSCs are cost-effective solar thermal collectors that utilise solar energy for heating. Previous studies (Eslami-Nejad & Bernier 2011; Kjellsson, Hellström & Perers 2010) confirmed that with the integration of FPSCs, the performance of the GSHPs can be increased. In this study, based on the work of Kjellsson, Hellström & Perers (2010) in Sweden, it was assumed that the system heating coefficient of performance (HCOP) of solar assisted GSHPs increases from 3.0 to 3.2, with the installation of 7.5 m^2 of FPSCs for 5 kW of heat pump nominal heating capacity.

Solar PV modules are the equipment that can convert solar radiation into electricity. In this study, solar PV modules are proposed to be installed to offset electricity consumption of the heating system for the shed. The PV array is sized to cover all the annual electricity used by the shed hybrid heating system. Hence, with the utilisation of the solar PV array, the cost of electricity for the shed heating system can be completely offset.

With the adoption of FPSCs and solar PV modules, a large amount of operational cost could be saved. Fig. 3 shows the annual operational costs of the different configurations of hybrid geothermal-solar-gas systems for the shed. With the FPSCs and solar PV modules, 50% operational cost reduction in comparison with the original gas-only system can be achieved for a shave factor of only 20%. In addition, with a shave factor of 75%, the annual heating cost can be effectively reduced to zero. It should be noted that as demonstrated in Fig. 3, the high operational cost savings can be achieved using hybrid geothermal-solar-gas heating system, however, this always comes at higher capital investment costs than the capital cost of the gas-only system. The next section discusses the lifecycle costs of hybrid systems to find a balance of capital cost and the operational cost savings.

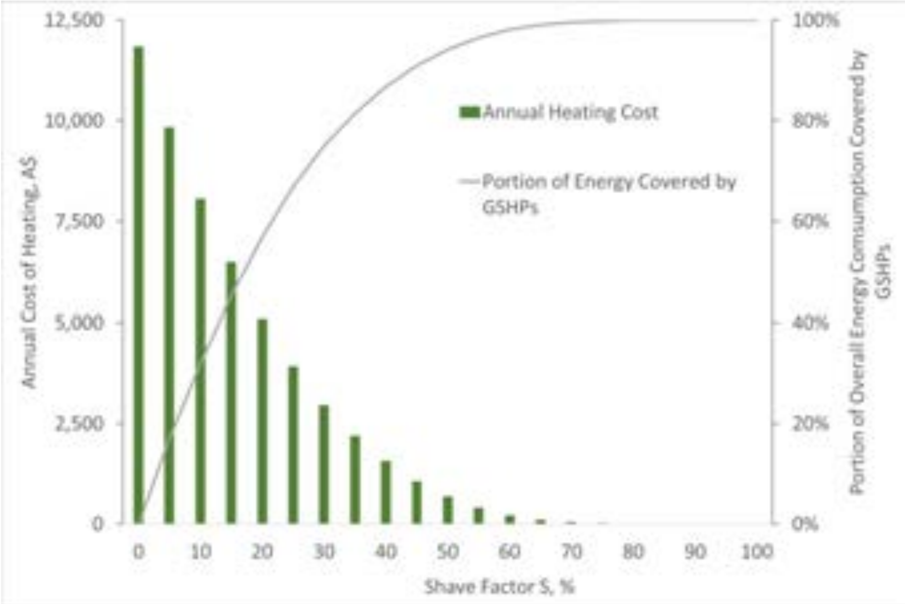

Figure 3 Annual Heating Cost of a Hybrid Geothermal-Solar-Gas System

4 Life Cycle Cost Analysis of Different Hybrid Systems

As discussed in the previous section, with the adoption of the hybrid geothermal-gas heating system, a significant amount of operational cost reduction can be expected (up to 60% as shown in Fig. 2). By employing FPSCs and with electricity offset from solar PV modules, the operational cost can be reduced even further down to zero (as shown in Fig. 3). However, high operational cost savings are often related to high capital investment costs of the systems.

For decision making in balancing initial investment and future return (operational cost savings), various methods have been applied, which include Simple Payback Period (SPP), Discounted Payback Period (DPP), Internal Rate of Return (IRR), External Rate of Return (ERR) and Lifecycle Cost Analysis (LCCA) (Lu et al. 2017). In this study, LCCA is used to guide the optimisation of size of different components of hybrid heating systems for the shed.

LCCA is a financial analysis that evaluates the financial feasibility of a project over a long period (Kirk & Dell'Isola 1995). This analysis considers the net present values of the capital investment cost, operational and maintenance costs and the final disposal cost. In this paper, the life cycle cost of the heating system is calculated using Eq. 2 (Markvart 1994):

$$LCC = C + \sum_{n=1}^{t} C_r \left(\frac{1}{1+d} \right)^n \qquad (2)$$

where, C is the initial capital cost, C_r is the recurring cost in a time period, d is the real discount rate, and t is the project life time in year.

The initial capital costs and life times of different components applied in the analysis are listed in Table 3. These figures are estimated based on average current market data for

the various system components. The costs of LPG heaters, GSHPs and ground loops are calculated per unit heating capacity. The cost of FPSCs is calculated per heating capacity of GSHPs. The cost of solar PV modules is calculated per installed peak electricity generation capacity of solar PV, while the overall installed capacity of solar PV panel is based on the annual electricity consumed by the system. The details regarding the sizing of these components are discussed in Section 5. The current energy prices and the energy efficiency of different components of heating systems were assumed to be the same values as provided in Table 2.

Table 3 Initial Capital Costs and Life Times of Equipment

	LPG boiler	HP	Ground loops	FPSC	Solar PV Modules
Initial Cost, (A$/kW)	100	750	750	A$ 180 per kW_h of GSHPs	A$ 1,250 per kW_p of PV capacity
Life Time, (years)	10	20	40	20	20

In this analysis, the price escalation rate for LPG was assumed to be the same as natural gas, which is 6.14% and the price escalation rate for electricity was assumed to be 6.20% (Lu et al. 2017). It should be noted that these rates were estimated based on the actual fuel prices in Australia from 2000 to 2015. As the project is assumed to be of relatively low risks, the real discount rate in this study is set to be 5.08%, which was derived from the typical current business loan rates of the major banks in Australia.

Fig. 4 shows the 40-year lifecycle costs of different configurations of a hybrid geothermal-gas heating system. As shown in the figure, the minimum lifecycle cost is found to be at the shave factor of 40%. This minimum lifecycle cost is 72% of the cost of the original gas-only system. When the shave factor is larger than 40%, the lifecycle costs of the system are higher than the minimum lifecycle cost because increase in capital investment and replacement costs outweigh reduction in operational costs.

With the adoption of FPSCs and solar PV modules, the minimum lifetime cost of the heating system (Fig. 5) is lower than the minimum lifetime cost of the system in geothermal-gas hybrid configurations (Fig. 4). From Fig. 5, the minimum lifecycle cost of the hybrid geothermal-solar-gas heating system is only 47% of the original gas-only system (A$294,843 vs A$624,277). This minimum cost corresponds to a shave factor of 50%. This considerable amount of saving is achieved due to the near to zero operational cost achieved by electricity offset provided by the solar PV modules (Fig. 3).

The results presented in Fig. 4 and 5 demonstrate that hybrid geothermal-gas and geothermal-solar-gas heating systems can be more beneficial than gas-only and geothermal-only systems. If geothermal-gas and geothermal-solar-gas systems are compared, the results show that geothermal-solar-gas hybrids with solar PV modules to offset the electricity used by heating system can have lower lifecycle cost (up to 53%) and be more financially attractive.

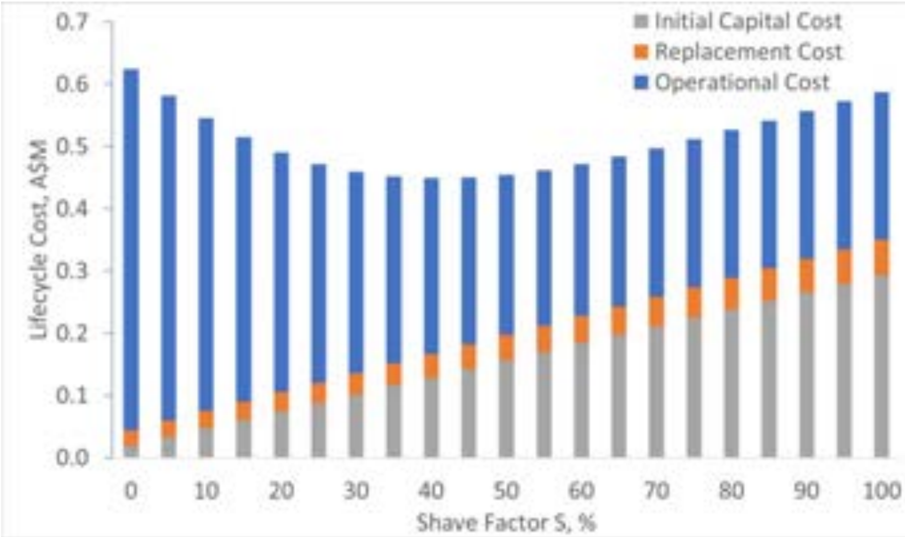

Figure 4 Lifecycle Cost of Hybrid Geothermal-Gas Heating Systems

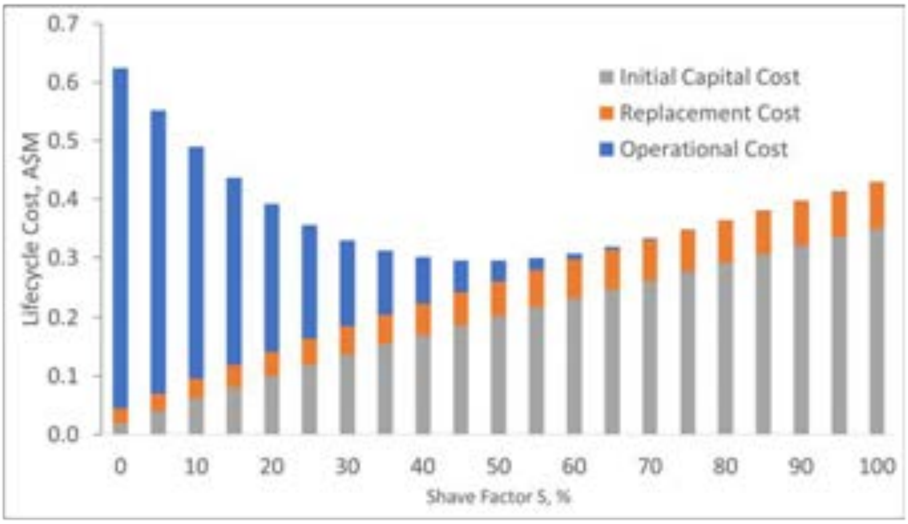

Figure 5 Lifecycle Cost of Hybrid Geothermal-Solar-Gas Systems

5 Future Investigation on Optimum Design for the Hybrid Geothermal-Solar-Gas System

Considering the results of the annual operational cost and lifecycle cost analyses (Figs. 2-5), a hybrid geothermal-solar-gas heating system has been proposed as a cost-effective and energy-efficient alternative to the current heating system of the chicken shed. The lifecycle cost analysis showed that a hybrid system with the shave factor of 50% is the most optimal configuration (Fig. 5) for the set of assumptions made. Such proposed hybrid system will be used for an experimental research of the performance of the system components and for validation of energy and ground heat exchanger models. However, due to budget constraint, an experimental hybrid system with a shave factor of 40% is being installed. Based on the LCCA results in Section 4, 52% reduction in the lifecycle cost can be achieved for a hybrid geothermal-solar-gas system with this shave factor of 40%. This is only 1% less than the maximum cost reduction when the hybrid is sized to the shave factor of 50%. The schematic drawing of the system proposed is shown in Fig. 6.

The heating is delivered by the four identical GSHPs connected in parallel to a main header. Each GSHP is coupled with a series of ground heat exchangers. The GSHPs are assisted by FPSCs connected to the ground heat changers, The FPSCs are designed to contribute to the heating energy extracted from the ground as well as to recharge the ground. The GSHPs are connected to a buffer tank to minimise heat pump on and off cycling. The existing gas burners installed in the shed will top up heating energy when needed.

6 Conclusions

This study evaluated the unique annual heating load pattern of a typical chicken shed in Peats Ridge, NSW, Australia. It proposed an energy-efficient and cost-effective heating system for the shed. Considering the annual heating demand of the shed, two alternative hybrid heating systems for the shed were considered: a hybrid geothermal-gas system and a hybrid geothermal-solar-gas system. For both systems, annual operational cost and lifecycle cost analyses were performed to optimise the sizes of the hybrids' components and determine the most cost-effective configuration of a hybrid. For the geothermal-solar-gas hybrid, solar PV modules are proposed to be installed to supply electricity to offset operational electricity costs of the heating system.

The results of the analyses suggest that both geothermal-gas (up to 28% lifecycle cost reduction) and geothermal-solar-gas (up to 53% lifecycle cost reduction) hybrids can be more economical than the original gas-only heating system of the shed considering the life cycle costs of the systems calculated for the 40-year lifetime of the shed. In addition, the geothermal-solar-gas hybrid heating system sized to 50% shave factor and supported by solar PV modules is the most cost-effective configuration (53% reduction in the life cycle cost) of the heating systems considered for the shed. Based on the analyses conducted, a preliminary schematic of the geothermal-solar-gas system proposed for the shed has been presented. After the installation, this system will be monitored and used as an experimental facility to investigate energy-efficiency of the system components and for validation of energy consumptions and ground heat exchanger models.

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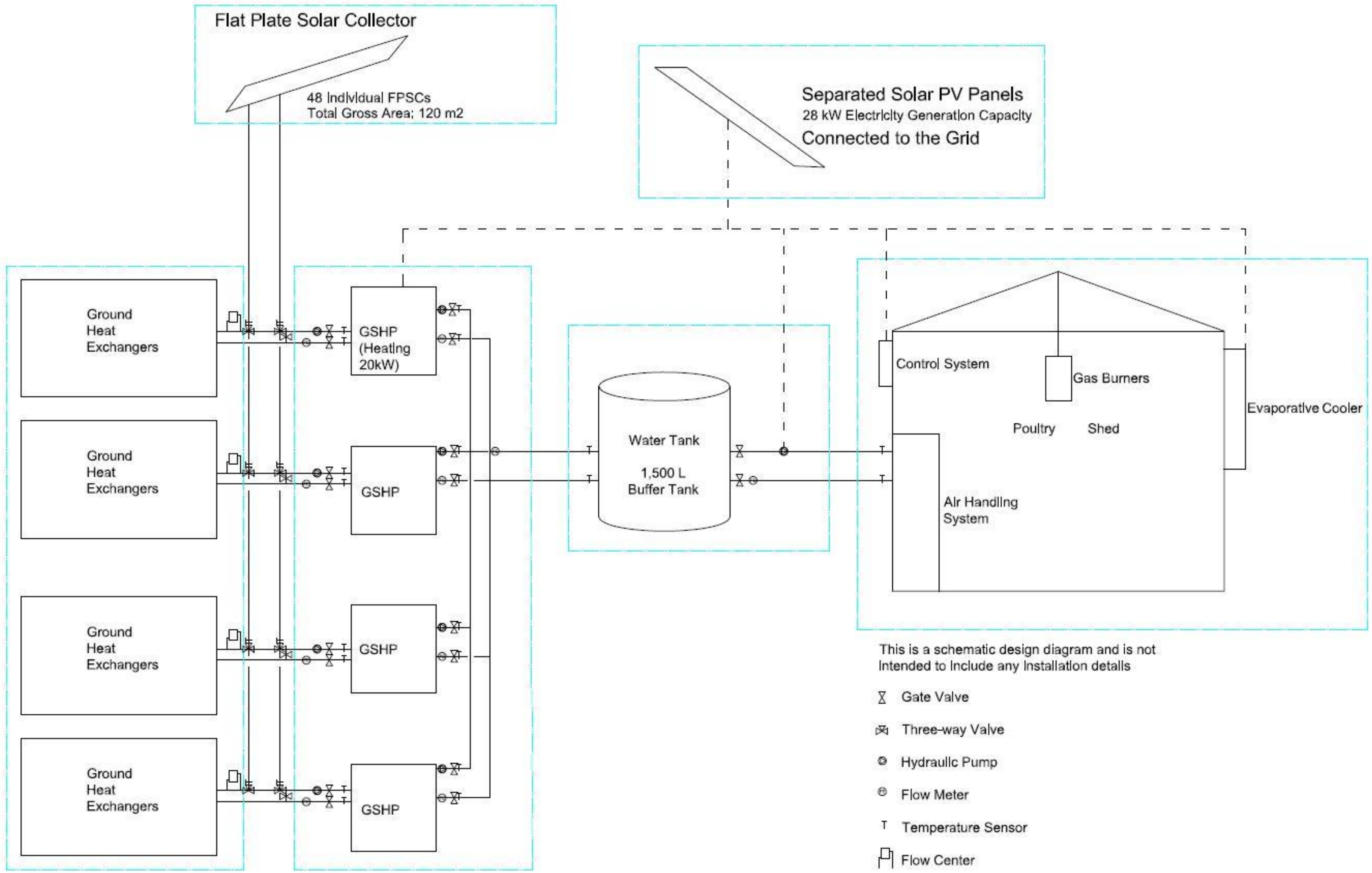

Figure 6 Schematic of a Hybrid Geothermal-Solar-Gas Heating System for the Shed

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HIGH STRENGTH STRUCTURAL GLASS FOR WALK-ON PHOTOVOLTAIC MODULES

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Abstract: *Solar photovoltaic (PV) technology has a great potential to enable zero energy homes. To enable more surface areas without losing the other functionality work-on PV modules have been considered. These modules can be installed on platform walk ways and flat roof tops. To protect PV cells of a module, glass panels have been used for the transparent covering. Majorities of previous studies were mostly about investigating the amount of dust-deposition and transmittance ability of various coated and uncoated glazing panels. The load carrying capacity under work-on conditions has not been substantially investigated. This paper presents an experimental investigation of load carrying capacity of PV modules covered by annealed and toughened glazing panels sizes of 270 mm × 270 mm × 5 mm and 450 mm × 450 mm × 6 mm respectively. A 10 mm thick stainless steel plate was kept underneath the glazing panels to incorporate the effects of the substrate. The glazing specimens were loaded by means of the spherical indenter up to the point of failure. The breaking load was then recorded. A similar experimental procedure was conducted without the substrate material for obtaining the minimum strength capacity. Results show that the load carrying capacities of both types of glazing panels are almost doubled when the substrate material is included in the design. This study serves to verify the importance of selecting suitable types of substrate and superstrate materials in PV modules for maximising its resistance from damage that can be caused by impact by the human body, fallen objects and hail.*

Keywords: *Structural Glass, PV Modules, Steel, Load Capacity*

1 Introduction

As world population had an aggregated increase over the past few decades, (currently total population is approximately 7 billion) energy consumption had also been increased simultaneously. It could result in potential shortage of energy resources for the future generation. The predicted results shows that the production of most of fossil energy resources (e.g. coal, oil, natural gas) will be declined within next 40 to 50 years until depleted (Cotella and Crivello, 2016). Consequently, most of researches have been focused on usage of renewable energy resources such as solar energy, wind power, wave and tidal power, etc. Solar energy is distinctive among other renewable energy resources as capturing of 0.02 % of solar power falls on earth would be sufficient in order to meet requirements of world's current energy consumption (Tester et al., 2012). Photovoltaic (PV) module is one of the most efficient technologies to capture the solar energy and has proven its capability and effectiveness on generating of electricity over the other conventional electricity generation methods. Importantly, it consists of special features such as direct conversion of solar radiation into electricity, reduction of greenhouse gas (GHG) emission, easy installation and maintenance, and cost effectiveness.

A PV module consists of mainly five layers as shown in Figure 1. Solar cells are usually laid over the encapsulant and substrate materials such as stainless steel, polymers, tiles or glass (Águas et al., 2011; Ke et al., 2013; Tao et al., 2010). The important aspect which should be considered when choosing a substrate material is the lesser absorption of the red spectral range in solar radiation as possible (Shah et al., 2006). Glass is used as the top covering surface of solar cells because of its superior optical transmission ability. The glass panel protects the solar cells from the inclemencies of weather and the direct impact of dust particles. Conversely, it reduces the efficiency of the solar panel due to losses of reflection and radiation absorption (Sánchez Illescas et al., 2008).

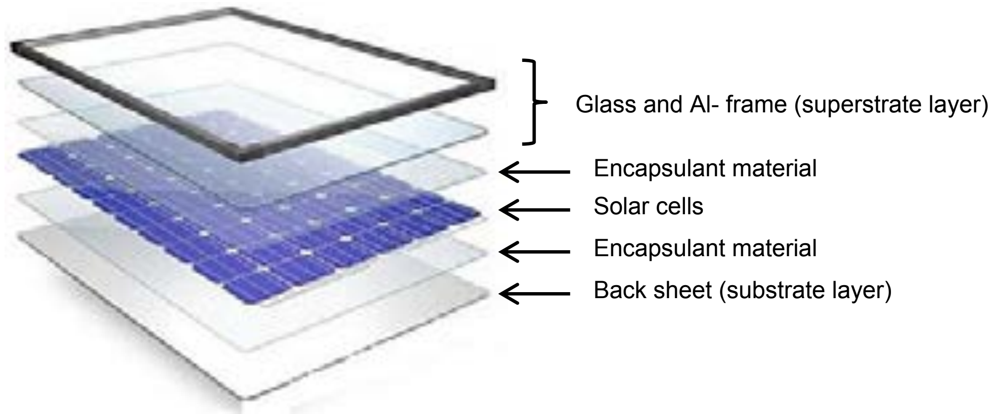


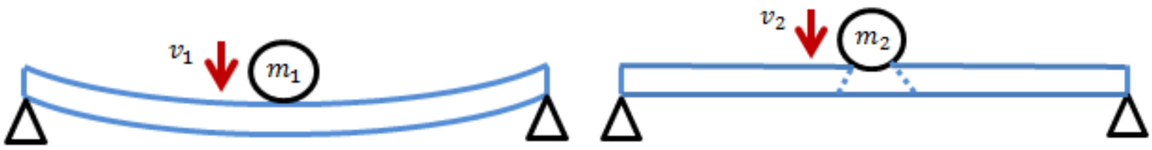
Figure 1. Structure of a PV module (DuPont, 2017)

Many previous studies on improving solar radiation transmission ability and the effect of airborne dust deposition on the glazing panels were conducted (Jiang et al., 2011; Said and Walwil, 2014; Sánchez Illescas et al., 2008; Scheydecker et al., 1994). There are few studies found in the literature on investigating the strength of PV modules over the impact of sand particles on the glass surface (Humood et al., 2017). Testing guidelines are stated in IEC61215-1 (2016) and IEC61215-2 (2016) for checking the strength of PV modules against the impact of hailstones. However, these impact experiments are limited to determining the qualitative behaviour (pass or fail criteria) of the PV module based on the provided testing guidelines. The key shortcoming of an impact test by the

gas gun is that the test gives no information on the resistant capacity of the specimen in comparison with the estimated impact action. Particularly, it was ascertained that under the same kinetic energy conditions impact force generated by different geometries of projectiles are different (Perera et al., 2016). Moreover, walking on PV modules is not recommended during construction or maintenance activities as there are no available guidelines to design the PV modules for walking conditions. Walking on current available PV modules can damage solar cells and which may result in great loss of its performance (Spertino et al., 2017).

PV modules are generally installed on the building envelopes such as outside walls, rooftops, atria. They can provide electricity as well as sun-shading function (Martínez et al., 2016). However, the space utilisation has not been taken into consideration when PV modules are installed into flat roof tops as current PV modules are not designed for the damage that can be caused by impact by the human body and fallen objects. This is a main drawback as maximum usage of space in a building is also an important factor.

The important element of a PV module when designing against the damage that can be caused by people or large objects is the top layer which is usually made of glass. Glass panels have a certain amount of resisting capacity against the impact loads. The specified load carrying capacity of toughened glazing panels is 120 MPa (Haldimann, 2006). However, the failure strength of a glazing panel varies substantially from specimen to specimen because of the inherent micro cracks in the surface (Griffith, 1921). Two types of failure modes namely flexural failure and Hertzian type of fracture can be identified in a glazing panel based on the size and thickness of the target and, severity of the force generated at the point of the contact and the support respectively (Figure 2) (Shinkai, 1994). In flexural failure mode, the fracture always starts from the opposite side to the impact and cracks radially propagate from the point of impact. This type of failure usually occurs when the glass plate is thin or the impact action is slow. In contrast, Hertzian failure pattern usually occurs with an impact of small projectiles on a glazing specimen and/or for high speed impact conditions. A hole is formed at the point of impact and radially propagating cracks are produces from the hole (Shinkai, 1994).



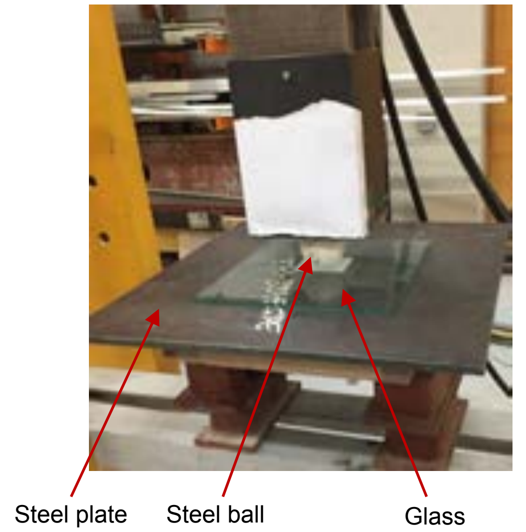
(a) Flexural failure mode (b) Hertzian failure mode

Figure 2. Fracture mechanisms of a glazing panel

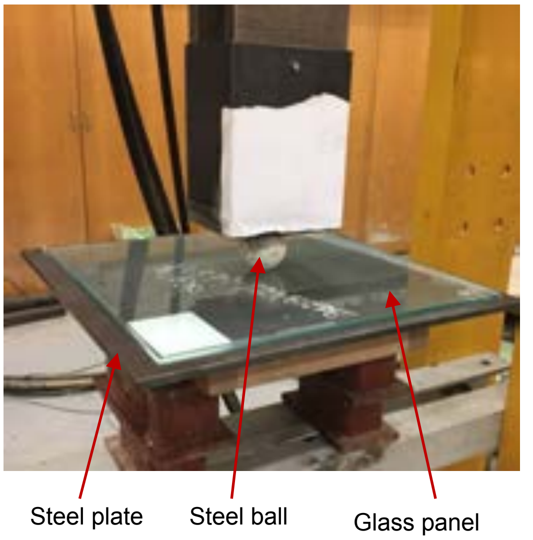
This paper presents an experimental investigation of strength of PV modules when subject to the point loading conditions. The loading capacity of a PV module mainly depends on the strength of top and bottom layers. In this study, two types of glazing panels (annealed and toughened) have been used for the top layer whereas a stainless steel plate was used for the substrate layer. Glazing specimens of size 270 mm × 270 mm × 5 mm (annealed) and 450 mm × 450 mm × 6 mm (toughened) were loaded by means of a spherical indenter up to the point of failure and the breaking load was recorded. Then, the breaking load was compared with the amount of ground reaction forces that can be generated by people walking or running on the PV modules. Experiments have also been conducted without the substrate layer in order to check the minimum strength of PV modules. The findings of both experimental investigations may be successfully used as a guideline to design a new PV module at its optimum load carrying capacity conditions (required strength vs cost of production).

2 Experimental setup

Quasi-static experiments have been conducted to identify the failure loads of PV modules covered by annealed and toughened glass specimens. The entire test setup is shown in Figure 3 for both types of glazing panels. Specimens of glazing panels of size: 270 mm × 270 mm × 5 mm size (annealed) and 450 mm × 450 mm × 6 mm size (toughened) were tested at a loading rate of 10 mm/min. A stainless steel plate of size: 500 mm × 500 mm × 10 mm was kept underneath of the glazing panels to incorporate the effect of the substrate material. All specimens were simply supported on a wooden frame on four sides, and subjected to a concentrated point load positioned at the centre of the specimen using a 62.5 mm in diameter steel ball by means of a 500 kN MTS machine. The mechanical properties of the glass specimens and the steel ball are listed in Table 1. It should be noted that the experiments were conducted by involving only the top and bottom layers of a PV module. The actual strength of PV modules should be higher than that of the tested specimens as the load bearing capacity of PV modules is well related to the other materials such as two layers of encapsulating material. Hence, the presented testing methodology in this study is conservative from the designer's perspective.



(a) For 270 mm × 270 mm × 5 mm size annealed glazing panels



(b) For 450 mm × 450 mm × 6 mm size toughened glazing panels

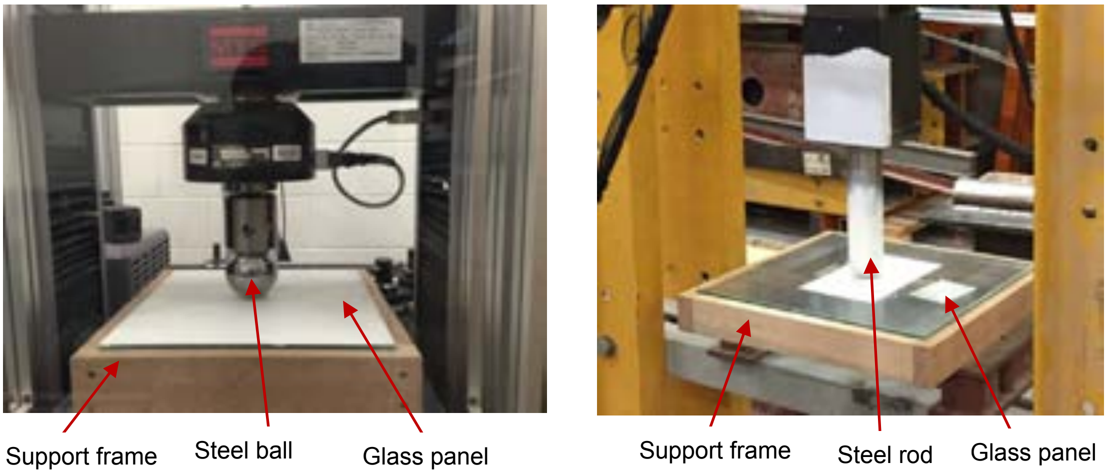
Figure 3. Experimental setup with substrate layer

Table 1. Properties of the soda-lime glass specimen and the steel ball

Object Description	Density (kgm^{-3})	Poisson's ratio	Young's modulus (GPa)	Fracture toughness (MPam$^{0.5}$)
Soda-lime glass	2500	0.23	68.5	0.75
Steel	7850	0.29	200.0	-

Experimental test programmes were also conducted to investigate the failure load of glazing panels without the substrate layer. The main objective of the current experiments is to check the minimum load carrying capacity of PV modules. Same size of glazing specimens were simply supported on a wooden frame. A 62.5 mm in diameter steel ball and steel rod were used to apply the point load on a standard MTS machine on annealed and toughened glass panels respectively. The area exposed to the loading was 250 mm × 250 mm (annealed) and 430 mm × 430 mm (toughened). All specimens

were tested at a loading rate of 600 mm/min to determine the failure loads in probabilistic terms. The experimental setup is as shown in Figure 4.



(a) For 270 mm × 270 mm × 5 mm size annealed glazing panels

(b) For 450 mm × 450 mm × 6 mm size toughened glazing panels

Figure 4. Experimental setup without substrate layer

3 Results

Total, four (annealed), and six (toughened) glazing panels were tested with the substrate layer of stainless steel plate at a loading rate of 10 mm/min. The cumulative probability distribution (CPD) of failure loads in both types of glazing panels were developed according to the *Log-Normal* distribution function (Figure 5) by the use of Minitab statistical software (Minitab Inc, 2014). Figure 5 shows that the capacity of toughened glazing panels is almost two times of the capacity of annealed glazing panels.

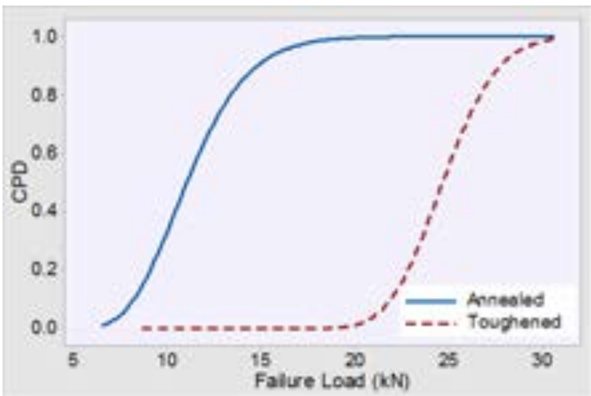


Figure 5. CPD of failure loads of both annealed and toughened glazing panels with substrate layer

Two broken specimens under each type of the glazing panels are shown in Figure 6. The recorded breaking load of these specimens for annealed and toughened were 9.5 kN and 25.1 kN respectively showing significant differences.

In total eleven (annealed), and eight (toughened), glazing specimens have also been tested at a loading rate of 600 mm/min without the substrate layer. The CPD curves of failure loads have been developed for both types of glazing panels as shown in Figure 7. It can be observed that when the substrate layer was removed the capacity of the glazing panels was decreased significantly (from Figure 5 and Figure 7). In addition, the

average strength increment is almost double when the type of glass is changed from annealed to toughen.

(a) Annealed glazing panel failed at 9.5 kN load

(b) Toughened glazing panel failed at 25.1 kN load

Figure 6. Images of two broken specimens with substrate layer

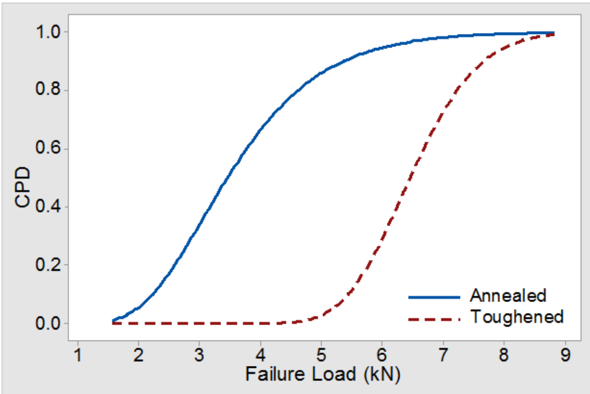
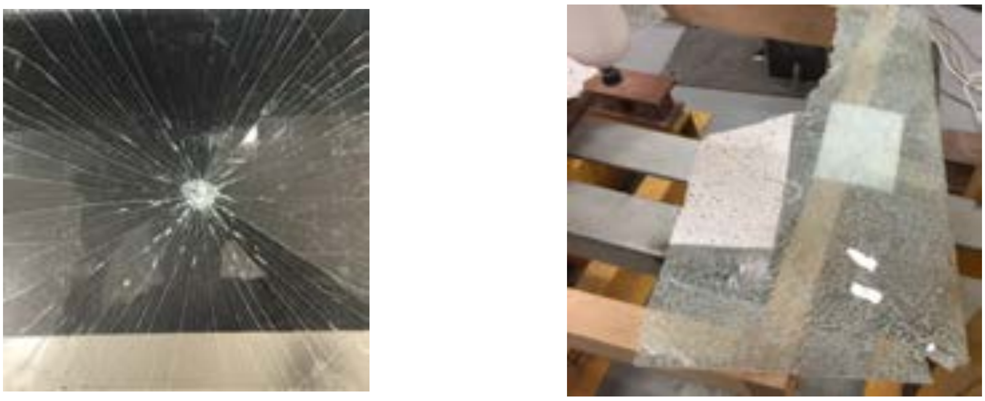


Figure 7. CPD of failure loads of both annealed and toughened glazing panels without substrate layer

Failure patterns of two broken specimens under each type of glass panels are shown in Figure 8 with respective failure loads. The number of radial cracks that are developed in annealed glazing panel with the substrate layer (Figure 6a) is less than the number of radial cracks developed without the layer (Figure 8a). The significant variation of this radial cracks is because the glass specimens are failed by Herzain type of fracture when the substrate material is used. The radial crack pattern is not obvious in toughened glass panels at failure as it breaks into thousands of tiny particles. The dominant failure pattern of glass panels with the substrate layer has been further investigated by comparing the deflection values at failure.

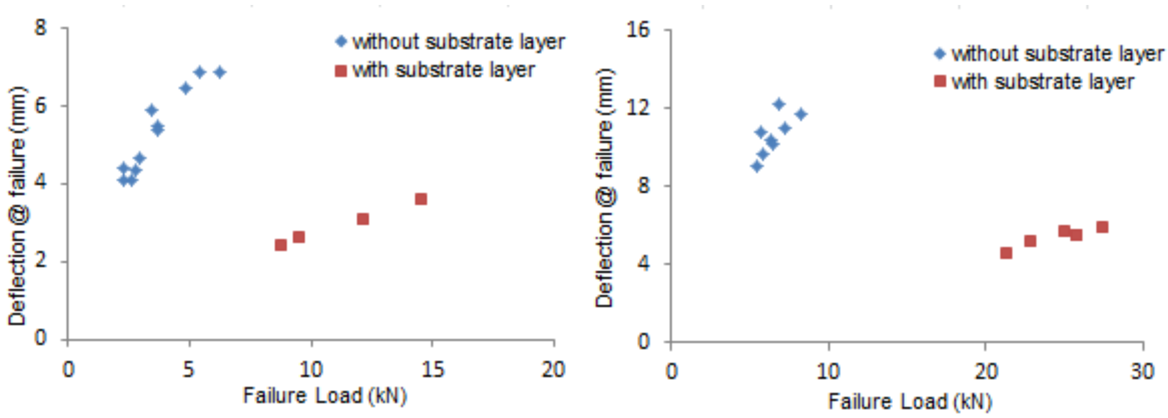
Glass specimens typically fail by flexural stresses (which is proportional to the value of deflection at the centre) under the quasi-static point loading conditions. The deflection values for specimens without substrate layer in Figure 9 are related when glass failed by flexure. It should be distinguished that all the recorded deflection values at failure with the substrate layer are less than the deflection values recorded without the substrate layer. Thus, glass specimens with substrate layer failed by punching (Hertzian type of fracture) due to the stresses developed at the point of load application. However, the glass panel with the substrate layer can withstand against a higher amount of load than the recorded failure load when it fails by bending as the glass panel (with substrate

layer) is required to deflect more than 4 mm and 8 mm for the failure initiated by flexure in annealed and toughened glazing panels respectively.



(a) Annealed glazing panel failed at 2.2 kN load (b) Toughened glazing panel failed at 3.5 kN load

Figure 8. Images of two broken specimens without substrate layer



(a) Annealed glass panels (b) Toughened glass panels

Figure 9. Deflection at the centre point of the glazing panel at failure

4 Discussion

Experiments were conducted in order to examine the strength of PV modules covered by two types of glazing with and without the substrate layer. In this section, the recorded failure loads have been adopted to compare the ground reaction forces that can be generated by people walking or running on PV modules.

The average value of ground reaction force generated by a person walking and running (at 6 ms^{-1} speed) on a floor is equal to be 1.5 times and 3 times of the body weight respectively (Nilsson and Thorstensson, 1989). The value of the ground reaction force developed by a person weight of 75 kg is estimated to be 1.1 kN (walking) and 2.2 kN (running). The minimum capacity of a PV module covered by toughened glazing specimens (with or without the substrate layer) is higher than the calculated ground reaction forces either in walking or running conditions. Thus, the probability of failure a PV module which is covered by 6 mm thick toughened glazing specimens is zero. When the PV modules are covered by annealed glazing panels (without the substrate material) the probability of failure by walking and running are 0 % and 10 % respectively. However, when the effect of substrate layer is considered the probability of failure becomes zero. The comparison of the results spectacles that the selection of type and

the thickness of the covering glazing panel, and the thickness of the substrate material is very imperative when designing a PV module against walking or running purposes.

Another important consideration is the slip resistance of the top glazing panel, especially when the module is wet with water. Slip resistance can be achieved by enamelling of the floor plate or by textured by sand blasting or acid etching, but these treatments reduce the solar radiation transmissivity of the glass panel (Institution of Structural Engineers, 2015). However, Said and Walwil (2014) found that the transmissivity of an anti-reflective coated glass is higher than the uncoated one. The rational is coated glass has higher surface roughness and which will not reduce the amount of irradiance (Duell et al., 2010). Therefore, anti-reflective coating of the top surface of a glazing panel increases both the surface roughness and transmissivity for solar radiation. We recommend undertaking a future study to investigate the improvement on slip resistance, solar transmissivity and the power output of PV modules with anti-reflective coatings. In addition, further experiments are also recommended to conduct by varying the thickness of the glazing panel and the substrate material to introduce a new PV module which is suitable for walking and running conditions without losing the performance of solar cells at a minimum product cost.

5 Conclusions

In this paper, the load carrying capacity of PV modules was investigated. Experiments were conducted on annealed and toughened glazing panels sizes of 270 mm × 270 mm × 5 mm and 450 mm × 450 mm × 6 mm respectively. A 10 mm thick stainless steel plate was kept underneath of the glazing panels to incorporate the effect of substrate material. Results show that the probability of failure of PV modules covered by toughened glazing panel is zero for both walking and running conditions whereas for annealed glazing panels is 0 % and 10 % for walking and running conditions respectively. When the substrate layer is incorporated the probability of failure becomes zero for both types of glazing specimens.

This is a significant investigation given that most of the currently available studies are related with the effect of dust deposition and improvement of solar transmissivity of PV modules. In contemporary design codes, checking the strength of PV modules under the walking or running conditions has not been clearly stated. Thus, the initial experimental results of this study may be successfully used as a guideline to design a new PV module which has a sufficient capacity against the damage that can be caused by the human body and fallen objects.

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COMPARISON OF THE QUANTITATIVE EVALUATION SYSTEM BETWEEN ESGB AND EEWH

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Abstract: *The Green Building Rating Tool (GBRT) is the cornerstone of the green building development. In China, the national GBRT named Evaluation Standard for Green Building was enacted in 2006 and updated in 2014 with the establishment of the quantitative evaluation system (QES) (abbreviated as ESGB 2014). Currently, a large number of comparative studies were mainly focused on evaluation contents in four levels, labeled as the general, category, criterion, and indicator comparison, instead of the quantitative evaluation system (QES). Thus, this paper seeks to comparatively study on QES between ESGB and EEWH, the GBRT adopted in Taiwan, so as to fill this research gap partially, and the up-to-date version of two GBRTs (ESGB 2014 version and EEWH 2015 version) were chosen as the two samples. Five steps were conducted in this study, including the confirmation of similarity of two GBRTs' QES, comparison of rating system (RS), Comparison of score conversion system (SCS), discussion, and propose suggestions. Based on those works, two enhancing suggestions for ESGB's QES were offered: 1) It is suggested ESGB increase the number of certified grades gradually, replacing its three-levels rating system by a four or five grades one; 2) An index reflecting the "environmental load" is strongly recommend to be developed and utilized by ESGB.*

Keywords: *Green Building Rating Tool, GBRT, Quantitative Evaluation System, QES*

1 Introduction

1.1 Research background

As the negative environmental influence of building industry has awakened considerable attention, the "Green Building" movement is gaining momentous, which directly promotes the dramatic development of the Green Building Rating Tool (GBRT). GBRT is an effective tool to assess the impact of building on the environment (Huo et al. 2017; Wu et al. 2016) and evaluate the "Green Building", hence, dozens of GBRTs including BREEAM, LEED, CASBEE, and others, have been built worldwide to facilitate the development of green building (AbdelAzim et al. 2017). In China, the Ministry of Housing and Urban-Rural Development (MOHURD) issued a GBRT in 2006, named Evaluation Standard for Green Building (MOHURD 2006), and updated this standard with the establishment of the quantitative evaluation system (QES) in 2014 (abbreviated as ESGB) (MOHURD 2014).

1.2 Current research gap

Lots of comparison studies (Zhang et al. 2017; Li et al. 2017) among ESGB and other world-leading GBRTs such as BREEAM and LEED have been conducted, in order to improve ESGB. However, the comparisons were primarily focused the on evaluation contents in four levels, labeled as the general comparison, category comparison, criterion comparison, and indicator comparison (Li et al. 2017), and a few attention was placed on the quantitative evaluation system (QES). Obviously, more emphasis needs to be placed on QES, because that the quantitative evaluation is less likely to be impacted by the subjective judgment relative to the qualitative evaluation. Thus, quantitative assessment approach is strongly suggested by some world leading GBRTs, such as BREEAM, the earliest established GBRT in the world, adopted " Use quantified measures for determining environmental quality" as one of the basic development principles" (BRE 2014).

1.3 Comparative study case choosing

For the comparative study case selection, a GBRT utilized in Taiwan named EEWH is a suitable peer for ESGB, which can be evidenced by, at least, two reasons: 1) EEWH is a relatively mature system with QES, which was built from 1999 with 7 times revision till now (Fig. 1) and included QES since 2005 with 4 times revision until now (Chang 2012) (Tab. 1). In this context, EEWH's QES is much mature than ESGB (establishing QES in 2014 without revision). Additionally, the Tab. 1 illustrates the comparison of some general information between ESGB and EEWH. 2) The EEWH's development experience matches the needs of ESGB better relative to some western GBRTs, such as BREEAM and LEED. Reportedly, according to studies, Asians on average are thinner and shorter than Westerners, which directly lead to the default occupancy levels of ESGB are much higher than the other schemes (Lee 2012). In this context, the development experience of EEWH in line with ESGB's upgrading demands better compared to the GBRTs established by westerner world. In addition, ESGB and EEWH are established under same Chinese cultural context and similar lifestyle. Bearing in mind the magnitude impact of culture and lifestyle to the understanding of green building,

Figure1: The establishment timetable of major global GBRTs

Table 1: Basic comparison between EEWH and ESGB

Name of GBRTs	EEWH	ESGB
Established year	1999	2006
Revision times	7 times	Once
Revision years	2001, 2003, 2005, 2007,2009, 2012, 2015	2014
Including QES year	2005	2014
QES revision times	4 times	None

EEWH deserves more attention in order to support the polishing of ESGB. However, currently, most studies have ignored EEWH, for instance, a study(Li et al. 2017) published in 2017 which seeks to systematically review the existing literature on green building assessment methods didn't contain any content associated with EEWH. Furthermore, a review article published in 2014 (Zuo and Zhao 2014), which focuses on the critical review of the existing body of knowledge of researchers related to green building, didn't mention any information related to EEWH at all.

Overall, this study seeks to comparatively study on the QES between ESGB and EEWH and offer some improvement suggestions to ESGB ultimately. The primary contributions of this study are: 1) serving as the key input and information for authorities of QES in GBRTs and 2) providing a useful reference to the evolving of QES related to the green buildings that may be applicable in other contents.

2 A brief introduction of ESGB and EEWH

2.1 ESGB

In China, the Chinese GBRT titled as a national standard (Evaluation standard for green building) (ESGB 2006) was enacted by MOHURD in 2006 (MOHURD 2006) with 6 indicator groups, embracing conservation of land and outdoor environment, energy conservation and energy utilization, water saving and water resource utilization, material saving and the material resource utilization, indoor environment quality and operation management. Subsequently, this early form was revised in 2014 (MOHURD 2014) with the official addition of one more indicator group (construction management) and the establishment of QES. From the Tab. 2, the discrepancy of the green building rating standards between two versions of ESGBs is not hard to be observed. For instance, the rating standard of ESGB 2014 is relatively simple, which mainly relies on "the total score", marked as T_S in this paper. Specifically, in ESGB 2014, on the condition of meeting prerequisite, the green building grade dependents entirely on the score interval that T_S suited in (MOHURD 2014), shown as Tab. 2. On the contrary, the rating standard of ESGB 2006 is relatively complex, which asks to meet least indicator number of 6 indicator group respectively (MOHURD 2006) since it lack of the QES (Tab. 2).

2.2 EEWH

In 1999, the highest advising agency of architectural research and development (ABRI) established the EEWH (the Taiwan's GBRT), which is abbreviated from the evaluation aim of Taiwan's green building: ecology, energy saving, waste reduction and health. Based on the studies into Taiwan's subtropical climate and the energy use, water supply, sewage discharge and environmental conservation patterns of local buildings, seven indicator groups including Greenery, On-site Water Retention, Daily Energy Saving, CO2 Reduction, Construction Waste Reduction, Water Resource and Sewage & Garbage Improvement were set in this initial version of EEWH. Subsequently, this early version was updated in 2002 and added two more indicator groups, named Biodiversity, and

Indoor Environment. Till then, EEWH was developed as a novel system with nine indicator groups. In 2011, the EEWH family was built by the National Cheng Kung University, so as to tailor to the discrepancies between different types of buildings. Meanwhile, ABRI amended the original version of EEWH (1999 Evaluation Manual for Green Building) and re-named it as the EEWH-BC (Basic Category). On the foundation of the basic version, the specific versions of other four building categories, named EEWH-EC (Ecological Community, 2009), EEWH-GF (Green Factory, 2010), EEWH-RN (Renovation, 2010) and EEWH-RS (Residential, 2011), were enriched to the initial framework of the EEWH family, which embraces five specific schemes currently. The applicable subjects of those five specific systems are detailed in the Tab. 3.

Table 2: Comparison of green building rating method between ESGB 2006 and ESGB 2014

Version	Prerequisites	Rating standards: Type	Rating standards: Evaluation content		Green building grade: One-star	Two-stars	Three-stars
GB/T 50378-2014	Meeting the requirement of whole control items and the score of each item group is no less than 40 points	——	Conservation of land and outdoor environment; Energy conservation and energy utilization; Water saving and water resource utilization; Material saving and the material resource utilization; Indoor environment quality; Operation management; Construction management		50≤Ts < 60	60≤Ts <80	80≤Ts
GB/T 50378-2006	Meeting the requirement of whole control items	Residential building	General items (40 indicators)	Conservation of land and outdoor environment (8 indicators)	4	5	6
				Energy conservation and energy utilization (6 indicators)	2	3	4
				Water saving and water resource utilization (6 indicators)	3	4	5
				Material saving and the material resource utilization (7 indicators)	3	4	5
				Indoor environment quality (6 indicators)	2	3	4
				Operation management (7 indicators)	4	5	6
			Outstanding items (9 indicators)		—	3	5
		Public building	General items (43 items)	Conservation of land and outdoor environment (6 indicators)	3	4	5
				Energy conservation and energy utilization (10 indicators)	4	6	8
				Water saving and water resource utilization (6 indicators)	3	4	5
				Material saving and the material resource utilization (8 indicators)	5	6	7
				Indoor environment quality (6 indicators)	3	4	5
				Operation management (7 indicators)	4	5	6
			Outstanding items (14 indicators)		—	6	10

Table 3: The members of EEWH family and their corresponding applicable subjects

Type	Specific EEWH Scheme	Applicable Subjects
Ⅰ	EEWH-BC (Basic Category)	Any new or existing buildings not covered in types Ⅱ, Ⅲ and Ⅳ listed below
Ⅱ	EEWH-RS (Residential)	New or existing buildings for accommodating specific groups for long or short terms
Ⅲ	EEWH-GF (Green Factory)	New or existing factories with primarily indoor operations
Ⅳ	EEWH-RN (Renovation)	Existing buildings which have obtained an occupancy permit for three years or more and with a renovated floor area not exceeding half of floor area of the existing building
Ⅴ	EEWH-EC (Ecological Community)	Neighborhood community units, newly developed residential communities, existing residential communities, agricultural ore aboriginal villages, science parks, industrial parks, campus towns, commercial areas and mixed-use residential/commercial communities

2.3 Version selection of ESGB and EEWH

The newest version of two GBRTs -ESGB (2014 version) and EEWH (2015 version)- was selected as samples for comparative study, in order to ensure the timeliness of this study. It is notable that, as illustrated in Tab. 3, the EEWH family (2015 version) embraces five members. Bearing in mind that EEWH-BC is the basic edition and other four specific schemes, EEWH-EC, EEWH-GF, EEWH-RN, and EEWH-RS, are established on the foundation of EEWH-BC. Therefore, EEWH-BC (2015 version) was chosen as the peer of ESGB (2014 version) in the following comparison, since EEWH-BC is the most typical one among five. In brief, ESGB (2014 version) and EEWH-BC (2015 version) were selected as two samples for comparison in this paper and marked as ESGB and EEWH respectively in the following chapters, to simply express.

3 Methodology

As shown in Fig. 2, five steps will be conducted in this study. Firstly, the similarity of QES between ESGB and EEWH will be verified to ensure the feasibility of the comparison on QES. Secondly, the comparison of rating system (RS) was conducted, with the main focus on the RS's number of certified level. Thirdly, similarly, the comparison of score conversion system (SCS) was also conducted subsequently, which primarily emphasized on the discrepancies of score conversion formula. Additionally, the differences in those two perspectives (RS and SCS) were discussed and, on the foundation of the discussion, some enhancing suggestions were proposed for ESGB's QES finally.

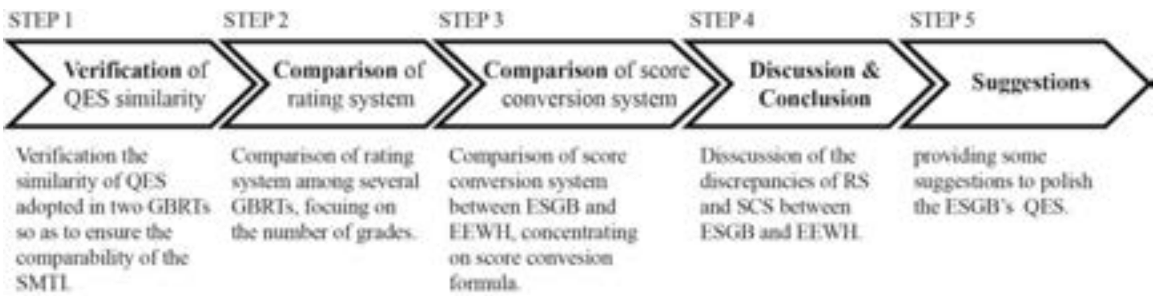

Figure 2: Comparison flow of the QES between ESGB and EEWH

4 Comparison of QES between ESGB and EEWH

4.1 The comparability validation in QES between ESGB and EEWH

As illustrated in Fig. 3 and Fig. 4, a similar hierarchical structure was utilized in both ESGB and EEWH's EQSs and matched with the model of Analytical Hierarchy Process (AHP)(Zahedi 1986 and Saaty 1980). AHP, developed by Thomas L. Saaty (Ali 2009), is a structured technique for organizing, formulating and analyzing complex decisions, based on matrix algebra and psychology (Chang et al. 2007 and Saaty 1990)."The hierarchical structure used in formulating the AHP model can enable all members of the evaluation team to visualize the problem systematically in terms of relevant criteria and sub-criteria"(Saaty 1990). The establishment regulation of this hierarchy model is mainly relied on decomposition (Chang 2012). To be specific, the initial step is decomposing the evaluation goal to several criteria under some specific rules, and a similar process will be conducted in the second and other steps to break down those criteria to the indicators suit in next level repeatedly, until obtaining a series of terminal indicators (TI) ultimately. "Each level in the hierarchy corresponds to the common characteristic of the elements in that level" (Saaty 1990). In addition, notably, The TIs didn't be reflected in both Fig. 3 and Fig. 4, in order to simply diagram. Actually, each indicator category located at Level 3 in Fig. 3-4 is also a similar hierarchy system where the TIs locate in the bottom level and each indicator category embraces several corresponding TIs. The similar QES structure utilized in two GBRTs ensure the feasibility of SMTI comparison between ESGB and EEWH followed. Furthermore, based on Fig. 3-4, it can be concluded that the QESs of ESGB and EEWH are similarly composed of three sub-systems, embracing the rating system (RS), score conversion system (SCS) and quantitative scoring system of terminal indicators (QSSTI), shown in Fig. 5, the research scope of this study is limited to the first two sub-systems of QES with yellow color in Fig. 5, since they directly determine the reliability of evaluation results of GBRTs.

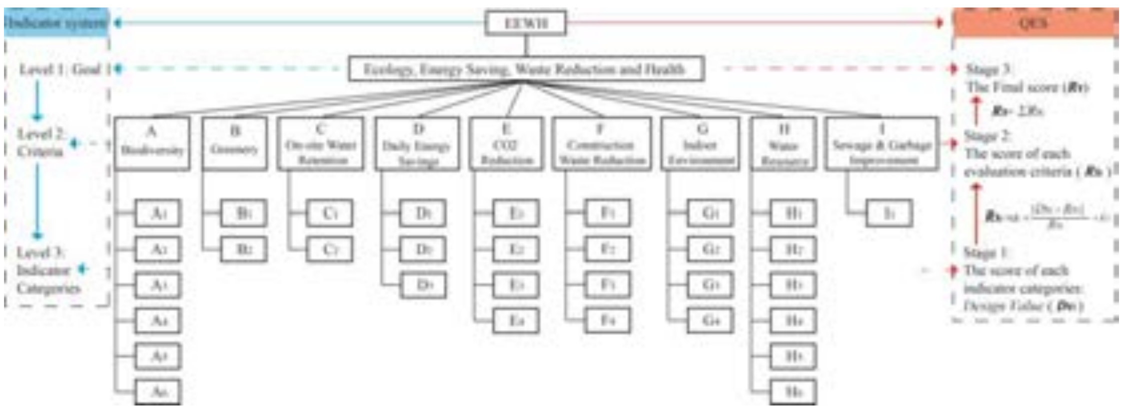

Figure 3: The diagram of hierarchical structure model of indicator system and QES in EEWH

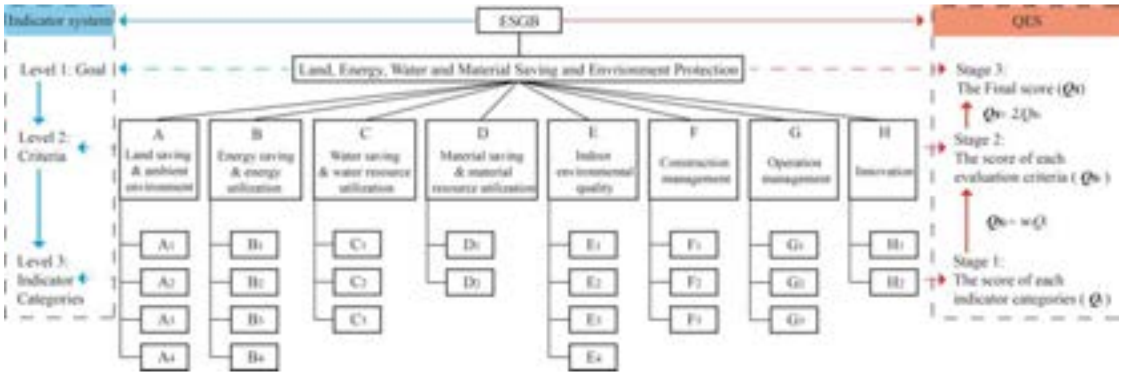

Figure 4: The diagram of hierarchical structure model of indicator system and QES in ESGB

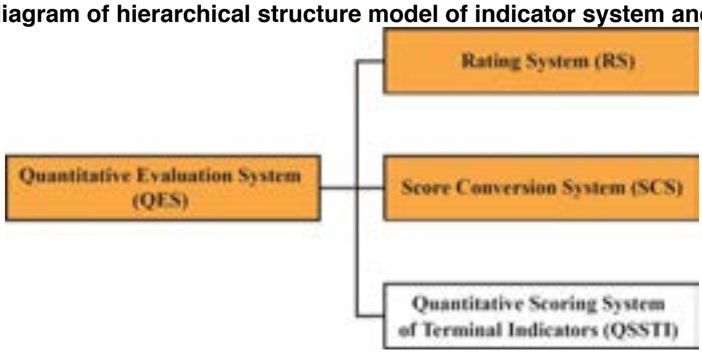

Figure 5: The structural diagram of QES's three sub-systems

4.2 Comparison of rating system between two GBRTs

As illustrated in Tab. 4, the Rs of ESGB and EEWH are established on the one-to-one mapping regulations. To be specific, two one-to-one mapping criteria were built between the green building grades, the final assessment outcomes of two GBRTs, and thresholds of "total scores" in ESGB and EEWH respectively. In other words, the "total scores" of two GBRTs is the decisive parameter to determine the grade of green building, which was marked as Ts and Rs in ESGB and EEWH correspondingly. In addition, Even though the discrepancies of thresholds of "total scores" between ESGB and EEWH is prominent (Tab. 4), It is unreasonable to discuss this difference directly, since the acceptable numerical comparison of threshold should based on some prerequisites, such as unified indicator system, scoring system of terminal indicators, score conversion system, and others. Thus, this section was merely limited to the perspective of the grading quantity.

Shown as Tab. 4, ESGB has classified the final evaluation result of green building into three grades, named One, Two and Three stars, and the performance of the green building is improving in line with the increasing of star number. In addition, the green building evaluated by EEWH is divided into five grades, labeled as Qualified, Bronze, Sliver, Gold and Diamond, and the Diamond indicates one of the most excellent of green buildings, certificated mere 2% of 3094 passed cases with it from 2005 to 2011. Apparently, the number of the grade in ESGB is much less than EEWH, with three and five levels respectively (Tab. 4).

Table 4: Comparison of the rating systems between ESGB and EEWH

GBRT	Total score	Score threshold and corresponding green building assessment grades						
ESGB	Ts	threshold		[50, 60)		[60, 80)		[80, 110]
		Grades		**One star**		**Two stars**		**Three stars**
EEWH	Rs	threshold	Type A	[20, 37)	[37, 45)	[45, 53)	[53, 64)	[64, 100]
			Type B	[18, 34)	[34, 41)	[41,48)	[48, 58)	[58, 100]
		Grades		**Qualified**	**Bronze**	**Silver**	**Gold**	**Diamond**

Notes: There are two types of evaluation in EEWH: a) The type A with the whole nine indicator groups needed to be assessed and b) the type B with eight indicator groups required to be evaluated (the evaluation of biodiversity indicator group is exempted).

The appropriate number of grades plays a vital position on QES of GBRTs, since that, if this quantity is restricted to a small number (e.g. 2 and 3), the RS of GBRT is unable to reflect the environmental impact of green building comprehensively, trustily, and reliably. On the contrary, the excessive number of green building level (e.g. 7 and above) may lead to cumbersome works on identifying the differences and boundaries between two nearby grades. Additionally, one of the primary purposes of RS is providing clear and visual symbols reflected the building performance to the public, so as to awaken the emphasis from not only professionals but also public on green building, and advocate, encourage and promote the development of green building ultimately. Thus, the complex RS with too many grades may confuse the non-professionals and lose their interests. In brief, the decision on the number of green building grade deserves more emphasis and discussion. The Tab. 5 compared the other four RSs of global-leading GBRTs, and it is notable that a 4-6 grades system is widely accepted.

Table 5: Comparison of the rating systems among other four global-leading GBRTs

GBRT	total score	Score threshold and corresponding green building assessment grades						
BREEAM	Final BREEAM score	threshold	[30%, 45%)	[45%, 55%)	[55%, 70%)	[70%, 85%)	[85%, 100%]	
		Grades	**Pass**	**Good**	**Very good**	**Excellent**	**Outstanding**	
LEED	points	threshold	[40, 50)	[50, 60)	[60, 80)		[80, 118]	
		Grades	**Certified**	**Silver**	**Gold**		**Platinum**	
BEAM Plus	Percentage of gained applicable cerdits	threshold	[40%, 55%)	[55%, 65%)	[65%, 75%)		[75%, 100%]	
		Grades	**Bronze**	**Silver**	**Gold**		**Platinum**	
CASBEE	BEE	threshold	(0, 0.5)	[0.5, 1)	[1, 1.5)	[1.5, 3.0) [3.0, +∞) and $Q\in$[3.0, 50)	[3.0, +∞) and $Q\in$[50, 100]	
		Grades	**Poor**	**Fairy Poor**	**Good**	**Very Good**	**Excellent**	
Green Star	Weighted Points Score	threshold	[10, 20)	[20, 30)	[30, 45)	[45, 60)	[60, 75)	[75, 100]
		Grades	**One Star**	**Two Stars**	**Three Stars**	**Four Stars**	**Five Stars**	**Six Stars**

Notes: The parameter of *Q* in CASBEE refers to environmental quality of building.

4.3 Comparison of score conversion system two GBRTs

The Tab. 4 illustrates the one-to-one mapping relationship between the “total score” and green building grade, which means the “total score” can determine the grades to a large extent. In addition, the function of SCS is shifting the score of TIs to the “total score” step by step, shown as the red arrows in Fig. 3-4 toward the Bottom to the Top direction in

the hierarchy framework. Obviously, the rationality of SCS may put a great impact on the reliability of the "total score" and evaluation outcome (the green building grade). Hence, this section compared the similarities and differences of SCS between ESGB and EEWH. The several primary conversion formulas of two GBRTs were listed as below：

$$Ts = \sum Ts_i + Q_{s8} = Q_{s1} + Q_{s2} + Q_{s3} + Q_{s4} + Q_{s5} + Q_{s6} + Q_{s7} + Q_{s8} \quad (1)$$

$$Ts_i = w_i \times T_i \quad (2)$$

$$Rs = \sum Rsi = R_{s1} + R_{s2} + R_{s3} + R_{s4} + R_{s5} + R_{s6} + R_{s7} + R_{s8} + R_{s9} \quad (3)$$

$$Rs_i = a_i \times R_i + c_i = a_i \times \frac{|Dv_i - Bv_i|}{Bv_i} + c_i \quad (4)$$

$$R_i = \frac{Dv_i - Bv_i}{Bvi} \ (i = 1,2,3,7,8,9) \ \text{or} \ R_i = \frac{Bv_i - Dv_i}{Bvi} \quad (5)$$

The first two and last three formula belonged to ESGB and EEWH correspondingly. In order to illustrate the similarities and discrepancies clearly, whole parameters appeared on formula (1) and (3); (2) and (4) are matched as Tab. 6 and Tab. 7 respectively.

Table 6: Comparison of the calculation regulation of total score between ESGB and EEWH

GBRT	Fromula	The meanings of each parameters in formula					
ESGB	$Ts = \sum Ts_i + T_{s8}$	Ts	The total socre	Ts_i	The score of each evaluation criteria	T_{s8}	The score of innovation criteria
EEWH	$Rs = \sum Rs_i$	Rs		Rs_i		—	

Note: The grey color means that the corresponding parameters can be found in ESGB and EEWH with same meaning in formula, and the blue color indicates mere one GBRT owns this parameter without corresponding one in the other GBRT.

Table 7: Comparison of parameters of evaluation criteria score calculation formula between ESGB and EEWH

Formula	The meanings of each parameters in formula									
$Ts_i = w_i \times T_i$	Ts_i	The Score of evaluation criteria	w_i	Weight value	T_i	The design score (value) of evaluation criteria	—	The benchmark value of evaluation criteria	—	Basic score
$Rs_i = a_i \times \frac{\lvert Dv_i - Bv_i \rvert}{Bv_i} + c_i$	Rs_i		a_i		Dv_i		Bv_i		c_i	

Note: The grey color means that the corresponding parameters can be found in ESGB and EEWH with same meaning in formula, and the blue color indicates mere one GBRT owns this parameter without corresponding one in the other GBRT.

The calculation regulations of *Ts* and *Rs* are similar. In brief, it is the sum of the scores of each evaluation criteria (Tab. 6). The mere difference is Q_{s8}, indicating the score of innovation criteria in ESGB, mismatch with EEWH's whole parameters in Formula (3) since EEWH didn't appoint score for innovation evaluation. Shown as Tab. 8, the encouragement approach of innovation is elevating green building grades directly rather the adding extra score.

Table 8: Comparison of encouragement mechanism of innovation between ESGB and EEWH

GBRT	Encouragement approach	Influence target	Detailed information
ESGB	Adding extra mark with maximum 10 points	The total score (T_s)	The sum of full marks of T_{s1-7} is 100 points, extra 10 points is set for innovation criteria of ESGB. Thus, the performance of evaluated case on innovation can also impact the total score (Ts) and green building grade to a considerable degree.
EEWH	Elevating green building grade	The green building grade	Judging by the evaluation committee, if two third of members in this committee confirms it contribution and educational meaning in ecological, energy saving, waste reduction and health perspectives and votes for it. The final assessment outcome will be upgrade one level (e.g. from gold to diamond).

On the foundation of Tab. 7, two discrepancies of the calculation regulation of Ts_i and Rs_i can be extracted: the mismatching of c_i and Bv_i between ESGB and EEWH. Interestingly, $\frac{|Dv_i-Bv_i|}{Bv_i}$ and T_i play the same role in formula (2) and (4), which is in charge of the calculation of the score of evaluation criteria, simultaneously, Dv_i and T_i represent the same parameter meaning - the design score (value) of evaluation criteria. Thus, another difference of SCS between two GBRTs is the utilization of Bv_i or not, which means the GBRT takes the environmental benchmark and load into consideration or not. Regarding the c_i, the purpose of setting it is in line with the free assessment of partial criteria possibility for some specific cases (ABRI 2015), and assign basic points to them, ensuring the fair treatment. The Tab. 9 illustrates the partial situation that some evaluation criteria of waiving assessment.

Table 9: The overview of free assessment of partial evaluation criteria in EEWH (partial)

Evaluation criteria		The condition of waiving assessment	Obtained score under free evaluation condition
Daily Energy Savings	Energy saving of air-condition system	The equipment room, warehouse, plant without air-condition system, or the space with few people staying	$R_{s42} = 1.5$
	Energy saving of lighting system	The buildings with whole assessment free space (storage room, parking lot, semi-outdoor corridor, warehouse, pantry, toilet and other non living space)	$EL = 0.8$ $R_{s43} = 1.5$
CO_2 Reduction		The low-rise buildings under five stories	$R_{s5} = 1.5$
Water Resource		Private hydrant in hotel guest rooms and ward units; Hydrant of mop basin or hydrant for cleaning purpose in other types of buildings	$R_{s8} = 1.5$

5 Discussion

Regarding the discrepancy of RS between ESGB and EEWH, understandably, the three-levels rating system matches with the initial development stage of ESEB well, however, the 4-6 grades RS is more suitable for GBRT, since it can indicate the real performance of green building more accurately, reliably and efficiently, with acceptable time and human resource cost. It is also the main reason why most of the globe-leading GBRTs are adopted a 4-6 levels RS. Thus, it is recommended that ESGB improves its RS and utilize four or five grades system as an alternative in the near future to match with its rapid development.

With respect to the differences of SCS between two GBRTs, the c_i of EEWH is arranged for the special cases meeting the requirement of waiving partial evaluation criteria. For the Bv_i, Essentially, it means that the GBRT whether takes the benchmark value of

original environment or the environmental load into consideration. Specifically, in EEWH, the excellent score and grade can only be obtained under the condition that the environmental favorable influence of evaluated case exceeds the benchmark value of the original environment. Thus, this parameter (Bv_i) ensure the real benign environmental benefits of the green building certified by EEWH (ABRI 2015), and a part of Bv_i values and it corresponding prerequisite are listed as Tab. 10.

Table 10: The overview of the benchmark value of evaluation criteria in EEWH (partial)

Evaluation criteria	Applicable condition	Bv_i Value
Biodiversity (Applicable to the base over one hectare)	The base located on an environmentally sensitive location or the statutory hillside	$BV_1 = BD_c = 70$
	The base settled in the coastal area	$BV_1 = BD_c = 55$
	The base situated park land or agricultural, scenic, specific area under urban planning	$BV_1 = BD_c = 60$
	The base located on the industrial area and others	$BV_1 = BD_c = 50$
	The base settled in science park and others	$BV_1 = BD_c = 55$
Greenery	School and park land $\beta = 500(\mathrm{kg/m^2})$	$BV_2 = TCO_{2c} = 1.5\times(0.5\times A'\times\beta)$ (A' refers to the minimum green area)
	Commercial and industrial land $\beta = 300(\mathrm{kg/m^2})$	
	Others $\beta = 400(\mathrm{kg/m^2})$	
On-site Water Retention	Whole campus evaluation	$BV_3 = \lambda c = 0.5$
	Others	$BV_3 = \lambda c = 0.5\times(1-r)$ (r refers to the building density) ($r > 0.85$, $r = 0.85$)

The EEWH's SCS set Bv_i with the purpose of taking the "environmental load" into consideration, ensuring the real environment benign impact of the certified green building. This idea is also accepted by some of the global-leading GBRTs, for instance, CASBEE developed the built environmental efficiency index (BEE) on the foundation of this idea, which is an index can determine the green building grades directly (Tab. 5). CASBEE assigns the scores for Q (Quality: Environmental quality of the building) and L (Load: Environment load of the building) separately and provides the index marked as *BEE* ultimately (Chew and Das 2008). As illustrated by Formula (6), the value of *BEE* is equal to Q divided by L.

$$BEE = \frac{Q}{L} = \frac{\text{Environmental quality of building}}{\text{Environmental load of building}} \tag{6}$$

Specifically, the Q refers to the environmental performance of a building, indicating the living comfort improvement of dwellers, and the L means the environmental load, showing the negative impact on the environment of a building. The CASBEE utilized the inverse relationship between Q and L and created the *BEE* index so as to seek the balance between building quality and environmental load and achieve the best quality one with the minimum negatively influence on surrounding environment. It is not hard to observe from the formula (6) that, the excellent performance of *BEE* can only be reached when environmental load (L) is relative low, since that, if the L is a fairly high value, the excellent performance of *BEE* is nearly impossible to be attained, no matter how outstanding the building quality (Q) is.

6 Conclusion and Suggestion

Two main conclusions can be extracted from the aforementioned discussion:

1. The 4-6 grades system is widely accepted by the RSs of most of the global-leading GBRTs, the 3-grade system of ESGB's RS seems can't meet the future development of ESGB.
2. The two indexes, marked as Bv_i and L, utilized by EEWH and CASBEE correspondingly, are directly reflected that two GBRTs have comprehensively taken the building performance and environmental load into account rather than focusing on the evaluation of building quality. Hence, in these two GBRTs, the high total score and certified grade can only be reached when the negative environmental impact of a building was efficiently controlled. Even though the index system itself has involved in the evaluation of environmental load, apparently, the Bv_i of EEWH and the L of CASBEE can reflect the environmental load more efficiently and directly and can adapt to various benchmark conditions of different bases the evaluated case located in better. Thus, it is wisdom that ESGB places more emphasis on the assessment of environmental load. In addition; takes a lesson from EEWH and CASBEE; and set a similar index reporting the environmental load efficiently and accurately finally.

In addition, Two main improvement suggestion listed as below were proposed for the QES of ESGB.

1. Regarding RS, it is recommended to increase the number of certified grades gradually, replacing its three-levels rating system by a four or five grades one step by step, so as to achieve the heterogeneities of evaluation and enhance the enthusiasm of certification.
2. The evaluation of "environmental load" is strongly suggested to be adopted by ESGB, since it can ensure the evaluation outcome (the total score and grade) reflect the benign environmental benefits or negative environmental impacts effectively and contribute to the adaptability of the diversity in the bases' benchmark condition. Specifically, an index, analog to Bv_i and L, indicated to "environmental load" is recommend to be developed and adopted by ESGB.

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RECONNECTING CHILDREN WITH NATURE: BIOPHILIC PRIMARY SCHOOL LEARNING ENVIRONMENTS

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Abstract: *More than half of all humanity live in urban centres, and people generally spend 80% of time indoors. This means that people are spending less time outside and in places that can be considered 'nature'. This is problematic, because quantitative and qualitative research shows that isolation from the natural world negatively affects human wellbeing and cognitive performance, suggesting that it is essential that nature is a constant part of humans' lives. This 'nature deficit' also impacts the development of personal bonds with nature which relates to learning to value and protect nature, and particularly affects young children. As children grow up in environments increasingly removed from nature, how will children form personal bonds with the living world if they spend their key developmental years removed from it? To address this question, this primarily design-led research focuses on primary school learning environment design and explores how spatial design can encourage a connection between child and nature. This paper discusses the results of a pilot study workshop held with children aged 5-7 exploring their preferences and opinions about nature, learning environments and play. These results are discussed in relation to how they could be applied to learning environment design to create a space which appeals directly to young children and encourages them to experience and interact with nature. Sustainability, particularly in the realm of built environment design, and within a 'strong model' of sustainability, can be understood as being made up of nested inter-relationships between ecology and climate; a sense of social wellbeing within wider ecological settings; and economic issues contained within a social sphere. This paper concludes that biophilic design focused on the psychological wellbeing and development of children can add to both social sustainability agendas, as well as the wider aspects of ecological sustainability.*

Keywords: *Biophilia, Biophilic Design, Classroom Design, Learning Environment Design, Children and Nature*

1 Introduction: Children, Nature and Biophilic Design

In an increasingly urbanised world, people spend less time outside or in spaces considered to be 'nature' (Petrović, 2017). In New Zealand for example, 80% of people's time is spent indoors (Public Health Advisory Committee 2002), and 59% of children are in front of a screen for more than four hours every day (Duncan & McPhee 2015). This potential 'nature deficit' (Louv, 2008) is of concern, because quantitative research indicates that this negatively affects human physical and emotional wellbeing, in several key ways. For example, stress levels, blood pressure and depression may increase, while concentration, and productivity may decrease (Beatley 2011; Browning et. al. 2014; Browning 2016; Heerwagen et. al. 1998; Mitchell et. al. 2016; Kellert 2005; Kellert et. al. 2008; Kellert & Calabrese 2015; Moss 2012; Wilson 1984). The development of personal bonds with nature may also be negatively affected, and particularly affects young children (Louv 2008; Moss 2012). As the next generation grows up in this increasingly urban and interior environment, an important question must be asked: how will children form crucial personal bonds with nature and learn to value it if they spend their key developmental years removed from the natural world? The formation of this personal bond with and value for nature is vital so that when children grow up to become the citizens and leaders of tomorrow, they still value and strive to protect the natural world (Louv, 2008). Thus, people's ongoing relationship and connection to nature is a critical factor in both environmental and social sustainability and is of particular concern to those who design the spaces people inhabit; namely architects, urban designers, landscape architects and interior architects.

Careful consideration must be given to the spaces in which children spend their time, so these can be designed to facilitate a positive relationship with nature. It is also important to pay attention to spaces children use because a lack of connection to nature, has been linked to sensory and attention difficulties, and to increased physical and emotional illness (Beatley 2011; Browning 2014; Mitchell et. al. 2016; Kellert et. al. 2008; Louv 2008; Moss 2012). In New Zealand, primary school age children spend approximately 36% of their time at school during waking hours in term time, so focusing on learning environments is important in this context.

A triangulation approach to the research was taken (see: Wang and Groat 2002), so that conclusions drawn from biophilic design literature, combined with observations of responses to nature and quality learning environments from a group of children, and outcomes of a process of design-led iterative research enquiry, when considered together led to important research findings.

This research primarily uses existing frameworks of biophilic design to investigate and develop spaces which enhance wellbeing and encourage children to interact with nature at both a conscious and subconscious level. Biophilia is the understanding that people have an innate connection to nature and the living world that affects our wellbeing (Wilson, 1984). Biophilic design is applying this theory to spatial design practice to enhance a sense of connection to nature, and thus increase human wellbeing (Browning 2014; Kellert et. al. 2008; Wilson 1984). In order to supplement the largely research-led design process undertaken in this ongoing research, a child-centred participatory pilot study focus group of year 1-2 students (ages 5 to 7) was conducted in Wellington, New Zealand in mid-2017. This was designed to test how the ideas and responses of junior school level New Zealand children might reflect or contradict those stated in international literature. The pilot study provided valuable insight into children's values of nature, their

ideas regarding what should and could be in a learning space, and which curriculum based activities could be done in different types of spaces.

The key findings from this were developed through design iteration and critical reflection processes into designs of functional learning spaces that directly reflected the children's preferences of nature and learning spaces, thus beginning to design spaces which encourage a bond between children and nature.

A survey of primary school teachers was also conducted to obtain insight into how teachers use their learning environments (both indoors and outside), what they think is suitable for future learning spaces, and what their opinions about connection with nature in an educational environment are. These results, along with an understanding of what makes quality learning spaces from literature sources, were used in conjunction with responses to children's thinking and wellbeing to test how biophilic elements can be applied in successful nature oriented learning environments. This paper examines results from the focus group workshop only, and discusses how they could be used to guide the design of primary school learning environments.

2 Children, Nature and Play Workshop

The pilot children, nature, learning and play workshop was designed to test and understand children's own perceptions of their learning spaces in relation to nature, with the idea that the workshop format could be scaled up in the future to gather responses from a larger group of children the future[1]. A small group of five children aged 5-7, both female and male[2], each from a different Wellington school that demonstrate a variety of teaching pedagogies participated. This age group was selected because the intended design outcome was a block of junior level classrooms. It is possible that results of a similar workshop would be significantly different if other age groups were observed.

The children played 3 'games' about learning spaces and nature. These games were designed to get the children thinking and talking about what they want in learning and play spaces, and why this is the case. During all three games, the word 'classroom' was avoided where possible by the researcher and 'learning space' was used instead to try to reduce responses reflecting predispositions of what a 'classroom' is or should be.

The first game, named 'favourite spaces', involved showing the children images of different learning and play spaces and asking them to choose their favourite by placing a sticker on it. This was followed by a discussion about why that particular option was chosen. In the second game, named 'pin the activity to the space', a variety of classroom and nature scenes were pinned to a wall and the children were asked to choose which of the spaces they would most want to do given curriculum based tasks in. Tasks included: reading, handwriting, maths, art, play etc. In the final game, named 'design a learning space', the children were provided with an empty physical model of a classroom with the roof removed, four walls, and an indoor and outdoor space with an opening between the two. They were told they could put whatever they wanted to in this learning space by choosing from a selection of cut out elements laid out on the floor. These elements were items ranging from typical classroom elements (chairs, desks etc.), electronic items (computers, ipads etc.), biophilic elements (plants, animals, water etc.), through to 'interactive play' elements (bean bags, soft furnishings etc.) (Fig. 5). Elements categorised as biophilic included things that reflected the qualities of biophilic design as

[1] Ethics approval was obtained from the Victoria University of Wellington Ethics Committee for this pilot study.

[2] In order to maintain confidentiality when discussing the children, gender pronouns have been replaced with the pronoun 'they'. Faces have been blurred in all images.

described in leading literature on the topic (see for example: Browning *et. al*. 2014; Kellert & Calabrese 2015; Kellert et. al. 2008). Climbing walls/nets and tepees or tents were categorised as biophilic because of their ability to create a sense of risk and refuge (Browning *et. al*. 2014; Kellert & Calabrese 2015; Kellert et. al. 2008). Reasons for why some elements were or were not selected focused on reasons for inclusion rather than reasons for exclusion of elements.

Figure 1: Game One- Favourite spaces

Figure 2: Game Two- Pin the activity on the space

Figure 3: Game Three – Design a learning space

Figure 4: Game Three – Design a learning space 2

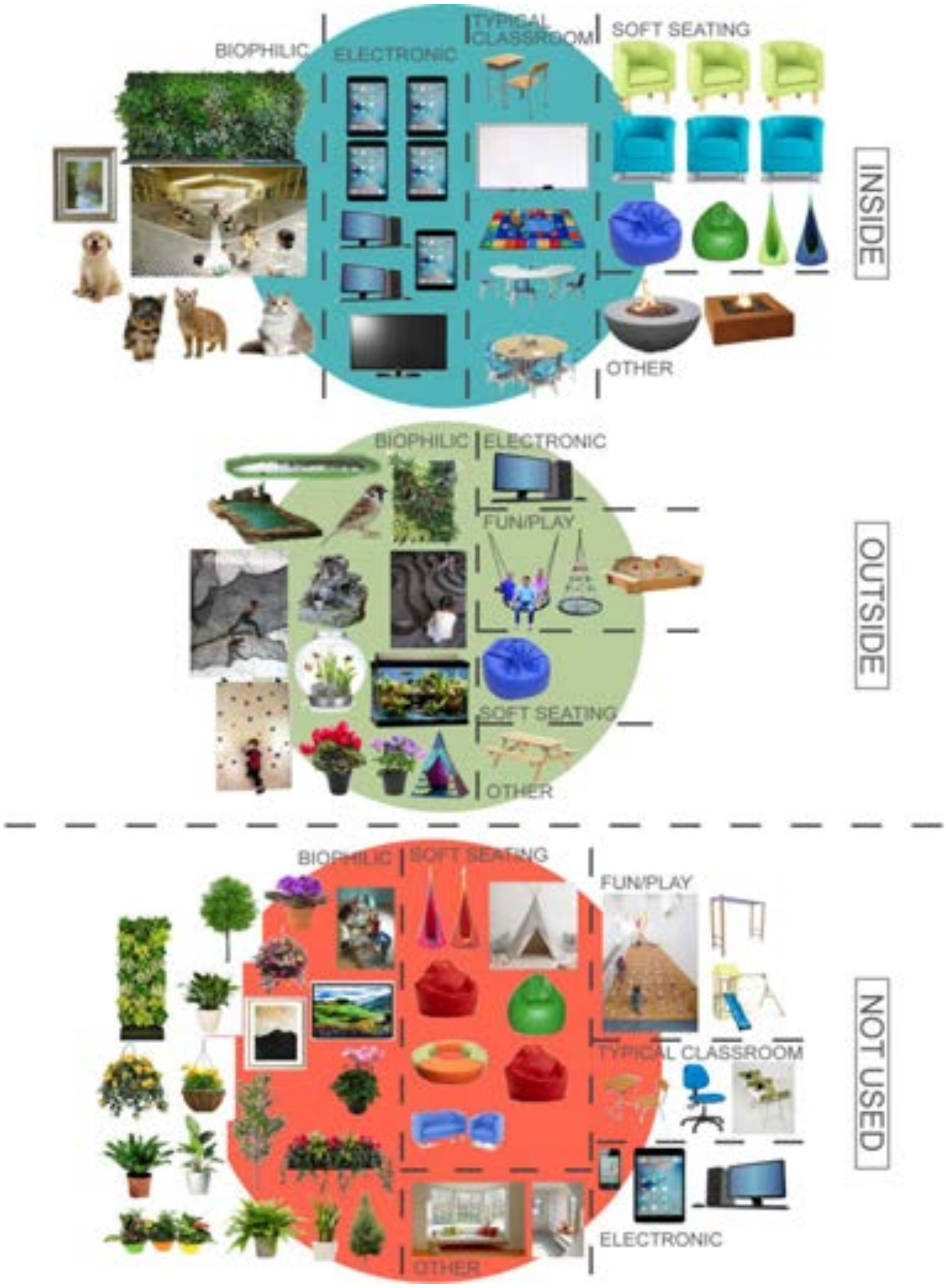

Figure 5: Elements children placed in the learning space in the 'design a learning space' game

3 Workshop Results Discussion

Through all three of the workshop games, some things were consistently discussed by the children including: a preference for being outside; excitement about climbing; attraction to water; and preference for bright colours (Fig. 6).

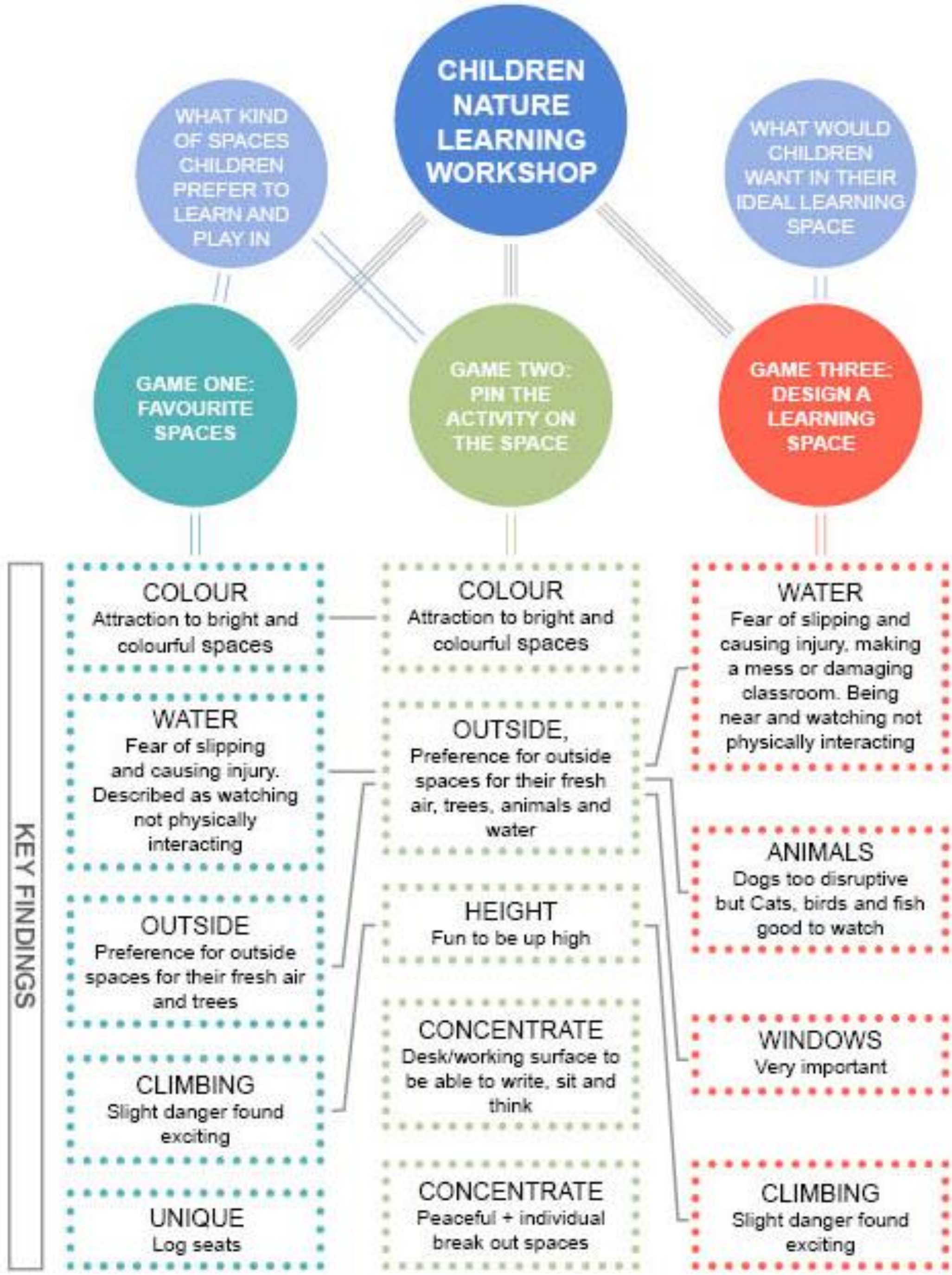

Figure 6: Summary of workshop results

3.1 Preference for the outside

The preference for learning and playing in outdoor spaces was consistent through the workshop and was continuously linked by the children to a desire for fresh air, trees, animals and natural views. In the second game 65% of the spaces chosen for the learning tasks were outdoor nature scenes, showing that the children were happy to have learning spaces be in these natural environments. However, in the third game the majority of the elements selected were placed in the 'inside' space of the model. This, along with the children's indoor placement of all of the 'typical classroom' elements

(white board, desks etc.) suggests perhaps that the children believe that learning is something that should be done inside. This differentiation between results could be because the 'inside' space in the model was physically bigger than the 'outside' space. Or because when given a physical model the children were more influenced by their predispositions of what a learning space should be, whereas in the second game by pinning nature scenes up alongside the classroom scenes it opened them to the possibility of doing these learning tasks outside. Regardless of this, the children still had a clear interest in and preference for the biophilic elements in the third game. They were the most used category of elements in the model and made up 6 of the first 15 elements to be selected and placed. Animals made up the majority of the biophilic elements added to the model in game three.

Natural views, and arguably fresh air, were incorporated into the model very quickly by the children adding a window. The children quickly pointed out that there were no windows in the model and put in a painting of a natural landscape scene to act as a window. It is interesting that this was important to the children because having views of nature has been quantifiably shown to improve mental engagement and attentiveness (Browning *et al.* 2014). Though it is unlikely the children are consciously aware of this affect, it does indicate that they value having a view to the outside and that they hold windows, and therefore connection to outside environments, and/or natural light as a critical aspect of learning environments.

Though trees were mentioned constantly throughout games one and two as reasons for choosing outdoor spaces over indoor ones for learning, and one of the two most preferred places to play in game one was in a tree itself, no trees were added to the model in the third game. However, all of the climbing nets were added, so it could be posited that children were attracted to the play/climbing aspect of the trees rather than the actual tree. It is also of note that the treehouse was one of the most selected scenes in game two (perhaps for its height and solitude). Excluding trees from the game three model could also be because of the trees provided. These didn't look like strong, climbable trees like those shown to the children in earlier games. As for the other plant elements, one green/living wall was added to the interior because 'it looked interesting', the other was added outside 'so that birds have a place to nest'. Two potted flowers were added because 'they are pretty'. Other than these instances the children had little interest in the other plants they could have selected in game three. This is an interesting observation because adding plants to a space is often one of the simplest methods for creating a sense of nature in biophilic design (Browning 2014; Kellert 2008).

It is also important to consider that the children's preference for the outside, and desire for easy access to it, could be due to its link to play. Typically, in New Zealand schools playtime is spent outside, so the outside may automatically be linked to play. However, the reoccurring comments made by the children regarding their preference for being outside because of trees, animals, water, views and fresh air, suggest that there is likely more than just the idea of play that attracts them to outside spaces.

3.2 Climbing, water and risk

Whenever discussing play or fun with the children, two spatial elements were continuously mentioned: places to allow climbing and water, both of which can be linked to qualities of biophilic design (Browning et. al. 2014; Kellert & Calabrese 2015; Kellert et al. 2008). Gullone (2000) points out that high vantage points are often appealing to people because in the past these would have enabled recognition of approaching

dangers or weather changes, and that 'trees with low trunks would have been valued by our ancestors who could have climbed them in times of danger. Trees with high canopies were advantageous in other ways as they did not block the view, nor did they permit enemies to hide behind them.' This is part of the reasoning behind the provision of views, and opportunities to climb being part of biophilic design. In a similar way, clean water is universally appealing to people likely because in an evolutionary sense being near water enhanced people's survival due to access to drinking water, the attraction of other animals to water that people could hunt, and water being a suitable defence against predators or enemies (Gullone 2000). While these reasons are not as relevant to modern contexts, the subconscious appeal remains in people.

Climbing was selected slightly more often by a greater number of children in the workshop than water. Children reported that it was the relative danger and risk in climbing that they were attracted to and found exciting. Whether it was a boulder, tree, treehouse, climbing web, or climbing wall, the excitement associated with climbing was consistent across all three workshop games. Creating opportunities to experience risk alongside obvious safeguards (such as a high tree house that has a hand rail to hold on to) is an aspect of biophilic design as described in detail by Browning et al. (2014). They point out that 'having an awareness of a controllable risk can support positive experiences that result in strong dopamine or pleasure responses. These experiences play a role in developing risk assessment during childhood. In adults, short doses of dopamine support motivation, memory, problem solving and fight-or-flight responses.'

In a similar way, several child participants in the workshop were able to articulate that part of the appeal of water was because it could be a bit risky and therefore intriguing. Along with the danger the children saw with the water, they also strongly felt that these wet elements should only be outside. When asked in the third game if the children would like it if the water learning space they designed could be inside, the children were quick to protest. Instead, they preferred for the water to be outside so that it didn't 'splash around the classroom' which they thought would result in being disciplined by the teacher, could cause damage to the classroom, or result in injury. This apparent fear of being disciplined for making a mess was also mentioned in earlier games. Perceiving water as attractive but still risky seemed to affect how the children thought they would interact with the water spaces. Interestingly, they describe the space as being experienced from a distance. This means they imagine being near the water and seeing fish for example, rather than playing in the water or touching it. When prompted, they said they wouldn't mind getting dirty, and several of the children were excited by the idea of being able to jump in the water. The hesitation towards playing in water could be related to a fear of making a mess and/or being told off as discussed above. Though the children's constant attraction to water is evident, they also seem uncertain about interacting with it physically rather than just visually.

3.3 Colour

Colour constantly attracted the children's attention and was one of the reasons behind decision making in all three games. In the second game, the children reported that over half of the classrooms selected as preferred learning or play spaces were chosen because they were colourful. It has been shown in studies that young children prefer bright colours (BRANZ 2007), which could explain the children's attraction to the images of the two classrooms which were filled with bright colours. It is also interesting to note that when asked in game one which space they preferred when presented with a colourful classroom and one with easy indoor-outdoor flow, all but one child preferred the classroom with easy access to the outside. Although not an absolute quantifiable

measure, this may indicate that though children are clearly attracted to bright colours, they may be just as, if not more excited to be outside.

3.4 Concentration

The children talked about needing to be able to concentrate in learning spaces. This was given as a reason for several space selections made in game two. Obviously, this is an incredibly important factor in creating functional learning environments. In all cases that classroom furnishings, such as individual tables or desks were mentioned by the children, they were related to the child's ability to concentrate. They stated that they were spaces in which they could 'easily write', 'sit and think', 'work carefully', or have their 'own space'. However, no other aspect of the classroom scenes were linked to their ability to concentrate. This raises the question, if these simple desk or table elements were brought outside, would the children still feel like they would be able to concentrate? If so, an image used, that depicted an outdoor deck with a table on it might have been selected more than it was. It could be that the children associated the interior classroom scenes with concentration as these are the spaces they are used to learning or concentrating in, so didn't recognise the table on the deck scene as a suitable working space. This seems plausible, and was reflected in the workshop because attributes of a space suitable for concentrating in were mentioned several times in relation to other nature scenes. One child preferred a lakefront scene for reading, writing and maths because they found the space 'peaceful', and another child preferred doing art in a garden scene which they also thought looked 'peaceful'. Together, 'peacefulness' and ability to concentrate in a space related to a quarter of the reasons why children chose any scene for a learning task.

4 Discussion: application of findings to design

Investigating how to create a sense of nature in learning spaces is a key aim of this research. Incorporating aspects of nature (either directly or as an abstraction) into learning space design that the children were stimulated by may encourage them to interact with these natural elements. The hypothesis of this research, is that creating these kinds of learning spaces could facilitate a heightened relationship between children and nature. If the children enjoy being in a space that they link to nature, then these positive emotions and feelings may transfer to and create a personal sense of value for nature itself (Louv, 2008). Though several factors discussed below (such as water, risk and climbing) were raised in the context of 'play' during the workshop, they shouldn't be disregarded when designing learning spaces. Learning through play is potentially an effective teaching method that is especially beneficial for younger children. This relationship between the excitement of play and the functionality of a learning space relative to a child's ability to concentrate is an interesting dynamic that would best be explored through further site and context specific design iterations.

4.1 Preference for the outside and water: application to design

The children had a general attraction for the idea of learning in outdoor spaces, especially in the first and second game. Though it would be difficult to create entirely outdoor learning spaces suitable for year round use in all weather and temperature conditions (see however: Slade, Lowery, & Bland, 2013), the idea of incorporating outside spaces for learning is of interest to children and could be explored further in typical New Zealand learning environments. This thinking provokes ideas of creating spaces that vary between being indoors and out, that are indoors but feel like outside spaces, or spaces in which the line between inside and out is blurred.

Mentioned multiple times during the workshop, the use of windows to create views out to these natural spaces will be an important feature of these kinds of interior spaces that feel connected to or like they are a part of the outside environment. Windows should be designed to maximise these views with specific consideration for children's eye levels. The view that windows look out onto should also be considered. Views of nature have been found to reduce stress (Browning et al. 2014; Osborne 2016), whereas a view onto other classrooms may be less emotionally and cognitively beneficial for the children. Negative impacts such as glare and solar heat gain cause by glazed areas should be avoided and minimised (BRANZ 2007).

When trying to create a sense of nature in an interior space, the most common and simple way to do this seems to be through the use of interior plants (Browning et. al. 2014; Kellert et. al. 2008). It is important to remember that this may not be the most effective method of creating a sense of the natural world within space however (Browning et al. 2014). Instead, methods of biophilic design should be used in carefully considered combinations that encourage interaction (physical, auditory, visual, tactile etc.) with natural elements. Consideration should also be given to the cognitive effects they have been shown to cause (Browning et al. 2014; Gullone 2000).

Interacting with animals was another reoccurring reason for why the children liked the idea of learning outside. Generally, the children were more interested in having smaller, passive animals, mostly birds, but also mentioned cats and bugs, for them to watch and listen to in their learning space. Consideration for this can be taken into design processes by including habitats on the school site that attract birds and allow them to nest, and by placing windows in the learning spaces so they look out onto these more biodiverse spaces. Such arrangements have been found to benefit psychological health (Browning et al. 2014). Aside from design to attract and house animals, innate attraction to animals can also be incorporated into design through the use of biomimicry, biomorphic design, or careful selection of materials and patterns, to recreate aspects, or the visual feel of certain animals. This method could be used to create a reflection of more exotic animals then birds and cats, and may prove to be more practical in some settings than use of actual live animals.

Though the children were evidently hesitant towards incorporating water into interior spaces, this was because of fear of damage, injury, and being disciplined for mess making. And some of these fears do reflect valid difficulties in designing a safe and functional indoor water space that the children would feel comfortable and able to interact with. However, bringing a water space into the classroom is not the only way to get children interacting with water. Instead a wet area could be added to an in-between, inside / outside space or other spatial elements could be explored (such as tanks, ponds, streams, channels, waterfalls, clear pipes, rainwater harvesting, wetlands, taps, pumps, fountains, shower heads, etc.).

4.2 Climbing and risk: application to design

Climbing was a continuously mentioned element of fun in the workshop and on its own can create a sense of relative risk in children which is a beneficial biophilic quality (Kellert et. al. 2008; Kellert & Calabrese 2015). Though it may seem counter intuitive, allowing children to experience a controlled sense of risk can be beneficial for the development of their risk assessment skills (Moss 2012). By exposing children to controlled risk, they are able to learn for themselves what is and isn't dangerous. Designing spaces that allow children to experience this should be encouraged where

possible. Further design opportunities that relate to an attraction to climbing, or obtaining vantage points, include careful consideration of vertical movement opportunities in learning spaces through for example the use of mezzanine floors, climbing ropes, webs, stairs, ladders, bridges, climbing walls / nets / frames, pits, dens, tunnels, stacking boxes, poles, trees etc.

Integrating the concept of climbing into learning space design may be even more effective at reconnecting children with nature if it is connected to a natural element. Combining these two biophilic concepts likely creates a stronger and more desired effect then using them separately, because it gets the children physically interacting with a natural element (i.e. a tree), rather than just looking at it. Such interactions are expected to create longer lasting connections between children and nature because it forms a more tactile, physical memory compared to simply looking at a tree through a window, or even looking at an image of a tree (or other natural element) (Browning *et al.* 2014).

These kinds of ideas of having a climbing web in a classroom, similar to those shown as 'used' in Figure 5, were proposed to the children which they became excited about. However, designs like this would create an interesting dynamic between the excitement of the climbing element and the concentration that might be needed to perform certain learning tasks.

4.3 Colour: application to design

Though it is clear that bright colours make spaces more attractive to children, excessive use of bright colours may be overstimulating and distracting for some children in learning spaces (Barrett *et al*. 2015; BRANZ 2007). Instead, colours can be used strategically to attract children's attention to certain parts of the space. For example, typical play, entry or some outside spaces can be used create a bright colourful aesthetic that will appeal to children. Colour should also be considered within the context of natural light, which changes in colour spectrum over the day, triggering important hormonal responses in people (Browning *et al.* 2014). It is of note that researchers have identified that greater gradients of colours exist in natural settings compared to human-built ones, and that when people have to differentiate between more subtle variations of a given colour, these similarities can trigger higher cognitive functions like memory, categorisation, and association (Gushiken 2012). Such qualities may be more difficult to obtain using a small number of contrasting block colours.

4.4 Concentration: application to design

As discussed, spaces that allow children to concentrate are a critical aspect of a functional learning space. In the workshop, the children linked improved possibility for concentration to the spaces with desks and working surfaces. This highlights the importance of including suitable focused work spaces and surfaces in learning space design, regardless of whether these are inside or outside. A sense of peacefulness, or refuge, retreat or sanctuary as described in detail by Browning et al., (2014) and Kellert et. al (2008), can be linked spatially to the creation of private cubbies and breakout spaces which give children their own personal work space. With this creation of unique pockets of space however, the teacher's ability to be able to see all of the learning environment must be considered.

Breakout / concentration spaces should be explored in combination with other aspects of nature and biophilic design, with consideration for effect on cognitive performance. For

example, thermal and airflow variability or having a presence of water, are both shown to improve concentration (Browning et al. 2014). By doing this, biophilic learning spaces not only develop child-nature relationships, but also improve the ability of children to learn.

5 Conclusion

As people continue to move into an increasingly urban and interior lifestyle, it is critical that the children that will grow into future leaders hold value for nature and the living world, so that the environment people depend on for survival, wellbeing, and important aspects of culture, can be protected, celebrated, and if possible regenerated.

Results from the pilot workshop described here suggest insights into what children think would make a fun learning space rather than what would constitute a practical learning space in many instances. They highlight what kind of natural elements and spaces children are likely to be attracted to, and demonstrate possible ways to incorporate these elements into a learning space that young children may positively respond to.

It should be noted that the number of participants in the workshop described was necessarily small, so results are not necessarily reliable as absolute truths. Nevertheless, results suggest directions for further design-led research investigations. This process has been undertaken as part of this ongoing research and in reported on in detail in a separate publication.

In conclusion, while it is important for children to be able to use their learning spaces for standard curriculum based learning, there is also an exciting opportunity for designers and architects to create spaces that not only improve children's cognitive performance and emotional wellbeing, but also encourage them to experience nature in a positive way. Creating a space that consistently exposes children to nature, encourages the formation of personal value for it, and takes advantage of the multiple potential wellbeing benefits of biophilic design can be a critical step in insuring more sustainable societies and perhaps in the future healthier ecosystems.

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EXPLORING THE IMPACTS OF PERSONALISATION ON THERMAL EFFICIENCY OF CHILEAN SOCIAL HOUSING

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Abstract: *The Chilean social housing program is a highly structured system of incentives and rules that although successful in meeting quantitative goals has neglected the quality of its outcomes. Over time, initiatives based upon user participation and self-help action have been disregarded to favour the efficiency of a housing delivery system in which mass production makes addressing diversity problematic, while an emphasis on the rapid delivery of a large number of units has abstracted the attributes of the developments from the requirements of the target households. Nonetheless, self-construction is ubiquitous among these estates, used as informal means to adjust the attributes of the built environment to the diverse needs and expectations of its occupants. The main objective of this study is to assess the potential impacts that such personalisation strategies can have on the residential quality of the dwellings, with a particular focus on one of the worst rated factors, i.e., their inadequate thermal performance. Accordingly, an on-site survey conducted on four housing developments of Concepción, central-southern Chile, was used to identify recurrent personalisation approaches to later evaluate the impacts of these modifications on thermal comfort and energy consumption. Overall, the results of this study evidence that common residential modifications such as extensions, subdivisions and change of envelope materials can have a strong impact on the thermal performance capabilities of the dwellings. Furthermore, it is shown that differences that may be subtle in spatial terms can have strong impacts on potential energy consumption for space heating, hence on the life quality of the occupants. It is suggested that the introduction of expert knowledge through information-support systems focused on assisting self-help action may be a suitable approach to ensure housing quality within the limits of affordability at different stages of the dwellings' life cycles.*

Keywords: *Personalisation, Energy Efficiency, Thermal Performance, Social Housing, Chile*

1 Introduction

According to estimates by the United Nations (UN), by 2050 over 2.5 billion people will be added to the world's urban population. While most of this unprecedented growth is expected to happen in cities that still struggle with urban poverty, inadequate infrastructure, and environmental quality problems, across the developing world many housing policies still rely on unsustainable practices that may be unable to ensure minimum standards of residential well-being to its occupants (UN Habitat, 2014; Golubchikov & Badyna, 2012).

The Istanbul Declaration and the Habitat Agenda understands housing adequacy as the capacity of the residential environment to meet the needs, aspirations and capabilities of its occupants beyond minimum functional requirements. Significantly, due to the multi-dimensional and dynamic nature of such household requirements, these residential conditions are expected to be achieved through enabling the straightforward involvement of the occupants in the development of their own dwellings. In this context, despite of a growing awareness of the need for a shift in the way housing is currently been developed and conceptualised, household-centred initiatives based upon participatory principles and self-help action are yet to scale up and become a feasible alternative to mass housing (Nientied & van der Linden, 1985; Stein, 1991; Bredenoord & van Lindert, 2010; Bouillon, 2012).

In the context of this growing housing crisis, the Chilean social housing program has been regarded as an example of successful governance (Rojas & Greene, 1995; Held, 2000). Its current regulatory structure, based upon an intricate system of household savings, demand-side subsidies, and restrictive building codes is responsible for a reduction of the country's accumulated housing deficit that has no precedents in history and thus has inspired the introduction of similar policies across the region. Although the quantitative advantages of this approach to housing has been ubiquitously recognised across governments and the academia, the sustainability of this policy is increasingly being challenged by persistent qualitative problems in the resulting dwellings (Haramoto et al., 2002; Rodríguez & Sungranyes, 2004; 2005; MINVU, 2009; Chamorro, 2013).

There is a substantial body of research dealing with qualitative issues in Chilean social housing, among which those studies focused on residential satisfaction have identified lack of personalisation and poor environmental performance as two critical factors.

In the context of the implementation of public policy instruments to assess residential satisfaction in social housing, Haramoto et al. (2002) conduct a secondary analysis focused on dwellings delivered between 1995 and 1998. In regards to the extent of self-construction, they report that most of the dwellings presented major modifications (83.2%) while few of them were unmodified (7.8%). They further report that close to half of the semi-detached and terraced houses were extended (45.9%, for 29.8% of the total) mostly to increase kitchens (69.5%) or to add a new bedroom (33.4%), while the total surface of the extensions tended to increase over time even though most of the dwellings were significantly extended since early stages of their life cycles. In terms of residential satisfaction, they explain that although most households declared being satisfied with their residential conditions (60.3%), they mentioned significant problems in terms of available space, building materials, and environmental quality in general. Significantly, when asked about residential conditions they would like to change, most of the household responses focused on extensions (61.4%).

As part of the same governmental initiative, Arriagada and Sepúlveda (2001) analyse residential satisfaction from the perspective of the household's life cycle after its impacts on the needs of the occupants and on their potential capacity to access financial resources. In this sense, they divide the population according to the age of the head of household and explore residential satisfaction in regards to their dwellings, neighbourhoods, and communities. Although they do not find any significant variation among groups when analysing satisfaction at the dwelling scale, they observe that households at their earliest stages (i.e., head of household between 18 to 33 years of age) declared the lowest satisfaction levels in direct contrast to those at the latest stages of their life cycles (i.e., head of household of 48+ years of age). They further observe that the size and acoustic privacy of the dwellings were the worst rated factors, similar to the structure, materials, environmental conditions (i.e., illumination, thermal insulation, ventilation), and installations (i.e., electric and sanitary) that were poorly assessed. Arriagada and Sepúlveda (2001) report that most of the extensions were found in households at late stages of their life cycles and speculate this might be related to increased residential satisfaction.

Further work in the context of this same governmental initiative by Morales and Arriagada (2002) explores residential satisfaction in the elderly population (60+ years of age). Although they observe that residential satisfaction in this specific age segment is significantly higher than in others, they suggest that these differences might result from lower expectations after a prolonged history of residential precariousness. More than two-thirds of the households were categorised as poor, while most of them used to live either in informality or in inadequate conditions before accessing social housing services. The authors further observe that regardless of their lower income and higher levels of satisfaction, the number of extended dwellings was similar to other age segments (~30% of the total), while the number of dwellings that had undergone minor transformations was significantly lower than average. Significantly, the authors report that the motivations behind most of the extension works and residential satisfaction issues were related to functional problems rather than environmental or spatial conditions as the ones found in the other age segments.

Closely related work by Jirón et al. (2004), but in the context of defining basic residential well-being standards for future housing developments, analyses the quality of housing complexes built between 1998 and 2004 in Valparaíso and Santiago, two of the largest metropolitan areas of Chile. According to their analysis, most of the occupants declared high levels of dissatisfaction with winter temperatures, acoustic privacy, and the size of the dwellings, while illumination, functionality and privacy were among the best-rated factors. The authors argue that these housing quality concerns can be improved with the introduction of minimum environmental performance considerations to the dwelling's design as well as with improvements to building standards and materials.

More recently, Acevedo et al. (2007) conduct a residential satisfaction survey on 354 social housing units built between 2001 and 2007 in Santiago, the capital of Chile, to explore correlates between different household and dwelling factors. They report that almost 70% of the surveyed households declared being either satisfied or highly satisfied with their dwellings, while only a few of them were highly dissatisfied (4.7%). Nonetheless, they also report significant dissatisfaction rates with the quality of the walls (48.9%) and thermal insulation (31.1%). The study further reports that close to one-third of the dwellings were extended (28.6%) while the end-use of most of these extensions was for new bedrooms. Interestingly, the authors find positive correlations between life quality satisfaction and both the environmental quality of the dwellings and the material

quality of their walls, suggesting that eventual improvements in the construction standards of extensions may lead to increases in residential satisfaction. In parallel, they find negative correlates between time living in a housing complex and residential satisfaction, meaning that satisfaction tended to decrease over the dwellings' life cycles.

Also in Santiago, Andrade et al. (2007; 2008) report residential satisfaction levels of 3,047 households living in social housing built between 2001 and 2005. Although they argue that according to their analysis residential satisfaction may be considered as fulfilled at the dwelling scale (i.e., 44.6% declared being satisfied, while 25.2% strongly satisfied), they also report significant issues in terms of environmental and construction quality. Among them, the quality of the walls and the thermal insulation of the dwellings were the worst rated (i.e., 63.4% and 47.7% of dissatisfaction respectively) while natural illumination and ventilation were among the best (i.e., 17.8% of dissatisfaction for both variables). This situation, according to the authors, may be a consequence of the precariousness of extensions as almost half of them were shacks (47%) and close to one-third of the dwellings were extended (29%) while almost all of them underwent some kind of modification (e.g., 63.5% of wall finishing works and 28.6% of floorings).

Overall, studies on residential satisfaction in Chilean social housing suggest that thermal performance and size of the dwellings are significant factors behind the households' perceived sense of well-being, while the persistent emergence of modifications, often of poor building quality, suggests that the way in which the dwellings are personalised may be a significant factor for such performance conditions. In parallel, a growing number of studies has started to analyse the environmental quality of the dwellings with a particular emphasis on thermal comfort and its impacts on household budget, general well-being, and sustainability as public policy (Sarmiento & Hormazábal, 2003; Paparelli et al., 2003; Jirón et al., 2004; Bustamante et al., 2009a; 2009b; Escorcia et al., 2012; Celis et al., 2012; García, & González, 2014). These studies demonstrate that regardless of significant improvements after the introduction of minimum insulation requirements for envelope assemblies (see thermal regulation Art. 4.1.10 in D.S. No. 47, 1992), the thermal performance capabilities of the dwellings are still poor due to low building standards (e.g., air tightness and thermal bridging) as well as the lack of adequate building performance assessment as means to inform the design of the dwellings (missing variables such as geometry, occupancy patterns, or HVAC systems). Significantly, none of these studies has explored the impacts that self-construction, extensions or other modifications may have on residential satisfaction through its effects on the thermal performance capabilities of the dwellings.

Although there is a substantial body of research focused on housing quality and satisfaction in Chilean social housing, there is only tangential evidence linking the household responses to personalisation. Self-construction has been shown to be ubiquitous, while active user involvement at different stages of the housing delivery has been shown to potentially result in enhanced residential satisfaction (Bunster et al., 2015); however, the impacts of these modifications on the quality of the residential environment have not been thoroughly assessed. In parallel, whereas self-construction of extensions is widespread and both the environmental performance of the dwellings and the quality of the envelope materials are often poorly rated, there is no empirical evidence linking those factors with energy consumption for space conditioning. In parallel, the impacts of personalisation strategies based upon participatory and self-help principles have not yet been analysed regardless of their increasing use in mainstream projects as means to enhance housing quality. Accordingly, this study aims to explore potential linkages between these factors in order to better understand the implications

that housing personalisation may have on the thermal performance of the dwellings and, thus, on both residential well-being and satisfaction.

2 Methods

2.1 Cases

A photographic survey was conducted on four housing developments of Concepción, central-southern Chile, and used to identify the most frequent modifications by dwelling type. These were later modelled and their annual accumulated hours of discomfort, as well as their total energy consumption for space heating purposes (kWh), were contrasted to benchmark unmodified dwellings. In order to constrain the analysis to the impacts that personalisation may have on thermal performance and minimise the influence of other factors, all possible orientations (as present in the housing developments for a single unit) were simulated whilst non-architectural conditions such as the size of the household, internal gains through artefacts or occupancy schedules were kept similar across cases. Whereas the benchmark dwellings were modelled using official architectural plans and technical documentation provided by the developers, the building materials, geometry, orientation and materiality of the modifications were estimated using sketches and photographic information.

The cases were selected aiming to cover mid-rise apartments, terraced and semi-detached houses developed by a (i) non-profit NGO that actively engages in participatory design activities and encourages self-construction and by a (ii) for-profit real estate/construction company that focuses on meeting no more than the standards defined by regulation. The materials and construction techniques of the different cases (Figs. 1-4) are summarised in Table 1.

Figure 1: Architectural plans of houses built in the TR housing development (from left to right: ground and first-floor layouts, frontal façade and transversal section)

Figure 2: Architectural plans of apartments built in the JPUS housing development (from left to right: two-apartment layout and frontal façade)

Figure 3: Semi-detached unit built for the SDH1 housing development (from left to right: ground and first-floor layouts, frontal façade and transversal section)

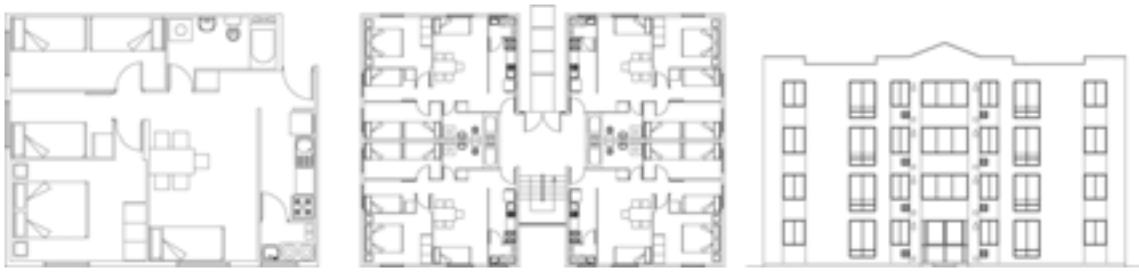

Figure 4: Apartment blocks built for the SDH2 housing development (from left to right: apartment layout, storey layout and frontal façade)

Table 1: Main building materials and construction techniques of the surveyed cases

		TR	JPUS	SDH1	SDH2
U value (W/m2K)	Walls	1.70	1.70	1.70	1.70
	Roofs	0.38	0.38	0.38	0.38
Structure	Ground	Masonry 154mm	Reinforced Concrete 150mm	Timber 70mm	Reinforced Concrete 150mm
	First	Timber 70mm			
	Roofs	Timber 80mm	Timber 100mm	Timber 80mm	Timber 100mm
Insulation	Walls	EPS 20mm	EPS 20mm	EPS 20mm	EPS 10mm
	Roofs	Glass wool 100mm	Glass wool 100mm	Glass wool 100mm	Glass wool 100mm
Floors		Concrete	Concrete	Concrete	Concrete
Windows		3mm single glazed PVC	3mm single glazed PVC	3mm single glazed PVC	3mm single glazed PVC
Doors		MDF	MDF	MDF	MDF

2.2 Location and Climate

The surveyed cases are located in Concepción, the largest metropolitan area of central-southern Chile. With a total population of 292,589 and a density of 1,318/km2, this city is characterised by its Temperate Maritime climate with warm summers and mild winters, and mean temperatures between 17°C and 8°C respectively for 70% of mean relative humidity (Fig. 5).

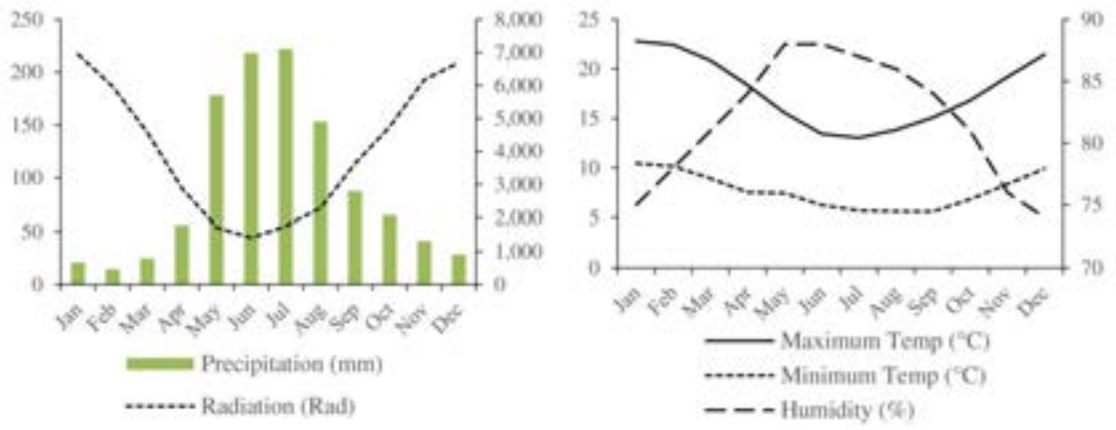

Figure 5: Mean climate data of Concepción according to official weather station measurements

2.3 Performance Evaluation

In order to assess the impacts of housing personalisation on the performance capabilities of different dwellings, a series of building energy simulations were conducted using DesignBuilder©. All the households were assumed to have the national average of four members, while the airtightness and infiltration of the buildings were defined after on-site measurements by Figueroa et al., (2013), hence concrete was assumed to have 9.0 ach, masonry 11.8 ach, and timber frame 24.6 ach. The thermal performance of the dwellings was assessed through daily hours of discomfort over a standard year (Predicted Mean Vote in ASHRAE, 2010) and the total energy consumption was estimated using a single HVAC artefact placed in the main public area using standard setpoint temperatures and schedules defined after field observations (20°C for heating and 27°C for cooling).

3 Results

3.1 Energy Consumption and Thermal Discomfort

The first set of housing modifications included in the evaluation was part of the JPUS estate. The most common modifications found with the photographic survey were three, i.e., (i) removal of bedroom walls and glazing of the balconies in order to extend the public areas, (ii) glazing of balcony and laundry apertures, and (ii) a change from plasterboard to pinewood panels in the lining of public areas (‘A’, ‘B’ and ‘C’ in Fig. 6 respectively).

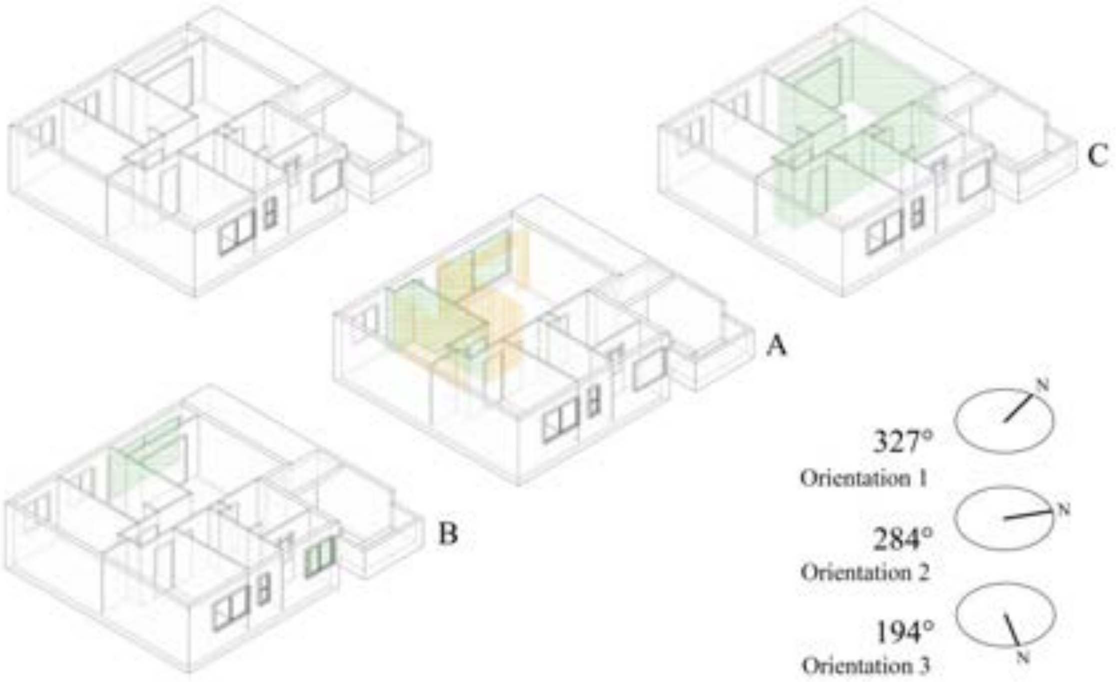

Figure 6: Modifications and orientations included in the JPUS evaluation, where green represents addition and orange removal of architectural elements

Fig. 7 summarises the results of the environmental performance simulations. Overall, the benchmark dwelling accumulated between 2,863.94 and 2,910.72 hours of discomfort (i.e., more than 121 days) and consumed between 8,460.54 and 8,894.16 kWh in space heating on an average year depending on orientation. In regards to the impact of the modifications, change 'A' significantly decreased the performance of the apartments with 925.6 extra hours of discomfort over an average year when contrasted to the benchmark apartment, while no significant differences were observed between orientations. In contrast, modification 'B' reduced the hours of annual discomfort by 908.6 only in one of the three available orientations, and modification 'C' had no substantial impacts on the performance of the dwellings. Significantly, the discomfort hours tended to accumulate in the warmest period between October and April, modification 'A' resulted in a significant reduction of energy consumption for space heating purposes due to overheating during the warmest season, and modification 'B' resulted in a higher demand regardless of season or dwelling orientation.

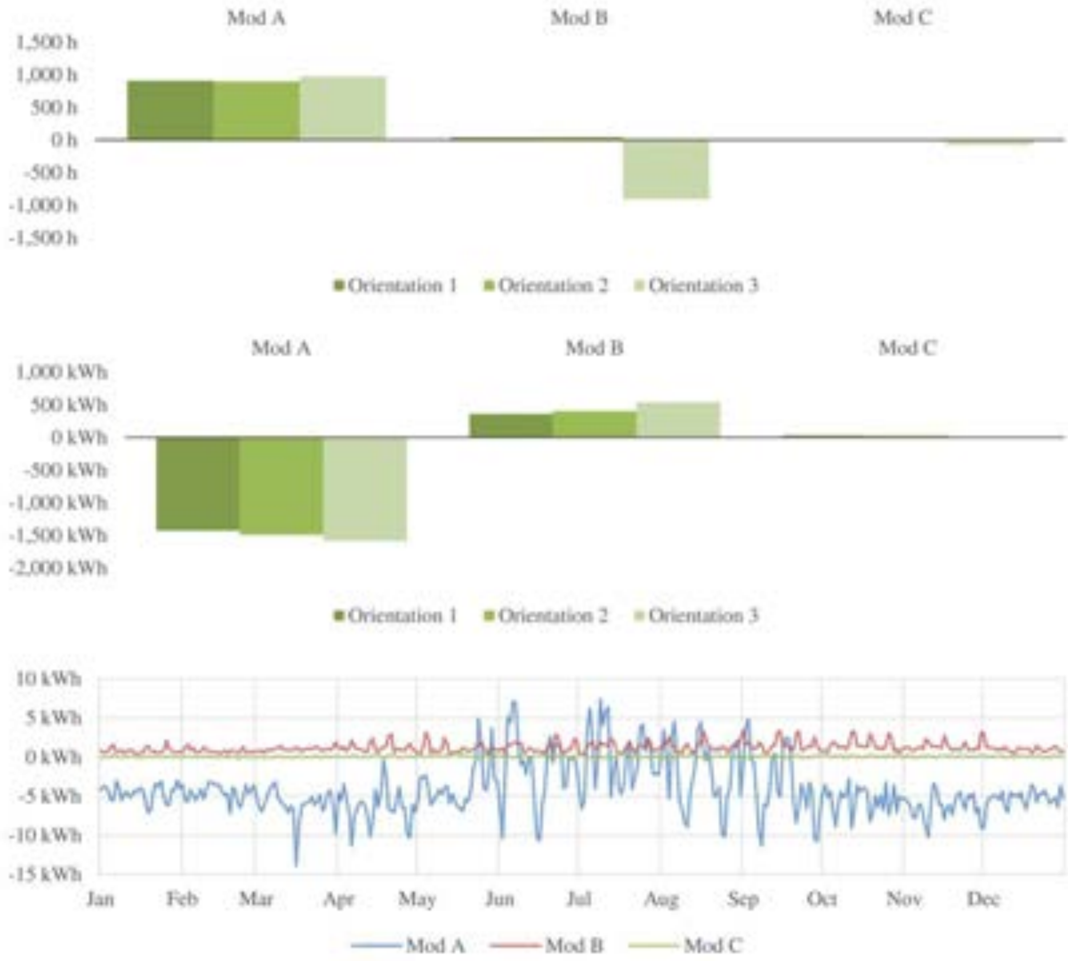

Figure 7: Differences in discomfort hours (first row) and energy consumption for space heating (second and third rows) by orientation and modification type over a standard year using an unmodified benchmark dwelling as reference (i.e., 0kWh) on JPUS cases

The second set of modifications included in the evaluation was part of the SDH2 housing complex. The most common self-built changes found among these dwellings were four, i.e., (i) glazing the laundry apertures, (ii) removal of kitchen partitions in order to extend the common areas, (iii) removal of bedroom partitions in addition to the former, and a (iv) change from plasterboard to pinewood panels in the lining of public areas (‘A’, ‘B’, ‘C’, and ‘D’ in Fig. 8 respectively).

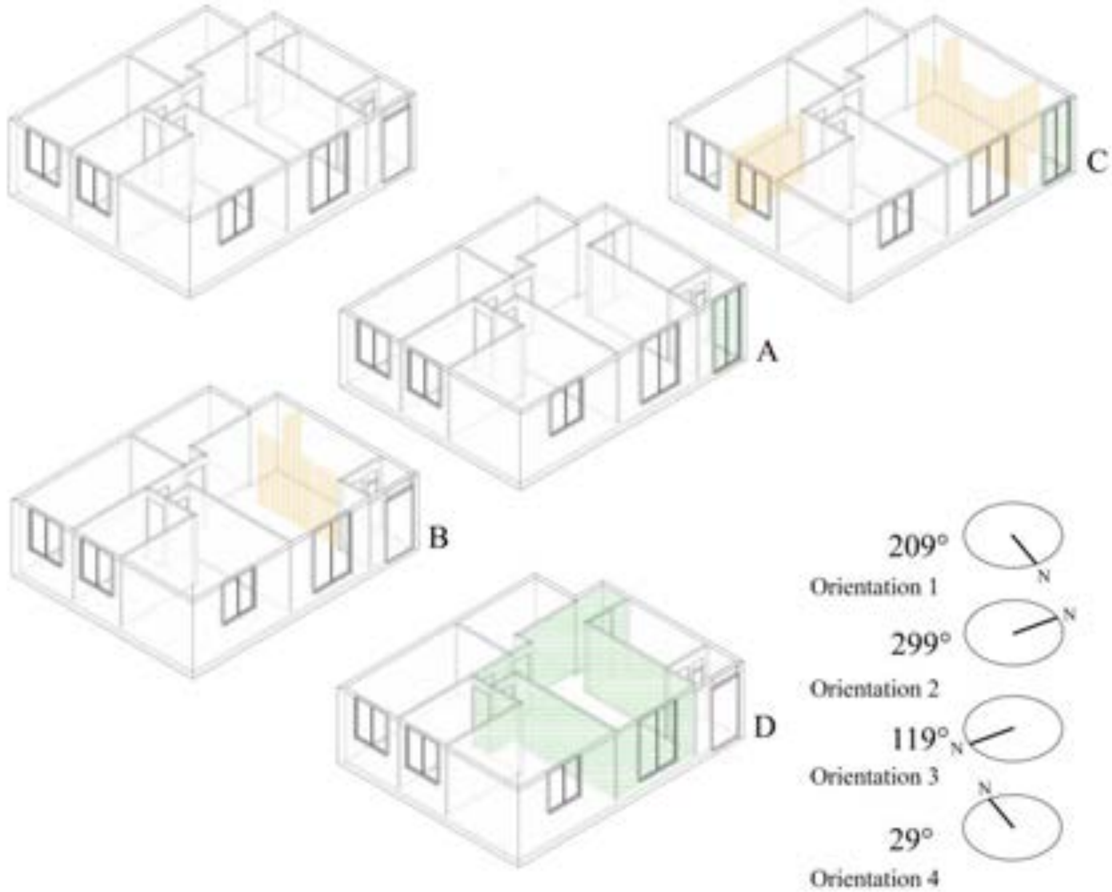

Figure 8: Modifications and orientations included in the SDH2 evaluation, where green represents addition and orange removal of architectural elements

The environmental simulation results are summarised in Fig. 9. The benchmark apartment accumulated between 2,879.08 and 2,897.72 hours of discomfort (i.e., more than 120 days) and consumed between 7,807.24 and 8,020.59 kWh in space heating on an average year according to orientation. In terms of the impacts of modifications, changes ‘A’ and ‘D’ were almost neutral while modification ‘B’ resulted in 17.32 to 23.90 and ‘C’ between 29.13 and 51.89 extra hours of discomfort per year. Similarly, modifications ‘B’ and ‘C’ resulted in an increment of 1,558.73 and 2,123.42 kWh energy consumption for space heating respectively. In contrast to JPUS, most of this consumption concentrated in the coldest season.

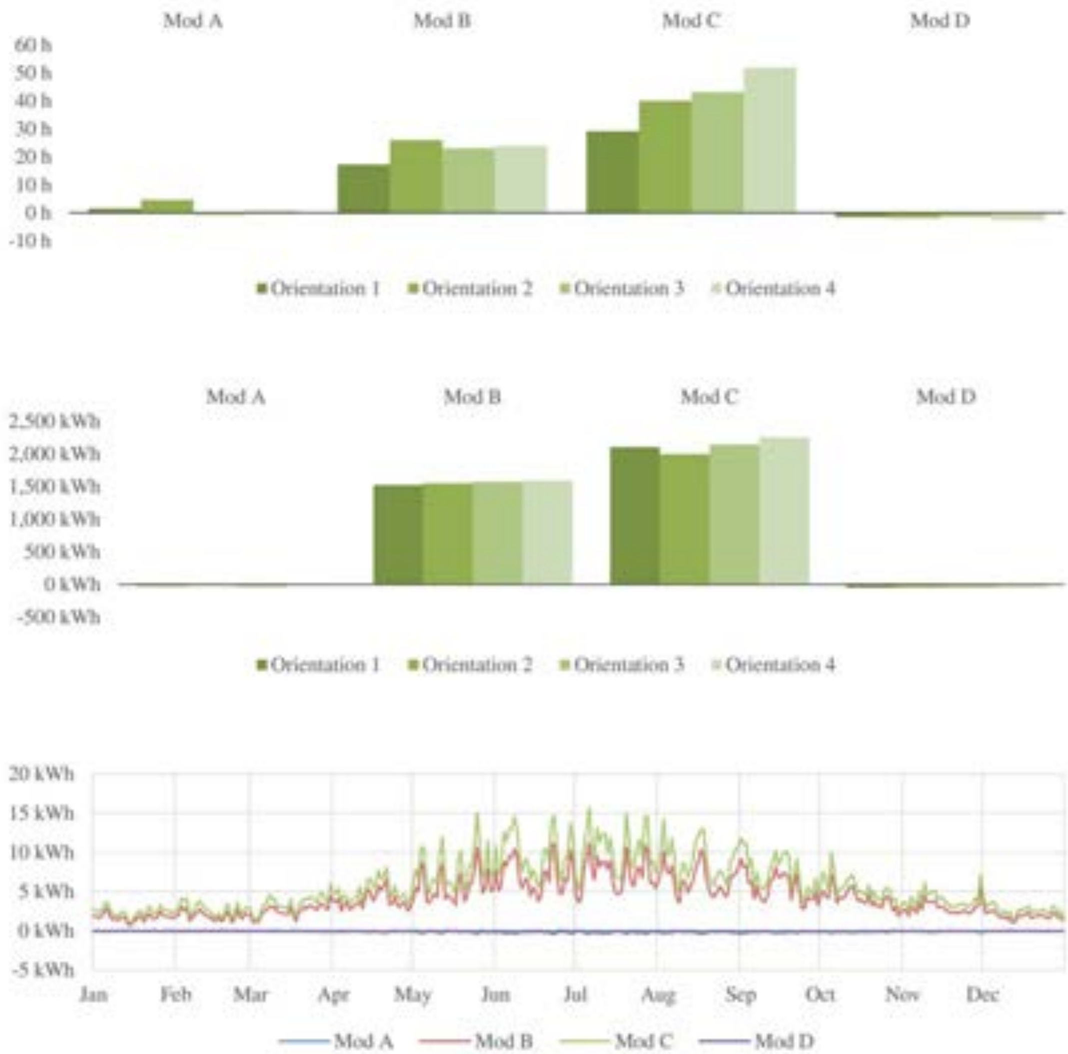

Figure 9: Differences in discomfort hours (first row) and energy consumption for space heating (second and third rows) by orientation and modification type over a standard year using an unmodified benchmark dwelling as reference (i.e., 0kWh) on SDH2 cases

Then, the third set of modifications analysed were the ones found in the TR housing complex. The most common modifications found where five, i.e., (i) addition of an opaque lightweight roof to the main entrances, (ii) masonry kitchen extensions with translucent roofs, (iii) lightweight translucent backyard covers, (iv) two storey masonry and timber frame extensions, and (v) addition of a pine wood layer to the walls of public areas at the ground floors (‘A’, ‘B’, ‘C’, ‘D’ and ‘E’ in Fig. 10 respectively).

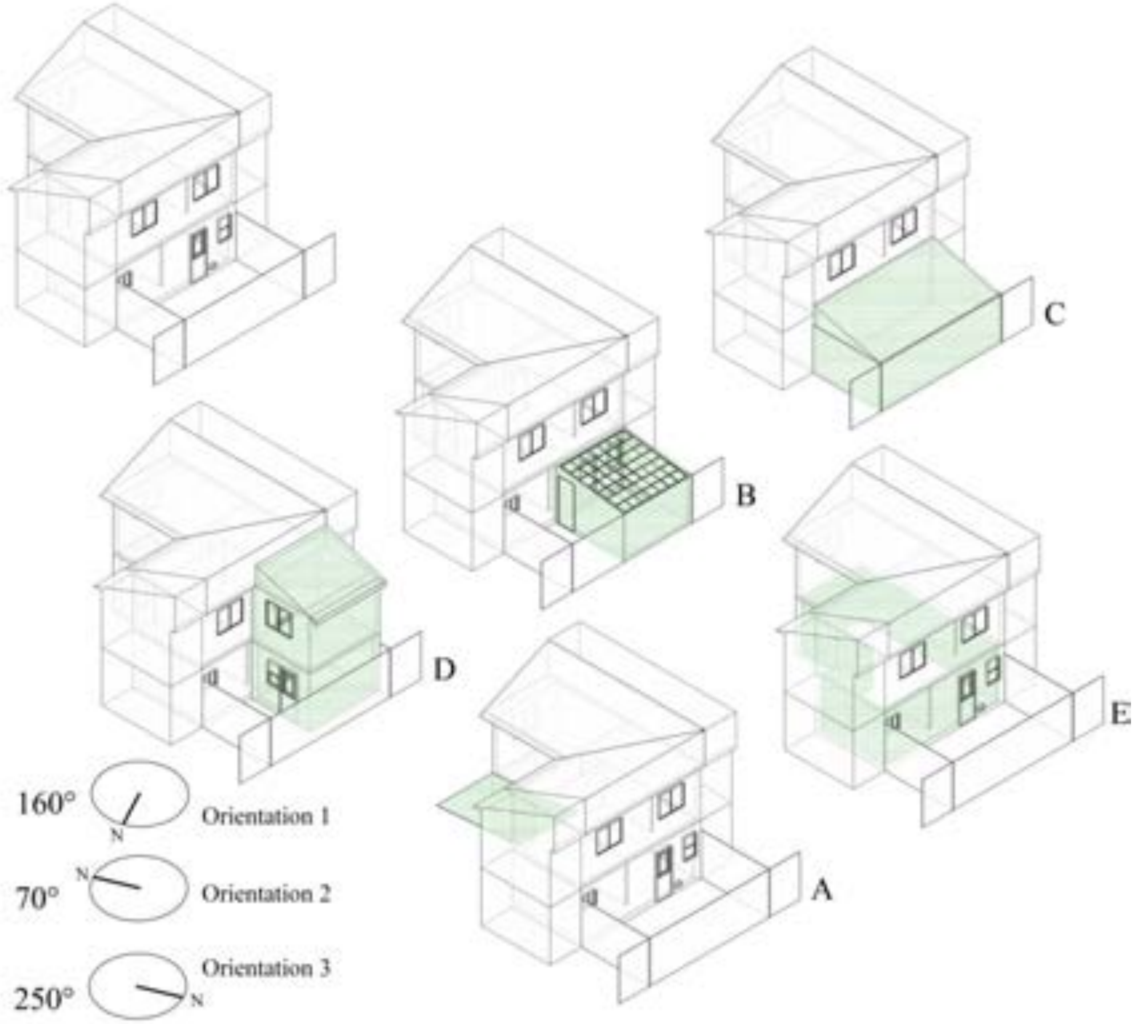

Figure 10: Modifications and orientations included in the TR evaluation, where green represents addition of architectural elements

The results of the environmental performance and energy consumption simulations are summarised in Fig. 11. Overall, the benchmark house consumed between 7,250.37 and 7,452.41 kWh and presented between 2,712.50 to 2,718.61 hours of discomfort (i.e., more than 130 days) on an average year depending of their orientation. In terms of the impacts of modifications, the results tended to diverge substantially. While modifications ‘A’, ‘C’ and ‘E’ had a small influence on the total hours of discomfort, modification ‘D’ added an extra 156.61 hours of discomfort per year and modification ‘B’ reduced them by a mean of 259.52 hours. In terms of energy consumption for space heating purposes, modifications ‘A’ to ‘D’ resulted in a slight increase of kWh (i.e., between 156.71 and 361.31, where ‘C’ and ‘D’ where the highest) while modification ‘E’ decreased consumption by 160.71 kWh. Significantly, these impacts on energy consumption were evenly distributed across warm and cold seasons.

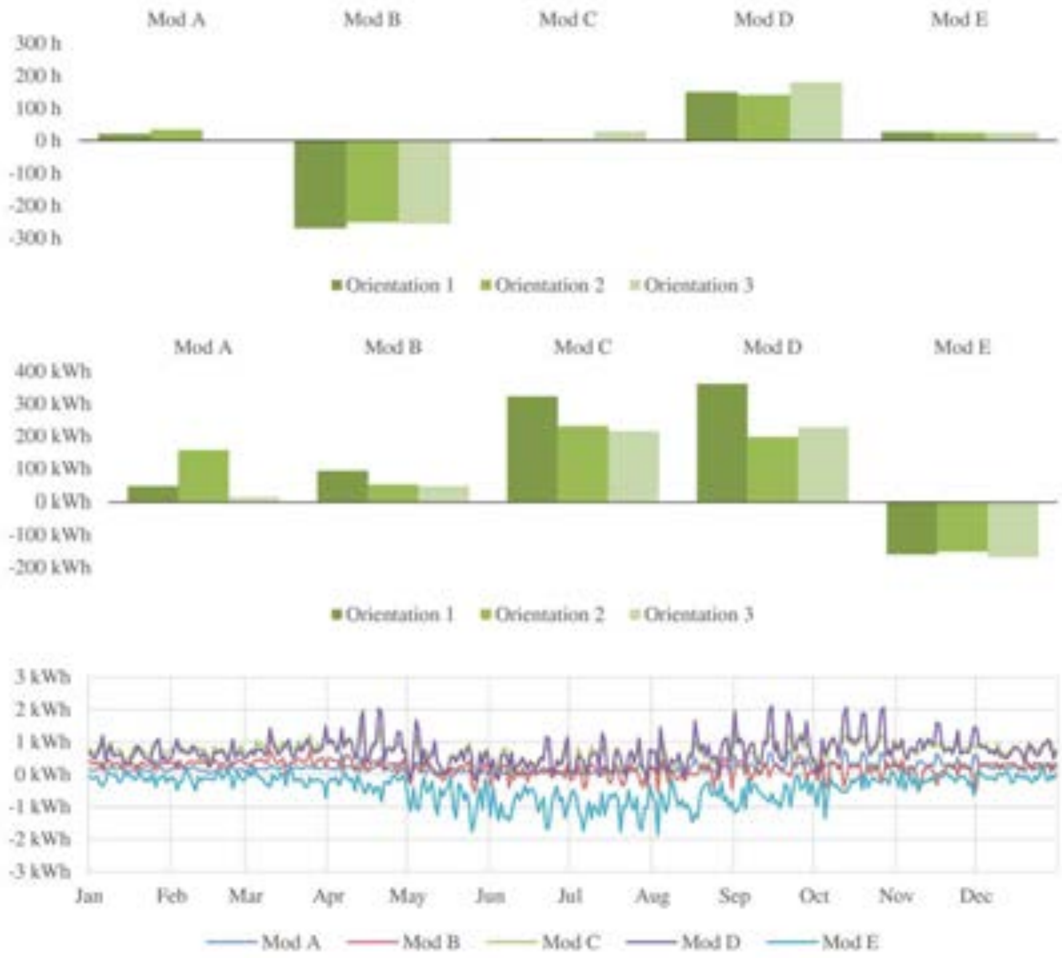

Figure 11: Differences in discomfort hours (first row) and energy consumption for space heating (second and third rows) by orientation and modification type over a standard year using an unmodified benchmark dwelling as reference (i.e., 0kWh) on TR cases

Lastly, the fourth set of modifications included in the evaluation was part of the SDH1 housing complex. The most common modifications found in these dwellings were six, i.e., a (i) ground floor timber frame fibre cement extension, a (ii) first floor timber frame extension, a (iii) timber frame extension with translucent roofing, (iv) lightweight translucent backyard covers, (v) opaque lightweight backyard covers, and a (vi) change of finishing materials in ground floors from gypsum plasterboard to pine wood (‘A’, ‘B’, ‘C’, ‘D’, ‘E’, and ‘F’ in Fig. 12 respectively).

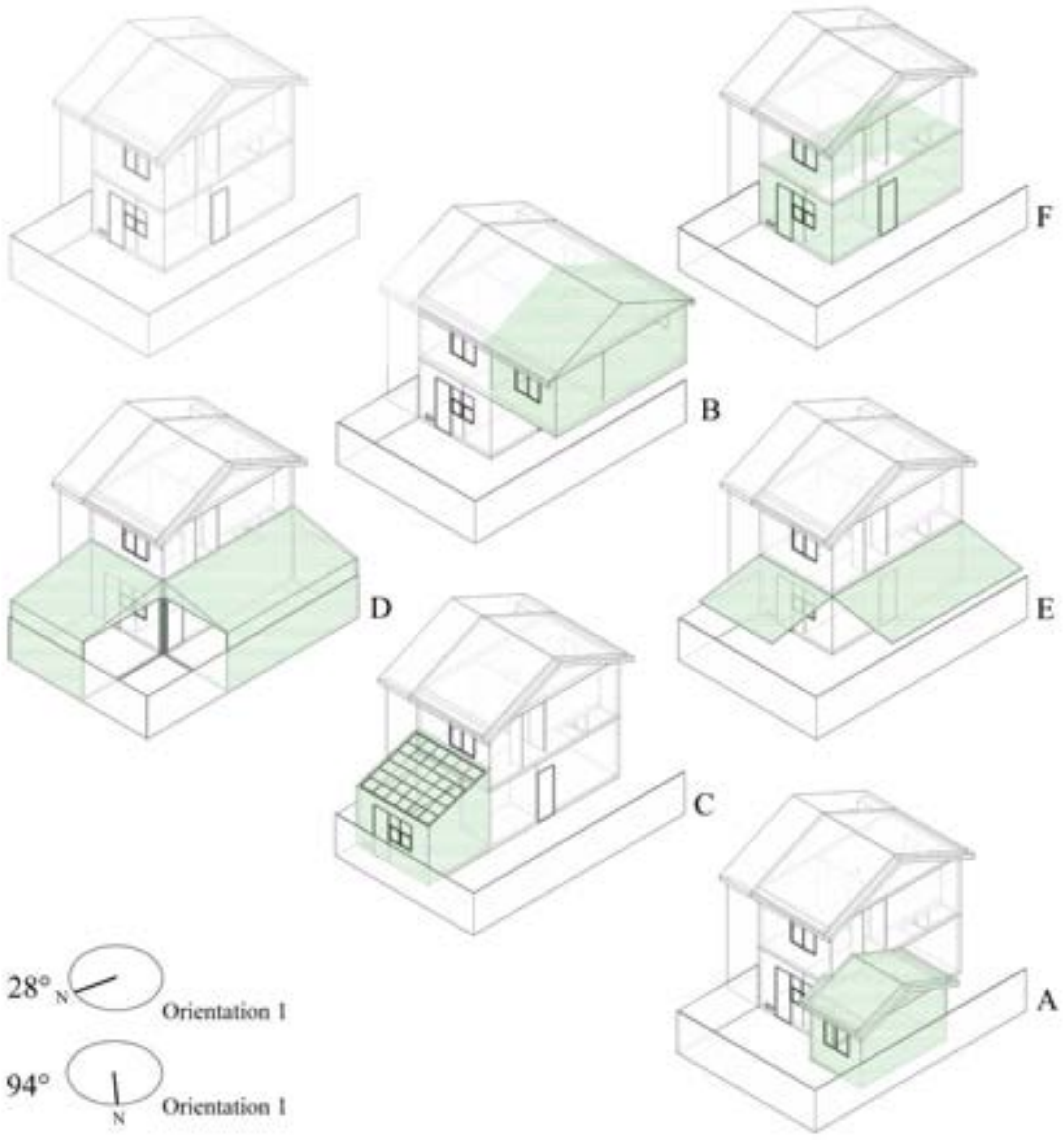

Figure 12: Modifications and orientations included in the SDH1 evaluation, where green represents addition of architectural elements

The simulation results are summarised in Fig. 13. The benchmark dwelling accumulated between 2,924.28 and 2,941.52 hours of discomfort (i.e., more than 122 days) and consumed between 12,731.64 and 12,757.42 kWh in space heating in an average year. In terms of the impacts of self-construction, modification ‘C’ showed the strongest effects by adding 1,057.62 hours of discomfort to the dwellings annually (i.e., more than 166 days in total), while modifications ‘A’ and ‘B’ added between 414.85 and 468.92 extra hours depending on their orientation. Significantly, modifications ‘D’ and ‘F’ reduced the accumulated discomfort by a mean of 390.28 and 108.78 hours respectively. These improvements in comfort had a strong impact on the annual energy consumption; while modification ‘D’ decreased the total by 9,633.94 kWh modification ‘F’ reduced it by

7,012.16 kWh. Most of this reduction concentrated in the cold season, while only modification ‘C’ increased consumption during winter.

Figure 13: Differences in discomfort hours (first row) and energy consumption for space heating (second and third rows) by orientation and modification type over a standard year using an unmodified benchmark dwelling as reference (i.e., 0kWh) on SDH1 cases

4 Discussion

The results presented in this paper evidence that personalisation can have a strong impact on housing quality and residential satisfaction. The act of modifying a dwelling tends to be a response to household needs not being addressed by the dwellings in their original state, suggesting that self-construction may enable the occupants to gain control over their own residential environment (Bunster et al., 2015). However, the particular way in which these modifications are materialised can also define the capacity of the dwellings to meet intricate functional and subjective requirements; hence, there is a latent need for the introduction expert-knowledge as means to guide the personalisation process.

According to simulation results, the thermal performance capabilities of the cases in their original state were consistently poor thus confirming the outcomes of former studies (e.g., Bustamante et al., 2009b; Escorcia et al., 2012; Celis et al., 2012). Accumulated

hours of discomfort exceeded 120 days across cases regardless of the material, orientation or type of dwelling, implying that without active space conditioning systems the average household is expected to be in discomfort almost 33% of the days of an average year. This may be a consequence of the poor airtightness of the dwellings, whose improvement may require a substantial transformation of the standards and practices currently in use by the construction industry (Figueroa et. al, 2013).

Beyond general performance considerations, these results suggest that the information available to the occupants at the time of conducting self-built modifications may have a substantial impact on the quality of their surroundings. As shown by the results, the size, location and materiality of extensions can be a defining factor behind the performance of personalised dwellings (as suggested by Acevedo et al., 2007; Andrade et al., 2007; 2008). Significantly, modifications that were similar in shape and location had contrasting impacts on energy consumption due to minor morphological and/or material differences, implying that the capacity of the users to use self-construction as means to enhance the quality of their residential conditions might be limited without thorough a-priory environmental performance assessment. This is evident in some of the most common modifications found, such as, e.g., changes from gypsum plasterboard to pinewood in public areas after aesthetic purposes, which had a strong impact on the thermal performance of some cases. Similarly, extensions and/or external roofs had contrasting impacts according to their materiality, whereas glazing of open apertures in apartment blocks tended to improve their performance regardless of specific architectural factors.

Building energy performance depends upon a multiplicity of factors that can be difficult to comprehend by both practitioners and occupants, hence restraining their capacity to foresee the impacts that different modifications may have on the thermal performance of a personalised dwelling. Former studies have argued that information-support systems may be a suitable approach to guide self-built modifications towards satisfactory outcomes at different stages of the dwellings' life cycles (Haramoto et al., 1983; Donath & González-Böhme, 2008) and thus may enable ensuring minimum energy performance conditions without breaching the limits of affordable production.

5 Conclusions

This paper analyses the impacts of different self-built modifications on the energy efficiency of Chilean social housing, aiming to identify linkages between personalisation and household satisfaction. In order to assess the most common modifications, a residential survey was conducted in four housing developments located in Concepción, central-southern Chile, and used to inform a series of building energy simulations. It was found that housing personalisation can have a strong impact on the thermal performance capabilities of different dwellings, regardless of their type, materiality or orientation. Furthermore, results show that similar interventions can have contrasting effects on energy performance, pointing to important difficulties for the occupants to foresee the impacts of self-built modifications on the capacity of their dwellings to meet their needs and expectations. Overall, these results support former studies that have argued for the use of information-support systems as means to enhance housing quality within affordability through the introduction of expert-knowledge to an otherwise unguided and sometimes deceitful personalisation process.

Acknowledgements

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CLIMATE RESILIENCE OF SELF-BUILT HOUSING UNDER A HOT ARID CLIMATE; ALGERIA

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Abstract: *Self-built housing remains a dominant response to the increasing urban population of the developing countries spanning from Asia to Africa and Latin America. Self-built housing still account for a large share of the housing production in Algeria. Under the hot and arid climate of southern Algeria, contemporary self-built houses seem to have little remaining of the traditional vernacular models, often recognized as well adapted to the environmental and climatic context. Comparatively, little is known about the contemporary architectural housing production and its thermal adaptation to the extremely hot local climate. Hence, the main objective of this paper is to examine and identify the bioclimatic attributes of the contemporary self-built houses in the desert city of Biskra, Algeria. For this purpose, one hundred individual houses were surveyed. Criteria included the house footprint, orientation, design and construction characteristics as well as the historical evolution of the built-up areas and space usage. A typo-morphological classification based on the house's footprint identified three main types. The bio-climatic adaptability of these models was first analyzed in qualitative terms. Then, a thermal simulation of the most recurrent and representative types was carried out. The results highlight the relatively good climatic adaptation of the contemporary self-built houses.*

Keywords: *Self-built Houses, Hot and Arid Climate, Typo-morphological Analysis, Thermal Performance, Algeria*

1 Introduction

Over half of the world population is living in urban settings, and it is projected to reach sixty percent by the year 2030 (United Nations, 2016, a). The United Nations estimated the urban population of the developing world to increase from 2.7 billion in 2011 to 5.1 billion by 2050 (United Nations, 2016, b). Virtually all this growth will be concentrated in urban areas of the developing world, namely Africa, Asia and Latin America (Cohen, 2006). The main resulting challenge is the provision of housing, that often enough cannot be met by the public sector alone. In this context, private self-built housing is, in most cases, the predominant response.

Contemporary self-built housing in many part of the developing world appears to be in radical rupture with their traditional or vernacular predecessors. A study of self-built houses in Brazil exemplified to some degree, a definite rupture in the evolution of the local vernacular houses (Kowaltowski, 1998). By contrast, vernacular architecture across the world is often presented as a symbiosis between context and climate while meeting users' specific needs, accommodating the values, economies and the way of life of the cultures that produce them (Oliver 2007; Zhai & Previtali 2010, Bodach et al. 2014). It generated solutions and typologies that are regionally specific and climatically adapted (Mingozzi & Bottiglioni 2007). A dominant housing typology seems to exist in every period of a city's expansion. For example, the courtyard house, although a dominant typology in many hot climatic regions, has often been replaced by row houses. This historical transition was dictated by the necessity to provide vehicular access to each plot of land (Shayesteh & Steadman 2016), which has become the most common and repeated typology within the contemporary self-built housing solutions to respond to public land management and zoning strategies.

In the context of this study, the house means a permanent building with one or multiple stories, with the owner occupying it fully or in part, while self-built houses are defined as individually developed houses that are controlled by the owner in an urban context, constructed using permanent materials, usually without engagement of formal developers (Khan 2008). This definition excludes squatters and slums. Self-built housing does not necessarily imply owners becoming masons, but engaging professionals when required to build different components of the house, albeit a single contractor could also be used for the entire construction process. The house means a permanent building with one or multiple stories, with the owner occupying it fully or in part. The construction is 'managed' by the owners, during their leisure time thus, no formal developers are used to manage the construction" (Khan 2008).

Self-built houses represent an extensive part of the housing production in Algeria, found in a rather similar typology throughout the different climatic zones of Algeria. Under the hot and arid climate of the southern part of that country, contemporary self-built houses seem to have little remaining of the traditional vernacular models, often recognized as well adapted to the environmental and climatic context. There are numerous studies about the bioclimatic performance of vernacular architecture in southern Algeria (Sebti et al. 2013; Fezzioui et al. 2009). In parallel, little is known about the thermal adaptation of the contemporary housing production. Such data is vital to evaluate the belief and results that all-present time buildings, under the hot climate are thermally inefficient (Tabet Aoul, 1996, Ali-Toudert 2005; Bouchahm 2011, Rumana 2013).

The imitation of 'modern' architectural models appears to be the primary source of inspiration in the current architectural housing production (Labaki & Kowaltowski 1998).

In design terms, it is in total contrast with traditional forms and composition, suggesting an indifference to the local climate. However, this assertion can only be substantiated with a rigorous investigation. Several questions and scenarios remain to be asked and answered: Would there be a conflict, for example, between the outer “modern” appearance of the house and an eventually traditional interior organization? Are there any traditional architectural devices climatically efficient which might have been integrated into the housing design and still regulate its thermal behaviour in a latent way? Would the search of thermal comfort still regulate the use of domestic spaces?

This research aims to investigate the climatic adaptation of contemporary self-built housing production while attempting to answer the above questions. The context of the study is the contemporary individual self-built plot houses found in the new housing developments of Biskra, in southern Algeria, an area known for its , hot and arid climate. Before investigating the modalities of the climatic adaptation of the contemporary lot houses, an identification of their characteristics was deemed necessary. Hence, a typo-morphological analysis was first carried out, with the objective to identify the contributing architectural design features to the climatic adaptation. The house footprint, the morphological and construction characteristics were investigated. A typo-morphological approach for this architectural analysis was used, resulting to in a typological classification. Finally, a thermal evaluation was carried out for the most recurrent and representative models.

2 The Typo-Morphological Approach and Analysis

The typo-morphological approach is a descriptive method that proceeds by decomposition, specification of elements while revealing their underlying structure and their interrelationships (Deloch1992; Moudon, 2004, Gokce 2017). The approach provides a complete framework based on the idea of “type” which is related to the origin, essence, characteristics and structural principles of forms (Caniggia and Maffei 2001; Conzen 2004). It represents not only the formal and spatial attributes of houses, but also the organizational and structural elements of houses within the city fabric. The typo morphology approach combines the volumetric characteristics of built structures with their related spaces to define a built landscape. The element that links built spaces to open spaces is the plot or parcel, the basic cell of the urban fabric. (Mudon, 1994, p. 290). The analysis has a methodological framework, which supposes, first the constitution of a corpus by inventory, followed by a preliminary treatment of this corpus by logic-empirical analysis, leading to the identification of a structural model to finally establish a typology (Deloch 1992).

An onsite investigation of one hundred (100) houses focused on plot size, house footprint, ratio of built to open space and location of built-up and open space within the plot. The house types are abstractedly presented using archetypal building method. The logic-empirical analysis, which followed the corpus’s constitution, took the house’s footprint as the object of the investigation. This criterion appeared to be a prominent morphological feature likely to serve as the basis of building up the structural model. It also permits to take into consideration two levels of the climatic analysis by considering first: 1) the relationship between the building and the plot of land, and 2) the associative characteristics of the plot houses and their relationship to the urban context. On the other hand, this criterion expresses the main logic that regulates the creation of plot houses in the new housing estates. The relationship of the building to the plot of land is initially fixed through an authorized construction ratio. Further, the house’s footprint has a dual effect on the architectural response as well as on the thermal behaviour of the building and as such allows both architectural and thermal reading of the studied

building. The significance of this factor led to its consideration as the criterion for the preliminary classification. The analysis of the surveyed houses in terms of footprint allowed the construction of the structural model.

The proposed structural model presents the plot house as a combination of three (3) elementary sections (also called segments or modules), with every section being subject to variations:

- Front module: garden
- Central module: living quarters
- Rear module: backyard.

The whole included in the perimeter of a generally rectangular plot (figure 1). The typological classification is based on this structural model (Deloch 1992; Duprat 1986). The corpus of the study was organized in homogeneous subgroups. Each subgroup was formed by considering structural similarities (presence, absence or elimination of any module, extension, partial or total occupation of the module) that can affect the essential parts of the house.

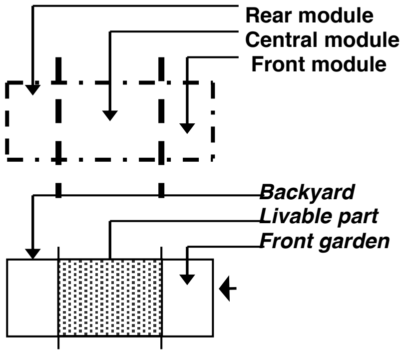


Figure 1: The classification structural model

The morphological analysis concluded with a graphic matrix that took into consideration both the structural model and the structural variations. This matrix shows also the variants resulting from the modifications affecting the three (3) elementary parts of the basic structural model (figure 2).

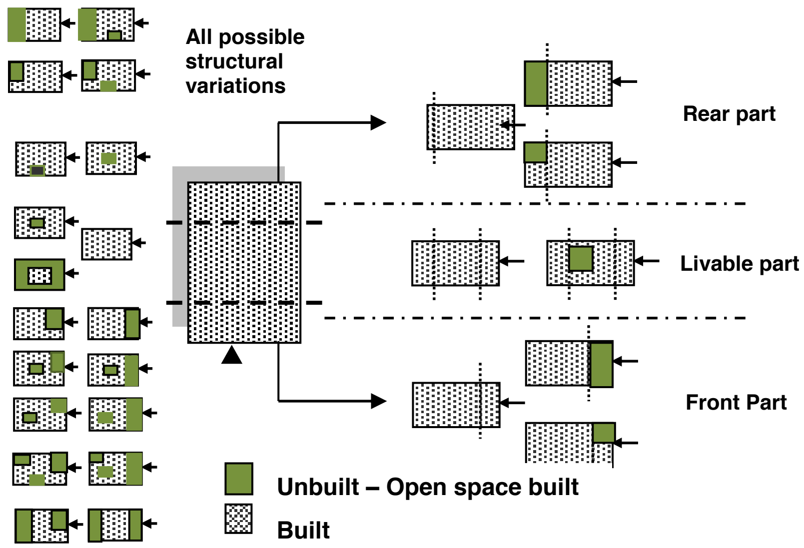


Figure 2: Architectural variants resulting from the modifications affecting the basic structure

Architectural types were defined according to the occupancy of the front module (Panerai1980; Deloch1992). This module which prefigures the appearance of the facade allowed to distinguish between two architectural types:

1. the house with a totally built up front part (typified **L**) and,
2. the house with a front garden (typified **R**), as well as a subcategory: the porch house where the front part is covered by the protruding first floor (typified **r**) (figures 3 & 4).

The variants resulting from these two major architectural types were classified according to the structural variations of either the central or the rear module.

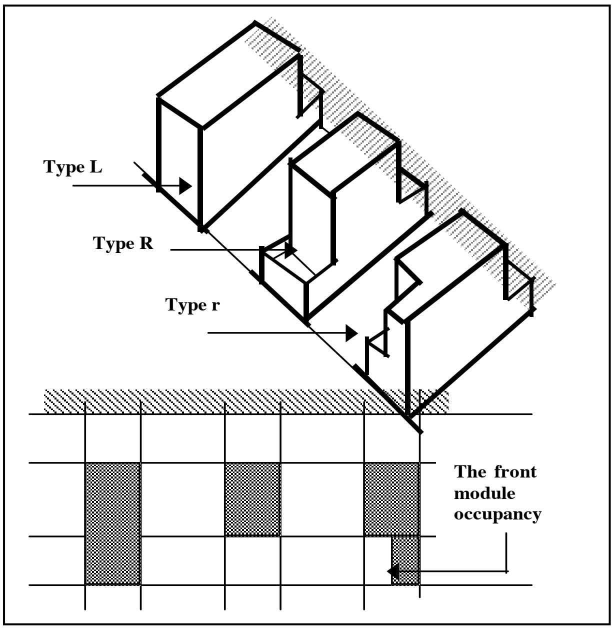


Figure 3: The architectural types defined according to the front module occupancy

Type L	Type R	Type r
		

Figure 4: Examples of Self-built houses classified based on the front module occupancy

This matrix was then used for the codification of the structural variations (figure 5). First, a distinction is made between the living part being totally built up (noted structure **T**) or partially built up and organized around one or several patios (noted structure **P**). Then, for each of these structures, substructures were identified according to the extent of rear part built-up. Finally, three alternatives emerged: first, the rear part being totally a yard, second, a yard with a protruding first floor, or third, a totally built up space and were respectively codified 0, 1, 2 (figure 5). Each of the cases on the table is then identified as an alphanumeric codification (ex RT0). It indicates then the typical structure

corresponding to: a) one of the two defined morphologies, and b) the variants obtained by structural modifications.

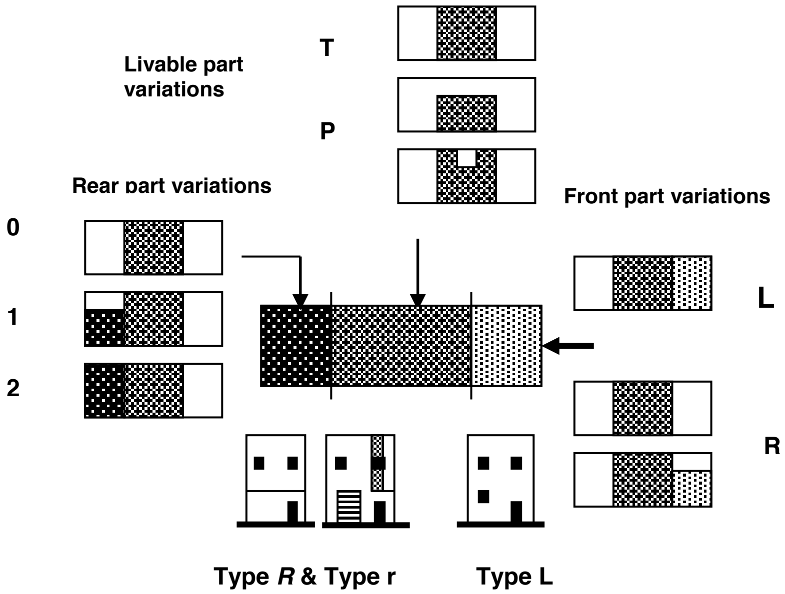


Figure 5: Codification of the structural variations

Based on this typological classification, a statistical analysis of the corpus was carried out to define the most representative variants to be subject to a thermal analysis. The distribution of the 100 plans was as follows: LT2 with 19 plans, rt0 with 18 plans, rt1 with 10 plans, rp0 with 09 plans, LP0 with 08 plans, rp1 with 07 plans, LT0, LT1, LP2 with 06 plans each and 05 plans for rT2 (table 1). The 18 remaining plans are divided into 7 groups of variants (from 1 to 4 elements) and therefore, were not included in the bioclimatic study.

Table 1: Statistical analysis of the housing corpus

Types	Configuration	Recurrence	Types	Configuration	Recurrence
[illegible]		19	LP0		08
r T0		18	r P1		07
[illegible]		10	LT0 LT1 LP2		06
[illegible]		09	r T2		05

3 The Bioclimatic Responsiveness of the Plot House

To evaluate the thermal performance of the self-built houses, a dual bioclimatic analysis (qualitative and quantitative), was carried out.

3.1 Qualitative evaluation

The qualitative approach being an initial synthesis of architectural devices, phenomenon's and space usage known as bio-climatically responsive of the architecture under study. In this regard, four determinant aspects were considered; the house footprint, the envelope, the building structure and materials as well as living spaces usage. Any element having a real or a latent impact on the climatic adaptation of the lot house was systematically monitored. The first level of observation i.e. the house's footprint indicated that the grouping mode of the houses by party walls, due to the small size of the contiguous plots, offers an obvious advantage as it minimizes the surface of the envelope in contact with the harshness of the external environment (figure 6). Further, it creates intermediate shaded spaces such as lateral and rear yards, patios, porches, and gardens that can provide ventilation and daylighting.

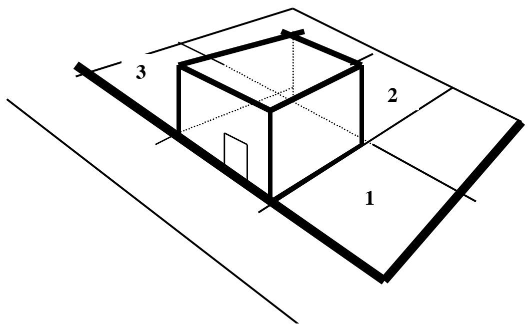


Figure 6: Grouping mode of the plots

The morphological analysis of the envelope revealed a set of characteristics of the plans, facades, micro-volumes, etc. common to many plot houses and climatically responsive of which the most important ones are:

- The compactness of the plan, which reduces the surface of the house in contact with the external environment, minimizing undesirable heat gains due to the hot air and the incidental solar radiations.
- The spatial house organization, as this study revealed that the two and three-floor houses dominate the spectrum. This presents an advantage since a three-floor building has an intermediate level, which may act as a "useful inertia", in other words a supplementary thermal mass capable of absorbing an important part of internal loads (Izard 1993).
- The totally or partially closed facade to the outside, where windows are rare and of a small size. Further, cantilevered volumes such as balconies, projections such as roofs, overhangs as well as loggias act as shading elements and represent an efficient mean to shade walls and openings (Tabet Aoul 1996).
- The plot house presents also, a device of partial but efficient sun shading effect that consists of high parapets (1.8 to 2m) around the terrace. The shadow they cast on the horizontal surfaces of the terrace is significant.
- The protected windows where several diversified window shading devices were identified ranging from overhangs, wooden shutters, venetian blinds to external and internal curtains. These devices constitute sizable additional sun protection measures.

Next the constructional characteristics of the envelope and the structure were examined. Concrete and concrete blocks are commonly used in the structure and the envelope of the house. The concrete blocks, such as those manufactured in Algeria are a heavy building material and as so of a good calorific capacity (Panerai 1980). Used mostly in exterior masonry (walls thickness is about 30cm to 40cm), they create an envelope of considerable thermal inertia. The calorific capacity of the concrete adds to the important mass of this building material. Furthermore, the generally light color of the facades of a low heat absorptance factor is an additional factor that positively contributes to the climatic adaptation of this architecture.

Finally, the survey of space usage revealed that the occupants moved around the house to take advantage of the most comfortable spaces during the day. The use of the central hall and the terrace can well illustrate this particular adaptation. First, the plan of the plot houses is frequently based on a large central space, a sort of a house central core that is relatively well protected from the rigors of the external environment. This space, recalling the traditional courtyard organization remains the coolest part of the house and as such, was the most used space during the day and the most preferred one for social interactions between the occupants. The accessible flat roof-terrace, on the other hand enables the practice of what is generally called: the daily “nomadism”. In fact, it is used during the hottest period of the year as the sleeping area. The high inertia of the envelope delays favourably during the day the transmission of heat. However, this becomes detrimental at night. In this case, the terrace becomes a viable alternative, enabling the occupants to sleep outdoors and benefit from the cooler night air.

In conclusion, this qualitative analysis as a first thermal assessment revealed some potentially positive bio-climatic building features that needed to be supplemented by a quantitative evaluation (Sriti 1999; Bouchahm 2011). Thermal simulation was carried out next for the most recurrent typologies.

3.2 Quantitative approach: the thermal analysis by simulation

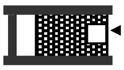
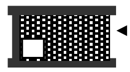
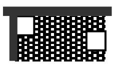
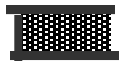
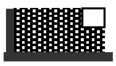
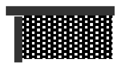
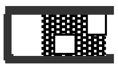
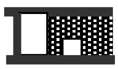
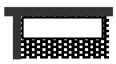
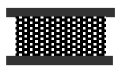
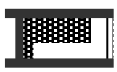
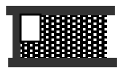
The software Dynamic Energy Response of Buildings (DEROB-LTH) was used in this study as it permits the assessment of the thermal behaviour in multizone buildings (Kvist 2005). The program consists of 8 modules. Six of the modules are used to calculate values for temperatures, heating and cooling loads. It can take account of 8 volumes and simulate buildings of arbitrary geometries. Simulations were carried out for the 21st of July, which represents the least favourable conditions in the hot season. Energy data were selected from the sun Atlas of Algeria (Capderou1985) while meteorological data were taken from Biskra's meteorological station.

4 Parametric Analysis

Twelve cases of the most representative types and variants as obtained from the typo-morphological analysis were selected for the thermal simulation (Table 1). Care was taken to properly model all the morphological details (Table 2). The orientation and the building material characteristics were considered as fixed variables. The orientation was taken as northeast/southwest. Although the survey highlighted random orientation according to the site and the existing street constraints, the chosen orientation would neither be the least nor the best orientation. The construction method and building materials were based on the most applied one. Hence, exterior walls consisted of a thickness of 30cm, made of the locally manufactured concrete blocks (density 1800 kg/m3, conductivity 0.72 W/m °C), with a 2cm mortar on both sides (conductivity 0.28). A light colour of 0.35 absorptance factor was considered for the external walls. A non-

insulated roof with 50 mm cork blocks (conductivity 0.32 and specific heat 0.96 and 0.60 absorptivity) was considered. For the windows' shade factor, a value of 90 % was considered as it represented the effect of the shade provided by the external wooden shutters that remain closed from 11am to 5pm. Internal load was evaluated according to the variation of occupancy of the house (6 persons in total) and the use of its appliances and summed up to 23 Wh/m2. Summer night ventilation was assumed to be equivalent to 20 ach/hr for part of the night (8pm to 6am) and 1ach/hr for the rest of the day. Figure 7 shows the operative temperatures obtained from the thermal simulation for all tested models.

Table 2: The main characteristics of the tested models

Types	Configuration	Surface & Vol.	Types	Configuration	Surface & Vol.
r T0		**a.** 198,5 **b.** 459,6 **c.** 31,05 **d.** 1310	**LT1- 3C**		**a.** 173,6 **b.** 366,56 **c.** 12,96 **d.** 1250
r T1		**a.** 200 **b.** 564 **c.** 11,65 **d.** 1264	**LT2- 3C**		**a.** 208 **b.** 256,1 **c.** 1,96 **d.** 769,6
r T2		**a.** 118 **b.** 274 **c.** 13,94 **d.** 737	**LT2- 2C**		**a.** 208 **b.** 407,1 **c.** 20,68 **d.** 1352
r P0		**a.**1 21 **b.** 291 **c.** 13,94 **d.** 744,5	**LP0**		**a.** 150 **b.** 374,8 **c.** 10,68 **d.** 975
r P1		**a.** 304 **b.** 754,8 **c.** 33,9 **d.**1863,5	**LP2**		**a.** 139 **b.** 262,67 **c.** 9,1 **d.** 903,5
R P1		**a.** 138 **b.** 365,94 **c.** 24,05 **d.** 897	**LT1- 2C**		**a.** 189 **b.** 458 **c.** 15,24 **d.** 1129,5
a. Plot surface ($m^{2)}$; **b.** Envelope surface; **c**. Glazing area; **d**. Volume (m^3) **C2, C3:** 2 or 3 **C**ontiguous plots.					

The following observations can be drawn from the results: among the twelve simulated houses, the one that illustrates the most favourable condition is a house with a front porch, a yard, and a three-side party wall (three contiguous plots). For this model (rT2), an operative temperature of 29.2°C was reached during the day, while the maximal registered temperature did not exceed 31.3°C (6 pm) (figure 7). During the day, the maximum operative temperature reached 31.3 °C and 32.2 °C respectively for the most favourable and the most unfavourable types, while the maximum outdoor temperature attained 38.8°C.

In general, in all houses there was a substantial difference in temperatures between the interior and the exterior ranging from 6.9 to 7.8°C. This occurred during the hottest hour of the day (3pm), reaching 31°C and 31.9°C, respectively for the most favorable case (rT2) and the most unfavorable one (LT2-2C) (figures 7 and 8). During the night, temperatures tended to get closer to those outside. However, night temperatures are much cooler (figure 8). The inertia effect is also significant. It is perceptible through the low amplitude of the internal temperatures: considering each model, the difference

between maximum and minimum internal temperatures does not exceed 3.5°C (figure 7).

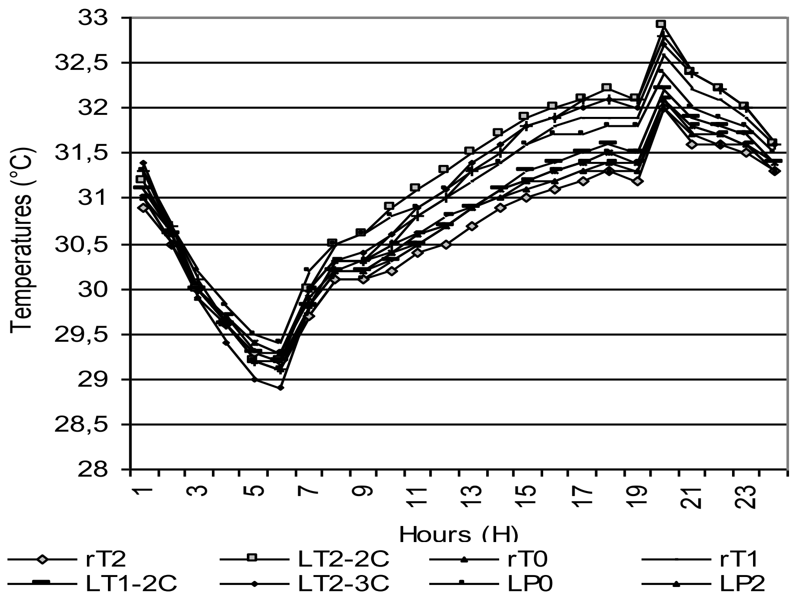


Figure 7: Operative temperatures for the 12 houses on the 21st of July

There is a night cooling effect through ventilation. However, its effect is limited as temperature rise rather early (figure 7).

The simulated thermal evaluation asserts of a certain degree of climatic adaptation of the plot house. However, it should be emphasized that the differences between the various models cannot be solely related to the house's footprint and the number of party walls which were the main classification criteria (Table 2).

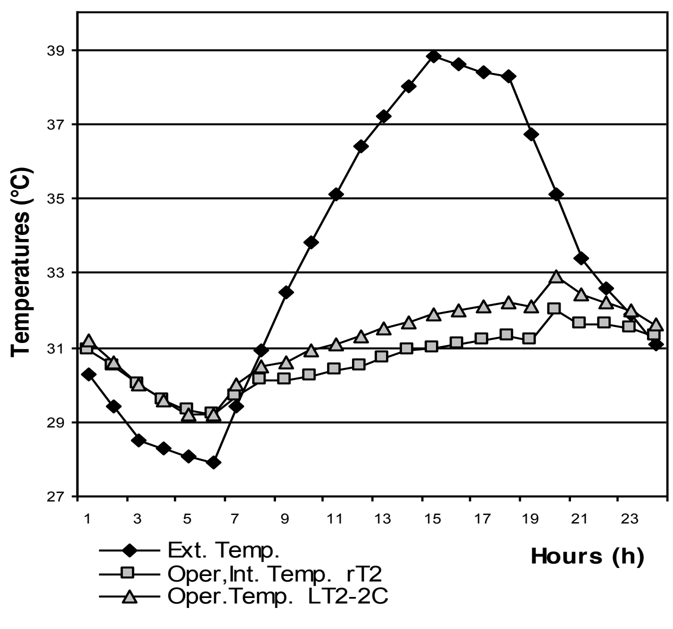


Figure 8: Operative temperatures relative to the most favourable model (rT2) and the least favourable one (LT2-2C)

Other morphological factors do certainly influence the thermal behavior of the analyzed examples, in particular:

- The external surface to livable volume ratio,
- The ratio of exposed surfaces versus the shaded ones,
- The ratio of window openings to the envelope surface, and finally
- The orientation of the exposed walls.

5 Conclusion

The present study aimed to test the climatic adaptation of contemporary self-built lot houses in the new housing developments of southern Algeria. The investigation carried out through a large survey, a typo-morphological analysis and thermal simulations asserts of a relatively good climatic adaptation. During the day, operative temperatures reached respectively a maximum of 31.3°C and 32.2°C for the most favourable and the most unfavourable types, when the outdoor temperature was 38.8 °C.

Thermal comfort may well be improved by the simple correct use of passive design principles. These passive means can be readily incorporated in the construction process. However, there is probably a limit to the effect of passive design measures on thermal comfort under such a hoy climate, if they are solely related to the building. Extra benefits will be gained through the site layout, compact mass plan, street height to width ratio and inclusion of vegetation and water bodies. The research taught the intrinsic need for a community design that will take into consideration passive building design and sensitive landscaping and urban design.

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NET ZERO FOSSIL ENERGY FOR HEATING DETACHED HOUSES IN HARBIN

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Abstract: *Following the recognition of the zero energy building concept, the zero energy mass customised houses have received more attention recently. This paper investigates the application of solar energy to achieve net zero on-site energy for space heating in a cold climate. As a case study, a cluster of 30 typical houses in Harbin, China was considered. Harbin is known for its coldest weather and longest winter among major Chinese cities. This study used TRNbuild software to model the house and consequently TRNSYS to determine the total heating load of the cluster of houses. The study focused on fulfilling the heating demand by using a ground source heat pump (GSHP) system. The total electricity consumed by the GSHP is covered by a grid-connected solar photovoltaic (PV) array. The required area of PV array to meet 100% of the annual electricity consumed by the GSHP was calculated. The results show the peak GSHP electric load required for the cluster of houses to be 99 kWh$_e$ with the total PV array area of 1961 m^2. The levelised cost of electricity (LCoE) generated by the PV array was found to be US$ 0.067 (RMB 0.44) per kWh$_e$ for 30-year project life. The cost of heat distribution network, the annualised life cycle cost (ALCC), and the unit heating cost (UHC) were also estimated for the system investigated.*

Keywords: *Cold Climate, Space Heating, Ground Source Heat Pump, Net Zero On-site Energy, Photovoltaic*

1 Introduction

The thermal energy demand especially for space heating is critical for residential buildings in cold climate zones (Ürge-Vorsatz et al., 2015). The energy demand for space heating in building sector in China is approximately 32% of the total final energy consumption by end-use (IEA, 2015). The demand for space heating is high in Harbin (heating dominated climate zone) due to severe cold weather (Xiliang, 2012). Fig. 1 shows the monthly average daily outdoor air temperature in Harbin based on the typical meteorological year (TMY) weather data file generated by Meteonorm software (Remund et al., 2016). From Fig. 1 it is expected that the space heating is required almost year-round, except the short summer period.

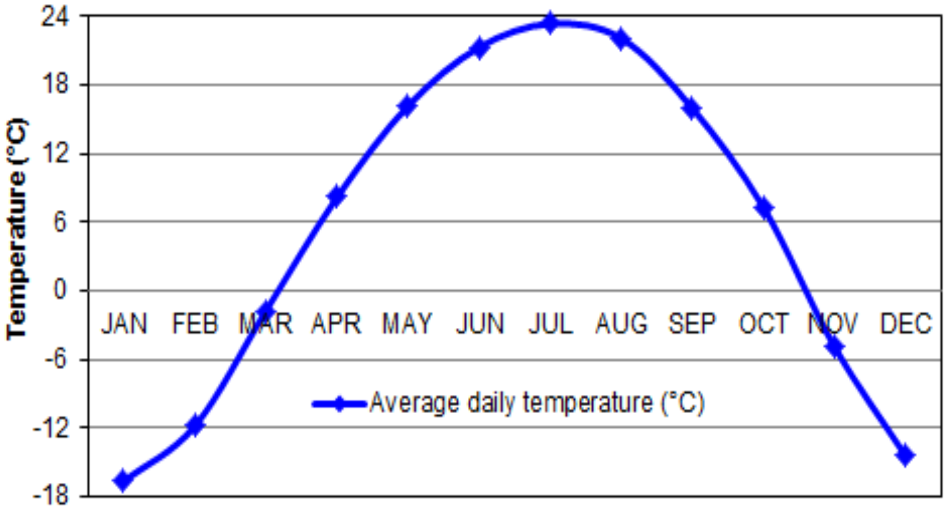

Figure 1: Monthly average daily temperature in Harbin

Due to insufficient infrastructure and lack of primary energy sources in most of the developing countries in cold climate zones, it is challenging to meet the space heating demand effectively and efficiently. A heat pump is a device that captures the heat energy from the ambient and upgrades to a temperature which is appropriate for the intended application. Low-temperature heat sources such as ground, air, and waste heat steam can be utilised for space heating applications. Due to higher energy efficiency and lower greenhouse gas emissions, the ground source heat pump (GSHP) technology is applied widely to fulfil the space heating demand in residential buildings in cold climate zones (Yang et al., 2010).

Due to higher space heating load in cold climates, the electricity consumption of GSHP is relatively higher compared to that of warmer climate zones. To meet this demand, an array of solar photovoltaic (PV) has been considered as an alternative to the fossil fuels based electricity from the national grid. There are different types of PV systems, including the on-grid, hybrid, and off-grid stand-alone. Among these, the off-grid stand-alone systems require backup battery banks, which is still an expensive option. However, the on-grid system, which does not require battery banks, can fulfil the electricity demand. The excess electricity generated can be sent into the main grid, and the deficit electricity can be obtained from the grid when the array is not producing electricity. The array can be sized to make the system net zero on-site energy in an annual time frame.

The concept of net zero energy (NZE) building becomes more attractive by researchers (Tian et al., 2015). Kurnitski et al. (2011) investigated life cycle cost of the energy system for a multi-building residential net zero energy building. They developed a seven steps procedure to achieve the cost optimal and calculated the net zero energy performance levels. Hernandez and Kenny (2010) proposed the life cycle zero energy building as well as use the net energy ratio factor for building design. An Italian pilot project for zero energy building based on examination with state of the art near zero energy was described by Dall'O et al. (2013). Some developing countries have targets on net zero energy buildings. A comprehensive analysis of the existing NZE building definitions and a selection of NZEB developments around the world are presented by Wells et al (2017). China started work on net zero energy building in recent years (Kurnitski et al., 2011). In this paper, a net zero energy space heating system for a cluster of 30 houses in Harbin was analysed by using TRNSYS simulation software tool.

2 Method

This study considers an on-grid PV system and a GSHP (Fig. 2). The major components of the system are PV array, inverter, controller, heat pump, and borehole heat exchanger. The analysis was done based on computer simulations and analytical calculations. The details steps are described in the following sections.

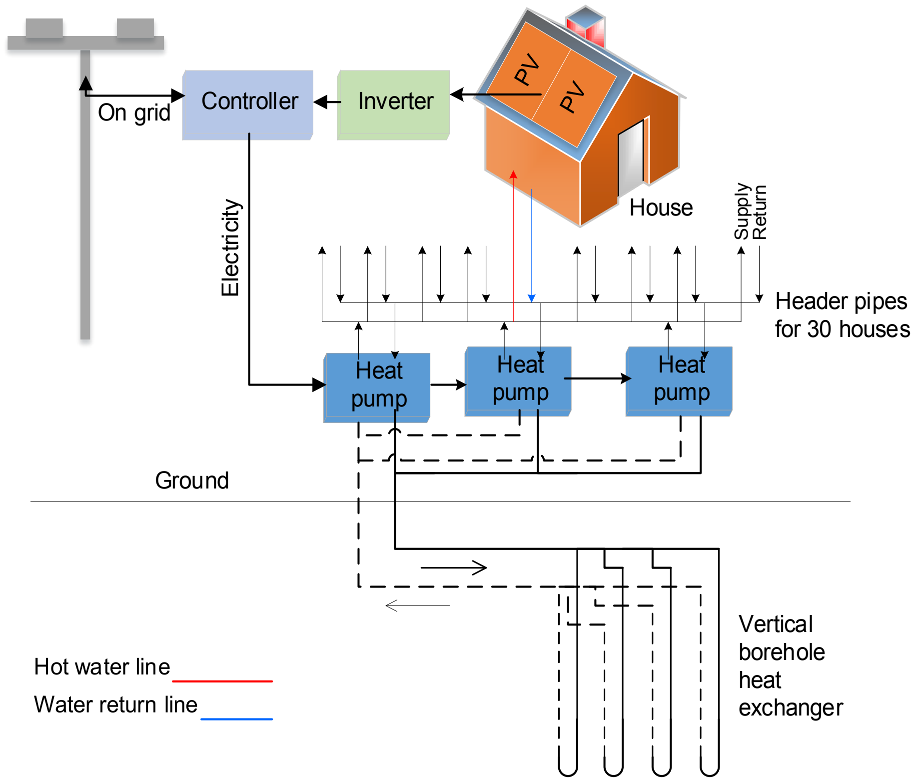

Figure 2: Schematic diagram of the ground source heat pumps with on-grid PV array

2.1 Selection of PV panels

The monocrystalline silicon module is known to have a better efficiency than polycrystalline, and thin-film modules (Green, 2005). The monocrystalline module is more suitable for cold climate zones because it has high performance ratio at a low ambient temperature (Muñoz et al., 2014). Under the same solar radiation intensity, performance ratio is the relation between the actual energy produced and energy that would have been produced in ideal conditions (Ueda et al., 2006). For sizing the PV

array four brands of modules available in the market were considered (Table 1). The rating of each PV modules is 340 W_p with a nominal voltage of 24 V DC.

Table 1: Parameters of the selected PV modules

Parameter	Module 1	Module 2	Module 3	Module 4
Brand name	Yingli solar	Jinko solar	Trina solar	JA solar
Model	YL340D-36b	JKM340M-72	TSM-340	JAM6(k)-72-340/4BB
Single panel Area (m^2)	1.9404	1.9404	1.9443	1.9424
NOCT (°C)	46	45	44	45
Module reference efficiency (%)	17.50	17.52	17.50	17.50
Temperature coefficient (K^{-1})	0.0042	0.0039	0.0039	0.0041
Reference	Yingli, 2017	Jinko, 2017	Trina, 2017	JA, 2017

2.2 Electricity Produced by a PV module

To estimate the instantaneous array efficiency, η, Eq. (1) (Klein and Beckman, 2001) was applied.

$$\eta = \eta_r \eta_{pt} \left[1 - \beta_t (t_c - t_r)\right] \tag{1}$$

where, η_r = module reference efficiency (%), η_{pt} = efficiency of power tracking (%), β_t = temperature coefficient (K^{-1}), t_C = cell temperature (°C), and t_r = reference temperature (°C). To determine the cell temperature at each hour Eq. (2) (Duffie and Beckman, 2013) was used.

$$t_c = t_a + G_T((\tau\alpha) - \eta) / U_L \tag{2}$$

where, t_a = the ambient air temperature (°C), G_T = total irradiance (W m^{-2}), U_L = overall heat loss coefficient of the module (W m^{-2} K^{-1}), and $(\tau\alpha)$ = transmittance absorptance product. For estimating the instantaneous temperature of PV module, t_c, the value of the instantaneous efficiency on the right-hand side of Eq. (2) can be substituted by $(\eta_r \eta_{pt})$ without serious error, since $(\tau\alpha) >> \eta$ (Klein and Beckman, 2001).

$$\eta \approx \eta_r \eta_{pt} (1 - \beta_t (t_a - t_r) - \beta_t G_T (\tau\alpha)(1 - \eta_r \eta_{pt}) / U_L) \tag{3}$$

The overall heat loss coefficient of PV modules includes convection and non-convection (i.e. radiation etc.) losses as shown in Eq. (4) (Aye, 2016).

$$U_L = h_c + h_{nc} \tag{4}$$

The convective heat transfer coefficient (W $m^{-2}K^{-1}$) estimated from wind speed, V (m s^{-1}) by Watmuff et al. (1977) is:

$$h_c = 2.8 + 3.0V \tag{5}$$

The overall heat loss coefficient of PV modules at nominal operating cell temperature is measured at wind speed of 1 m s^{-1} and the non-convective component of heat losses can be estimated by Eq. (6) (Aye, 2016).

$$h_{nc} = U_{L,NOCT} - 5.8 \tag{6}$$

Therefore, the overall heat loss coefficient of PV module can be expressed as:

$$U_L = U_{L,NOCT} + 3(V - 1) \tag{7}$$

As in (Duffie and Beckman, 2013) $U_{L,NOCT}$ is estimated by $800(\tau\alpha)/(NOCT-20)$. The annual electricity output per unit area of PV module, E, (kWh$_e$ m^{-2}) is estimated from hourly instantaneous efficiency and hourly insolation by Eq. (8), where time step Δt is one hour.

$$E=\sum_{i=1}^{8760}\frac{\eta_i G_{T_i}}{1000}\Delta t \qquad (8)$$

The required total PV area, A, in m^2 can be estimated from the total annual electricity load of the heat pump and the annual electricity output per unit area of PV module $A=L/E$. The next section presents the method of estimating the electricity demand by the GSHP together with the details of the TMY weather data and a typical house in Harbin.

2.3 Weather Data and Building Simulated

In this study, Harbin, China (longitude 126.5° east and latitude 45.8° north) was selected as a representative location of cold climate zone. The weather of Harbin represents the cold (continental) with dry and hot summer based on Koppen climate classification (Peel et al., 2007). This study considers a cluster of 30 typical detached houses in Harbin for determining the annual heating load. The dimensions of a typical house in Harbin are shown in Fig. 3. All houses were assumed to have the same orientation. The ceiling height of the house is assumed to be 2.4 m.

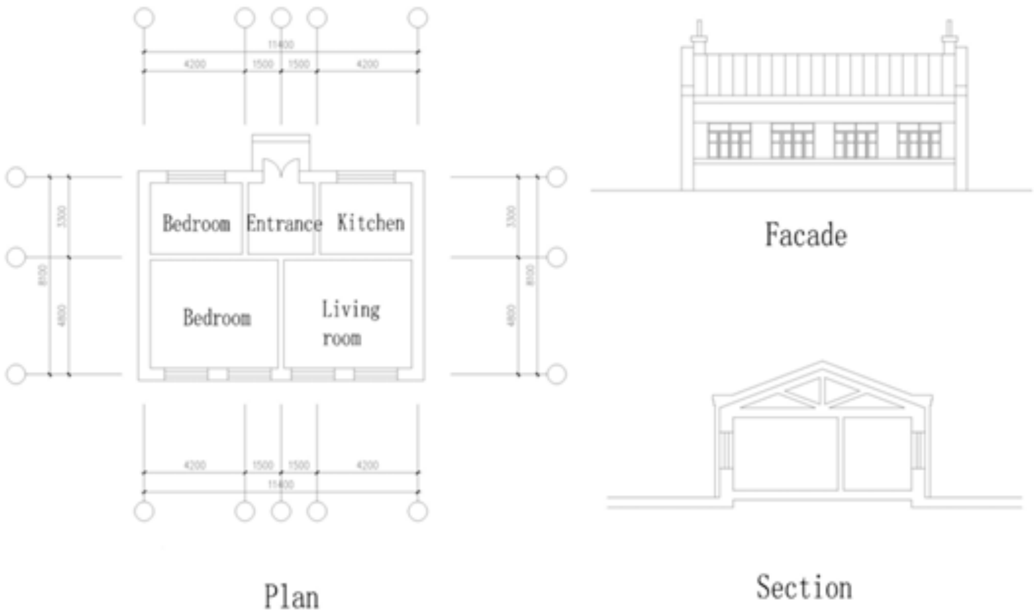

Figure 3: Dimension of selected typical detached house in Harbin, China (Qu, 2009)

The total heating load of 30 houses (total floor area 2086 m^2) was determined from heating load of one house by using computer simulation with hourly TMY data of Harbin. The thermostat setting for the rooms was assumed to be 18 °C during the day (from 6:58 am to 11:27 pm local time) and the night setback thermostat setting was assumed to be 16 °C as per reported sleeping time in Harbin (Wilt, 2017). The simulation study used TRNSYS17 with Type56 as shown in Fig. 4. The TMY weather data file generated by Meteonorm software (Remund et al., 2016) was based on 1991-2010 for solar radiations and 2000-2009 for dry bulb and wet bulb temperatures.

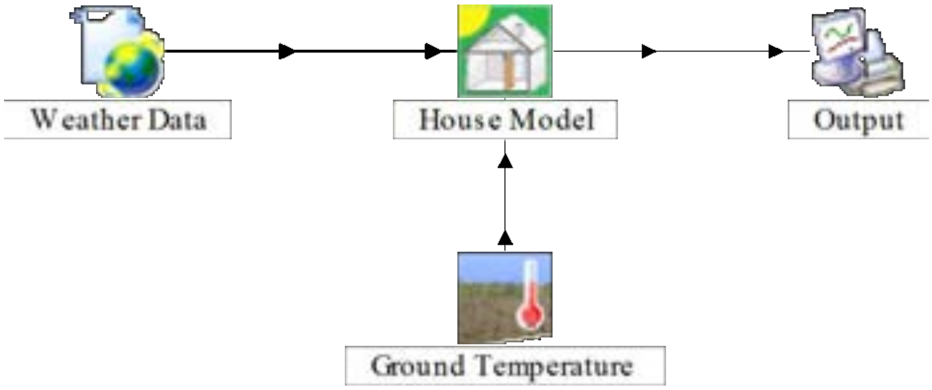

Figure 4: TRNSYS studio project assembly

The zone volumes of building model are present in Table 2. Building model in TRNbuild includes living zone (including entrance and bedroom area), kitchen zone, and attic zone. The thermophysical properties with layer thickness of building materials are presented in Table 3. The heat gain by the electric appliance and others activities that are considered in this model are shown in Table 4. Also, the heat gain schedules of the building model are presented in Fig. 5.

Table 2: Zone volumes and details of the walls

Zone volume (m^3)	Wall type	Area (m^2)	Category	Orientation
Living (143.79)	Wall	25.01	External	South
	Wall	12.61	External	North
	Wall	17.09	External	West
	Wall	10.05	External	East
	Floor	59.91	Boundary	Horizontal
	Ceiling	59.91	Adjacent	Attic
	Kitchen door	1.60	Adjacent	Kitchen
	Main Door	3.20	External	North
	Internal wall	13.45	Adjacent	Kitchen
Kitchen (23.12)	Internal wall	13.45	Adjacent	Living zone
	Floor	9.63	Boundary	Horizontal
	Ceiling	9.63	Adjacent	Attic
	Kitchen door	1.60	Adjacent	Living zone
	Wall	8.61	External	North
	Wall	6.45	External	East
Attic (70.11)	Roof	46.57	External	South slope (25°)
	Roof	46.57	External	North slope (25°)
	Ceiling	59.91	Adjacent	Living room
	Ceiling	9.63	Adjacent	Kitchen
	Gable wall	6.73	External	East
	Gable wall	6.73	External	West

Table 3: Thermophysical properties of building materials

Wall	Layer, thickness	Thermal conductivity ($kJ\ h^{-1}m^{-1}K^{-1}$)	Specific heat ($kJ\ kg^{-1}K^{-1}$)	Density ($kg\ m^{-3}$)	Reference
Floor	Carpet, 5 mm	0.216	1.360	186	IES, 2014
	Laminate flooring, 20 mm	0.259	1.400	480	IES, 2014
	Polystyrene board, 100 mm	0.108	1.380	25	IES, 2014
	Reinforced concrete, 120 mm	0.576	0.840	500	IES, 2014
Ceiling	Wooden board, 25 mm	0.436	0.837	593	IES, 2014
	Perlite, 25 mm	0.648	0.837	800	IES, 2014

Wall	Gypsum plaster, 15 mm	1.332	1.090	1220	Lhendup, 2013
	Brick, 183 mm	2.596	0.837	1922	IES, 2014
	Polystyrene board, 100 mm	0.108	1.380	25	IES, 2014
	Brick, 183 mm	2.596	0.837	1922	IES, 2014
	Tile, 9 mm	3.024	0.800	1900	IES, 2014
Roof	Wooden board, 25 mm	0.436	0.837	593	IES, 2014
	Iron sheets, 1 mm	258.480	0.452	7897	Edge, 2017
Door	Particle board, 32mm	0.367	1.300	590	IES, 2014
Internal wall	Gypsum plaster, 15 mm	1.332	1.090	1220	Lhendup, 2013
	Polystyrene board, 25 mm	0.108	1.380	25	IES, 2014
	Brick, 168 mm	2.596	0.837	1922	IES, 2014
	Polystyrene board, 25 mm	0.108	1.380	25	IES, 2014
	Gypsum plaster, 15 mm	1.332	1.090	1220	Lhendup, 2013

Table 4: Internal heat gains

Activity/electrical appliance	Value (W)	Reference
Living room: 1 persons seated, light work, typing	150	TRNSYS, 2012
Computer	230	TRNSYS, 2012
Lighting-CFL: 4 lights for bedrooms, living, and entrance	52	Firth et al., 2008
Kitchen lighting-CFL	13	Firth et al., 2008
Stove	500	Lhendup, 2013
Refrigerator	56	Harrison, 2016
Kitchen: 1 persons standing, light work	185	TRNSYS, 2012

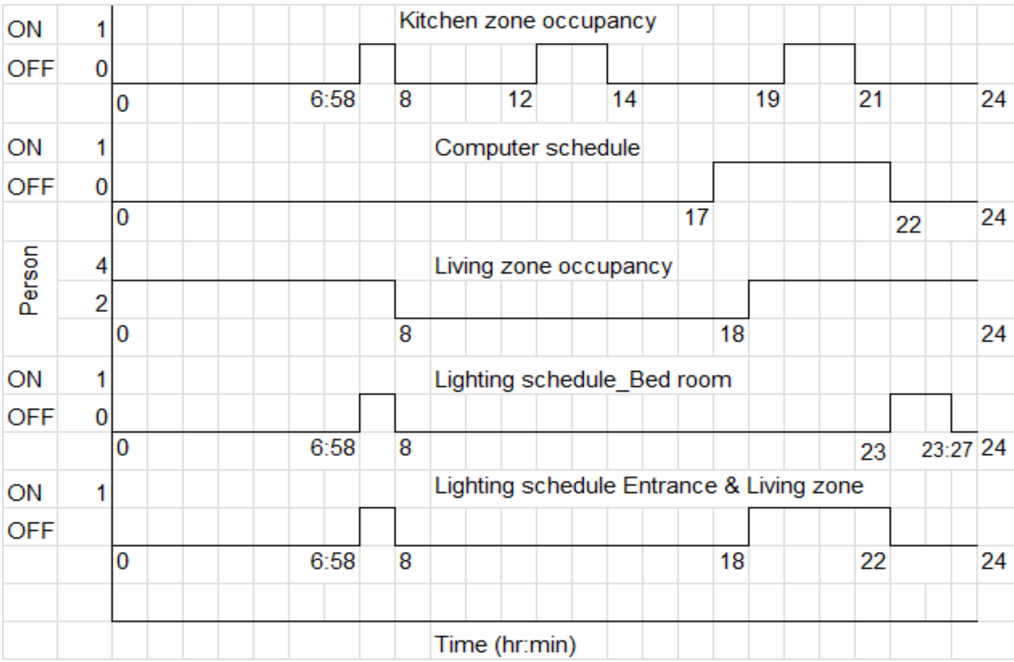

Figure 5: Schedules of heat gains

The annual electricity load of the heat pumps is estimated from the total annual heat load Q_H (kWh$_h$) by Eq. (9) (Aye, 2015).

$$L = Q_H / HCOP \quad \text{where} \quad Q_H = \sum_{i=1}^{8760} \dot{Q}_{H_i} \Delta t \tag{9}$$

where, $\dot{Q}_{H_i}$ refers to the hourly heating rate (kW$_h$) of building calculated by the TRNSYS simulation and $HCOP$ is the annual average value of the heat pump heating coefficient of performance.

2.4 Cost Analysis

The initial costs of the PV system include the costs of PV modules and balance of system (BoS) components (Goodrich et al., 2012) and installation. The levelised cost of electricity supplied by the PV system, $LCoE$ was determined by using Eq. (10) (BREE, 2012, Branker et al., 2011).

$$LCoE = \sum_{y=1}^{t} \frac{I_y + M_y + F_y}{(1+d)^y} \Bigg/ \sum_{y=1}^{t} \frac{E_y}{(1+d)^y} \tag{10}$$

where I_y, M_y, and F_y refers to capital investment cost, maintenance cost, and fuel cost respectively. The electricity generation (kWh_e) in year y is expressed by E_y. The amortisation period for the analysis was assumed to be 30 years project life.

The costs of GSHP and heat distribution network were also considered in the analysis. The radial with linear heat distribution network was considered in this study due to minimal rate of heat distribution cost per kWh_h (Nussbaumer and Thalmann, 2016). Fig. 6 shows the radial with the linear heat distribution network.

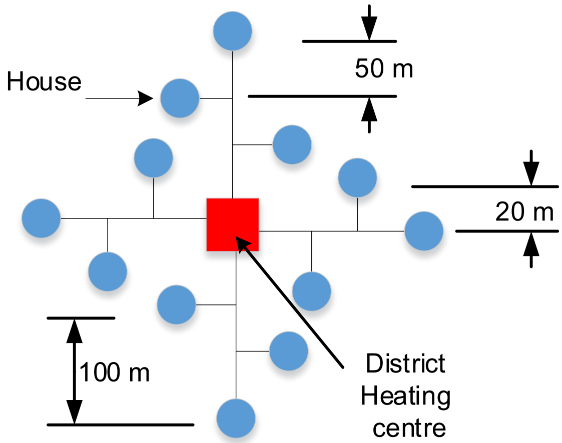

Figure 6: Concept of radial with linear heat distribution network for the community

The initial setup cost of heat distribution network (C_{HDN}) was analysed by using Eqs. (11-12) (Nussbaumer and Thalmann, 2016).

$$C_{HDN} = \frac{I_{HDN} \cdot a}{q \cdot T} \tag{11}$$

$$a = d \sum_{y=1}^{t} \frac{(1+d)^y}{(1+d)^y - 1} \tag{12}$$

where I_{HDN} is an investment cost of the heat distribution network, q is the heating load (kW_h) at the heating centre. T is the annual heating load hours for heat production, and annuity factor express by a. The real discount rate is d, and t is the project life year.

The length of the borehole, L_{BHE}, (m) for GSHP system was determined by using Eq. (13) and Eq. (14) (Sailer et al., 2015).

$$L_{BHE} = P_{ground} / (N_{tot} \times P_{BHE}) \tag{13}$$

$$P_{ground} = q_{hp}(1 - 1/HCOP) \tag{14}$$

where N_{tot} is the total number of boreholes, P_{BHE} is specific heat extraction rate (kW_h per borehole), P_{ground} is the rate of heat to be extracted from the ground (kW_h), and q_{hp} refers to total heat pump heating capacity (kW_h).

The annualised life cycle cost, $ALCC$ and the unit heating cost, UHC of the proposal were quantified in this study. The UHC was determined by using Eq. (15) similar to unit cooling cost (UCC) (Wu et al., 2013) and the $ALCC$ by using Eqs. (16-18) (Markvart, 2000).

$$UHC = ALCC / Q_H \tag{15}$$

$$ALCC = LCC / Pa \tag{16}$$

$$LCC = C + \sum_{y=1}^{t} C_r \frac{1}{(1+d)^y} \tag{17}$$

where C is the initial cost of the system and C_r is the future cost at year y.

$$Pa = \left(\frac{1}{1+d}\right)\left[\left(\frac{1}{1+d}\right)^t - 1\right] \Big/ \left(\frac{1}{1+d} - 1\right) \tag{18}$$

For the analysis, some assumptions on system component costs were made (Table 5).

Table 5: Component costs (assumptions)

Parameter	Value		Reference
	US$	RMB	
Piping cost with insulation (m^{-1})	98.5	640	Ying, 2017
Open field (40%) trench costs (m^{-1})	32.5	211	Nussbaumer & Thalmann, 2016; Ying, 2017
Street (60%) trench costs (m^{-1})	62.9	409	Nussbaumer & Thalmann, 2016; Ying, 2017
PV module (W^{-1})	2.3	14.7	Rigter and Vidican, 2010
Inverter (quantity 3) (kW^{-1})	123.1	800	Zou et al., 2017
Controller (quantity 3) (kW^{-1})	12	78	Du, 2017
Heat pump (quantity 3) (kW^{-1})	292	1898	Lhendup, 2013
Borehole drilling (m^{-1})	20.7	134.5	Yu and Cheng, 2015
PV panels annual maintenance cost (m^{-2})	15	97.5	Shah et al., 2016
PV installation cost (W^{-1})	0.8	5.4	Rigter and Vidican, 2010

2.5 Assumptions and Justifications

The PV system was assumed to be connected to the grid and without battery banks. The feed in tariff is US$ 0.10 kWh_e^{-1} (RMB 0.65 kWh_e^{-1}) (Rheatsao, 2016). Fig. 7 shows the required electricity from the grid in winter months and surplus electricity in summer. The excess electricity sent to the grid has a transmission loss of 5% (Eltawil and Zhao, 2010). To compensate the transmission loss, 3.37% extra electricity is required on top of the annual heat pump load.

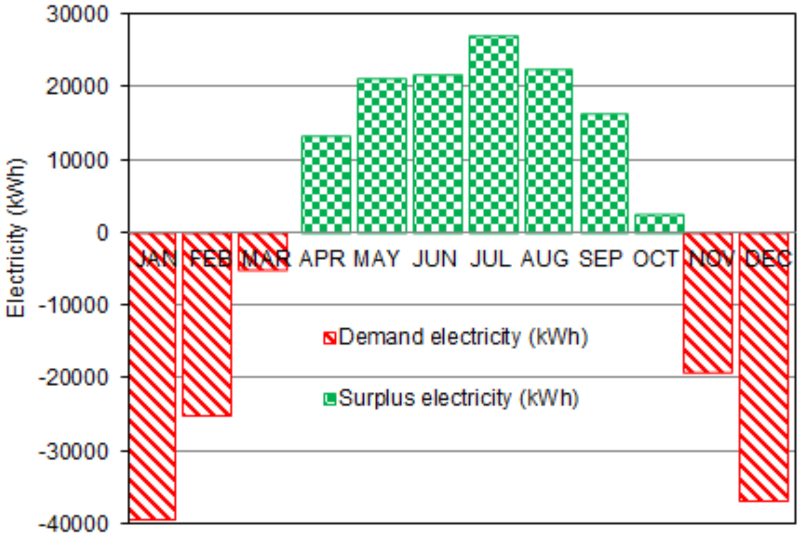

Figure 7: Buying and selling electricity to the grid

Other parameters assumed are shown in Table 6. Based on community service concept a cluster of 30 houses was considered. The multi-building application of seasonal thermal storage is more financially viable than the single house application (Lhendup, 2013). The analysis was done based on fulfilling the 100% annual electric load of the heat pumps.

Table 6: Assumed values for various parameters

Parameter	Value	Reference
Transmittance absorptance product of PV module (-)	0.9	Duffie and Beckman, 2013
Efficiency of power tracking (%)	90.0	Duffie and Beckman, 2013
Exchange rate (RMB per US$)	6.5	Farmer, 2017
Real discount rate (%)	10.0	BREE, 2012
Annual average heating coefficient of performances (-)	3.5	Aye, 2015

3 Results and Discussion

3.1 Heating Load and Energy Produced

In this study, hourly heating load and an electric load of heat pumps for 30 detached houses were investigated. The peak heating load found is 347 kWh_h in January with the peak electric load of 99 kWh_e. On the other hand, the maximum electricity produced occurred in summer where the peak power generated is 147 kWh. The annual electricity produced by PV system is 103 kW $m^{-2}a^{-1}$. Fig. 8 shows the heat pump load and total energy produced by PV modules for each month and cumulative values. The load is high in winter season from October to March whereas the solar panels generate energy all year-round (less in winter and more in summer). The electricity produced is higher than the demand of the heat pump in summer (from April to September). The project would require a certain initial amount of money if it starts from January. Thus, from January to March electricity will need to be bought from the grid and after March the energy produced will be sold to the grid and make up for the initial spending early in the year.

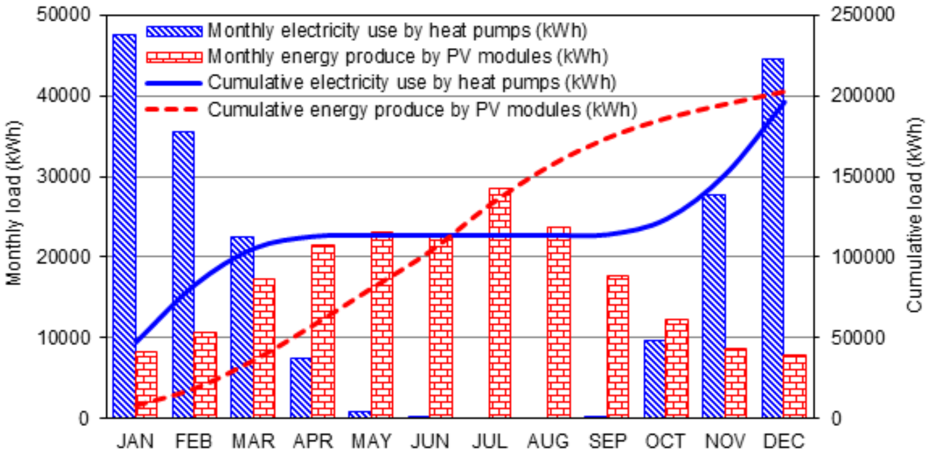

Figure 8: Heat pumps load vs. total energy produced by PV modules

3.2 Photovoltaic (PV) Array Sizing

Fig. 9 shows the total PV modules area for fulfilling the electric load of the heat pump. The total area of PV was found to be 1961, 1965, 1967 and 1963 m^2 for Yingli solar, Jinko solar, Trina solar and JA solar respectively. Similarly, the number of PV modules was determined for these four brands of PV. The total required numbers of PV modules were found to be 1011, 1013, 1012 and 1011 for Yingli solar, Jinko solar, Trina solar and JA solar respectively. The minimum PV area was found for Yingli solar. Therefore, Yingli solar brand PV panel *(YL340D-36b model)* was selected for the cost analysis.

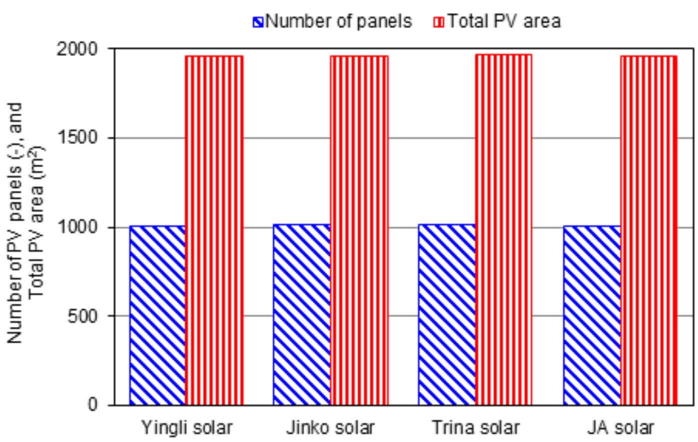

Figure 9: Required PV modules and areas

3.3 Cost Analysis

Fig. 10 shows the initial cost breakdown of the PV system. The cost of the PV modules was found to be the major cost component (39%) of the system. The whole system has three main sub systems, these are PV array for producing electricity, GSHP for heat generation and HDN for supply the space heating to building. In the GSHP sub-system, the heat pump cost (5%) was less than borehole drilling cost (13%) including piping where total length of borehole required was found to be 4138 m. The total cost of HDN was found to be 31% out of entire system cost. The total initial system cost, C_{HDN}, *LCoE*, *ALCC*, and *UHC* for the system investigated over 30 years project life period are presented in Table 7. The *LCoE* were found to be US$ 0.050 (RMB 0.32), US$ 0.060

(RMB 0.39) and US$ 0.067 (RMB 0.44) kWh_e^{-1} for 5%, 8% and 10% real discount rates respectively. The values found are comparable to the range of $LCoE$ values RMB 0.460-0.598 for large scale grid connected PV systems in China reported by Zou et al. (2017). The values of $LCoE$ found indicates that the grid connected PV power generation is lower than the grid electricity price in Harbin, US$ 0.088 kWh_e^{-1} (RMB 0.57 kWh_e^{-1}) (Travel, 2017). In addition, the current feed-in tariffs (excluding tax) are higher than the $LCoE$ of PV systems with 5% discount rate at most regions in China as reported by Ouyang and Lin (2014). Further UHC was found to be US$ 0.35 kWh_h^{-1} (RMB 2.27 kWh_h^{-1}). However, UHC of space heating were reported to be US$ 0.12 kWh_h^{-1} (RMB 0.80 kWh_h^{-1}) for an GSHP system connected to the grid (Chai et al., 2012) and US$ 0.038 kWh_h^{-1} (RMB 0.24 kWh_h^{-1}) for gas supply system (Mendes et al., 2014). The reason for higher UHC is that the proposed system includes not only GSHP, but also PV system and HDN. However, it is a net zero fossil energy.

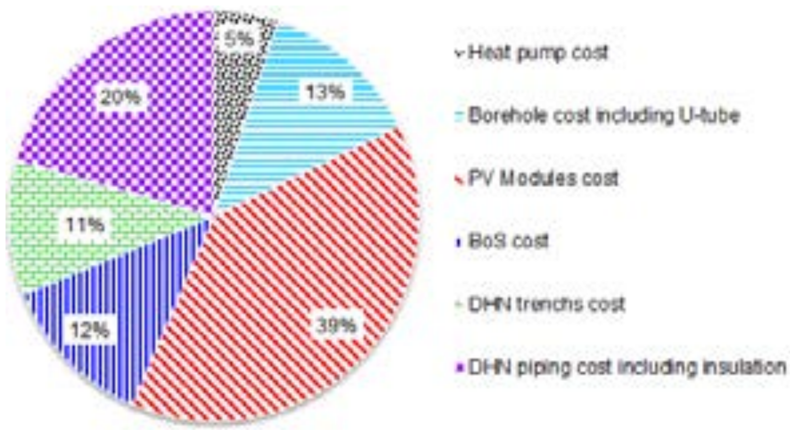

Figure 10: Breakdown of initial costs

Table 7: Initial and life cycle costs

System category	Parameter	Value	
		US$	RMB
PV + GSHP + HDN	Total initial cost (million)	2.010	13.06
HDN	C_{HDN} (kWh_h^{-1})	0.038	0.25
PV	$LCoE$ (kWh_e^{-1}) @ 10% real discount rate	0.067	0.44
PV + GSHP + HDN	$ALCC$ (a^{-1}) @ 10% real discount rate	239,708	1,558,104
PV + GSHP + HDN	UHC (kWh_h^{-1}) @ 10% real discount rate	0.350	2.27

3.4 Limitations

The proposed system is expected to promote the use of solar energy for space heating in cold climate zones. The PV array of the system investigated is grid connected and it has no battery banks. The system cannot operate when the available solar radiation is low and the grid electricity supply is not available. The analysis was done by computer simulations using TRNSYS software tool. Therefore, some assumptions were required to make in this study; which may limit the applicability of the results. The results presented were based on the TMY weather data and the financial data applied were typical for Harbin. Therefore, for the time the weather deviated from the average and for other locations the outcomes cannot be generalised.

4 Conclusions

This study focused on the improvement of solar energy utilisation for space heating in cold climate zone. Specifically, the investigation determined the required PV array size for meeting 100% of the electric load of heat pumps for space heating in Harbin, China to achieve a net zero on-site energy in an annual basis. For this purpose, a cluster of 30 detached houses was considered. The space heating load (kWh_h) of the cluster and the heat pump electrical load (KWh_e) were estimated by using TRNSYS. The PV array area required was found to be 1961 m^2 where the number of the modules was 1011 for model *YL340D-36b*, Yingli solar brand. The total annual electricity produced by the PV system was found to be 202 MWh_e per year. The initial cost of the proposed space heating system was found to be US$ 2.01 million (RMB 13.06 million).

Acknowledgements

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Nomenclature

a	annuity factor (-)
A	area (m^2)
$ALCC$	annualised life cycle cost (US\$ a^{-1}, RMB a^{-1})
C	the initial cost (US\$, RMB)
C_{HDN}	cost of heat distribution network (US\$, RMB)
Cr	future cost (US\$, RMB)
d	real discount rate (%)
E	annual electricity output per unit area of PV module (kWh$_e$ m^{-2})
E_y	electricity generation in the year (kWh$_e$)
F	fuel cost (US\$, RMB)
G_T	total irradiance (W m^{-2})
h_c	convective heat transfer coefficient (W m^{-2}K^{-1})
h_{nc}	non-convective heat lost coefficient (W m^{-2}K^{-1})
$HCOP$	the annual average heating coefficient of performance (-)
I	investment cost (US\$, RMB)
I_{HDN}	the investment cost of the heat distribution network (US\$, RMB)
L	annual electricity load (kWh$_e$)
L_{BHE}	length of borehole heat exchanger (m)
LCC	life cycle cost (US\$ a^{-1}, RMB a^{-1})
$LCoE$	levelised cost of electricity (US\$ kWh$_e^{-1}$, RMB kWh$_e^{-1}$)
M	maintenance cost (US\$, RMB)

$NOCT$	nominal operating cell temperature (°C)
N_{tot}	total number of borehole (-)
Pa	present worth factor (-)
P_{ground}	heat extracted from ground (kW_h)
P_{BHE}	specific heat extraction rate per borehole (kW_h)
Q_H	total annual heat load (kWh_h)
$\dot{Q}_H$	hourly heating rate (kW_h)
q	connection heating capacity (kW_h)
q_{hp}	total heat pump capacity (kW_h)
RMB	Renminbi (currency unit of China)
T	annual heating load hours (h)
t	project lifetime (a)
t_a	the ambient air temperature (°C)
t_c	cell temperature (°C)
t_r	reference temperature (°C)
Δt	time step (h)
TMY	typical meteorological year
U_L	overall heat loss coefficient (W $m^{-2}K^{-1}$)
$U_{L,NOCT}$	overall heat loss coefficient at *NOCT* (W $m^{-2}K^{-1}$)
UHC	unit heating cost (US\$ kWh_h^{-1}, RMB kWh_h^{-1})
UCC	unit cooling cost (US\$ kWh_r^{-1}, RMB kWh_r^{-1})
V	wind speed (m s^{-1})

Greek symbol

$(\tau\alpha)$	transmittance absorptance product (-)
β_t	PV module temperature coefficient (K^{-1})
η	instantaneous array efficiency (%)
η_{pt}	the efficiency of power tracking (%)
η_r	module reference efficiency (%)

Subscript

BHE	borehole heat exchanger
e	electricity
h	heat
hp	heat pump
HDN	heat distribution network
$NOCT$	nominal operating cell temperature
r	refrigeration (cooling)
y	year

MODULAR NET ZERO CARBON HOUSE: PROTOTYPE DEVELOPMENT FOR MASS CUSTOMISATION

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Abstract: *Modular construction and prefabrication are increasingly gaining significance due to their potential for cost savings, improved energy efficiency and quality control, as demonstrated by various examples around the world. Due to the repetitive nature and volume of mass production, design quality can become a challenge and sustainability is often neglected, particularly in large-scale projects. This has recently led to the development of mass customisation/personalisation strategies being applied to housing and to the establishment of the international Zero Energy Mass Custom Home (ZEMCH) Network.*

The objective of this paper is to present a modular Net Zero Carbon Housing approach developed under these premises and illustrated with three project examples. The concept won the Sustainable Housing for Life Design Award 2015 and is currently being developed for industrial deployment with a prefabrication manufacturer. The design is highly flexible and adaptable to different locations and user needs and thus attracted interest at the University of Melbourne for it to be taken up as a prototype for Australia within the ZEMCH Network.

Inspired by biomimicry, the concept is based on passive solar principles, natural materials and minimised building footprints, combining enclosed modules and connecting decks/breezeways to embrace the Australian outdoor lifestyle. A lifecycle approach determines the point in time when embodied carbon is paid back. Design variations in different climate zones have been simulated in order to compare lifecycle carbon and relative construction costs.

The proposed holistic sustainable design approach shows promising ways to achieve cost-effective mass customisation because a limited number of prefabricated elements allow for a variety of different configurations. This enables a personalised design to suit individual social needs and response to local site- and climate conditions. The lifecycle performance target aims at net positive contributions to the surrounding social- and ecosystems.

Keywords: *Modular Construction, Prefabrication, Mass Customisation, Net Zero Carbon, ZEMCH Network*

1 Background

1.1. ZEMCH Network and prototype development

The international Zero Energy Mass Custom Home (ZEMCH) Network aims to tackle issues arising from the delivery of socially, economically and environmentally sustainable built environments in both developed and developing countries for people with different socio-economic backgrounds (ZEMCH Network, 2017). Homebuilders are encountering a production gap between the need for product standardisation (i.e., mass production) that helps reducing construction costs and the need for product customisability towards satisfying the diverse demands of contemporary consumers (Noguchi, 2004). The ZEMCH Network was established in 2010, aiming to enhance industry-academia research and development (R&D) collaborations on the delivery of zero energy mass custom homes. Initially, a number of collaborative study tours were organised in order to observe the state-of-the-art production and sales facilities of leading low to zero energy/carbon sustainable housing manufacturers in Japan, which also practice inclusive design. The first technical tour was held in 2006, later called the 'ZEMCH Mission to Japan' (ZEMCH Network, 2017). Members to date have joined from 40 participating countries, with the majority being from Australia, Brazil, Canada, India, Italy, UK and USA. In some of these countries, ZEMCH prototypes have been developed, mostly for cold climatic conditions.

This paper contextualises and describes a modular Net Zero Carbon House concept which attracted the interest at the University of Melbourne for it to be taken up as a prototype for Australia in the ZEMCH Network when presented at the 7th Annual Modular Construction & Prefabrication Summit 2016. The concept won the Sustainable Housing for Life Design Award 2015, administered by the Byron-, Lismore- and Tweed Shire Councils in New South Wales, Australia (net Zero Design in collaboration with Thomson Adsett Brisbane). It was designed and further developed for industry application by net Zero Design and is illustrated below with three projects up to Schematic Design phase. An ARC Linkage grant application is currently being developed in collaboration with the University of Melbourne and a partner in the modular construction industry.

1.2 Modular construction in Australia

Modular construction and prefabrication is an emerging market in Australia, although has not yet reached economy of scale. Its most significant development has been within the mining sector where its use to reduce costs has contributed to a perceived image of monotonous design and low-quality construction. Continuously falling cost for renewable energy technologies and the declining business case for coal has resulted in the reduced need for this application, hence manufacturers are shifting towards more innovative forms of modular construction.

More established overseas markets demonstrate convincing benefits of modular construction such as minimal material use, waste, downtime, efficiency and reduced time in production and construction, quality control, value engineering, high-level thermal performance, safer working conditions, etc., leading to improved construction methods and reduced carbon footprints.

The challenges and opportunities associated with the uptake in the country are increasingly being discussed in the construction industry such as at the Annual Modular & Prefabrication Summit which is now in its 8th year (Annual Modular Construction and Prefabrication Summit, 2017). Partly, the adoption is restrained through biases due to

the repetitive nature of prefabrication. Cost efficiencies increase with scale, and the business case is expected to become more attractive once prefabrication is soundly established in Australia. This will be most effective if based on supply chain management, energy efficiency and waste minimisation, equally important factors for the environment and economy. Advanced manufacturing processes and more built examples are needed in order to demonstrate that design quality and customisation do not contradict the premises of modular construction.

1.3 Ecological footprint

Australia and the United States are countries with the largest homes worldwide. The average floor area of a new detached house in Australia has doubled from 1950 to 231 square metres, which is five times larger than the average home in Hong Kong (The Urban Developer, 2017). Further, the average number of people per household has been declining resulting in an average of 88m^2 per person (Australian Bureau of Statistics, 2016). The National Construction Code (NCC) sets minimum energy efficiency requirements for the thermal performance of buildings, which is well below regulations in other industrialised countries and has been under review for renewal. The energy efficiency of residential buildings is governed by the Nationwide House Energy Rating Scheme (NatHERS). Australian homes are among the highest operational energy users globally, and major upgrades are required for the existing housing stock. The residential sector accounts for 57% of final energy use of all building types in Australia in 2016-2017 (EY, 2017). Housing affordability is a further significant issue across Australia, with the entry into the property market becoming more difficult.

Modular construction has the potential to reduce construction cost and environmental impacts. Sustainability initiatives are often treated as an add-on resulting in higher cost. The key for both sustainability and modular construction is integration in the early design stages where close to 90% of the costs are determined. With increased environmental awareness and demonstrated cost-saving potential of sustainable architecture, clients are increasingly interested in smaller buildings with higher quality over large footprints for low cost per square metre. In the context of population growth and human consumption, buildings will need to reverse the environmental impact of their regions if a net reduction in global CO_2 emissions is to be achieved, as called for by the Intergovernmental Panel on Climate Change (IPCC, 2013).

1.4 Mass Customisation

Mass customisation can be understood as a post-industrial response to the limitations of serially manufactured products. However, the desire for uniqueness in manufactured products stretches back millennia (Harzer, 2013). One of the earliest examples of this approach can be seen in the vast terracotta army of 8,000 soldiers, commissioned in 210 BC by the first emperor of China, Qin Shi Huang. The figures were created with a standard mould for heads, arms, legs, and torsos for assembly to then be further personalised with premanufactured components such as beards, hats, and individual facial features (Portal and Dan, 2007).

As proposed by Tseng et al. (1996: 153), *"mass customization aims to provide customer satisfaction with increasing variety and customization without a corresponding increase in cost and lead time".* In mass production, economies of scale enable lowering the costs of individual items by spreading production investment over a large number of repeated units. In this context, whereas mass production can be efficient when targeting universal needs that may thus disregard product differentiation, mass customisation takes advantage of the possibilities of computer-aided design and manufacturing (CAD/CAM)

systems as means to increase the potential flexibility of these products towards meeting the heterogeneity and dynamism of consumer's expectations (Davis,1987; Pine II, 1993).

Despite its growing adoption in design and manufacturing, mass customisation is often perceived as an oxymoron and is still a baffling concept outside the academia. After all, the key idea of mass customisation is to individualise objects that are mass produced, with the aim to improve efficiency as a result of standardisation, assembly lines, and thus repetition. However, given the technological advances of the past decades, these assumptions may no longer be accurate. With the widespread adoption of internet connectivity and the increasing computerisation of current practices, the 'market-of-one' paradigm is starting to become a reality. Widely known online companies are now able to target the specific preferences of individual customers and gain competitive advantages through personalised relationships that can enhance user experience. Parallel processing, big data, and knowledge extraction algorithms are not only changing the way in which people relate to social media, but also the ways in which they conceive objects and engage with the physical environment. Domotics (i.e., home automation) is a clear example of how technology-enabled personalisation has started to become mainstream. Centralised cooling and space heating systems, automated illumination, home entertainment and safety systems can ease everyday life, adapt to changing environmental conditions, and even identify recurrent behavioural patterns to generate ambiences for enhanced user experiences. In parallel, computing is also extending the possibilities of product-service systems. The increasing availability of 3D scanners, digital cameras, GPS technology, and affordable 3D printing is transforming people's capacity to manage complex information as well as knowledge exchange among peers, including relationships between customers and providers. Technology such as, e.g., the Microsoft Kinect© can collect accurate body measurements to be sent online to manufacturers to develop tailor-made jewellery and garment (e.g., Grimal & Guerlain, 2014) while smartphones and digital cameras can be used to generate 3D models to be digitally printed and home delivered through platforms such as Autodesk's 123Catch© or insight3d©.

In a series of articles, Piller et al. (2010; 2013) argue that mass customisation is characterised by three core capabilities: (a) solution space development, (b) a robust process design, and (c) choice navigation. These capabilities can be used to illustrate the key concerns that should differentiate mass customisation from mass production.

The first capability, i.e., *solution space development* according to Piller et al., refers to the identification of attributes in a product or service among which the needs and preferences of users tend to diverge and therefore the introduction of certain levels of differentiation may result in benefits for the providers. If the problem of mass production is to identify the universal needs and preferences of a target group, in mass customisation, they argue, the problem is to match the heterogeneity of their needs and preferences with the potential variability of a cost-effective product.

The second capability, i.e., *robust product design* according to Piller et al., refers to the problem of increasing product variability without compromising performance. Mass production enables cost-efficiency by spreading infrastructure costs over a large number of repeated units, hence an increase in variability would require major infrastructural changes, thus potentially rendering production economically unfeasible. According to Piller et al., in mass customisation this increase in variability can be achieved through the incorporation of, e.g., automation technologies, modular value chains, or postponement in product differentiation when investment costs are justified.

The third capability, i.e., *choice navigation a*ccording to Piller et al, refers to the problem of supporting the selection of alternatives for users whilst helping them to avoid the problems associated with information overload or lack of knowledge. This, according to the authors, might be achieved through, e.g., interactive online configurators, user interfaces to facilitate understanding of interacting variables, or through adaptive web technologies able to match the preferences of a given user with the offering of personalised alternatives.

1.5 Modular construction in Mass Customisation

Larson et al. (2001) propose three core components to enable the introduction of mass customisation principles to housing design and development, i.e., (i) a *preference engine*, (ii) a *design engine*, and (iii) a *production system*. Whereas the preference engine should be concerned with the establishment of a framework for the users to engage in the development of their dwellings in order to build a user profile, the design engine should use this information for the definition of housing alternatives able to meet user preferences whilst acknowledging the possibilities and limitations of a predefined production system. In this sense, modular construction provides the means to customise housing within the limits of affordable production.

Based on the definitions outlined above, the modular Net Zero Carbon House concept shows a promising outlook on cost-effective mass custom housing. The proposed system consists of a limited number of prefabricated elements that can be arranged in a variety of different configurations which leads to two key advantages, namely a (1) high level of design flexibility to meet user demands as well as a (2) cost-effective production process. Once assembled, the components may be easily visualised by the customer as modules of a predefined size, comprising internal spaces, core, decks and breezeways.

2 Modular design concept

2.1 User profile

User circumstances and site conditions determine the spatial requirements for a building. Creating a user profile to customise the design, as suggested by Larson et al., requires social and environmental key input parameters. The approach undertaken to define these conditions in the proposed context of mass custom housing is outlined below.

Social preferences: Based on the design competition brief, the modular system was developed aiming to accommodate changes over the life course of a family; e.g., first a couple alone, then with children, later renting out space when the children have moved out, etc. The design flexibility allows for a personalised response for the initial construction as well as staged developments and future changes through the addition of individual modules or conversion of existing ones. The central thermal chimney doubles up as storage space and services core for the connection of wet areas and other components.

Environmental preferences: While individual social preferences are easy to communicate, the environmental function of a building can be a more complex task. This includes bioclimatic factors such as utilising the sun, breezes and vegetation, in combination with building physics and material choices, for ensuring thermal comfort, a healthy indoor climate, and minimising ecological footprints.

The flexible and adaptable system not only responds to the people who will live in the dwelling but also to individual site- and climatic conditions. Sloping land, solar conditions,

prevailing breezes, landscaping and other site characteristics can be integrated into the design through a unique configuration of the modular components. Even for constrained sites such as on southern sloping hills or with exposure to the hot western sun in Australia solutions can be found. This provides an alternative for volume home builders who maximise the number of saleable lots by sacrificing solar orientation.

Choice navigation: In order to create a home with design flexibility and holistic sustainability targets, complex information needs to be synthesised, tailored to the user and communicated in simple terms. Piller et al. refer to this customer support as the capability of *choice navigation*. Net Zero Design works closely with clients throughout all project stages, using 3D visualisation and energy performance modelling. The results can be validated and optimised via real-time monitoring during operation. At a larger scale, this could be supported by user interfaces, adaptive web technologies etc. as suggested by Piller et al. The users are a central part of the sustainable design process which enables them to engage with the building in order to optimise its operation and maximise living quality.

2.2 System description

The proposed modular Net Zero Carbon House offers an alternative to the units with large footprints commonly built in the Australian Housing sector. The focus is on minimised internal floor space and indoor-outdoor connectivity to suit the Australian lifestyle and save cost. In this sense, the unique configuration of the modular components, internal modules in multiples of $20m^2$ and connecting decks/breezeways, along with the modular façade design, achieves the above-described design flexibility. Modular options are easily visualised and clients can choose from different elements to suit their budget and individual preferences.

The proposed prefabricated system consists of timber cassette decks and custom-designed wall panels, mounted on screw-pile foundations that adjust height differences and minimise ground disturbance. Full height glazed elements maximise daylight and facilitate natural ventilation. These are interchangeable with the wall panels for individual façade design. A thermal chimney functions in addition as storage space and services core. The lightweight, prefabricated timber structure is fully demountable without any permanent structure such as concrete used on site. Natural, non-toxic materials with low embodied energy are used throughout. Timber was chosen as the main construction material due to its low environmental impact as a renewable resource and warm atmosphere. Landscaping and biophilic elements are an integral part of the design; hence permaculture and aquaponics are applied in current projects. Green roof- and green wall elements can also be included in the modular range.

2.3 Biomimicry inspiration

Nature runs on sunlight, fits form to function, uses only the energy it needs and turns waste into resources. Biomimicry has gained widespread acceptance in the sustainable architecture community, the development of sustainable building materials and the textile industry (Pullman, 2012). Benyus defines biomimicry as *'innovation inspired by nature'* and a *'new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems'*, hence suggesting to emphasize sustainability as an objective of biomimicry (Benyus, 1997).

In this context, natural systems served as precedents for the modular Net Zero Carbon House concept, aiming to find a suitable form for passive solar design and create resilient structures and resource cycles. On the micro-level, resilient and self-organizing

cell structures such as in wood fibres informed the modular design (Fig. 2, Alexander, 2004), resulting in the combination of closed modules and connecting decks and breezeways to allow for design flexibility and respond to both the natural environment and local climate. On the macro-level, water and nutrient cycle in the forest and tree canopy structures were investigated for energy, water and carbon cycles. The elevated structure, raised roofs, awnings and thermal chimneys for solar control and airflow were derived from this, as shown in Fig. 1 below.

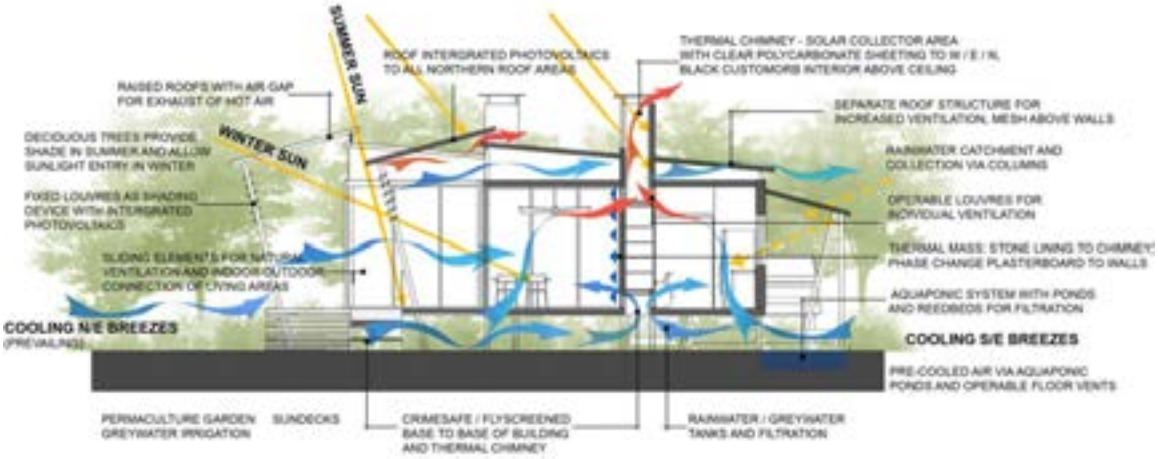

Fig. 1 & 2: Sustainable Housing for Life Design Award 2015: Passive Solar Design, Biomimicry inspiration (Fig. 2 from (3) Alexander, 2004, (5) Webb, 2005, (6) MCAD, 2011)

2.4 Life-cycle approach / net zero carbon performance

Zero emission targets for buildings are increasingly being discussed and adopted in many countries around the world in order to address the impacts of material extraction, operational and transport demands. An incentive for this is the rapidly falling prices for renewable energy technologies, e.g., since 2000 photovoltaic module prices have decreased by 20% every two years with each doubling of cumulative worldwide production (Irena, 2011).

The World Green Building Council (GBC) is calling for net-zero operational carbon for all new buildings from 2030 and 100% of buildings by 2050 (WorldGBC, 2017) and introduced its global 'Advancing Net Zero' project at the Climate Change Conference COP21 in Paris (COP21, 2015, World GBC, 2016). The project is supported by ten participating GBC's worldwide to date. The GBC Australia has developed a 'Carbon Positive Roadmap' to engage industry, occupants, government and NGO's (GBCA, 2017). National Carbon Offset Standards for Buildings and Precincts were launched in October 2017 (Australian Government, 2017); voluntary operational carbon neutral certification for buildings is now available as an extension of NABERS Energy and Green Star – Performance. A pathway through the Australian Government's Carbon Neutral Program can be applied to precincts and may be available for buildings in the future.

Since the building sector is a major contributor to emissions, drastically improved regulations will be required to work towards the 1.5 degrees global warming target set at COP21. However, the business case is an attractive incentive in itself. Leveraging the transition to zero emissions is most powerful through community engagement by communicating the various additional benefits of sustainable living, demonstrated with more built examples. The need for a holistic approach to sustainability is reflected in frameworks such as Living Building Challenge (LBC, 2017), Positive Development (Birkeland, 2008), Regenerative Design (e.g., Lyle, 1994, McDonough & Braungart, 2002, Mang et al., 2016), Cradle to Cradle (McDonough & Braungart, 2002, 2013), One Planet Living (Bioregional, 2017) and Circular Economy (e.g., Lovins & Braungart, 2014). Hes and Du Plessis' book 'Designing for Hope' provides a summary of leading concepts introduced in international building research and practice (Hes & Du Plessis, 2014).

The underlying framework for the proposed modular Net Zero Carbon House is the one of net Positive Development (Birkeland, 2008), which suggests that buildings can function as active parts of ecosystems and *'give back to nature more than they take'* over their life cycles. Carbon is used as one quantitative measure to demonstrate that net positive life cycle performance is possible through amortization of embodied carbon by renewable energy gains and biomass sequestration (Fig. 3). A theoretical case study showed that the embodied carbon of a six-story mixed-use building could be amortised within 11.5 years (Renger, Birkeland & Midmore, 2015).

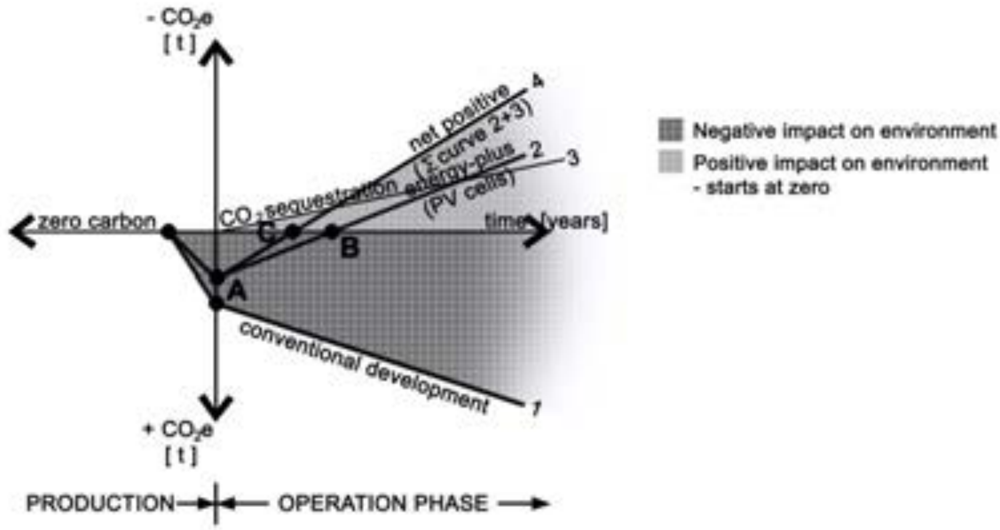

Fig. 3: Carbon Amortisation Performance (CAP) method (from Renger, Birkeland & Midmore, 2015)

The modular Net Zero Carbon House tests the method in practice. Clients are provided with an estimated point in time when embodied carbon is paid back. In order to reach this point as early as possible in the lifecycle, the proposed system is based upon a minimised physical footprint, without compromising on spacious feel by providing indoor-outdoor connectivity and multifunctional spaces. Embodied carbon is reduced by the use of natural, low embodied energy materials, as well as efficiency in the prefabrication process. The buildings are energy self-sufficient in operation, aiming at net positive energy production. Embodied and operational carbon as well as on-site offsets are quantified in order to determine net zero carbon performance over time. This will be optimised and validated in post-occupancy evaluation.

3 Project examples

Net Zero Design's modular house concept is illustrated below with three projects examples in the Concept- and Schematic Design stages.

3.1 Tallowood Ridge Residence, Mullumbimby, New South Wales

This site enjoys views of Tallowood Ridge, the adjoining creek reserve with rainforest vegetation and Mt. Chincogan. The building is integrated with the landscape; maximizing views to the mountain and natural habitat throughout (Fig. 4).

Figure 4: Tallowood Ridge Residence, Mullumbimby, New South Wales

Modular design: The residence is adapted to the sloping land in a split-level configuration. The first module includes living room and kitchen, the second module a library on the split-level and one bedroom each half a level above and below. This allows an efficient use of the site and interior while creating private areas for guests and opportunities to rent out space. A large feature deck connects the modules, extending the internal living areas.

Sustainability: A strong emphasis is set on the use of natural and non-toxic materials from sustainable sources. Net positive energy performance is targeted, using a 6 kW grid-connected PV system with battery storage and remote feed-in control technology. Other features include two thermal chimneys, 30kL rainwater tanks, natural greywater recycling, composting toilet, outdoor spa, permaculture and aquaponics. The project will be showcased as a precedent for Zero Emissions Byron (Zero Emissions Byron, 2017).

3.2 Ocean Shores, Secondary Dwelling, New South Wales

Initially, a '*treehouse-character*' was envisioned for this secondary dwelling in a unique rainforest setting adjacent to Brunswick Heads Nature Reserve, integrated with the steep embankment at the front of the site (Fig. 5). This is challenged by bushfire regulations, and an alternate solution sought to retain the native rainforest vegetation with high moisture content. However, bushfire regulations for second dwellings are more stringent in Australia than for the main residence, this was not accepted and the clients decided not to sacrifice a large number of trees for the construction of the building.

Figure 5: Ocean Shores Secondary Dwelling, New South Wales

Modular design: The project informed module sizing in multiples of 20m^2, which allows the maximum floor area of 60m^2 for a second dwelling in Byron Shire. A variety of configurations even for a building of this size were explored. The chosen design consists of two combined and a single module, connected by a breezeway and oriented to catch the sea-breezes from the north-east. The layout enables a spacious feel through the connecting outdoor areas; breezeway, a large front deck, and a smaller rear deck shielded from the main weather side. The small footprint resulted in the design of innovative storage options through a double floor cassette for kayak storage, sunken furniture, batteries and tanks.

Sustainability: The building is positioned on a steep slope towards the west with exposure to the hot afternoon sun. The main advantage of this modular configuration is an enhanced capability for natural ventilation by catching the north-eastern sea-breezes. In response to microclimatic conditions, the western façade is fully enclosed and features a full height thermal chimney / trombe wall for passive cooling in summer and heating in winter. The bushfire regulations were a constraint in particular because shading and cooling functionality could have been provided by the existing trees. Due to shading from the trees to the north, the second dwelling was planned to be connected to the 6kW PV system on the existing house. Screw-pile foundations allow an easy integration with the sloping land, and a rain garden was envisaged to filter the storm water before returning it to the groundwater table.

3.3 Sustainable Smart Homes, Brisbane, Queensland

The client's project vision was to create an innovative form of urban living to promote sustainability and smart home technology. The project includes the raising, relocation and refurbishment of a pre-1946 Queenslander in a character zone on the fringe of the Brisbane CBD to create habitable space and small-scale non-residential use on the ground floor. In addition, it explores the 'Tiny House' concept, which is gaining popularity in different parts of the world, with 3-4 self-contained modules on the land to provide an alternative to the large Australian residential footprints and contribute to housing affordability for young adults (Fig. 6).

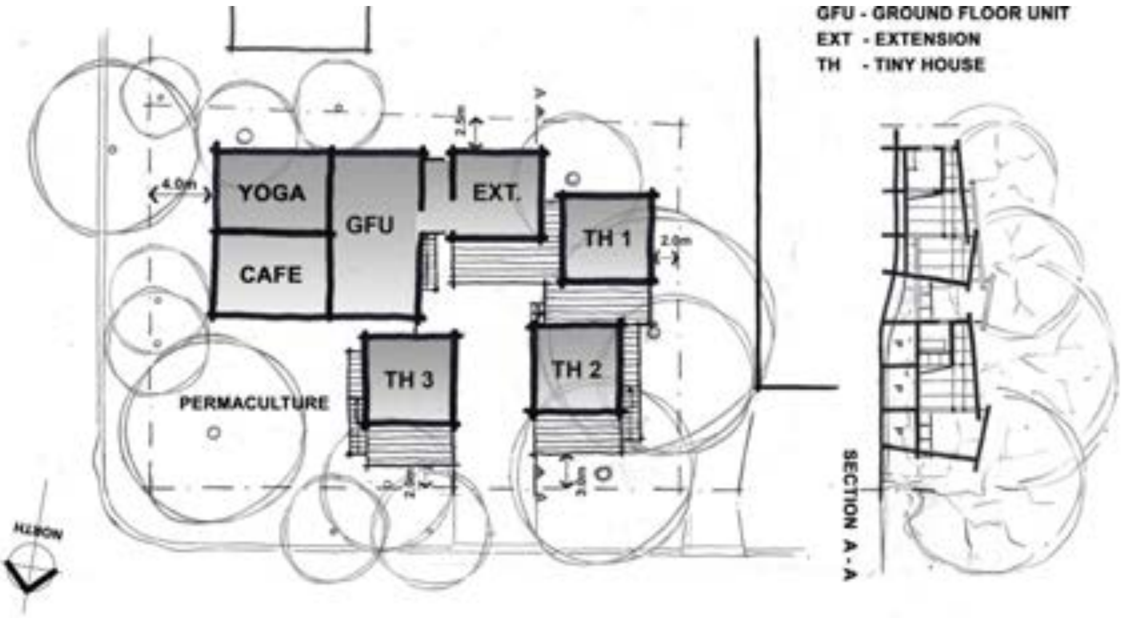

Figure 6: Sustainable Smart Homes, Brisbane, Queensland

The Tiny House concept is not yet regulated in Australia, and a staged Development Application (DA) process is being adopted in close collaboration with the town planner. It includes a change of use to multiple dwellings and the addition of a yoga studio and café in the final stage for the residents and community.

Modular design:
The smallest application of 1-2 modules of 20-40m^2 per entity was explored for the Tiny House approach, resulting in the design of a connected structure with decks and breezeways. One module is designed as an extension to the existing residence which enables a simplified planning process and saves infrastructure charges prior to conversion into self-contained units in the next stage. Other design flexibilities include a mezzanine level and two elevated modules close to the secondary street frontage with three carparks each on the ground level, enabling an efficient and moderate integration of car parking on the site.

Sustainability: The project integrates ecological, social and economic aspects as a pilot project and showcase for sustainable urban living, maximising medium-term rental cashflow from the dwellings to finance future stages. It features smart home technologies such as building automation, renewable energy systems, water recycling and biogas. The retrofit part of the project reduces the impacts on the environment.

A main characteristic of the site is its established vegetation; the buildings are carefully integrated with the trees and character precinct, making sustainability features visible to the community. Central to the design is a permaculture garden with local organic produce for the residents and food preparation in the on-site café. Interaction with the streetscape is envisaged aiming to attract visitors. The client is currently deciding on the preferred DA strategy.

4 Further performance optimisation strategies

4.1 Building Information Modelling (BIM) approach

The projects are documented in Autodesk Revit Architecture© software. Scheduling and material take-offs are used to quantify the prefabricated system elements which enables the addition of various parameters including cost, thermal properties and embodied energy. This also assists with a simplified carbon amortisation calculation over time. In order to test operational performance, the design has been simulated in Autodesk Green Building Studio© / Insight 360©. It will be subject to natural ventilation simulation in future work. The Revit model can be used for contractor engagement and cost planning (4D / 5D BIM) in the future if suitable, as well as for post-occupancy evaluation.

4.2 Early tendering process

In order to retain best possible control over sustainable design quality and cost, an early tendering process is being adopted. Material quantities for prefabrication and local construction are automatically extracted from the Revit model as basis for an initial cost estimate. This is updated in the software during the further project development and allows cost comparison during all stages. Early contractor engagement in a collaborative process minimises risk and ensures full transparency for the team and client. Five builders in Byron Shire and the prefabrication manufacturer have taken part in this process to date.

4.3 Post Occupancy Evaluation

Real-time monitoring will be used to validate and optimise the net zero carbon life-cycle performance during operation. The aim is to investigate if/how zero carbon life cycle performance can be achieved in the Australian residential sector and to develop future-proofing strategies for measures that are not economical at the current time. With improved export conditions of renewable energy in Australia, carbon amortisation will be reached earlier in the lifecycle. In the meantime, batteries with controlled feed-in technology could assist.

4.4 Application to different climate zones

Applying the modular design in different locations requires further work on how to optimise energy efficiency through the layout. A number of configurations have been simulated in different climate zones in order to inform the design for the cities of Brisbane, Melbourne and Cairns (Fig. 7). CO_2 equivalents from embodied and operational impacts and relative construction cost of these options were compared to a standard brick veneer building with slab on the ground and single glazing.

Figure 7: Module configurations for energy efficiency optimisation, where (A) Separate, (B) Connected (glazing), (C) 2 modules combined, and (D) 3 modules combined

The results shown in Fig. 8 below evidence that carbon emissions from the modular house can be significantly reduced compared to an Australian standard home. In most

cases, this can be achieved with lower construction costs even with high-performance windows. Note that only costs of varied elements were included, e.g., cost of electrical services was assumed to be the same. Compact forms are more suitable for colder climates, the tropical environment in Cairns shows the least environmental impact, where optimal passive solar design can best be used to operate the buildings entirely with natural ventilation.

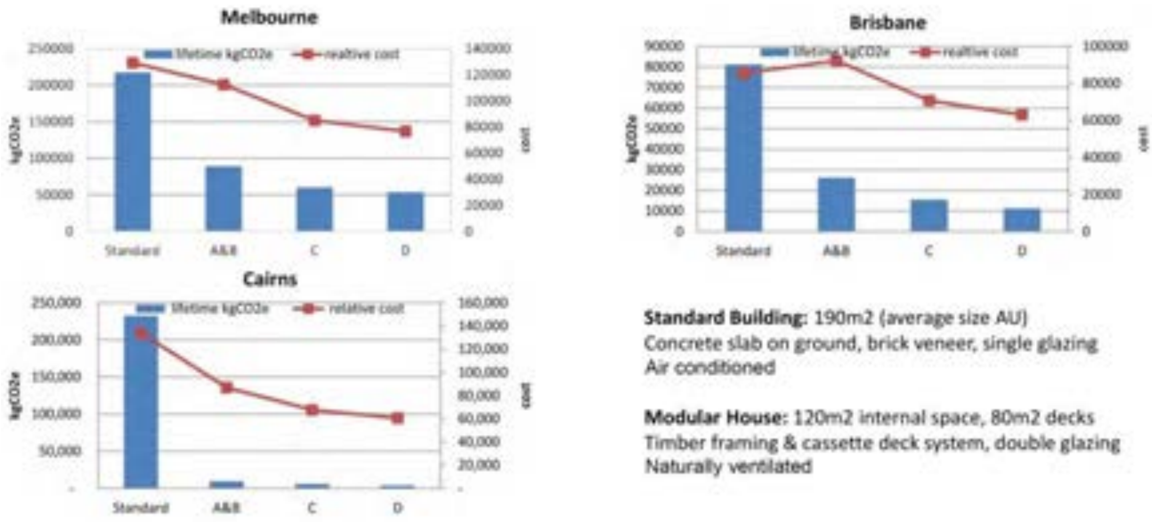

Figure 8: Sustainable Housing for Life Design Award 2015: Life cycle comparison - CO_2e and relative cost, calculations by Sustainability House, Adelaide

5 Conclusion

The development of prototypes within the ZEMCH Network seeks to contribute to the uptake of modular construction and prefabrication in Australia through sustainable mass custom designs. In this sense, the presented modular Net Zero Carbon House provides a flexible and adaptable concept with a limited number of modular components which allows for a variety of different configurations. This enables a customised response to individual social needs and local site- and environmental conditions, with the outlook on a cost-effective production process. The proposed system offers an alternative to the commonly built large footprints in the Australian Housing sector through a minimised internal floor area and connecting decks/breezeways to suit the Australian lifestyle. Minimised space, efficiency in modular construction, natural/low embodied energy materials and passive solar principles are the basis for a holistically responsible, sustainable design that adds value and enhances a healthy living environment.

The buildings presented in this paper will explore constraints and opportunities for zero carbon lifecycle performance in Australia and develop future-proofing strategies to reach the point zero as early as possible in the lifecycle. An early tendering process and contractor engagement in a collaborative approach aim to optimise sustainable design quality and control costs. Post-occupancy evaluation will optimise performance during operation. The modular Net Zero Carbon House concept is designed as an integral part of the surrounding ecosystems. It contributes to moving beyond more buildings with lower impact than the norm towards net positive contributions to nature and society. The proposed holistic sustainable design approach aims at creating an interpretive experience to facilitate user engagement and inspire net-positive thinking.

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ENVIRONMENTAL BENEFITS OF VEGETATED GREEN WALL IN HOT ARID CLIMATE OF AL-AIN, UAE

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Abstract: *Recent studies investigate that the use of vegetated green walls has the ability to control heat gains, improve indoor thermal comfort and reduce energy demands. In reference to the experimental study carried out by the authors to reduced heat gain through green façades in the UAE hot climate, Living Wall system can reduce the peak time indoor air temperature by 5-7 °C for the month of July, and reduce the peak air conditioning energy demand by up to 20%. Additionally, the use of plantation can reduce wind effect and helps to control the humidity within the building zone. To get a clear picture of the financial incentives of using greenery system, cost-benefit analysis was investigated, taking into consideration the cooling load reduction while the related environmental benefits were ignored at that stage. The result concluded that, from economic point of view, the installed vegetated living wall system might not be the best economic sustainable option as the installation and running costs are extremely high and the payback period reaches 18 years. More reduction in the payback period can be achieved once the environmental impacts are included to make the use of greening systems financially viable. Green wall techniques have a number of benefits being a component of urban green infrastructure and contribute to a range of ecosystem services including, habitat provision for urban biodiversity, intercepting precipitation, improving air quality, reducing noise pollution, securing points in green buildings certification systems. To get a clear picture of the real financial incentives of using vegetated green wall technique, this paper investigates energy saving and environmental benefits of vegetated living wall in hot arid climate of Al-Ain city.*

Keywords: *Al-Ain, Cost Benefit Analysis, Energy Efficiency, Environmental Benefits, Vegetated Living Wall*

1 Introduction

Vegetated green walls are considered as a component of urban green infrastructure and contribute to a range of ecosystem services including habitat provision for urban biodiversity, intercepting precipitation and reducing run-off rates, improving air quality, reducing noise, and improving the aesthetics of the cityscape (Wolf 2013, Francis & Lorime 2011, Wong, et al. 2010, White & Gatersleben 2011). The term of "vegetated green wall" is used for both living wall and green façade. Living Walls are self-sufficient vertical gardens composed of pre-vegetated panels, vertical modules or planted blankets (Caplow 2008). The common living wall systems are: Modular Living Walls; Vegetated Mat walls; and Landscape walls (Kontoleon & Eumorfopoulou 2010, Perini et al 2011). As shown in Fig. 1, modular living wall system consists of standard units that hold growing media and plants. Vegetated mat wall system has two layers of synthetic fabric which support plants and growing media. Landscape walls are constructed from stacking material with room for growing media and plants. Green façades are made up of climbing plants that growing directly on a wall or supporting structure. The plant grows up 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.

Modular living wall Vegetated mat wall (BlogSpot) Landscape wall (BlogSpot)

Figure 1: Vegetated living wall systems

Vegetated living wall technique provides a wide range of benefits for buildings, inhabitants, and the environment. It helps buildings become more energy efficient by reducing cooling loads, absorb storm-water, and lead to reduced carbon emissions. This technique acts as building skin protective barrier which provides better solar protection that reduces the effect of the external heat gain. A number of studies have explored the thermal performance of vegetated surfaces on building skin (Wong et al 2010; Haggag et al 2017; Green over Grey). 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 [9] Wong et al. Studies have shown 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(Green over Gray,2017). The level of the thermal influence of the vegetation depends on several parameters including the covering percentage of the façade, the density of plant foliage, and the direction of the building façade. Other parameters such as the solar absorption coefficient of exposed surfaces; the specification of external building materials; and the colour of the external surface have significant effect on the temperature profiles of the building envelop (Kontoleon & Eumorfopoulou 2008).

Plantation has also been used as a barrier against urban noise pollution. Plants and the trapped layer of air can absorb, reflect or deflect sound waves. Therefore, vegetated

walls have an acoustical insulation that is far better than that of bare wall (up to 30 db reduction) [3]. The use of vegetation on building façades can also help to address the lack of green space in urban environments. Plants improve human health, capture airborne pollutions, and filter harmful gases. Additionally, vegetated wall techniques can protect building surfaces and extend the lifespan of the building skin. This protection comes mainly from keeping rain off the building while allow moisture to escape, reducing the expansion and contraction of building materials and protecting walls against wind and solar radiation.

2 The use of vegetated living wall

A modular living wall system was installed on a school building façades, using planter units fixed on the building façade with drip irrigation pipes and a variation of plant species (Fig. 2). The school building is located in Al-Ain city, UAE at latitude: 24 degrees, 16 minutes North and longitude: 55 degrees 36 minutes East, and the tested façade is directed to south east. The city is characterized by a very hot and dry climate with a summer daytime temperatures range from 35◦C to 50◦C and a winter daytime temperatures ranging from 25◦C to 35◦C. Rainfall is infrequent and falling mainly in winter, with an annual average rainfall of 10 cm (UAE weather page 2017).

Figure 2: Vegetated living wall installed on school building façades (Liwa International School), Al-Ain, UAE

Two identical class rooms have been tested by the authors: one with external bare wall and the other with vegetated living walls (Haggag, Hassan & Elmasri 2014). To determine the impact of thermal performance, temperatures at four locations were recorded for both bare and vegetated walls: ambient air temperature; external surface temperature; internal surface temperature; and internal air temperature. The experiments were conducted during the hottest summer period (July–August) to guarantee the highest ambient temperature and solar radiation intensity. From the measured temperature data, the cooling load for the bare and green wall were calculated and compared to determine the effect of green wall on cooling load reduction of the selected spaces. To understand the impact of heat transfer through vegetated and bare walls, the temperature mapping was investigated for both walls. The solar radiation incident on the bare wall directly started heating the external wall surface while in case of the vegetated living wall, the radiation was partially blocked by the vegetation which produced shading on the wall surface and yielded temperature regulation. In order to determine the temperature regulation effect of vegetated green wall caused primarily by shading, the outdoors ambient temperature, external surface temperature, internal surface temperature and internal ambient temperature were plotted for seven consecutive days in month of July, using Omega (DaqPRO) data loggers.

The study concluded that the external surface peak day temperature on bare wall was around 54ºC while the peak day temperature on the vegetated wall remained at an average of 48 ºC (Fig. 3). A similar trend was observed for the rest of the duration of experiment in the month of August with slight variation in the magnitude of the temperature regulation. The reduced external surface temperature on vegetated green wall is an evidence to yield a reduced internal surface temperature compared to bare wall. The internal surface temperature on the bare wall stays at an average of 52 ºC while the internal surface peak temperature on the vegetated green wall stays at 46 ºC which shows a similar trend and magnitude of temperature regulation as of external wall. The study emphasizes that since the internal wall is in thermal communication with the indoor air through convection, the drop in internal surface temperature yields a drop in indoor ambient temperature with vegetated green wall compared to bare wall with average difference of 6 ºC. By intervening the heat transfer with vegetated green walls , all the three temperatures are consistently lower than the bare wall which indicates the reduced heat transfer and resulting cooling effect produced by the vegetated wall, however indoors temperatures attained through this single intervention 45 °C-47 °C are still far from the comfort temperature of 26-28 °C.

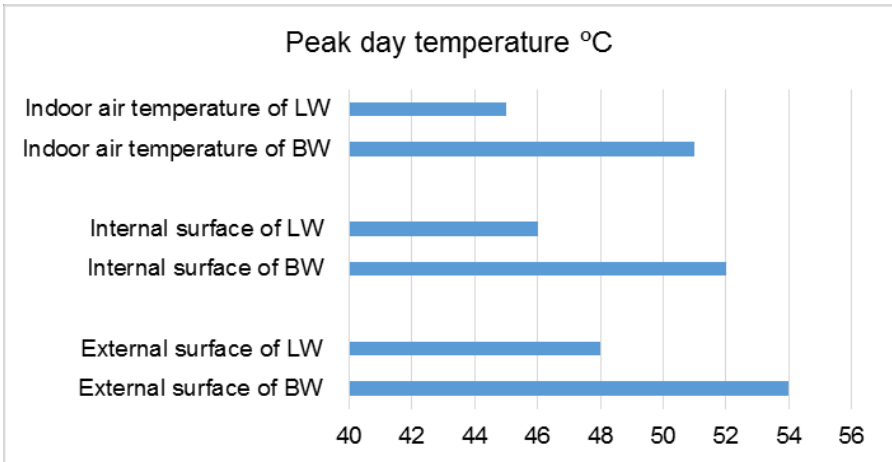

Figure 3: Peak day temperature of Living Wall (LW) and Bare Wall (BL) of external surface, internal surface and indoor air temperatures.

The experimental result investigated that the daytime external surface temperature difference is consistently above 5ºC. The temperature difference between the bare and vegetated living walls is positive during daytime however this difference is negative at night time. This shows that in a colder climate, the insulation effect of vegetated green wall can be exploited to keep the heat absorbed during daytime indoors from escaping to outdoors and keep the space warmer for thermal comfort and reducing heating load. In hot climates, this would tend actually reverse the ambient cooling effect at night by reducing external wall cooling rate. It was also emphasized that the internal surface of the vegetated living wall remains cooler than that of the bare wall with a consistent difference of 4-6 ºC during peak daytime, and 1-2.5 ºC during lowest peak nigh time. It means that in both day and night conditions, the former maintains lower temperature than the later

To validate the experimental results, indoor and outdoor temperatures were processed to calculate the heat gain through the wall. The heat gain was compared with the simulated heat gain through the same bare wall using eQuest energy modelling software. After the experiment and simulated results reached agreement for the bare

wall test room, the cooling load for the living wall test room was calculated from experimental measured indoor and outdoor temperatures (Haggag et al 2014). The cooling load of the bare wall test room was compared with the living wall in order to determine the effect of the vegetated living wall on cooling energy savings. The simulated result of the vegetated living wall was compared with the experimental result of the same wall for cooling load. It was observed that the cooling load of simulated living wall was in agreement with the cooling load of the same wall for the test duration with a variation below 5%. Based on validated simulation models, the cooling load was predicted for the whole year for the bare and vegetated living walls to calculate the yearly cooling load reduction achieved by vegetated living wall. As presented in Fig. 4, the cooling load of the vegetated living wall remained consistently lower compared to the bare wall. The results show that the cooling load reduction reaches 1.01 MWh, resulting in 20% energy saving for cooling demands.

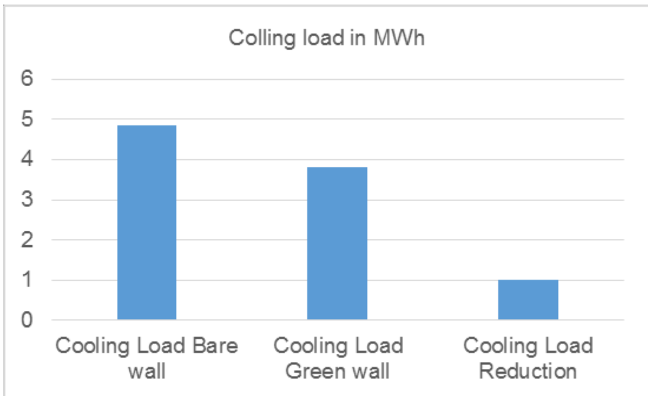

Figure 4: Comparison of experimental cooling load for the bare and vegetated green walls

The study investigated that the use of vegetated living wall improves the thermal performance of the building façade. The decreased temperatures are achieved by heat gain reduction due to incident radiations being blocked by plants and soil mass; the evaporative cooling caused by the irrigation system; and heat resistance due to low thermal conductivity of the plants acting as heat insulators. Despite the cooling load reduction, it is not clear that the vegetated living wall system is economically sustainable. To investigate its economic benefits, the study conducted a Cost-benefit analysis of the analysed living wall system. The cost-benefit analysis was based mainly on determining simple payback period considering the capital and operating costs, energy savings and increased rental value.

3 Cost-benefit analysis of vegetated living wall

The study investigates a Cost-benefit analysis of vegetated living wall of the case study, considering economic benefits related to energy saving, improvement of property value and durability of building façades. At this stage the environmental benefits of air quality improvement, carbon reduction, climate and biodiversity improvements, habitat creation, and sound insulation are not included in the analysis. By reducing surface temperature of a building façade, greenery systems can protect building surfaces and extend the lifespan of the building skin by keeping rain off the building allowing moisture to escape, reducing the expansion & contraction of building materials and protecting walls against wind and solar radiation (Haggag et al 2014).

A class room with an average façade area of 10 m^2 was tested and the total cost has been calculated as shown below and summarized in Table 1. The economic benefit of

the tested greening system is calculated through the energy savings caused by reduced cooling load and increased rental rate due to the increased property value. The economic and environmental benefits of the vegetated living wall system are summarized in Table 2.
Cooling load reduction (Fig. 4) = 1.01 MWh/year
Average yearly rent for the tested space = 10,000 US$
Increased rental rate for green building façade = 4 %
1/4 of the façade is covered with plantation, so the increment applies to 25 % of the rent.
Added property value of tested space due to greening = 0.04*10,000*0.25 = 100.00 US$
Local cost of electricity = 320 AED/MWh = 87.12 US$/MWh
Energy cost savings=electricity cost*cooling load reduction=87.12*1.01=88.00 US$/year.
Total savings = saving on rental + energy cost saving =100.00+88.0 =188.00US$/year.
Payback period = 3,337 / 188 = approx. 18 years.

Initial and installation costs, maintenance and running costs of the tested vegetated living wall are considered in the study and compared mainly with cooling load reduction, and property value. Installation costs of the vegetated living wall were obtained from local companies available in the UAE. The initial and installation costs cover plant species and growing media, planter boxes, irrigation system and water. As shown in Table 1, the initial cost of the analyzed green façade including irrigation system and the local cost of used water was 235.20 US$/m^2, while the installation cost reaches 41.00 US$/m^2.

Maintenance and running costs depend mainly on the type of greenery system. Living wall system is more expensive than any other direct and indirect greening systems. It requires high maintenance costs to cover plants pruning and plants adjustment, irrigation, planter boxes replacement, plant species replacement, and pipes replacement. Plant removal and transportation to landfill was added to the maintenance costs. Façade renovation can also be added to the maintenance cost (Perini & Rosasco 2013), however it is not included in this analysis due to its variation and life cycle. As a result, the total maintenance cost reached 57.50 US$/m^2/year.

Table 1. Cost of vegetated green wall per tested building façade.

	Category	Cost in US$ (1 US$ = 3.67 AED)	Time frame
Initial cost	Plants species & growing media	280 US$	One time
	Plastic planter boxes	1800 US$	One time
	Irrigation system	260 US$	One time
	Water cost for irrigation	12 US$	Annual
	Total initial cost	2352 US$	
Installation cost	Planter boxes	320 US$	One time
	Irrigation system	90 US$	One time
	Total installation cost	410 US$	
Maintenance cost	Pruning	110 US$	Annual
	Irrigation	95 US$	Annual
	Planter replacement (5%)	60 US$	Annual
	Plant species replacement (10%)	160 US$	Annual
	Pipes replacement	150 US$	Annual
	Total maintenance cost	575 US$	
Total cost for tested façade area		3,337 US$	
Tested façade area		10 m^2	

Total cost/m2	333.7 US$

Table 2: Economic and Environmental benefits of vegetated green wall in hot arid climate

	Category	Benefit
Economic Benefits	Energy savings	88.00 US$/year-
	Added property value	100.00 US$/year
Environmental Benefits**	Improving climate and biodiversity	Not included
	Visual impact on architectural fabric	Not included
	Street noise reduction	Not included
	Urban heat island	Not included
	Total Economic Benefit	188.00 US$/year
	Payback Period	18 years

** Environmental benefits are not included in the cost-benefit analysis at this stage.

The cost-benefit analysis results conclude that the used modular vegetated living wall system with plastic planter boxes might not be the best economic sustainable option, as the installation and maintenance costs are high compared with other indirect greening systems such as greenery system with plastic mesh). The most favourable economic conditions take place when the payback period is low. However, as shown in Table 2, the payback period of the tested vegetated living wall reaches 18 years. In comparison, the payback periods for other indirect vegetated walls can reach 12-16 years (Perini & Rosasco 2013; Haggag et al 2017). The authors expect to achieve reduced payback period once the environmental benefits are quantified and included in the analysis. At this stage, the study highlights the main environmental benefits of using the vegetated living wall system.

4 Environmental benefits of vegetated green walls

Building facades, particularly in hot climate are under permanent environmental impact. Sun and heat gain, storm water runoff, air quality and airflow, urban biodiversity and urban heat island have great influences on energy efficiency of building façades. The use of vegetation on and around buildings can protect building façades and offer benefits such as reduction in building energy consumption, mitigation of urban heat island effect, improvement of air pollution, noise control, ecological preservation, green credentials, and building surface protection (Berard, U. et al 2014).

4.1 Increasing energy efficiency in building

Vegetated living walls provide a wide range of positive effects for buildings, inhabitants, and the environment. It helps buildings become more energy efficient and reduces 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 (Haggag et al 2014). A number of studies have explored the thermal effect of vegetated green surfaces on building envelop. Alexandri and Jones in their study have concluded that vegetated walls could mitigate raised urban temperatures and achieve energy saving for cooling buildings by up to 32% (Alexandri & Jones 2008). It also reduces energy loads in buildings as Bianco et al. measured equivalent thermal transmittance values of a green modular system and they showed a 40% reduction when compared to a plastered wall (Bianco et al. 2016). Vox et al. argued that daylight temperatures observed on the plant walls were lower up to 9°C during warm days (Vox et al. 2016). In another experiment in Greece, for a wall facing West and partially covered with creepers (Tsoumarakis et al. 2008),

measurements showed that vegetation cover reduces temperature peaks. Similarly, a real building with green facade on East underlined the external surface temperature cooling effect by about 5°C (Eumorfopoulou & Kontoleon, 2009). The plant type/specie and characteristics of substrate are the main factors which impacts both energy and CO_2 performance (Charoenkit & Yiemwattana 2016).The thermal performance of two different vertically greenery systems (Double-skin green façade & Green wall) were analysed in reference to bare wall and it was found that a high potential for energy savings during cooling season for green wall (58.9%) and double-skin green facade (33.8%) in comparison to the reference system in a Mediterranean climate.(Coma et al. 2017).

4.2 Improving climate and biodiversity

Vegetated wall helps in improving microclimate both in winter and summers using vegetation, functioning as a complementary insulation layer on one hand and providing shade on the other hand. It provides evaporative cooling effect as a passive design strategy. Vegetation absorbs large amounts of solar radiation (Jim & He 2011) while the effect of evapotranspiration of plants can further reduce the impact of solar radiation, showing increased humidity levels and surface temperatures lower than bare surfaces (Kontoleon & Eumorfopoulou 2010). Vegetation can reduce urban heat island effect and smog (Anon 2017). Plants clean the air by absorbing flow and dust, and freshen the air by consuming carbon dioxide and restoring oxygen. Vegetation in buildings provides shelter to natural habitat as lack birds, sparrows and greenfinches were found between the climbers of green facades in Berlin. Green roofs, Green facades and vegetation in general functioned as food source for insects and a nesting or breeding opportunity. (Kingsbury & Dunnett 2008; Razzaghmanesh & Razzaghmanesh 2017).

4.3 Visual impact on architectural fabric

Vegetated wall technology has a visual impact on the architectural fabric. The use of vegetated walls as visual attractants increases the value of the building. Moreover, vegetated walls can help to address the lack of green space in urban environments. Plants improve human health, capture airborne pollutions, and filter harmful gases. In addition to absorbing heat and increasing thermal performance, the green wall helps to filter the air moving across it.

4.4 Street noise reduction

In urban environments, plantation has been used as barriers against urban noise pollution. Plantation has a high potential to be used as sound insulation tool for buildings but with some design adjustments e.g. improving the efficiency of construction joints (Azkorra, et al. 2015). Plants, growing media, and the trapped layer of air can absorb, reflect or deflect sound waves. Therefore, vegetated walls have an acoustical insulation that is far better than that of bare wall (up to 30 db reduction) (Kontoleon and Eumorfopoulou 2010). The degree of sound insulation provided by the vegetated wall 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. In terms of sound control, the choice of the appropriate type of vegetated wall technique depends mainly on the site conditions, climate conditions and the function of the inner space.

4.5 Economic benefits and life cycle cost

Environmental benefits of living walls can be translated into Economic benefits as Plantation on building façades increases the property value. Des Rosiers, et al. (2007), in their study, estimated that vegetated walls increase the property value by 3.9%. Other study explored that an increase in quality of greenery level on building façades increases price of the property by 1.4% in Tokyo and 2.7% in Kitakyushu (Japan). Perini and

Rosasco argued that direct green façade has an average payback period of 20 years where as the indirect green façade can be sustainable depending on the material used for the supporting system, whereas living wall systems were not sustainable because of high installation and maintenance costs (Perini & Rosasco 2013). It was argued that mitigating the urban heat island effect with trees, green roofs and green façades can reduce the U.S. national energy consumption for air conditioning up to 20%, saving of more than $10B in energy use. Sánchez & Brajkovich who conducted life cycle cost analysis for vegetated wall systems for three different climates namely London, Barcelona and Dubai (Sánchez & Brajkovich, 2014). It was found that the vegetated walls system provides a 14% of energy savings in London, a 30% in Barcelona, and a 40% in Dubai climate. Whereas the vegetated walls indirect system provided 9%, 12% and 30% energy savings in the same cities respectively.

4.6 Green credentials

Vegetated green walls can help securing points in Green Buildings Certification Systems e.g. LEED in USA, Estidama in UAE, BREEAM in UK, etc. This technique can be used as a tool to claim points in credit categories covering issues of sustainability, energy savings, indoor air quality, health & wellness, and acoustics. (Green over Grey, 2017)

5 Conclusion

The use of vegetated green walls can improve the thermal performance of building facades on one hand and adjust the urban microclimate on the other hand. The study concluded that vegetated wall technique can reduce peak time indoor air temperature by 5-7◦C during summer period in the hot-arid climate of Al-Ain city, UAE. It reduces the peak air conditioning energy demand by 20%. Additionally, it can reduce wind effect and help control the humidity within the building zone. From economic point of view, the study investigated that the vegetated living wall system might not be the best economic sustainable option as the installation and running costs are extremely high since the payback period reaches 18 years, taking into consideration the cooling loads reduction while the related environmental benefits were ignored at that stage. It is expected to achieve more reduction in the payback period once the environmental benefits are quantified to make the use of greening systems financially viable. Vegetation can protect building façades and offer benefits such as reduction in building energy consumption, mitigation of urban heat island effect, improvement of air quality and sound insulation, improvement of climate and biodiversity, and secure green credentials.

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BRIDGING THE GAP BETWEEN TECHNICAL EDUCATION AND ETHICAL COMMITMENT TO A SUSTAINABLE BUILT ENVIRONMENT

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Abstract: *The role of building professionals in shaping a sustainable built environment is an internationally agreed agenda. Educating and training tomorrow's professionals who abide by and deliver an ecologically sensitive design is a critical mission that has been extensively embraced by architectural, design and engineering schools worldwide. Similarly to many schools worldwide, the Architectural Engineering program at the United Arab Emirates University has included sustainability throughout its curriculum, resulting in students technically knowledgeable and well prepared to approach and design green buildings through building energy efficiency optimization, material selection and integration of renewable energy systems. However, while the program has increased and deepened the technical knowledge, the analytical and problem-solving skills in these areas, it has not necessarily translated into a higher awareness level and ethical commitment to sustainability. This may be particularly evident in the Gulf countries, where high earnings coupled with subsidized energy, do not reflect the true energy cost. The ethical commitment to sustainable development in the built environment remains yet to be fully reached. These observations may not represent all contexts but it stresses the need for a contextually grounded sustainable education. This paper presents first briefly, the Architectural engineering program's achievements in this targeted area, along the identified sustainability awareness gap. Then it highlights some course activities developed to raise awareness and reinforce commitment to green design. The course content and objectives are outlined but more importantly it describes some activities that seem to have had an impact and triggered self-reflection and potentially responsiveness. Above all, this paper aims to raise the issue of ethical commitments to sustainability and foster a wider discussion on the need for the development of contextual educational strategies to really meet the sustainability targets.*

Keywords: *Sustainable Built Environment, Educational Strategies, Ethical Commitment, Awareness, Context, Architectural Engineering*

1 Introduction

Humanity is at unprecedented crossroads. The implications of a rapid population growth coupled with an unprecedented resources intensive urbanization led to critical environmental issues. Land, food, water, air, the very elements needed to live on are becoming scarce and highly coveted resources. The recognition of climate change and global warming as a major risk has set sustainability as a world-wide agenda, triggering multidimensional initiatives.

In this context, the United Arab Emirates (UAE), quite similarly to most Gulf countries, witnessed tremendous economic and urbanization expansion in the last forty years with however minimal consideration of resources and energy-related implications. The built environment in the UAE for instance, accounts for 70% of energy consumption, mainly used in cooling, compared to the global average of 40%. A fact that positioned the UAE as one of the world's largest energy consumption per capita, a situation worsened by its harsh weather conditions (World Energy Congress 2011, Amaya 2013, Khondaker et al. 2016) (Fig. 1).

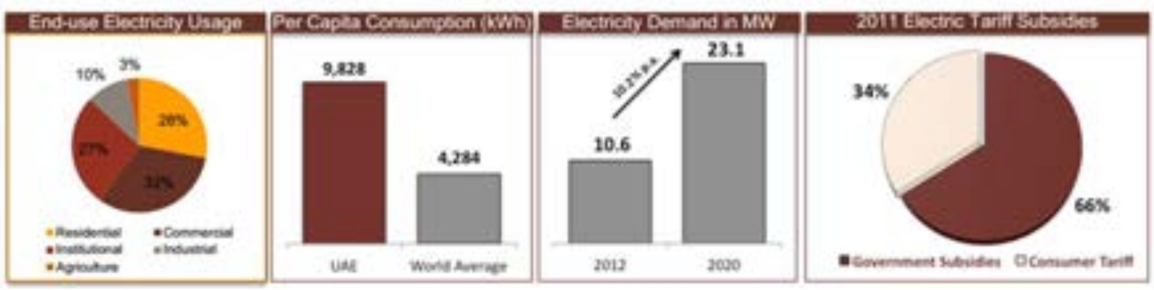

Figure 1: UAE electricity consumption; status and prevision (Amaya 2013)

The UAE government recognizes the energy–carbon reduction challenge and identified a number of key indicators for change in the Economic Vision 2030, including reducing power demand by 15% by 2020 from the 2010 levels (UAE Ministry of work 2015). The identified challenges to reach the target lie in a number of issues including lack of policies directed to energy efficiency, limited standards related to products and system performance and perhaps more importantly the lack of public awareness and education related to the critical need for resources conservation (Amaya 2013).

The UAE government is now committed to a sustainable growth through the development of a green economy and a sustainable built environment, leading to a diversified portfolio of actions and sometimes unique initiatives. Masdar, a UAE renewable energy business venture based in Abu Dhabi, is an example of the government's initiative to invest in, develop and establish the sustainable energy industry in Abu Dhabi and around the world. Further, the establishment of a building rating system, called *Estidama*, hosting national and international events such as the Energy Summit, World Energy Day and the intent to host the 24th World Energy Congress 2019 in Abu Dhabi are all part of efforts to transform it into the world's capital for energy.

Along these efforts, education for a sustainable development has been recognized as vital and set as a strategic target since the 1992 Rio Earth Summit. UNESCO dedicated a decade from 2005 to 2014 for the development of sustainable education (AASHE 2010) a target now commonly and largely integrated in higher education (UNESCO,

2012, EDUCATE, 2012, AASHE, 2015, AASHE, 2017). However, effectiveness remains contextually grounded and calls for improvements (Corcoran & Wals 2004). Hence, the broad focus of this paper lies in stimulating a debate on the optimal integration of sustainability in education, while the focused target is to explore ways encourage to reach out to future professionals on the ethical commitments to sustainability in general and sustainable built environment in particular

It reports on an architectural engineering program's technical achievement to deliver green or high performing buildings versus the limited awareness and potentially ethical commitment to a sustainable future. It shares some sample activities, part of an elective course that aimed to build students' overall awareness. Finally, it stresses the need to bridge the gap and calls for creative educational approaches that take into consideration the socio-economic and cultural context.

2 Sustainable Education and the built environment

Education in general and higher education in particular is facing its greatest challenge in meeting its responsibility to prepare its graduates into a responsible, knowledgeable and innovatively creative workforce that can respond to today's socio-economic and environmental challenges (AASHE 2017). In this context, education for a sustainable built environment is an incumbent imperative. Higher education is a leverage point for advancing sustainable built environment. "All construction professionals have an obligation to ensure that the buildings and urban spaces that flow from the design process are a product of careful and responsible practice. This has not always been the case and, rightfully, the finger has in part been pointed at academia for not providing the education that would help such professionals respond to contemporary sustainability challenges" (Corcoran & Wals 2004, Altomonte et. Al 2014). In addition, often enough engineering professionals move into management, policy and government, financial institutions, and do not always follow traditional engineering paths (Beder 1998). Thus, engineers' potential contribution beyond their original field of expertise may span to all these areas using their technological knowledge to improve and promote sustainable business and policy outcomes (Altomonte et. al 2014).

The sustainable education target had been recognized and embraced worldwide. The Association for the Advancement of Sustainability in Higher Education lists academic programs in sustainability and related fields within over 500 organization in Northern America alone (AASHE 2015). Intensive research spurred around the integration of sustainability in higher education (AASHE 2015, AASHE 2017) highlighting challenges, gaps, framing issues while exploring models and best practices (Altomonte et. al 2014, Desha et al 2003, Gough & Scott 2003, Moore 2005, de la Harpe Thomas, 2009, Waas et. al 2010, Arjen, 2002, McFarlane, A.G. Ogazon. 2011). Similarly, several institutions within the UAE advocate the delivery of an undergraduate and/or graduate program articulated around a sustainable built environment.

While the importance of education to foster a sustainable life has been internationally accepted as a critical agenda item spurring numerous initiatives, achievements and performance are yet to be verified. The ethics of sustainability in particular may largely be affected by economic and political discourses (Dower & Dower, Kibert et. al 2010). Further, the meaning attached to a phenomenon might be largely culturally nested (UNESCO 1996). Hence, approaches in one socio-cultural setting might be quite different in another and call for a critical appraisal of education effectiveness. Further, in high levels of material affluence and consumption societies, education may fall short of reaching its target by only imparting scientific and technical skills (AASHE 2017).

2.1 Sustainability in architectural engineering program at UAEU

The Architectural Engineering (AE) program at the United Arab Emirates University (UAEU) embedded education for a sustainable built environment across the curriculum, as every academic area within the program contributes to sustainability. It embraced an integrated design teaching and thinking approach as the complexity of buildings exceeds the expertise on isolated individual systems or components. This attribute has been recognized as one of the main program strength in its 2016 reaccreditation by the Accreditation Board for Engineering and Technology (ABET). Students are particularly knowledgeable at designing high performing or Zero Energy buildings through building energy efficiency optimization, material selection and integration of renewable energy systems. Although the program has deepened students' technical knowledge, heightened their analytical and problem solving skills in these areas, this has not necessarily translated into a higher awareness level and ethical commitment to the sustainability issue. A recognized gap that called for the "need to refocus many existing education policies, programs and practices so that they build the concepts, skills, motivation and commitment needed for sustainable development" (UNESCO 2002).

This may be particularly evident in the Gulf region, where high incomes and subsidized utilities overshadow the true energy usage. The ethical commitment to the sustainable development in the built environment remains yet to be fully reached. In the light of recent economic adjustments, there is evident pressure to consider ways to raise sustainability awareness and ethical commitment versus technical expertise. In light of these concerns, a set of basic activities have been embedded in an elective course, attempting to build a complete picture and raise awareness.

2.2 Sustainable Built Environment; Course Target, Achievement and Challenge

The Sustainable Architecture and Urban Environments in Hot Climate (ARCH532 2017) is an elective course typically taken in the student's 4^{th} or 5^{th} year. It is one among a limited number of select courses that account for the Bachelor/Master (BS/MS) dual degree that undergraduates with a strong academic record may take as part of an accelerated BS/MS Program. The course is developed to complement the core curriculum courses and spans over a range of scales and topics. Upon successful completion of this course, the intended outcomes are that students will be able to, a) Define the environmental impacts of urbanization / buildings and discuss implications of using non-renewable energy, b) Identify the appropriate urban and architectural responses in hot arid and hot humid climates, c) Recognize the requirements of Green Buildings and select optimum strategies and d) Assess critically the strategies used in green buildings that responds to climate and meets the fundamental requirements of energy efficiency and water conservation.

The main topics addressed in the lectures included climate change and global warming, the ecological footprint, urbanization and the environment, Urban Heat Island and sustainable urbanism, Green rating system and high performance buildings, energy and water conservation in the built environment, Building retrofitting strategies and performance. Sub-topics within these lectures in the form of mini research-presentation-discussions carried in the second and third week and led by the students themselves addressed the importance of biodiversity preservation, explored climate change and extreme weather events and their regional impacts with a purpose to clearly apprehend the related health, economic, social and environmental consequences. Framing the initiatives to address these issues through international protocols was also addressed. In

this context, some of the activities seem to have triggered more enthusiasm, inquisitiveness into the topic. Some of the most seemingly impacting ones are presented here

2.3 Sample activities; content and outcomes

The select sample of activities presented in this paper are linked to the first three lectures (*climate change and global warming*, *the ecological footprint* and *urbanization and environmental impacts*). The common underlying objective was to engage students in critical reviews and debates ranging from the socio-behavioural review of personnel lifestyle, to urban and architectural design decision and their environmental implications.

2.3.1 *My Ecological Footprint; How Sustainable is your Lifestyle?*

A warm up lab activity invited students to individually calculate their ecological footprint via a freely available online footprint calculator, in order to estimate how "sustainable" their lifestyle is. The output in the form of the number of planets earth needed to sustain their lifestyle was compared first with their group members and the world average with the objective to identify variances and discuss the underlying causes of the differences.

This basic evaluation and analysis emphasized disparities linked to lifestyle, consumer behaviour and lack of awareness. Ecological footprint differences among students in particular triggered a scrutinization of the underlying reasons. It highlighted that means of transportation was a critical factor that had urban design implication as well as links to personnel choices; i.e. individual cars versus public transportation. Variation with world average triggered a discussion that identified contextual specificities such as the extreme hot climate and limited water, as specific regional influential factors. This very basic activity in this affluent context reflected primarily the risk of social and global awareness outcomes, as students evaluated their roles as individual consumers and future professionals with choices and decisions carrying social, economic and environmental consequences.

2.3.2 *The Newspaper Review*

Another warm-up activity occurred in a lab session, where students were given copies of a local daily newspaper, *Gulf News,* spanning over a week period. They were asked to identify topics that may be linked to climate change, global warming, urbanization and environmental impacts as well as any related mitigating initiatives. Then, a brief summary of one topic was shared with the class.

The first striking observation for all was the recurrent or daily related events from natural disasters such as flooding, hurricanes or drought and their consequences on vulnerable populations causing varying damages; to displacements, migration, starvation, diseases, deaths as well as negative impacts on lloss of eco-systems, biodiversity or animal natural habitats were all recurrent topics. They also noted the large number of initiatives ranging from adhesion to international protocols, energy related events such as conferences, trade show exhibit and many local or regional initiatives to increase renewable energy usage. In brief, it carried a broader perspective on environmental risks, impacts and the need to adequately address them.

2.3.3 *World carbon emissions by country; roles and responsibilities*

Another activity, designed as role-play scenarios, relied on critical inquisitive data mining that aimed to build a critical approach to first hand data. First, students were provided with Figure 1, depicting a world atlas of pollution in the form of CO2 emissions by country for a given year. Then, they were asked to review the data, discuss it in small

groups, then through class discussion explain it and comment on the status, roles and responsibilities, with an underlying quest to identify the particular nation's most responsible factors for climate change as per its CO2 emissions. The currently high emitting countries were quickly blamed for their extremely high emission and therefore their contribution to the detrimental global warming phenomenon.

Next, the class was divided into 4 groups (3-4 students) each representing either the United States, China, Europe or the developing countries. They were asked to consider that they are delegates of these entities attending international climate summit where reduction on CO2 emissions will be imposed. Their role is to best defend the country's position regarding CO2 emission and reduction measures. Time was given to search and build the right arguments to defend their country's position prior to a general argument-presentation-debate. This activity resulted in an extremely engaged and lively debates that broaden their views to the concept of "climate justice" and equity. The notion of historical responsibilities and the right for growth and development were sustained with very creative arguments. They realized that all have a common goal but different responsibilities.

Additionally, attending and participating in local initiatives (energy summit, sustainable cities, DEWA and EGBC competitions) provided numerous opportunities for engaging students in sustainable driven initiatives, offering valuable connections and prospective career impacts.

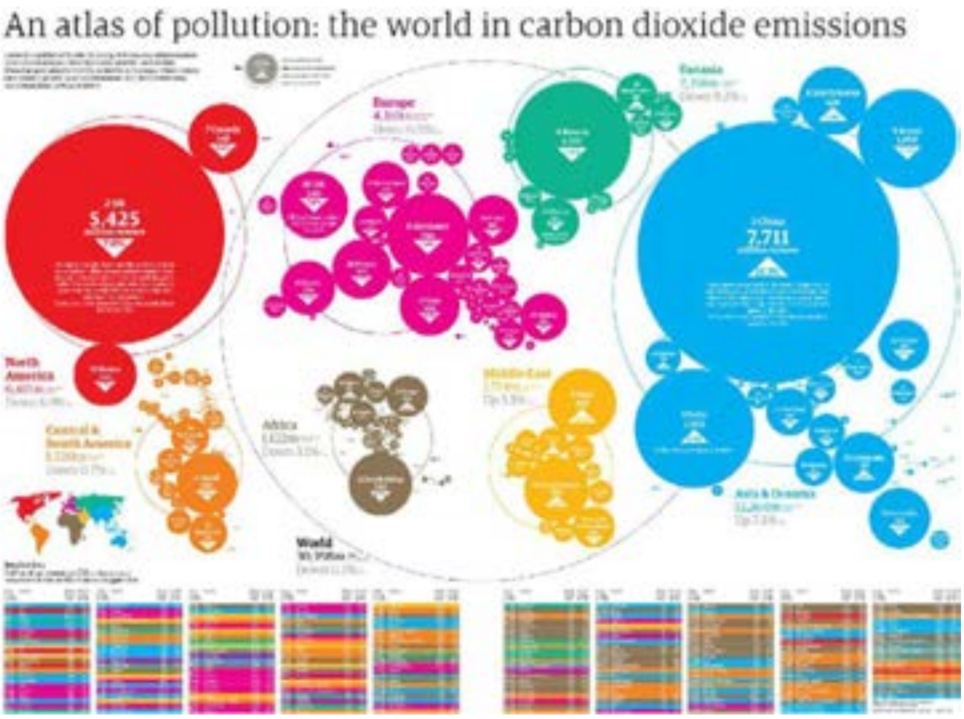

Figure 2: An atlas of pollution: the world in carbon dioxide emissions (The Guardian 2012) [23]

2.3.4 Households behavior and energy

Finally, the course term project addressed the retrofitting of their own home to greener standards, focusing on energy efficiency and water conservation. The inquiry explored all parameters affecting energy usage in the home, including, house design, materials, landscaping and occupants' behavior and energy usage. The latter was investigated

through a short interview exploring occupants' behavior in relation to their space and appliances usage, their quest for thermal comfort and adaptation as well as their level of awareness in relation to their energy consumption. All were with nationals living in large detached villas. Although the outcome of the interview was not of a research level, it overwhelmingly triggered a comprehensive critical review of households' space usage, daily behavior practices and more importantly it highlighted a lack of awareness.

2.3.5 Evaluation of the Course Outcomes

The overall course outcomes are traditionally evaluated via direct and indirect assessments including students opinions, exams and projects. In this regard, a specific question was included in a written exam aiming to check students' perception of the most prominent course learnings. Hence, students were asked the following "*Comment on what you have learned in this course and how it may benefit your studies and/or professional work?*

Over 90% of the respondents indicated that the prominent outcome has been the increased awareness of environmental impacts and the need for a holistic approach to sustainability as expressed by one student: "*This course provides eye-opening knowledge about just how detrimental our lifestyle is to us and our environment. Everything from the urban form to daily life of the individual have many issues that can be easily solved with a little awareness from the planners….*". It specifically highlighted the gap between the acquired technical knowledge and the wider causes and implications of choices as stated by another student "*Before this course, I was thinking that being sustainable means designing buildings that are efficient, operate with PV and reduce their energy consumption. While through the first part of the course, I realized that identifying the problem, causes and impacts will assist in finding the best solution.. Prior to any design decision, or a quick fix solution we need to define and rethink how it could affect when applied…*". Similarly, another respondent mentioned that "… *the course opened my eye to a lot of things, especially when we started with global issues of climate.. I was shocked that all this is happening… I learned that there is a lot of things in the architects' hands .. It's our responsibility to distribute/spread awareness and convince people for a greener world…*". The impact of a raised awareness seems to have outweighed the remaining parts of the course as stated: *"The beginning of the course has been an eye opener in terms the impacts on the environment and the problems and challenges facing it. It connected me to my activities as a human being living in the earth… "my footprint" I also realized the extent of urban design decision such as sprawl and transportation impacts which in turn will affect the environment.."*

The gap between the needed basic knowledge was further stressed by another student: "… *I have calculated what an ecological footprint was and even calculated my own, which in turn had me change a few aspects of my life... I have also learned that there are active form of duties that we have not been prepared for…. I have realized that a lot of information learned here should be general knowledge for all but people do not have any awareness about the issues and are not being taken very seriously, as well as being able to correct others , that alone helps me converse convincingly with people on issues much above my impact level…, making them aware of issues that can and will threaten us all*". Additionally, a potential impact on future career choices where evidenced in a number of responses as indicated by one ".. *I would like to continue my studies towards sustainability and have a big change in my career, because the solutions are available we just need to be aware…..It really opened my eye to a bigger perspective not just design and construction but also how our choices and decisions as individuals and professionals will affect on a bigger scale.*."

Although limited to a small sample and requiring further validation, these responses are a clear indicator of the gap between technical knowledge acquired and in this context the critical need to effectively reach out to embrace sustainable development. Beyond the inherent ambiguities involved in defining sustainability, there are calls to insure that such initiative are moving in the right direction. This leads to the question of "*What is a more appropriate form of environmental education research? ... [I]t is one which includes consideration of both human consciousness and political action and thus can answer moral and social questions about educational programs which the dominant form [of research paradigm] cannot"* (Robottom & Hart 1993).

3 Conclusion

This paper aims, first, to foster a wide debate on optimum ways to include sustainability in higher education in general and more specifically in the context of the Gulf countries. The rapid changes that have taken place in the region shaped citizens beliefs and attitudes grounding them in luxury and consumer culture, part of a global culture of materialism that leaves little room for real ethical commitments to sustainable development. In this context, it questions outcomes of sustainable architectural education grounded mainly in technical knowledge, with a risk of limited real impacts.

It presents a selected sample of course activities that engaged students to inquisitively and critically assess the deeper and ramified amplifications of resources intensive choices ranging from lifestyle to urban planning decision, building design and material selection. The outcome of the course, although covering various related topics, seems to have appears to be mainly the raised awareness of the implications of these choices on the environment and natural resources. This raises the critical need to address the ethical commitments to sustainability in education contextually. It stresses the challenges facing sustainability in education and the need to go beyond curriculums orientation to explore teaching strategies and techniques.

It ultimately stresses the role of education in general and higher education in particular to continuously challenge and critique value knowledge claims. Part of this challenge lies in engaging students in environmental, economic and socio-scientific arguments and calls for a critical review of how the sustainability concept is conveyed, as it requires its contextualization and consideration of conflicting values, beliefs, norms and interests.

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THERMAL IMAGING ASSESSMENT OF BUILDING ENVELOPE PERFORMANCE IN THE UAE EXISTING HOUSING

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Abstract: *The electricity consumption per capita in the United Arab Emirates is one of the highest in the world. The built environment accounts for 70% of energy consumption, mainly used in cooling to mitigate the local extreme hot climate. A condition further exacerbated by the lack of an energy building code until 2010. Hence, the existing building stock of which the residential sector is a major component is a prime target for an energy efficient retrofit. This paper aims to investigate the thermal leakage from residential building's envelope using thermography, in order to identify the impact of time, workmanship and construction quality on the building thermal efficiency. The objective is to identify energy upgrade opportunities and prioritize retrofitting solutions. Residential units in two housing complexes built over a decade apart were selected for testing in Al Ain city, UAE. The impact of orientation was first verified and ruled out. Testing at critical points including corner wall junctions, roof junction, windows frames and external glazed sliding doors was carried out. Results were compared among units of the same housing complex and between units across the two housing complexes considered. The auditing highlighted a number of common thermal behaviour and variances, including a critical need for building envelope insulation as expected. Newer units, however, had significant thermal anomalies around building's junctions, indicating that building's age may not be the main referent for a retrofitting priority. Workmanship and construction quality may be a more impacting factor, calling for construction quality assurance beyond the specification of minimum values of insulation.*

Keywords: *Housing, Thermal Leakage Assessment, Thermal Imaging, Construction Quality, UAE*

1 Introduction

The United Arab Emirates (UAE) witnessed tremendous economic and urbanization growth in the last forty years, however with minimal consideration of resources and energy-related implications. The result positions the UAE as the world's largest energy consumption per capita, with the building sector accounting for 70% of the consumed energy, used primarily for cooling due in part to its extreme hot climate. The residential building sector forms the dominant part of the urban infrastructure and accounts for its largest energy usage. Amid growing concerns of carbon emissions and the impacts of climate change, the local government undertook considerable multi-faceted initiatives to curb the unsustainable development trends. It identified the importance of targeting building energy use as key to reducing the country's energy consumption. Further, given the fact that the building energy code was not implemented until 2010, it further stressed the critical retrofitting need of the massive existing building stock to greener standards as a strategic step in the sustainable development of the nation's economy.

In this regard, this paper aims to investigate the thermal leakage from residential building's envelope using infrared thermography, in order to identify the impact of building's age, workmanship and construction quality on the building thermal efficiency. Field assessments of representative housing units in the City of Al Ain, UAE were carried out in August 2017. The objective is to identify energy upgrade opportunities and prioritize optimum retrofitting solutions.

2 Contextual Background

Population and urban growth in the UAE coincided with its rather recent economic boom, a result of its immense oil revenues. The total population of Dubai, for example, has grown by 1000% over the last 40 years alone (Elassawy 2017). The UAE's urban population will grow to 7.9 million by 2020, an average annual growth of 2.3 per cent from 2010, according to the World Urbanization Prospects report by the United Nation department of economic and social affairs (Fig 1). City dwellers in the UAE will account for 86.7 per cent of the country's population by 2020, up from 84 per cent in 2010 (United Nations, 2015).

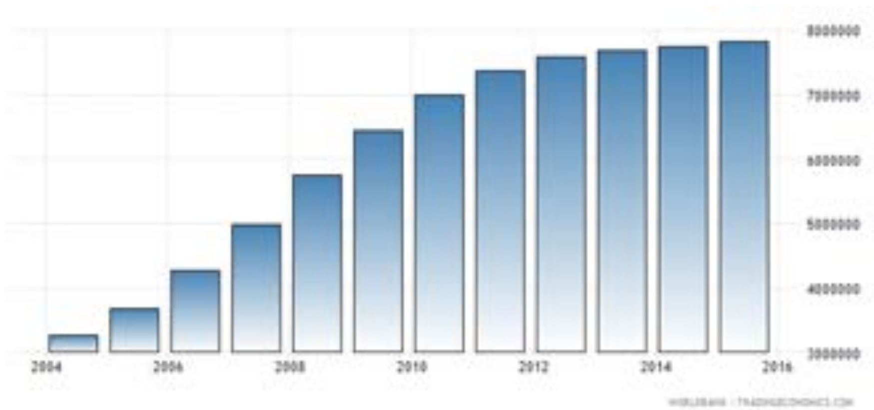


Figure 1: Urban population growth in the UAE from 2004 to 2015 (United Nations, 2015)

A similar trend was observed in Al Ain city, the context of this study, where the population almost doubled between 2005 and 2015, reaching over 738 000 from 440 000 in 2005 (Statistics Center of Abu Dhabi, 2016). It resulted in urban sprawl given the mandated low height, low density city pattern. Figure 2 illustrates Al Ain's urban growth from 1972 to 2000 (Issa & Shuwaihi 2011). The main urban growth triggers in Al Ain are

its geographic location, economic and social development, population growth and family pattern, government developmental policies and transportation development (Issa & Shuwaihi 2011).

Amidst the country's overall growth, the residential sector developed mainly in the form of extensive housing programs provided either by the government to its citizens or privately developed for the rental market. The residential sector accounts for a significant amount of newly constructed detached houses, amounting to about 65% according to National Statistics Center (Abu Dhabi Government, 2010, Statistics Center, 2013). The majority of these housing programs are in the form of detached or semi-detached houses, the most demanding type of houses in terms of cooling, especially under the local extreme hot climate (St Clair, 2009).

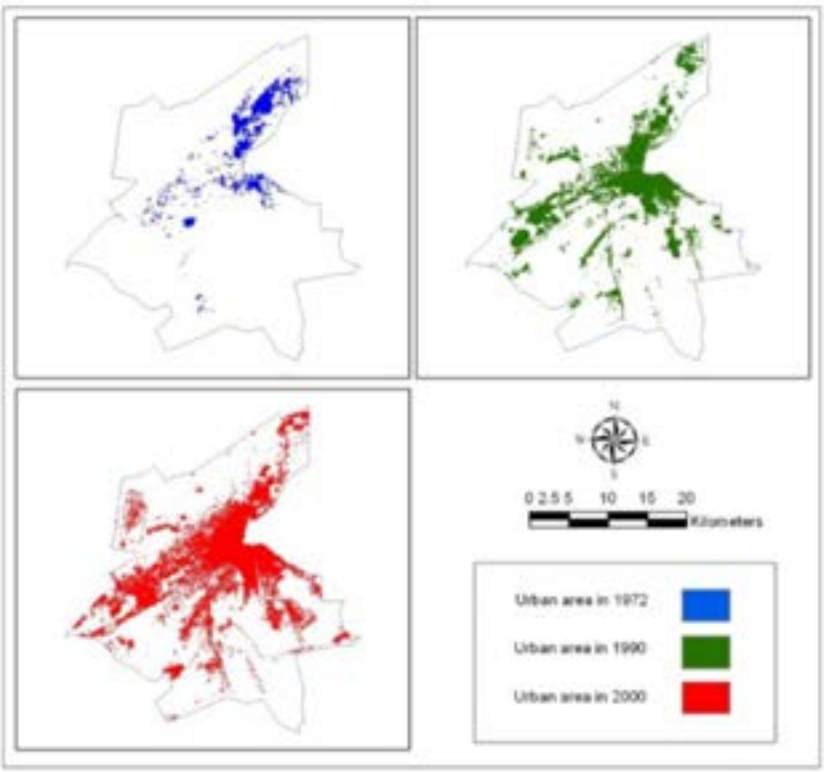


Figure 2: Urban growth in Al Ain from 1972 to 2000 (Issa & Shuwaihi, 2011)

The UAE's desert climate, characterized by extreme high summer temperatures and high solar radiation (Fig 3), imposes serious challenges to both designers and owners alike. The design challenge resides in adapting the intended design to the extreme hot climate of the UAE, while the owner has the challenging task to alleviate the high running energy cost. Temperature, humidity and solar irradiance are the most influential climatic factors in the UAE, where the National Bureau of Statistics recorded the maximum annual temperature average as being 45 °C in August with a minimum of just 13 °C in January (Taleb 2016).

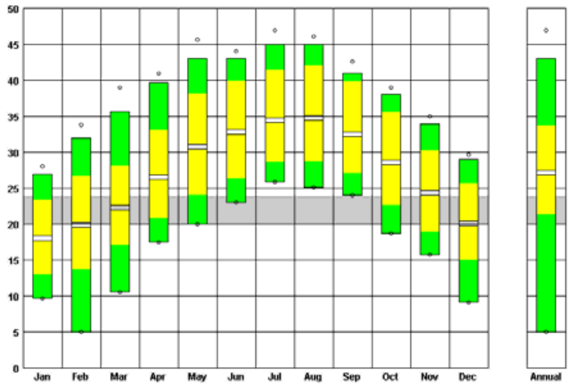


Figure 3: Al Ain's ambient temperature (Climate Consultant Software)

In terms of energy usage, the built environment in the UAE accounts for 70% of energy consumption, mainly used in cooling, compared to the global average of 40%. A fact that positions the UAE as one of the world's largest energy consumers per capita, a trend that is expected to increase (World Energy Council, 2011, Amaya, 2013, Khondaker et al, 2016). The residential building sector forms the dominant part of the urban infrastructure and account for the largest energy usage and carbon emissions in UAE (Amaya 2013, Al Faris et al 2016). The energy usage of the residential sector in 2013 in Al Ain city accounted for 40% (Fig. 4) (UAE Ministry of work, 2015). Energy consumption in the UAE residential sector represents the largest share and has proved to be primarily influenced by the building characteristics. Unlike the climatically adapted vernacular houses, contemporary internationally styled houses in the UAE disregarded the climatic, construction methods and cultural context and relied on active cooling and ventilation systems for thermal comfort (Al Sallal et al, 2013). Furthermore, the growing energy consumption in Middle Eastern countries is considered a potential threat to the regions competitiveness and economic growth (Horman et al, 2012).

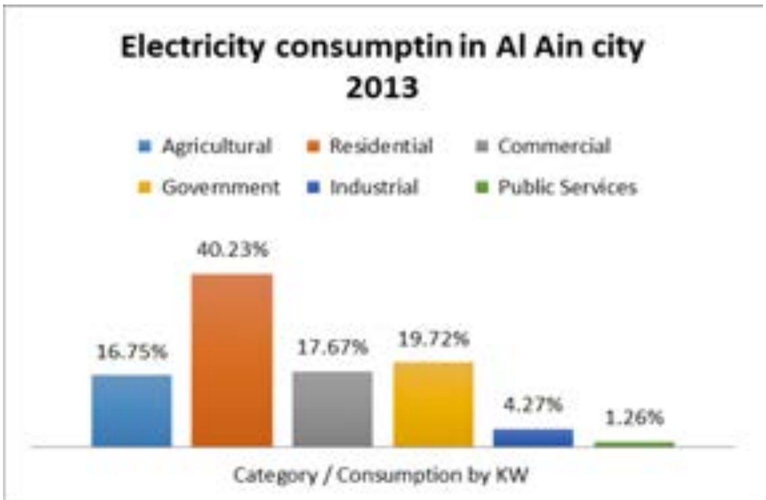


Figure 4: Electricity consumption by sector in Al Ain (Energy and water statistics, 2015)

The thermal performance of the construction methods and materials used in housing were not controlled until rather recently, despite the harshness of climate and its impact on buildings cooling needs and increasing electrical demands (Friess et al, 2012). In fact, it is until 2010, that the Urban Planning Council in Abu Dhabi Emirates established ESTIDAMA, the local sustainability framework (Estidama, 2015). ESTIDAMA aims at achieving sustainability and energy conservation in buildings through the provision of

guidelines for newly constructed buildings. Similarly, the Green Regulations and Specifications in Dubai (2011) was established as a first step towards implementing green building strategies. It came into effect in 2011 as mandatory for governmental building while remaining voluntary for private ones. The focus in both resides in the specification of minimum U-values for walls and roof. The UAE government recognizes the energy–carbon reduction challenge and has identified a number of key indicators for change in the Economic Vision 2030, including reducing power demand by 15% by 2020 from the 2010 levels (UAE Ministry of work, 2015). Along consideration of the required measures in new construction, there has been a wide government call to address the existing building stock in a collective target to reduce energy demand by 30% by 2020.

There is a large body of research literature and a range of organizations that have extensively examined green building design and energy efficiency in a variety of climates (Friedman, 2012; Torcelleni, 2006). However, very few specifically address the UAE context and its local housing typology, construction methods and the resulting overall energy consumption of buildings in this environment. In this context, a review carried by Abdellatif and Othman (2006) based on a field survey of low-cost houses built between 1977 and 1986 in Mussafah, Abu Dhabi, indicated the need for a better management, specifications and selection of adequate materials to sustain the impacts of the local climate. Radhi (2009) highlighted in his case study in the residential sector of Al Ain city that global warming is likely to increase the energy used for cooling buildings by 23.5% if Al Ain city warms by 5.9 °C, while the net CO2 emissions could increase at around 5.4% over the next few decades. He identified thermal insulation and thermal mass as important parameters to cope with global warming, while window area and glazing system are beneficial and sensitive to climate change. On a different study, Friess et al (2012) identified a potential of up to 30% of energy savings in Dubai villas through appropriate external wall insulation strategies including control of thermal bridging. These studies are indicators of the large energy savings potential in the residential sector of the UAE that have yet to be comprehensively assessed. Additionally, the UAE has a large recent housing stock built prior to the implementation of energy efficiency measures that will need to be upgraded to meet the new energy efficiency targets. Onat et al (2014) clearly identified green retrofitting as the most effective policy strategy for the residential sector, yet it remains an unexplored area in the UAE context. Green retrofitting of the existing housing stock will be an essential key to reducing the UAE's carbon emissions so that it can achieve the ambitious carbon reduction targets (Backer, 2009).

In this context, there is a large untapped potential for energy savings measures that can be implemented in the new housing programs and retrofitted in the existing stock. While efficiency schemes are known and may include a number of options such as better air conditioning, lighting and insulation in existing buildings, the contextual evaluation remains to be assessed, especially in the vast existing building stock.

3 Methodology and Case Study

3.1 Infrared thermography

The objective of this research is to investigate the thermal leakage from residential buildings' envelope using thermography and identify the impact of age, workmanship and construction quality on thermal performance in a corpus of housing units built prior to the implementation of the local building energy code (Estidama, 2010). Infrared thermography (IR) is a non-destructive tool used widely in diagnosing buildings for energy defects. It enables to detect and locate energy loss from building envelope by auditing façade through thermal bridging, and identifying locations of air leakage. The

use of IR thermal thermography for building diagnosis is an established and stabilized method. It is used to obtain empirical data for the actual thermal bridging performance. This method is particularly useful at the post-construction stage energy efficiency assessment where the designed U-values could be compared to the measured values. It can also be useful tool for retrofitting grant providing authorities to assess gains in thermal performance of the retrofitted building envelope. (O'Grady et al, 2017). The application of thermography at various phases of the construction process has emerged from field tests on housing projects in Wales, UK (Taylor et al, 2013). Four types of "in-construction" test have been gleaned: checks on the installation of insulation; identifying air leakage through building envelope; assessing insulation continuity and the severity of thermal bridge; investigating the performance of building services. Early diagnosis of performance issues in new buildings is important because it facilitates remedial work to be carried out in a timely and appropriate way. Building defects affect the thermal behaviour of the building's envelope which contributes to an increased thermal leakage. Building defects such as poor installation of insulation elements, gaps in the building's fabric and thermal bridging through structural elements are related to quality defects originating in the design and construction process or linked to the decay of the building's envelope properties overtime (Alencastro J, el al, 2018).

There are environmental conditions required for IR thermography investigation. The temperature gradient between the interior and the exterior of the investigated building should be at least 10 C (FILR). The target is typically an exposed structural element and the measurement is performed from the interior of the building. The definition of emissivity and reflective temperature factors facilitates the data correction of the measurements. The temperature conditions, including the ambient temperature and the relative humidity at the point of investigation are also recorded. There are two approaches for thermography inspections: passive and active. The passive approach measures the temperature difference under natural conditions, while the active approach requires an external source to create the temperature gradient (Kylili, el al, 2014). For analysing and measuring thermal images there are two approaches 'Qualitative' and 'Quantitative' analysis. Qualitative analysis evaluates differences in measured radiation by visual inspection of colour patterns within a thermal image. Quantitative analysis adds to this by seeking to quantify thermal gradients for numerical analysis (Fox el al, 2014).

3.2 Case Study

There are two main types of residential buildings in Al Ain city. One is in the form of detached private villa mainly for nationals whereas the rental private marked is dominated by development of housing complex in the form of multiple units of similar layout. Al Andalus and ABC housing complexes were selected as case studies for this research (Fig. 5). Al Andalus complex consists of 196 attached units that were completed in phases running from 1999 to 2001, and ABC complex consist of 30 attached and semi-attached units that were completed in 2011. Both housing complexes were constructed before the implementation of the building energy code, and adhere to the same construction methods that are customarily found in the residential buildings built in the same period in the UAE. The external conduction gains through the building can be measured by three main building envelope elements, which are the external walls, roof, and glazing systems. Table 1 shows the building characteristics of the residential units in the housing complexes. Residential units in both housing complexes share the typical construction detail of exterior wall and roof system (Fig.6). Since both housing complexes were completed before the implementation of the building energy

code (Estidama, 2015), the exterior walls and roofs lack any kind of thermal insulation, which is duly expected to highly affect the house energy consumption.

(a) (b)

Figure 5: Layout and and exterior view of (a) Andalus Housing complex – (b) ABC Housing complex

Table 1: Building construction characteristics

Exterior wall construction			
Material	Thickness (cm)	Thermal conductivity W/mK	R-value m^2K/W
Plaster	2	0.77	0.03247
Concrete blocks	20	0.546	0.3663
Plaster	2	0.77	0.03247
Total U-value = 2.319 W/m^2K			
Roof construction			
Plaster	2	0.77	0.03247
Hollow core slab (2100 kg/m^3)	15	1.4	0.1071
Light weight concrete (1200 kg/m^3)	2	0.41	0.2439
Total U-value = 2.849 W/m^2K			
Glazing			
In residential units double gazing is used with a U-value of 3.679 and total shading coefficient of 0.825, which is similar to other buildings built in the same period.			

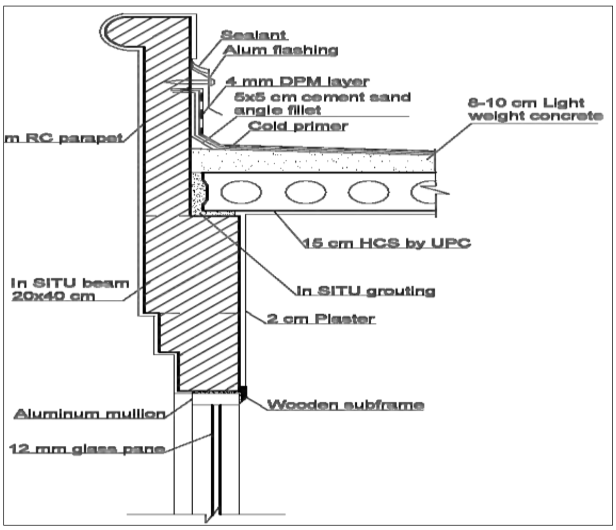


Figure 6: Typical detail exterior wall and roof slab

Building orientation is the most important parameter that has an impact on passive solar gains, and identified as one of the greatest repercussions on the energy demand of a building. The impact of orientation was only tested in Al Andalus housing complex (Fig. 7) due to an accessibility limitation.

Five units were selected with slight variation of orientation as per the general layout (Fig 7) and testing was conducted through infrared thermography in similar testing conditions.

Figure 7: Selected units and orientation in Al Andalus housing complex

Unit	AA-65(1)	AA-69(2)	AA-72	A-37	A-50
Orientation	SSW - 202.5	SSW - 202.5	SSW - 202.5	SW – 225	SWS – 247.5

Thermal imaging investigations were conducted in the residential units to evaluate the relationship of thermal leakage and building defects by assessing wall and roof junctions and around openings which are considered the weakest components of the envelope. The results, thermal images, of the five residential units were qualitatively analyzed to assess the impact of orientation on thermal leakage.

3.3 Test procedure

The measurement of the internal and external environmental conditions are summarised in Table 2. As noted before, temperature difference between inside and outside must be guaranteed and maintained during the entire test. IRT passive approach was used as no artificial thermal excitation was applied to detect the effect of thermal leakage. For the indoor temperature, residents have been asked to keep the air conditioning on for four hours prior the test to keep the indoor temperature constant.

Table 2: Environmental conditions

Al Andalus housing complex Sky: Clear Wind: WSW 13 Km/h Time: 17 – 17:30 Average outdoor temperature 41 C	Unit 1 Indoor temp. 22 C	Unit 2 Indoor temp. 32 C	Unit 3 Indoor temp. 22 C	Unit 4 Indoor temp. 28 C	Unit 5 Indoor temp. 29 C
ABC housing complex Sky: Clear Wind: W 13 Km/h Time: 17 – 17:30 Average outdoor temperature 42 C	Unit 1 Indoor temp. 27				

4 Results and Analysis

4.1 Orientation impact

Higher surface temperature were observed at the junction between exterior wall and opening in the living room for all units, indicating higher levels of heat gain at the sill. A qualitative analysis of this leakage as shown in Figure 8, indicates that the three units have similar temperature variation. Unit 4 results exhibited lower temperatures than the other two units, but this likely to be linked to the indoor temperature variation. The orientation of the three units is mostly south west orientation with slight deviation. Taking in consideration the time of the test (5:30 pm) and orientation, unit 5 should have the highest surface temperature. But according to the results, Unit 2 has the higher surface temperature. Therefore, the impact of the orientation parameter on the thermal leakage appears minimal within the units and orientations considered.

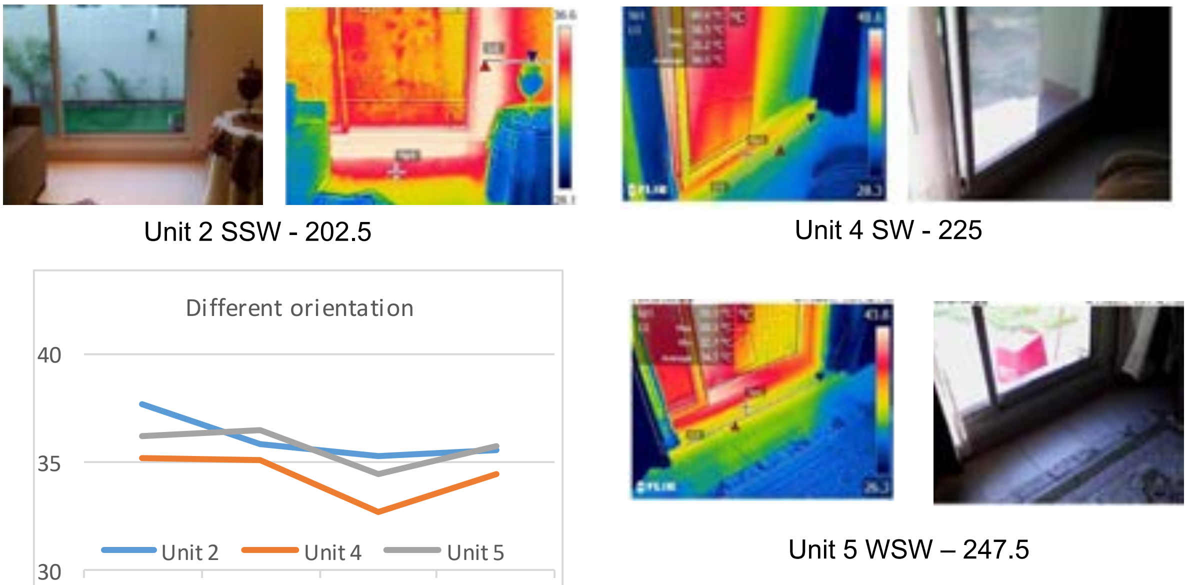
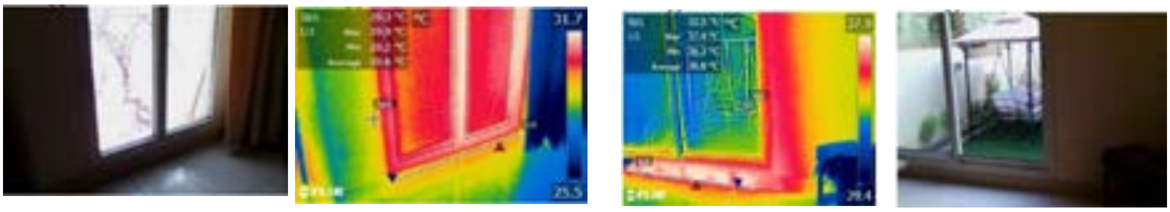


Figure 8: Qualitative analysis of thermal leakage in exterior opening

The thermal images of Unit 1 and Unit 2 sliding door sill which have the same orientation (SSW 202.5) are compared in Figure 9. Unit 2 shows a higher surface temperature in the opening junction than Unit 1. Eliminating the impact of orientation, the surface temperature variation explanation points to construction defect. Defects can be classified as design defects, workmanship defects, and lifetime defects (A. Aissani, el al, 2016). Since, the compared units are in the same residential complex, which means they share the same architectural design and construction details, we ruled out the design and workmanship defects. Considering the age of the building, the defect can be classified as lifetime defect.



Unit 1 SSW – 202.5 Unit 2 SSW – 202.5

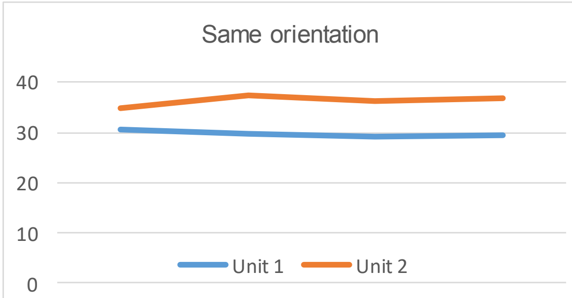


Figure 9: Qualitative analysis of thermal leakage in exterior opening sharing the same orientation

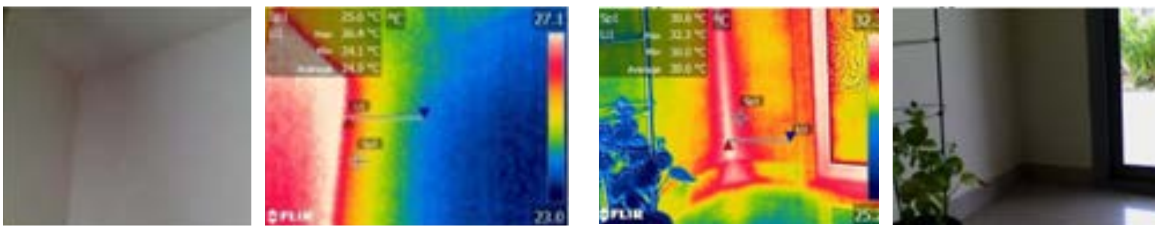
4.2 Thermal leakage and building defects; Building age impact

The scope of this test is to explore the relationship of thermal leakage and building defects in two housing complex built over a decade apart. Thermal images of two residential units in ABC complex and Al Andalus complex were compared at the following building locations: wall corner junction, sliding door and roof junction.

4.2.1 Corner junction

The thermal image of Al Andalus shows higher surface temperature of the exterior wall compared to the other wall indicating the critical need for thermal insulation retrofitting. The thermal image of ABC shows thermal anomalies around the corner junction, the thermal leakage is likely due to construction defect (Fig.10).

Corner junction Al Andalus SSW – 202.5 Corner junction ABC ESE 112.5



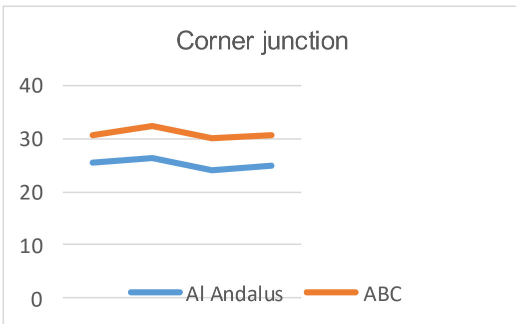


Figure10: (a), Thermal images of corner junctions in both buildings (b) Thermogram of the corner junctions showing the temperature variations in both building

4.2.2 Sliding door

The thermal image of the older Al Andalus unit did not show surface temperature variation that indicate thermal leakage, while its newer counterpart in the ABC unit shows thermal anomalies between sliding door frame and the exterior wall. This is likely caused by construction defect related to poor sealing. (Fig.11)

Sliding door - Al Andalus SSW – 202.5 Sliding door - ABC ESE 112.5

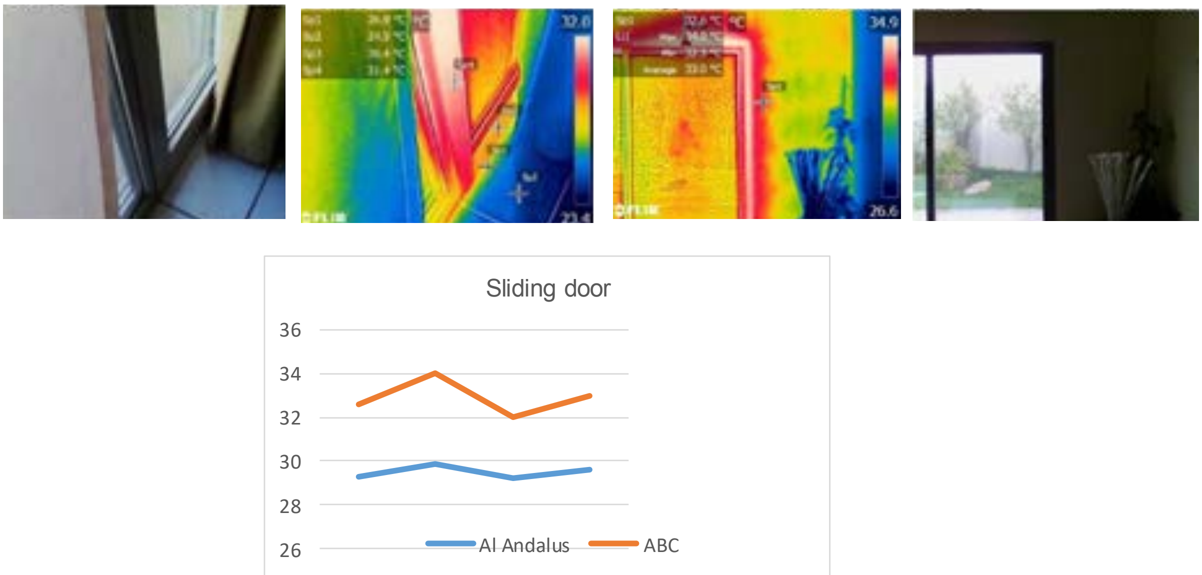


Figure 11: (a), Thermal images around sliding door in both buildings (b) Thermogram around sliding door showing the temperature variations in both building

4.2.3 Roof junction

Both the thermal images of the Al Andalus and ABC units showed high surface temperature of the roof indicating the need for thermal insulation. Retrofitting these units by adding thermal insulation layer on to the roofs will likely enhance their energy efficiency (Fig.12).

Roof junction Al Andalus SSW – 202.5 Roof junction ABC ESE 112.5

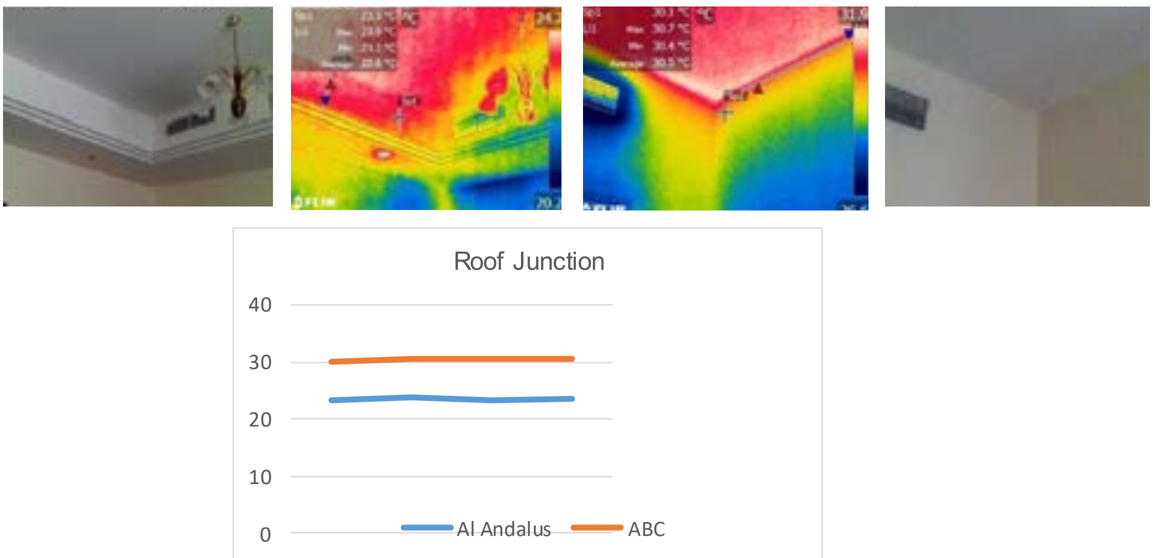


Figure 12: (a), Thermal images around roof junction in both buildings (b) Thermogram of roof junction comparing the temperature variations in the two building

The auditing of the two representative units from the two residential complexes built ten years apart highlighted a number of common thermal behaviour and some variances. First, as expected it identified the absence of insulation, in exposed building envelope such as the roof and exterior walls in both sample units, as a critical remediation strategy. On the other hand, the more recently completed units (ABC housing complex), exhibited significantly more thermal anomalies around building junctions than its older counterpart (Al Andalus housing). This underscores that building age may not be the main reference point for retrofitting priority. Workmanship and construction quality may be the more impacting factor, calling for construction quality assurance beyond the minimum specification values of insulation.

5 Conclusion

This field experiment investigated the thermal behaviour of residential buildings' envelope through infrared thermography audit under the hot climate of Al Ain city, the United Arab Emirates. The objective was to identify energy upgrade opportunities and prioritize retrofitting solutions in the existing residential building stock as most of it was built prior to the enforcement of the local 2010 building energy code. The investigated buildings were residential units in two different housing complex, built ten years apart (2000 and 2010), that shared similar construction methods and materials. A field investigation was carried out in August 2017, comprising of 5 units from the older housing complex and 2 units from the newer one. The results highlight the strong relationship between workmanship, construction quality and the thermal behaviour of the building's envelope. The absence of walls and roof insulation was a common indicator of a critical need to upgrade their thermal performance. Unexpectedly, the results showed more thermal anomalies in the newer units than the older indicating that thermal behaviour of the two buildings was more a function of workmanship and construction quality than simply building age. The infrared thermography auditing, for example of the sliding door in the newer units showed surface temperature variation that indicates construction defect in the connection between opening frame and the exterior wall, which led to significant thermal leakage. The comparison of auditing results between the older and newer residential units in the two housing complex, highlighted better construction quality thus minimizing thermal leakage in the older unit, therefore indicating that building age may not be the main referent for a retrofitting priority. This further stresses the need to address construction quality assurance in addition to the specification of minimum insulation values.

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AN ASSESSMENT METHOD FOR CUSTOMIZABLE ATTRIBUTES IN SOCIAL HOUSING PROJECTS

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Abstract: *In the last few decades the production of social housing projects in Brazil has been based on traditional strategies for cost reduction, strongly based on the mass production paradigm. By contrast, there is an increasing diversity of customers' requirements for housing, due to changing lifestyles and diverse household profile. Frequently, this results in housing units that are inadequate to dwellers needs, dissatisfaction in relation to the expected benefits. Mass customization is an alternative strategy for house building companies to improve value generation for customers and obtain competitive advantage, once it aims to fulfil clients' requirements by providing some degree of flexibility in housing units, while keeping costs and delivery time within market expectations. In order to choose the housing attributes to be offered, house building companies should be able to assess the value of customizable attributes as well as estimate the additional costs. This means that methods for assessing the value of different product alternatives are necessary. This paper proposes an adaptation of conjoint analysis to assess customer's value by evaluating different housing alternatives from a financial perspective. Furthermore, this adaptation was tested with potential customers of a social housing program from Brazil, named My House My Life Program. The research study was divided into the following steps: (i) identify customizable attributes; (ii) define attribute levels; (iii) design the conjoin analysis experiment, resulting in alternatives (i.e.: combination of customizable attributes) that have their costs estimated; and (iv) assess the alternatives by using online questionnaire answered by potential customers. The Nested analysis of variance (ANOVA) technique was used for data analysis. The results provide an assessment of the relevance and the cost-benefit relationship for each alternative.*

Keywords: *Mass Customisation, Housing, Conjoint Analysis*

1 Introduction

Over the last few decades, the Brazilian government has attempted to reduce the huge housing deficit through different social housing programs, such as PAR (Residential Leasing Program) and PMCMV (My Hose My Life Program), that have implicitly adopted mass production concepts (Formoso et al. 2011; Kowaltowski & Granja 2011; Klink & Denaldi 2014; Hentschke 2014). Although housing production has increased substantially, these programs have been criticized for high costs and low quality of the housing units (Klink & Denaldi 2014). Furthermore, by using single design solution for housing units, housing developers neglect the significant requirements diversity that exist among beneficiaries, due to changing life styles and different household profiles, reducing the benefits achieved by users (Formoso et al. 2011; Kowaltowski & Granja 2011; Noguchi & Hernández-Velasco 2005; Hentschke 2014). For that reason, previous studies indicate that many changes are made by dwellers after occupation (Formoso et al. 2011; Hentschke 2014).

Mass customization (MC) strategy has been presented as an attractive alternative for housing production as a way to balance the understanding of customers' diverse requirements and value generation with keeping costs similar to mass production (Formoso et al. 2011; Tillmann 2008; Rocha 2011; Noguchi & Hernández-Velasco 2005; Schoenwitz et al. 2012; Hentschke 2014). MC means using flexible processes and organizational structures to produce a variety of products or services, to meet customers' requirements, through pre-defined options for a price and lead time similar to mass production (Hart 1995). In housing, this strategy can be applied to attend customers' needs through flexibility of combining standardized components to build a customized solution, maintaining costs within expected for house building companies and allowing profitability (Formoso et al 2011; Noguchi & Hernández-Velasco 2005).

One of the major challenges in the application of MC is finding the balance between value generation through the understanding of customers' needs and minimize production resources consumption (Machado 2005). The implementation of MC in Brazilian housing context presents several barriers, such as the rules and regulations of social housing programs, the late offer of customization as a response to customers complaints, limitations in terms of information management, and the lack of modularity in design and construction components (Tillmann & Formoso 2008). Still, it is necessary that producers understand customers demand for customization (i.e. their specific requirements)(Formoso et al. 2011).

Towards the goal of understanding customization demand, there is a need for specific techniques to identify consumers' preferences with the aim of limiting the scope to a set of alternatives to be offered (Ferguson et al 2014; Fogliatto and da Silveira 2008). According to the same authors, conjoint analysis technique is one of the available techniques that can be used for investigating customers' preference diversity. However, some adaptations are necessary for dealing with the complexity involved in mass customizing housing (Ferguson et al. 2014). The number of attributes of a housing unit is very high, increasing the complexity of the decision making process, and the burden of choice. Different studies have applied conjoint analysis to estimate housing preferences (Brandli and Heineck 2005; Louviere and Timmermans 1990; Molin 2011; Molin et al. 2001; Orzechowski et al. 2005). Those studies allow house building companies to obtain an understanding about the preferences of potential customers, estimate responses to their offer and return of investment (Molin et al. 2001). Moreover, conjoint analysis models describe and predict customers' choices by estimating statistically the demand for housing, from their responses to a specific set of hypothetical alternatives and choice

of the alternative that offers major utility (Louviere & Timmermans 1990; Molin et al. 2001).

The aim of this paper is to adapt and apply the conjoint analysis technique to assess customers' value and preferences for customer profiles from a financial perspective. Within this context, the housing alternatives were built upon relevant housing attributes and additional cost for their customization, which were shown to the respondents in the prop cards. Although other housing preference studies include price as a two level factor (Brandli & Heineck 2005; Molin 2011), in this case the price resulted from the presence or absence of factors combined in the alternative with different profit percentages. Usually, in conjoint analysis models the independency of the factors is necessary. Moreover, one of the contributions from this paper is to propose an alternative price analysis as a nested factor in the alternative. The proposed approach was applied in a sample of potential customers of the PMCMV from Rio Grande do Sul, Brazil.

2 Mass Customization

The new production paradigm, named Lean Production (Womack et al. 1990) has played a key role in the emergence of mass customization. This new context of production allowed the companies to start offering a diverse range of products with competitive prices (Paiva et al. 2004; Silveira et al. 2001). MC has been a strategy widely used in manufacturing as an alternative for generating products that meet the needs of customers with a competitive edge for the entrepreneur (Machado 2005). Its goal is to reduce time and cost of production with the generation of a broader variety of products, resulting from the combination of changes In supply chain management, product design and production management (Guruswamy 2004). In other words, MC encompasses the entire production process from the product design, manufacture, and delivery to the final customer (Duray 2002; Pine 1994).

In the construction industry, MC has been adopted by leading companies in the housing sector in some countries, such as Japan, England, United States, and Germany, typically using prefabricated components (Barlow et al., 2002 and Schoenwitz et al. 2012). In fact, some studies have pointed out that advancements in production management have proven to be key enablers for mass customization in the sector (Barlow & Ozaki, 2003). According to Brandão (2002), in Brazil mass customization occurs mainly through allowed flexibility, where the customer can choose to replace finishings or demand other minor product changes, being required an additional payment. Moreover, some studies have indicated that customers are willing to pay a premium price in order to obtain a customized product (Franke & Hader 2014).

Choice menus are tools to guide customers through the decision making process of configuring their own product (Piller 2004), by presenting to them the solution space containing the range of customization units (Rocha 2011). According to Franke and Hader (2014) one particularity of MC is that products are decomposed into attributes, dimensions and levels, similarly to conjoint approach, in the choice menu and solution space. Beyond a conveying information to customers and guiding them through the customization process, the choice menus can be seen a learning tool (Franke & Hader 2014). This means, it can be used as a feedback to the organization (Franke & Hader 2014; von Hippel 1998), and as channel to customers enhance their preference insight level, which allows them to choose the most adequate alternative for their needs and increases value generation in the process(Franke & Hader 2014). Thus, a practical understanding of the affective and cognitive reactions to the choice menus and the

customers' preference insight are essential to design choice menus. As a promising research field, the design, implementation and interaction of choice menus with customers has received little attention in MC literature (Franke & Hader 2014; Piller 2004).

3 Conjoint analysis

The choice for a product is hardly based in only one characteristic, so the alternatives in general are configured by multiple attributes (Green & Wind 1975). Conjoint analysis is one possibility for handling this kind of situation, in which options vary simultaneously through two or more attributes (Green et al. 2001). In this case, the consumer assesses the value of attributes and do trade-offs between preferred characteristics to choose, since no alternative is clearly better than another (Green & Wind 1975).

The concern of understanding customers' decisions about multiple attribute products have been investigated since the 70s by emerging marketing research methods, such as multidimensional scaling and conjoint analysis (Green & Wind 1975; Green et al. 2001). Conjoint analysis is a technique that measures consumers' preferences and the likelihood to buy through decision trade-offs when facing hypothetical products by analysing survey responses (Green et al. 2001). This analysis can support decision making about design or modification of multi-attribute products and services, and enhance the market competitiveness by improving their utility levels from customers' point of view (Green & Wind 1975; Green et al. 2001). The core goal of conjoint analysis is define factors utilities and indicate the importance or contribution of each attribute to the overall utility (Green & Wind 1975; Molin 2011).

The method to build a conjoint analysis model and estimate utility can be divided into the following steps: (i) select relevant attributes, (ii) define their levels, (iii) define the kind of measurement task, (iv) chose the experimental design, (v) collect data from a sample of (potential) customers, and (vi) analyse data (Molin 2011). The first and second step are related to the definition of a range of attributes (i.e. factors) and levels in which they can vary to characterize the product domain, based on reliable source of information, such as previous research with customers' or company knowledge (Louviere & Timmermans 1990; Green et al. 2001). Subsequently, researchers must define the kind of measurement task, usually from choice, rating and ranking (Molin 2011) or either the conjoint analysis with two stages stimulation, which combines choice and rating (Battesini & Caten 2005). In the fourth step, the experiment is designed to limit product alternatives from all the possibilities to be presented to customers, usually by using full or fractional factorials (Green et al. 2001; Louviere & Timmermans 1990). Generally, these alternatives will be shown in prop cards, which can use pictorial material to make it easier for the respondents to understand and to reduce ambiguity (Green et al. 2001). Then, the questionnaire is applied to a sample of customers that make a general judgment of the selected alternatives according to their preferences (Green & Wind 1975; Louviere & Timmermans 1990). Finally, the overall assessment must be decomposed in utility scales to infer partial values for each attribute level, with the purpose of predicting customers' choice among alternatives (Green & Wind 1975; Green et al. 2001).

In choice-based conjoint analysis, respondents choose one alternative from two or more alternatives that can vary in one or more attributes of the product (Elrod et al. 1992; Green et al 2001). This approach of conjoint analysis is very popular due to the ability to deal with the choosing complexity of exposing a wide range of alternatives, which can diverge between attributes and levels (Green et al. 2001). This approach presents many

advantages over the rating or ranking, such as: better forecast of customer behaviour, due to the main focus on what would be really chosen by them; forecast of choice shares without the need for conjoint simulators; and general view on the topic; (Elrod et al. 1992). There are also some shortcomings on the use of choice-based conjoint analysis, such as, for instance, difficult interpretation of this models due to the confusion between individual choice process and heterogeneity of respondents. However, this is still more effective than trying to estimate choice from rating data (Elrod et al. 1992).

In housing, Louviere and Timmermans (1990) highlight as a limitation to the use of conjoint analysis the double-edge problem related to the large number of attributes and levels in which housing products can vary and the use of factorial experiments to describe housing alternatives, limiting the range of possibilities to cope with the human cognitive abilities. Generally, housing conjoint analysis studies discuss broadly the attractive type of project and residential environment which are chosen by customers (Louviere & Timmermans 1990; Molin et al. 2001). It has been hardly used to define housing solution space and customizable attributes (Orzechowski et al. 2005). In customized housing, it is necessary to limit the number of attributes and combinations by focusing on options that add value to customers avoiding confusion and dissatisfaction, as mentioned before.

4 Research method

This research project was divided into stages, similar to the five stages suggested in the literature (section 3). Each one of these stages are presented bellow.

4.1 Definition of attributes and levels

The definition of attributes was initially based on previous studies on the demands for customization in social housing (Hentschke, 2014; Tillmann, 2008). For defining the attributes, data on changes in housing were ranked from the most to the less frequently one, considering only changes performed by more than 10% of the respondents. As a result, five factors were considered: finishings; water and electricity services; safety; dimensions and layout; and price. Attributes levels were defined by the possibility of customizing a set of product characteristics, as the presence (+1), or not, by choosing a standard version of the factor delivered by construction companies, as the absence (-1), as summarized in Figure 1.

The price of each attribute or factor was defined according to the minimum cost of construction work[1] to be performed and additional percentages related to indirect costs and profit margin for the construction company. For defining price levels, a base line was established from a percentage of 160% applied to the cost and a standard variation of 10% (i.e. Lowest Price= ∑present attributes cost*1.5; Highest Price= ∑present attributes cost*1.7) was applied to define each level, as described in Figure 1. Afterwards, the prices of all attributes were summed up according to their presence or absence in the alternative, to represent its final price.

[1] The minimum cost of the construction work was stablished based on SINAPI (a Buinding Cost Index System run by the Brazilian Government) and an average amount of construction work in housing units of PMCMV.

ATTRIBUTE	LEVEL	DESCRIPTION
FINISHINGS	-1	Housing units with ceramic tiles only on wet areas and all rooms painted in white
	+1	Possibility of choosing floor finishings, walls painting and lining
WATER AND ELECTRICITY SERVICES	-1	Housing unit with standard option of sanitary ware, laundry tub and electricity services
	+1	Possibility of choosing sanitary ware and adding a shower cabin; remove laundry tub to install washing machine; add an air conditioning outlet; change the position or add power outlets
SAFETY	-1	Housing unit without fences
	+1	Possibility of choosing fences and doors and window bars
DIMENSIONS AND LAYOUT	-1	Standard room size housing unit
	+1	Possibility of increasing the size of the laundry room and kitchen, and addition of barbecue place; change position or add walls of the kitchen and laundry in apartments
PRICE	-1	Varies according to the available customization items in the alternative; Cost of the construction work of present attributes, with a profit and indirect costs margin of 50% (∑present attributes cost*1.5)
	+1	Cost of the construction work of present attributes, with a profit and indirect costs margin of 70% (∑present attributes cost*1.7)

Figure 1: Attributes, levels and description

4.2 Definition of the measurement Task

In this phase the type of response scale that will be requested from the respondents is defined (Molin 2011).The measurement task chosen for this study was the conjoint analysis with two stages stimulation, proposed by Battesini and Caten (2005). In the first phase, the respondents are asked to choose from a group of alternatives, while in the second stage they rank (i.e. establish a preference order) the favourite ones. This conjoint analysis approach was chosen due to its similarity to real buying process and potential to reduce respondents effort of choosing without compromising the capacity of modelling consumers' preferences (Battesini & Caten 2005).

4.3 Experimental Design

By combining the 5 two-level attributes the factorial 2^5 would result in 32 different alternative to be analysed by respondents, making it confusing and unfeasible. As mentioned before, in conjoint analysis studies fractional factorial is often used because of the need to reduce the number of alternatives, bringing it back to manageable proportions (Molin 2011). Thus, for making it easier for potential customers to choose, the fractional factorial of $½*2^{5-1}$ was used in this study, resulting in 16 alternatives randomly blocked in 4 groups of 4 alternatives, as shown in Table 1. The resulting alternatives in the factorial were represented in prop cards (Figure 2), using pictographic elements and colour to improve the understanding of possible customization options.

Table 1: Experiment planning

Block	Finishing	Water and Electricity Services	Safety	Dimension and Layout	Price	Price in Reais	Price in Dollars	Apartment Alternative Name (code)
1	-1	+1	+1	-1	+1	9250	2927.22	AA
1	+1	-1	-1	-1	-1	6550	2072.79	AB
1	+1	-1	-1	+1	+1	10250	3243.67	AC
1	-1	+1	+1	+1	-1	9400	2974.68	AD
2	+1	+1	-1	+1	-1	13450	4256.33	AE
2	-1	-1	+1	+1	+1	5300	1677.22	AF
2	+1	+1	-1	-1	+1	14200	4493.67	AG
2	-1	-1	+1	-1	-1	2500	791.14	AH
3	-1	+1	-1	-1	-1	5100	1613.92	AI
3	+1	-1	+1	+1	-1	10900	3449.37	AJ
3	-1	+1	-1	+1	+1	8450	2674.05	AK
3	+1	-1	+1	-1	+1	11050	3496.84	AL
4	+1	+1	+1	-1	-1	14100	4462.03	AM
4	-1	-1	-1	-1	+1	0	0	NA
4	+1	+1	+1	+1	+1	19500	6170.89	AO
4	-1	-1	-1	+1	-1	1850	585.44	AP

Figure 2: Prop Cards examples

4.4 Data collection from a sample

The target audience for this research study was the population of the Metropolitan Region of Porto Alegre and surrounding areas, potential beneficiaries of the PMCMV. Furthermore, the respondents should be interested in purchasing a new home and have a monthly family income in the range of $835.75 to $2810.12. The survey was available online during a month.

The data collection protocol was developed considering all project phases, through group discussions with specialists, with the aim of measuring the utility of each factor for potential customers of PMCMV program and their willingness to pay for available housing customization alternatives. In addition, some socio-demographic questions were included to identify the market segment for which the alternatives or factors are most attractive. The main section of the survey was questioning respondents' preferences about different alternatives, as planned in fractional factorial, by choosing their favourite alternative in each block. Afterwards, the respondent should rank the chosen alternatives from one to four, from their most to the least preferred one.

The protocol was refined in terms of language by face to face testing, on paper, involving both by postgraduate students and outsiders. Subsequently, the protocol was configured in *Survey Monkey®* as an interactive online questionnaire, with some changes to fit in the online platform. The functionality of the questions was tested with approximately 10 online respondents, and then made available to respondents. The survey was then disseminated by email and social media.

4.5 Analysis

Initially, a descriptive data analysis was made. Then, an analysis of variance (ANOVA) was performed in order to estimate the importance of the five factors for potential customers PMCMV. To enhance the discrepancy between preferences, the ranking order was transformed in a new scale that varies between 10 to 100, facilitating the analysis through the statistical analysis and interpretation of the obtained results. The highest preference level received a 100 grade. Until the fourth choice of the second stimulation phase the grades decreased 10 points, and then the least preferred received 10 as a grade. Furthermore, this procedure prevents the direct interpretation of the magnitude of each factor level. Nevertheless, the scores enable estimating the main effects and state which are the most relevant customization factors from potential customers' perspective. The price was considered as a nested factor (i.e. depends on the level of others in each alternative), and was therefore included in the analysis.

4.6 Limitations

The main focus of this research was methodological, by applying and adapting conjoint analysis to understand custom housing preferences, and its results present some interpretation limitations. Firstly, the price was stablished based on a Building Construction index costs, instead of a real prices practiced on the market, meaning that they can be economic unfeasible or under the expectations for construction companies. Second, the methods used to reach the respondents, as mention before, did not allowed to target the research to the adequate market segment and a meticulous sample selection, although, there were filter questions such as the interest in buying a new home and the family income.

5 Results

Figure 3 illustrates de absolute frequency of the first choices of respondents in each block of alternatives. In the first block, the favourite alternative of the respondents was the alternative with the possibility of customizing finishings, dimension and layout and

higher price. The alternative AE, which allows the customization of finishings, water and electricity services, and dimensions and layout, with a modest price, represented half of the choices in the second block. In the third block more than 50% of the first choices was for the alternative AJ, which combines the possibility of customizing finishings, safety devices and dimension and layout, with a modest price added. Finally, in the fourth block the alternative of customizing every factor for a premium price was the favourite for 28 respondents, and the alternative AP follows with 25 respondents' preference, only being able to customize dimensions and layout. It is noteworthy that three out of the four least chosen alternatives included the possibility of installing safety devices. This corroborates some respondents' comments about felling already safe when living in apartments. Finally, the alternative AN, representing a standard housing unit, was only chosen by 5 respondents (6.3%), which indicates that offering a choice menu is relevant for most clients.

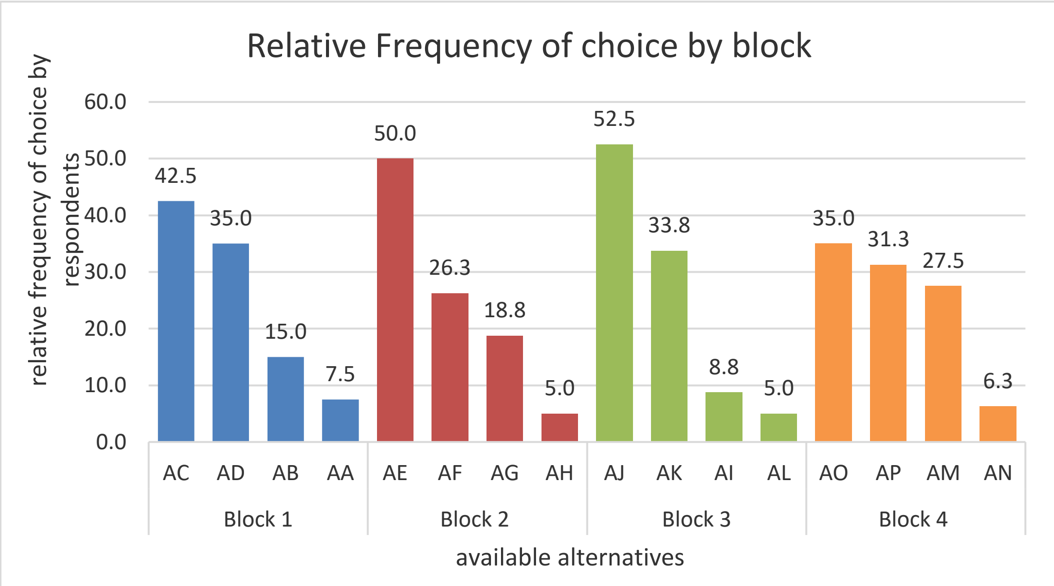

Figure 3: Absolute frequency of 1 first choice by block

A summary of the second stimulation stage is presented in the Table 2. Each alternative of the fractional factorial has its corresponding price and absolute frequency of the ranking spot. The alternatives AE (possibility of customizing everything but safety for a modest price) and AO (possibility of customizing all factors by a premium price) were the most frequently chosen between all 16 different possibilities, showing the relevance of offering customization. In second place, AE was chosen by 16 respondents. AJ (possibility of customizing everything but water and electricity services by a modest price) and AK (customization of water and electricity services, dimensions and layout for a premium price), in third place, were chosen by 11 respondents. Finally, in fourth place the most chosen alternative was AJ, by 15 respondents. Additionally, is possible to notice through the colour graduation that the least frequently chosen alternatives (i.e. AA, AH, AI, AL and AN) do not offer the possibility of customizing finishings or dimensions and layout, highlighting the importance of those factors for potential customers.

Table 2 indicates that potential customers are willing to pay a premium price in order to customize their housing units, since by choosing the alternative they were aware of the additional value to be pay. Furthermore, the favourite alternatives of the first and second place have reasonable values added, from U$3243.7 to U$6170.9. In addition, the first

option for 18 respondents was the highest price available, and only 3 respondents chose the cheapest alternative.

Table 2: Absolute Frequency of the alternatives ranked in the second stimulation phase

BLOCK	CODE	Finishings	Water and Electricity Services	Safety	Dimensions and Layout	Price	Price in Reais	Price in Dollars	1 °	2 °	3 °	4 °
1	AA	-1	+1	+1	-1	+1	9250.0	2927.2	1	1	3	1
	AB	+1	-1	-1	-1	-1	6550.0	2072.8	1	2	4	5
	AC	+1	-1	-1	+1	+1	10250.0	3243.7	5	11	7	11
	AD	-1	+1	+1	+1	-1	9400.0	2974.7	5	3	9	11
2	AE	+1	+1	-1	+1	-1	13450.0	4256.3	16	16	6	2
	AF	-1	-1	+1	+1	+1	5300.0	1677.2	3	6	6	6
	AG	+1	+1	-1	-1	+1	14200.0	4493.7	5	5	3	2
	AH	-1	-1	+1	-1	-1	2500.0	791.1	1	1	2	0
3	AI	-1	+1	-1	-1	-1	5100.0	1613.9	1	0	6	0
	AJ	+1	-1	+1	+1	-1	10900.0	3449.4	6	10	11	15
	AK	-1	+1	-1	+1	+1	8450.0	2674.1	6	6	11	4
	AL	+1	-1	+1	-1	+1	11050.0	3496.8	0	2	1	1
4	AM	+1	+1	+1	-1	-1	14100.0	4462.0	5	6	4	7
	AN	-1	-1	-1	-1	+1	0.0	0.0	3	1	1	0
	AO	+1	+1	+1	+1	+1	19500.0	6170.9	18	4	3	3
	AP	-1	-1	-1	+1	-1	1850.0	585.4	4	6	3	12

The ANOVA results are shown in Table 3, relating the customizable attributes, with the influence of the factor in the grade assigned to the alternative and the significance of the factor for customers. Table 3 shows that the presence of finishings, water and electricity services; and dimensions and layout are the favourite customization attributes for customers (p-value<0.05). For instance, the absence of flexibility in dimensions and layout in the alternative has the highest impact in customers' preferences (p-value<0,0001). The safety factor has no statistical significance in this analysis (p-value>0.05), corroborating with previous evidence of low frequency of modifications in apartments found by Hentschke (2014). Additionally, when the factor price is nested within the factor finishings it is statistically significant (p-value<0.05). These results confirm the relevance of the factors or product attributes which might be considered in the configuration of the solution space by companies that adopt a mass customization strategy.

Table 3: anova results for apartaments

Attribute/ Factor	Level	Grade	P-value
Intercept	-	58	
Finishing	Presence	0	0,0002
	Absence	-8	
Fittings and Installations	Presence	0	0,0009
	Absence	-7	
Dimension and Layout	Presence	0	<0,0001
	Absence	-21	
Security	Presence	0	0,0705
	Absence	4	
Price (with presence of Finishing)	Higher profit	0	0,0197
	Lower profit	8	

6 Discussion and Conclusion

This paper proposed an adaptation and application of conjoint analysis to identify the preferences of PMCMV potential customers in the Metropolitan Region of Porto Alegre, Brazil. Furthermore, the application of conjoint analysis in custom homes can support the definition of the solution space and bring benefits related to the learning process by the similarity between choosing process and selecting from hypothetical alternatives.

The most frequently chosen alternatives and the results of the ANOVA reinforce the relevance of offering customizable attributes in housing, specially, in finishings and dimensions and layout, as shown in previous studies. This means, that construction companies should focus on offering a limited range of options according to their consumers' preferences and improve the value generation process, including: floor finishings, different paint colours for walls, lining, little layout changes (e.g. adding or removing walls between living room, kitchen and laundry). Furthermore, the offer of finishings with a fair price is one of the most significant factors of choice for potential customers, and it is easier to be implemented than other factors. These insights can support detailed market studies about customization units to be offered by home builders.

As mentioned in the literature review, potential customers are usually willing to pay a premium price for obtaining custom goods. This statement is corroborated by this study, as potential customers chose alternatives to custom their house, being aware of the additional price. Moreover, it is noteworthy that they selected the alternative according to their needs and not only focusing on the price, once the favourite alternatives are not the cheapest ones available and the most expensive alternative was one of the favourites. Thus, construction companies could make a careful choice of the alternatives that offer the best profitability. However, customers' willingness to pay for customization in housing has been only superficially explored in this study and should be further investigated.

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EXPLORING DEMANDS FOR MASS CUSTOMISED PREFABRICATED HOUSES IN BRAZIL

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Abstract: *Housing shortage has been a challenge faced by many countries around the world. In Brazil, the housing supply capacity was less than the demand by about 5.4 million dwellings in 2011. To address this shortfall, the Brazilian government launched 'Programa Minha Casa Minha Vida' (My House, My Life Program) in 2009 with the aim of reducing housing shortage. The program was divided into three stages, the first and second stages of the program were completed in 2014 and 2016, respectively. The third stage is now ongoing, a grand total of 4.6 million dwellings are expected to be delivered at the completion by the end of 2018. However, there is significant lack of information on reliable housing demand and supply predictions for the coming years in Curitiba. In addition, the consumers' feedback from first and second stages showed that lack of choice and design customisability have been an issue. Therefore, quantifying housing demand in Curitiba is extremely important for planning purposes and better houses. Mass customised prefabricated houses have enormous potential to deliver high-quality in large scale with shorter time by providing options for the consumers. The aim of this investigation is to develop a housing demand model of mass customised houses for the city of Curitiba. The potential for future mass customisation in Curitiba is explored as the demand of various house sizes are predicted up to 2025. Based on the Brazilian Census data from 2010, population profiles and diversity of family's structures are used as influencing parameters in the model. The outcome of the proposed model can be used as guideline or public policy for delivering appropriate mass customised houses which would fit future needs and desires of people. The predicted results show substantial reduction in size of the family living at the same dwelling, which will certainly impact on the future of the housing market. It was interpreted that there is a need of more compact one and two-bedroom dwellings, reducing the demand of four-bedroom dwellings in Curitiba.*

Keywords: *Housing Demand, Curitiba, Mass Customised Prefabricated Houses.*

1 Introduction

Currently, Brazil is the fifth largest country in the world by both area and population, which accounts to approximately 200 million people. Originally inhabited by various tribal nations and colonised by Portugal, Brazil received massive immigration of people from all over the world during the last century, which played a significant role in the population growth, composition, structure and history of the country. At that time, most of the immigrants moved to Brazil to work on agriculture. Between 1960 and 1980, 43 million people moved from rural towards urban areas as a result of an intense migratory (Brito 2006). This significant move of rural population to urban areas in the 60's has affected the structure of cities in Brazil (Sahota 1968). Since then, city centres and metropolitan areas have doubled their sizes in substantially fast, resulting in over 81% of the total population living in urban areas in 2010 (CAIXA, 2011).

The country has faced many challenges to provide shelter for many due to the rapid growth in urban areas. The current Brazilian housing deficit is estimated at 5.4 million of dwellings (IPEA, 2013). In 2009, the Brazilian Government launched 'Programa Minha Casa Minha Vida' (My House, My Life Program) with the aim of promoting production and acquisition of new units across the country. It has provided thousands of families with a total of 2.4 million dwellings across Brazil from 2009 to 2016. However, there were major concerns on the overall product quality of these new developments due to high demand, budget constraints and insufficient time of construction. Firstly, the business model launched to produce these units turned out to be less attractive to developers and builders due to low profitability and lack of technical capability (CBIC, 2014). Secondly, the adjusted cost and price of construction for each fiscal year was underestimated compared to the unit cost of construction per m^2 (CUBE) released by the Brazilian Chamber of Construction Industry (CIBIC). As a result, deliberated delivery of houses under quality standards, lack of engagement of customers during design decision making, and lack of qualified workforce were some of the major concerns regarding the delivery of more houses in Brazil. In addition, no attention was given to inadequacy in terms of layout and incompatibility with family structure received no attention when the discussion goes around the major concerns in new dwellings in Brazil (Amore, Shimbo & Rufino 2015). Formoso, Leite & Miron (2011) have previously identified the need for professionals responsible for residential developments to deliver a more customised houses in Brazil.

The effects of housing supply and demand has direct engagement with rental and home purchase and impacts on the local economy and welfare (Fahey & Norris 2009). Currently, the housing deficit in Curitiba is estimated by the Brazilian Government according to data from two soucers: the Brazilian Census data (IBGE,2010) and the Brazilian Ministry of Cities (IPEA, 2013). However, these data only provide an overall estimate on the shortage of dwellings, current number of dwellings and density, without detailed information regarding family structure and demand of houses per housing sizes and typologies. It is known that approximately 80% of the population lives in dwellings with 1 to 3 bedrooms and the average density is estimated at 2.88 persons per house in 2010 (IBGE, 2010). Despite Curitiba having a reasonable housing density overall, it is unclear whether the available house sizes are appropriate to most of the families that are currently living in the city. The private market estimates housing supply usually on ad hoc basis, and the local authorities and governments are in charge of estimating social housing, which is predicted by using census data. The regional Syndicate of Dwellings and Condominiums (SECOVI-PR) and the Regional Council of Engineering and Agriculture (CREA-PR) are two private organisations in charge of releasing information

related to dwellings in Curitiba. The former provides data on existing houses and apartments available for renting and buying, and the latter only provides data on new and renovated houses apart from apartments which submitted project documentation for technical approval. These two organisations were contacted for obtaining information. According to local authorities, there is lack of reliable data which provides a thorough view on the current scenario of dwelling sizes and typology in Curitiba. For this reason, it was not possible to use data from either sources as inputs for the model. This highlights the fact that dwelling typologies and future changes in family structures should be quantified and assessed to further predictions on housing demand in Curitiba. Moreover, as the number of people per family and the size of the dwellings have decreased in the last years, it is important to identify the consequence of changes in family structure for the foreseeable future. Therefore, the aim of this study is to explore housing demand for the city of Curitiba.

2 Mass Customised dwellings

Emerged from mass production, mass customisation can be defined as "*the ability to provide customized **products** or **services** through flexible processes in high volumes and at reasonably low costs*" (Silveira, Borenstein & Fogliatto 2001). From product design to offsite construction, assembly and additional custom services, mass customised houses provides higher level of choice which is delivered in a collaborative, flexible and transparent manner (Silveira, Borenstein & Fogliatto 2001). Due to advantages of its processes, a higher level of finishing is provided, bringing the quality to a higher standard level as a consequence (Yokota, Granja & Picchi 2014). Lower product cost and higher efficiency show the potential towards mass customised production, which can be considered as a competitive advantage for the delivery of more affordable houses (Noguchi & Hernàndez-Velasco 2005). Many countries such as Sweden, Germany, the UK and the US have adopted prefabrication in the construction industry. However, the Japanese prefabricated manufacturers are leading the mass customised homes scenario with a more comprehensive approach which focuses on sustainable development, considering not only individual customers wants and needs but also the tendency of net zero-utility-cost of mass custom homes delivery (Noguchi 2012). Therefore, changes in family structure over the past years should be considered for estimating housing demand.

3 Method

Curitiba is the capital of Parana State, considered the eighth largest city in Brazil, and the largest city in south of Brazil (IBGE, 2010). Curitiba holds the fifth position in the Brazilian GDP ranking, and its main production focuses on industry and services, which has increased in the last decades due to industrial, commercial and services activities in the area. Curitiba's metropolitan area has a total population of over 3.2 million, while the city corresponds to approximately 1.7 million. According to the Brazilian census, 527,233 families were living in Curitiba in 2010 while 575,899 dwellings were available at the same period (IBGE,2010). Despite the number of dwellings being slightly higher than the total number of families, singles living in one dwelling were substantially high, corresponding to 14% of the total dwellings. Overall, approximately 44.0% of the dwellings indicated density equal to 1 person per bedroom, while 47.5% of the dwellings presented density 1 to 2. Density 3 corresponded to 6.42% of the dwellings and 1.88% for more than 3 persons per bedroom (IBGE,2010). Although Curitiba shows quite reasonable figures for density per dwelling when compared to other cities throughout Brazil, there is a significant reduction of large family sizes, especially the ones with 5 or more persons. Also, it was identified substantial growth in families with 2 to 3 persons.

Change in marriage and divorce rates has affected family structures. In 2010, it was identified that a total of 51% of the families were supported by single parents with children, 26% by couples with children and 23% by couples without children (IBGE, 2010). The marriage rate in Curitiba has decreased in the past years, and couples are getting married and having children later. Estimations in population show substantial changes on total of young people to elderly in the near future due to ageing effects. So, "What will be the impact on the demand of future hous sizes?" is the question to be considered.

The model developed (Figure 1) was based on the Brazilian census data of 2010, provided by IBGE (2010). The model was implemented in an excel spreadsheet to estimate future population growth, family structure and required number of houses in various typologies. The first part of the model identifies the number of people in each of five age groups. Population growth per age group is estimated from 2010 to 2017. By estimating the population in 2025, it is possible to correlate age groups in family structure. Eight family groups are defined according to the Brazilian census 2010 (IBGE, 2010). Housing demand is estimated for the baseline according to the Brazilian Census 2010. Housing demand is predicted for 2025 according to the expected number of families and housing deficit. Change in density, change in family structure and housing sizes are identified.

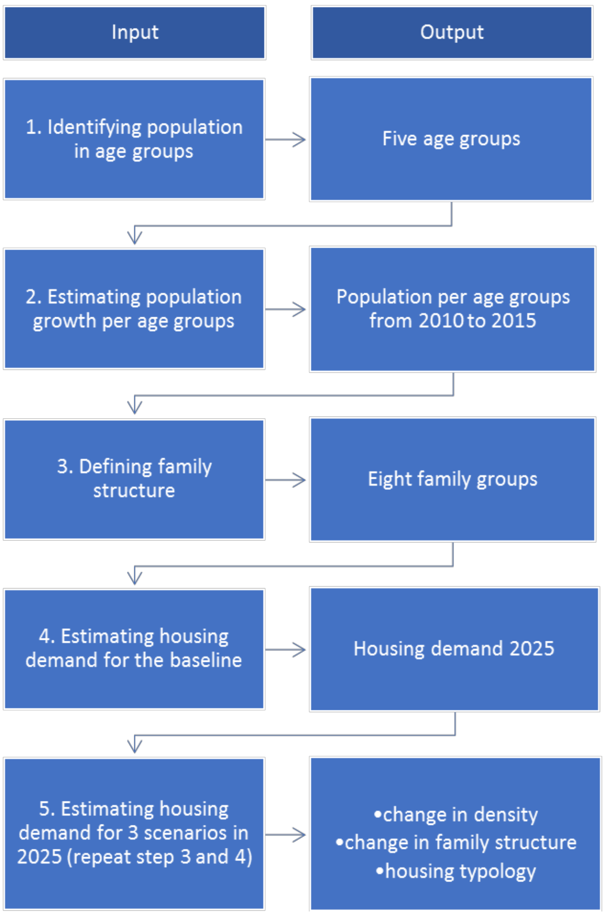

Figure 1: Method

3.1 Estimating population in age groups from 2010 to 2025 in Curitiba

Birth rate, death rate per age group, and net overseas migration were obtained through the Brazilian data Census 2010 (IBGE, 2010). Population per age is identified

as Pop_t^n where n is the age, and t is the year of prediction. The estimation starts at year 2010 and it is predicted by 2025. The total number of new-born in each year is represented by:

$$Pop_t^0 = BR_t - DR_t^0 - NOM_t^0 \quad (1)$$

where, BR corresponds to birth in Curitiba, DR is the death, and NOM is the net migration out of the city of Curitiba. The next year population in each age was estimated by Equation (2).

$$Pop_t^n = Pop_{t-1}^{n-1} - DR_t^n - NOM_t^n \quad (2)$$

where Pop is the population, n is the age, and t is the year of prediction.

3.2 Identifying population in age groups

Five age groups ($Group_m$, m=1,5) were defined for estimating population growth. Infants and dependants from 0 to 19 years old are in $Group_1$. In Brazil, the adulthood starts at age 18. However, in this model we considered people under 19 years old are dependant as people usually cannot afford living in individual house straight after their adulthood. $Group_2$ is formed by people with age from 20 to 29, generally who are already studying or working. Usually, this group has higher number of people starting their career and, eventually, getting married. $Group_3$ has people from 30 to 44 years old who are about to reach their financial stability, usually forming their own family, having children and purchasing their first property. $Group_4$ is represented by people from 45 to 59 years old that usually lives with their family, which is predominantly formed by parents, children or teenagers and, in some cases, grandparents. Finally, $Group_5$ refers to retired people from 60+ years old. We consider people over 60 years retired as it is possible to retire according to whether length of superannuation contribution in private or public services in Brazil. The age of retirement for women and men is 60 and 65 years, respectively. The sum of age groups provides the total population which is the sum of the entire population in all ages in year t, and it is described as:

$$Group_m = \sum_{n=n1}^{n2} Pop_t^n \quad \begin{cases} m=1 & n1=0 & n2=19 \\ m=2 & n1=20 & n2=29 \\ m=3 & n1=30 & n2=44 \\ m=4 & n1=45 & n2=59 \\ m=5 & n1=60 & n2=102 \end{cases} \quad (3)$$

3.3 Defining family structure

Family structure is defined to identify future changes in family size and its impact on the size of houses. The Brazilian Institute of Geography and Statistics (IBGE, 2010) classifies the Brazilian population in eight family groups according to its family structure, according:

- Single,
- Couple without children,
- Couple with children,
- Couple without children living with parents,

- Couple with children and parents,
- Single parent with children,
- Single parent with children and parents,
- Others.

3.3.1 Estimating family structure for 2010

Predictions on family structure were based on number of people in each of the eight family groups previously defined by age groups for 2010. Changes in number of people per age group is considered the main driver which influence on family structure. Other aspects such as birth and dead rate, divorce and marriage should be considered in a long-term estimation. However, firstly, the number of people in each category of family structure by age groups in 2010 was identified. Two indicators from the Brazilian Census data: The Census data was adjusted based on ratio of people per family group and people per age group according to IBGE (2010).

3.3.2 Estimating housing demand for the baseline

Three inputs: number of people per family, size of houses (number of bedrooms), and current density were used to estimate the ratio of people per dwelling sizes. It was found on the Brazilian Census data the sizes of dwellings vary from 1 bedroom to 6 or more bedrooms per dwelling, and these inputs were cross checked in one matrix to estimate the current housing demand, then, being adjusted by trial and error. The outcome was predicted according to density per dwelling by family groups and dwelling sizes. Assumptions were necessary for family structure and density. For instance, it was assumed that half of the families with 2 persons were couples without children (50%), while the other half were single parent with one child (49%). For families with 3 persons, it was assumed that couple with children corresponds to the majority (53%), followed by single parents with children (30%), single parent with children and one parent (14%), and couple without children living with one parent (3%). For families with more than 4 people per house, it was assumed that the majority were couple with children (60%), followed by single parent with children and parents (14%), couple with children living with parents (10%) and single parent with children (10%).

3.4 Estimating housing demand for three scenarios in 2025

Three factors were considered for estimating housing demand in 2025: change in family structure due to marriage and divorce rates, and changes in housing density due to family structure.

3.4.1 Factor 1: Change in family structure due to marriage and divorce rates

Changes in housing demand due to marriage and divorce were included according to the prediction for Curitiba in 2025. Firstly, one new private dwelling was considered for each new marriage as we assumed all couples cohabiting a new dwelling, rather than partners cohabiting with relatives. Secondly, a new private dwelling was added for each divorce. We assumed the couple who is divorcing will live separately rather than cohabiting with others or cohabit with relatives. The average marriage and divorce rates from 2004 to 2010 in Curitiba were used as data input. The estimated average marriage rate is 9.57 per 1,000 people per year, while the divorce rate is 1.91 per 1,000 people per year.

3.4.2 Factor 2: Change in housing density due to family structure

In 2010, the average housing density was 2.88 person per house. We run the simulation changing the input to both higher and lower densities equal to 2 and 3. By dividing the total population per density rate, it is possible to predict the average number of families

in Curitiba by 2025. A 0.6% drop in people's density per house is predicted from 2010 to 2025.

3.4.3 Factor 3: Change in housing size according to density

We combined both estimated density and family structure to predict demand on housing size by 2025. According to the Brazilian census data in 2010, 13.21% of the total population lives alone in one dwelling, 30.23% of the population are 2 persons per dwelling, 28.12% corresponds to 3 persons per dwelling, 19.41% is 4 persons per dwelling, 6.61% is 5 persons, 2.43% is 6 persons or more. For the following years, we assumed a variation of 2.0% for 1 person per dwelling, 2.0% for 2 persons, 1.0% for 3 persons, -3.0% for 4 persons, -3.0% for 4 persons, and -3.0% for 5 or more persons per dwelling from 2010 to 2025.

4 Results and Discussion

Based on the Brazilian census 2010, population growth from 2010 to 2025, change in family structure based on five age groups, change in family structure and housing sizes per bedroom were predicted.

4.1 Population growth from 2010 to 2025

Population growth from 2010 to 2025 in Curitiba was estimated according to the data input from the Brazilian census 2010. In 2017, the total population of Curitiba was estimated at 1,751,895 people (IBGE, 2017). The results show a future growth of 9.3% by 2025, which will result in a total of 1,916,034 people living in the city. Such increase in population of this prediction matches with equivalent results to recent estimated population carried out by the Brazilian census (IBGE, 2017). It is predicted a decrease in infants and young adults with age up to 29 by 2025, which will reduce from 46% to 37% from 2010 to 2025 (Figure 2). On the other hand, there is a clear increase in adults, mature and elderly people in the same period. There is a real relevance in the increase on proportion of adults and mature people in the housing market as $Group_2$, $Group_3$ and $Group_4$ are the major homeowners or the groups that are willing to purchase a new property for many reasons. Financial stability, formation of new family, marriage, and divorce are some of them. As the need of new houses will increase substantially, labour force will be needed to supply housing demand. It is also clear that ageing population will become an issue in the future as the young generation will drastically reduce while adults, mature and elderly will become the major part of the population in the near future.

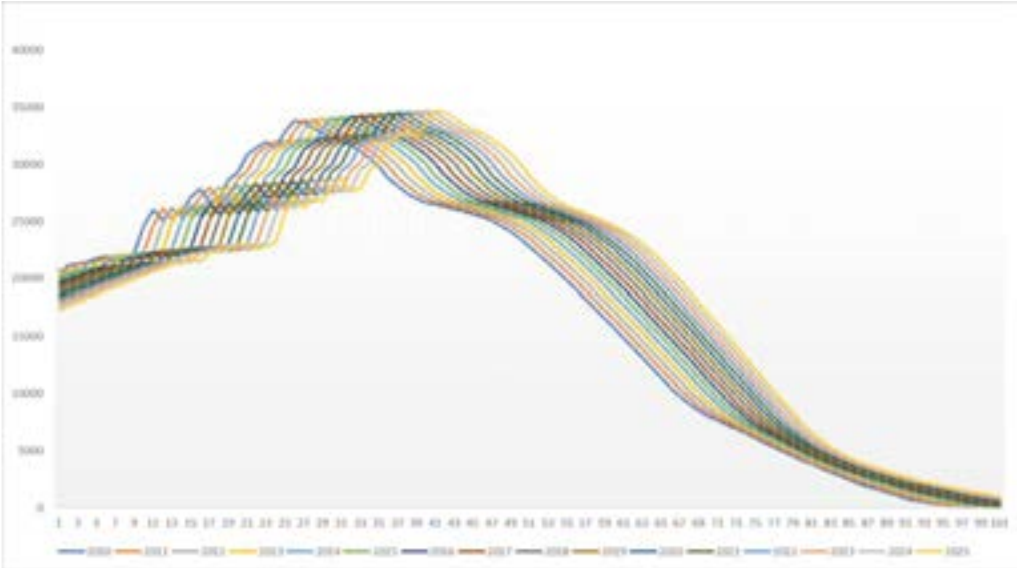

Figure 2: Population Growth per age group in Curitiba from 2010 to 2025

4.2 Family Structure

As it is predicted a growth of 11% in population by 2025 in Curitiba, possible changes in family structure by age groups were analysed. In 2010, family structure was mainly based families formed by couple with children (Figure 3). However, another factor that was highlighted in the results of this analysis is the concentration of families formed by single parents with children. It was observed that there are more single parents with children than couple without children. Also, in the past years, there was a high increase in singles living in one dwelling because of increase in job opportunity in Curitiba, which could be related to the fact that the city has the biggest economy of south of Brazil with highest GDP in south of Brazil (IBGE, 2017).

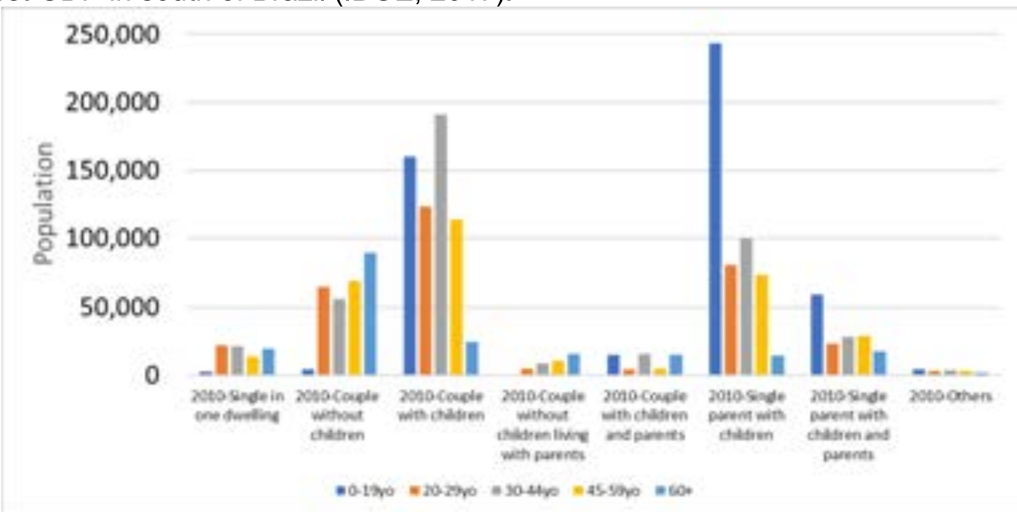

Figure 3: Family Structure in 2010

The results of family structure from 2010 to 2017 show a significant increase in families formed by couple without children and couple with children. It is observed slight increase in couples without children who are in $Group_4$ and $Group_5$, and a minor growth in couple with children in $Group_2$ as opposed to a decrease in $Group_4$ for the same family group. There is also a reduction in number of single parents with children in $Group_2$,

$Group_3$ and $Group_4$. The family structure distributed for all age groups in 2017 is shown in Figure 4.

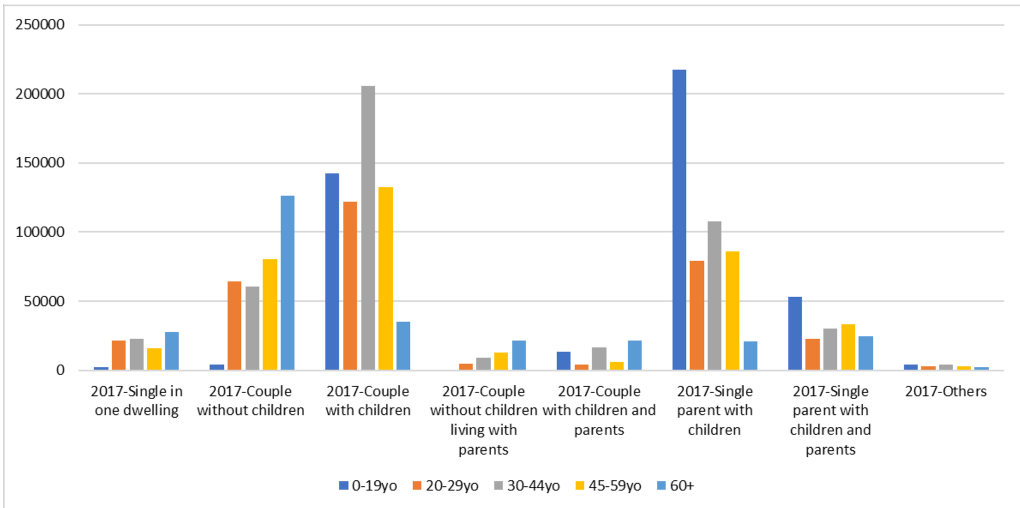

Figure 4: Family Structure in 2017

For the year 2025, predictions were then compared to the trends obtained for 2017. Significant increase in couples without children in $Group_2$ and $Group_3$, and reduction in couples without children for $Group_3$ and $Group_4$ is expected by 2025. Also, an increase on single parents living with children was observed for $Group_1$, $Group_2$ and $Group_3$ whilst $Group_4$ and $Group_5$ shows decrease in number of families. The results for couples without children living with parents and couples with children living with parents shows a slight decrease overall. It was also observed that the majority of $Group_1$ are living with single parent, which may be the consequence of divorce.

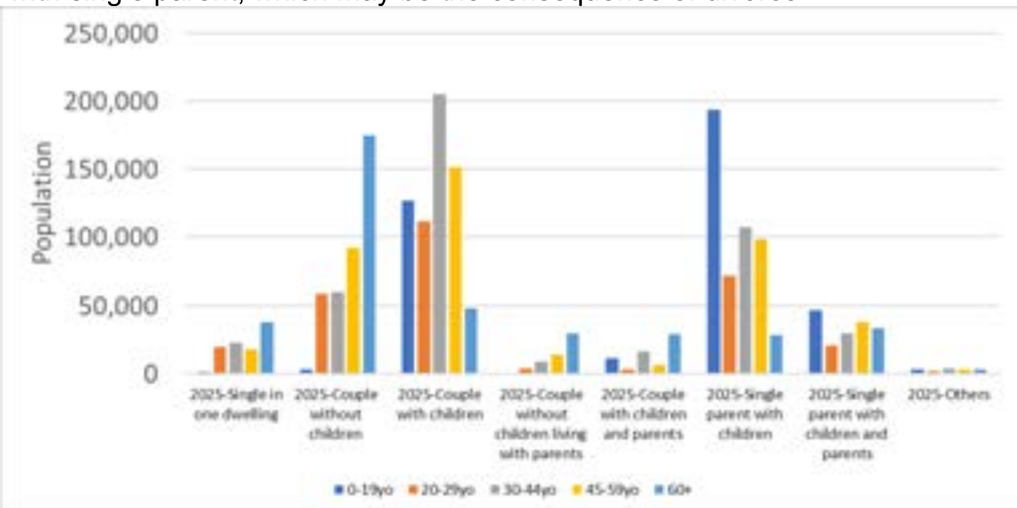

Figure 5: Family Structure in 2025

The results show substantial changes on family structure according to the estimated population growth for the next eight years. There is a clear concentration on families formed by couples without children, couples with children and single parents with children, which is increased as the years go by according to the results from 2017 and

2025. However, it is important to highlight the results show limitations as the ratio per family structure remains the same, and only population growth per age is considered.

4.2.1 Family structure change for the three main groups: couple with children and single parent with children and singles in one dwelling,

The three major categories of family structure were observed closely for better understanding on the impact of housing demand by 2025. It was observed that the couple with children is most significant family group which accounted for 35% of the population in 2010. As people in $Group_2$, $Group_3$ and $Group_4$ are the potential homebuyers of new properties, it highlights that families formed by couple with children has considerable influence in the future housing demand. In addition to that, youths and adults in $Group_2$ and $Group_3$ that lives with parents might be the ones getting married and forming a new family. Another factor related to this trend is the potential divorces, which comes predominantly from this family group. The second family group is single parents with children. Not only parents with children are considered here, but also widowed living with their daughter/son. This family group represents 19% of the total population in 2010, according to the results from the model developed. As single parents only share houses with their children, there is a high proportion of people in $Group_1$, which means approximately half of this family group are children and the other half are the single parents. As there is a high number of people in their $Group_1$, this group is also likely to influence in the housing market as $Group_1$ starts to move into $Group_2$. Singles living in one dwelling is the third most representative family group. They account for 17% of the population and are predominantly in $Group_2$, $Group_3$ and $Group_5$. This is the group which might reduce the need for houses, as the majority of this group has the potential to get married and form a new family.

4.4 Change in housing size

It was observed significant increase in specific dwelling sizes due to the estimated population growth, family structure and density (Figure 6, 7 & 8). There is substantial increase in dwellings with one dormitory, which represented 16% in 2010 and it is estimated at 23% in 2025. Two dormitories increased only 1% increase while three dormitories dwellings increased 4% in the same period. However, it was observed substantial decrease in three dormitories with four persons, four dormitories with four persons, and dormitories with four persons. The results from population growth linked to density and dwelling sizes show that effects of fertility and ageing population will call for smaller houses, reducing the need of houses with four or more bedrooms. Overall, dwellings with five persons and six persons per family remain same. Probably due to small amount of population allocated in those type of families.

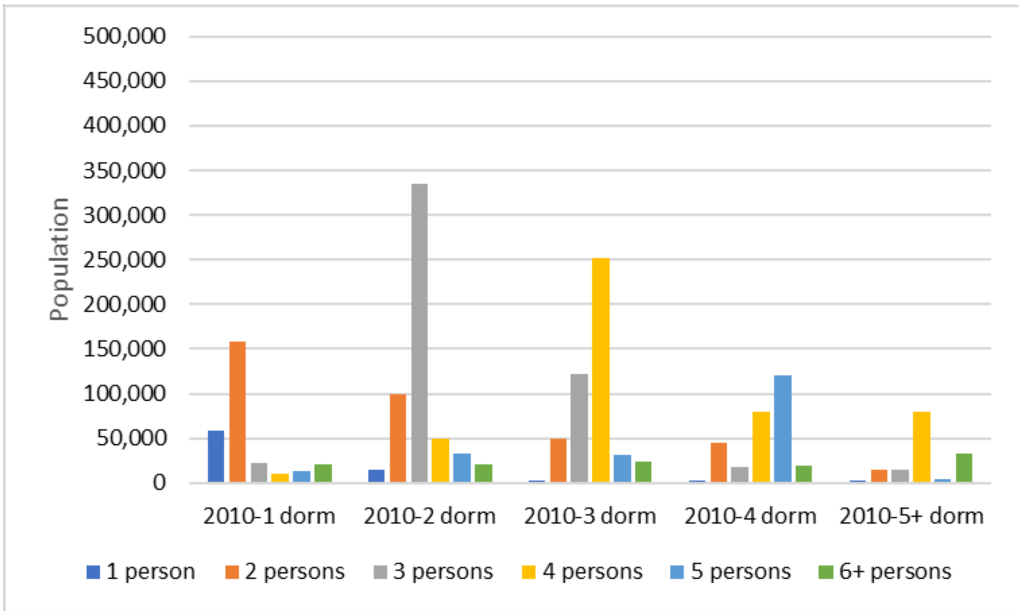

Figure 6: Family Structure in Curitiba by age group in 2010

From 2010 to 2017, it was observed that there is an increase in one dormitory dwellings for houses with density up to 1, and overall decrease in dwellings with density greater than 1.5. Also, there is an overall reduction of dwellings with more than four dormitories.

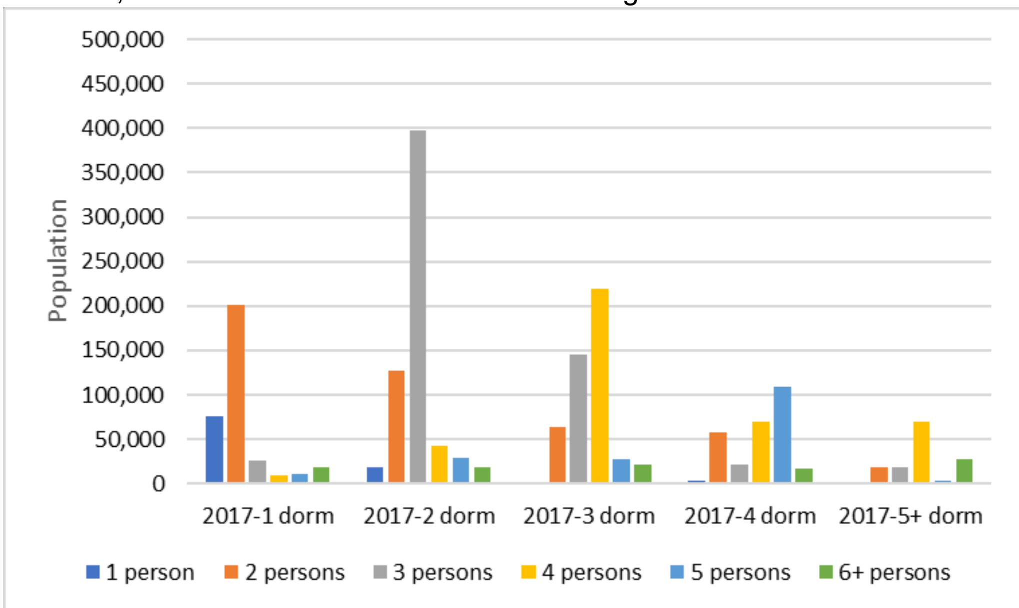

Figure 7: Family Structure in Curitiba by age group in 2017

By 2025, 80% of the population is expected to be living in dwellings with up to three bedrooms, according to the predictions of this paper. The graph shows predominance of two bedrooms dwellings (22%), followed by three bedrooms (24%) and 1 bedroom (23%).

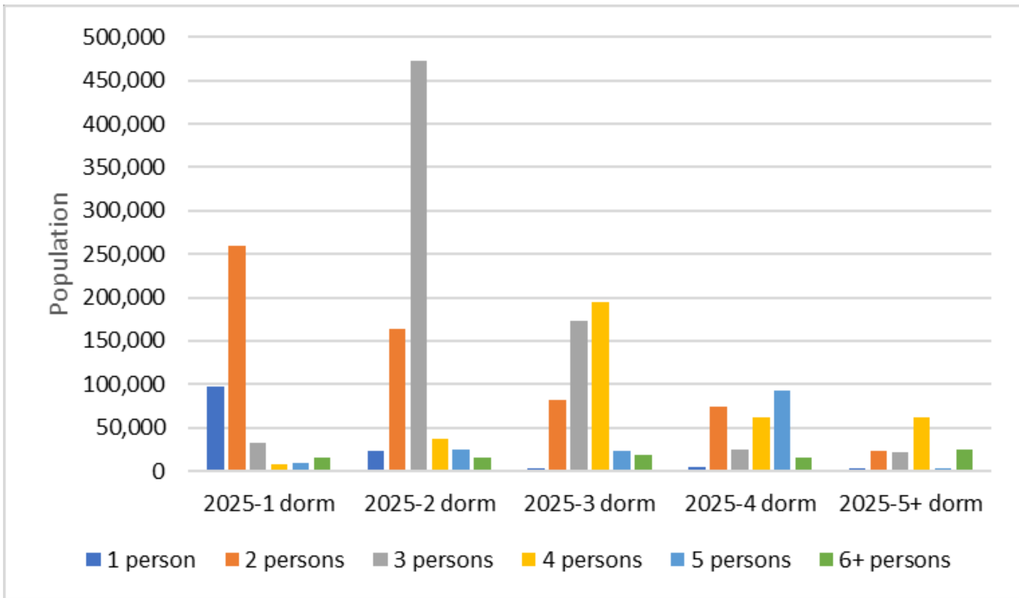

Figure 8: Family Structure in Curitiba by age group in 2025

5 Conclusions

This paper developed a housing demand model for the city of Curitiba. By using data from the Brazilian census, it is possible to predict housing demand based on possible changes in population growth and family structure in the future. In this paper, a baseline is used as input to estimate housing demand in 2025. Population growth and family structure change are predicted according to five age groups and eight family structure types. The results of this paper highlight the importance of a more comprehensive method for housing demand, which identifies opportunities for the delivery of mass customised houses for planning purposes.

The model developed can be used as a tool for further development of guidelines or public policies for delivering appropriate mass customised houses which would fit future needs and desires of people. Moreover, the outputs generated by the model can be used by companies which are investing on market research by understanding future trends of potential customisation of houses. Therefore, professionals who oversee developing new products would have more information about their costumers' needs, and, as a consequence, being able to deliver customised products according to reliable data.

It is important to highlight the results found in this paper show limitations as the ratio per family structure are the same for all years and no variations are considered, according to the Brazilian Census. Only population growth per age is considered in this study. The developed model can be used for estimating housing demand for each building size in other cities. However, data availability might be an issue for applying the model in other cities. Not only housing demand, but also the housing deficit should be considered for the future of supplying sufficient number of new dwellings in appropriate sizes which would be adequate for the new families based on their structure. For future studies, it is suggested the inclusion of other variables such as income, changes in lifestyle and job career should be considered.

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SENSITIVITY ANALYSIS OF BUILDING ENVELOPE PARAMETERS AFFECTING THERMAL COMFORT

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***Abstract**: The ever-increasing attention towards implementation of environmentally sustainable building design approaches necessitates the prediction of indoor environmental quality (IEQ) during design stage. Building performance simulation tools are able to predict key performance indices of buildings including IEQ. Among different aspects of IEQ, thermal comfort has been reported as one of the important aspects for occupants. It is necessary to understand the effects of design parameters on the performance of building in order to provide acceptable thermal comfort levels. However, due to the possibility of various design strategies, the selection of the most appropriate combination is a challenging task. Thus, the determination of effective parameters is of great importance in order to streamline the design process. The design parameters related to building envelope are among the most important items that have major influence on building thermal performance. Although prefabrication offers several benefits in terms of saving on-site time, saving money and better waste management, it affects envelope thermal performance due to introduction of lightweight components. While there is a body of research reporting the effects of passive strategies on building thermal performance, the influence of lightweight prefabricated envelope components is not well-documented in the current literature. This paper aims to perform a sensitivity analysis (SA) to identify the relative importance of major building envelope design parameters affecting thermal comfort of a prefabricated house in Melbourne, Australia. The envelope parameters investigated are: infiltration rate, solar heat gain coefficients and sizes of windows, and thermal resistance of insulation for exterior walls, floor and roof. The ranges of these parameters are based on the building components particularly used by prefabrication building industry in Australia. A typical three-bedroom prefabricated house in Melbourne was considered and the results of the SA are presented.*

***Keywords:** Prefabrication, Building Envelope, Thermal Comfort, Energy Efficiency*

1 Introduction

Prefabrication offers benefits to the building construction industry by reducing on-site time, overall cost and on-site waste. Furthermore, due to new technologies and automation of the processes, better quality houses can be delivered with prefabrication. Modular building construction is a type of off-site manufacturing in which about 70% of the construction is carried out off-site. Modules are factory-produced 3D (volumetric) or 2D (flat pack) preassembled building components which are transported to the site for installation. Although prefabrication is a growing industry in most developed countries, the performance of prefabricated components in terms of energy efficiency and indoor environmental quality is not well-documented in the current literature. Due to the lightweight nature of prefabricated components, the overall thermal performance of the building can be significantly affected. Therefore, it is important to investigate the effects of envelope design parameters on the energy use and indoor environmental quality (IEQ) in prefabricated buildings.

Previous studies showed that passive building design strategies such as envelope, geometry, and airtightness have significant effects on energy consumption (Chen, Yang & Zhang 2015) and thermal comfort. Ortiz et al. (2016) found reduction in hours outside the comfort zone during cold season by improving external insulation of walls and roof and changing the window type. They concluded that addition of internal insulation increases the hours above thermal comfort range during summer. Also, the type and size of glazing have significant impacts on building energy consumption and indoor thermal comfort (Yildiz et al. 2012).

Building performance simulation plays an important role during the design stage to achieve higher indoor air quality, more comfortable and more energy efficient buildings. In building simulation, some design parameters have greater effects on total energy consumption and thermal performance. This indicates that for improving building performance more attention should be given to these parameters. The relative importance of design parameters on building performance can be verified by carrying out a sensitivity analysis (SA). It is an analysis to investigate the effects of different design parameters on performances using a building simulation model. The analysis before optimisation can help to identify the most influential design parameters. The results will help in optimisation to select design parameters properly and/or to set appropriate constraints to optimisation (Tian 2013). Major design solutions should be proposed based on sensitivity index of design parameters affecting related performance parameters depending on the building location, climate and other circumstances (Chen, Yang & Zhang 2015).

There are six sequential steps for a SA of building design parameters: defining input variables, creating building model, running energy simulation, exporting simulation results, performing SA by running the simulation iteratively, and reporting SA results (Tian 2013). There are two types of SA: local and global analyses. Local SA, also known as differential method investigates the responses of output by applying changes to one input parameter at a time. This method requires a baseline case to make comparisons as well as a sensitivity coefficient to interpret the output (Chen, Yang & Zhang 2015). The limitation of this method is that the input data are assumed to be linear so that their impacts are superimposed to obtain the total uncertainty (Yildiz & Arsan 2011). It means that in order to obtain realistic results, local SA requires other variables to be assumed constant. This method addresses little about the relationships among input variables. On the other hand global SA focuses on the effects of uncertain inputs distributed over the

entire input space (Tian 2013). It is able to investigate the effects of several input parameters at once (Chen, Yang & Zhang 2015). Therefore, global SA is regarded to be more reliable. However, this method requires more computing time compared to local SA approach (Tian 2013).

There are several methods that can be implemented to carry out a global SA. Regression, screening based, variance based and meta-model based methods are among the common global SA approaches used in building performance evaluation (Tian 2013). Regression method is the most widely used SA method in building energy simulation. Fast and simple implementation are the advantages that made this method popular in this field. Standardised Regression Coefficient (SRC) and Standardised Ranked Regression Coefficient (SRRC) are two indicators that show the sensitivity levels by using regression method (Tian 2013). These coefficients standardise input and output variables by subtracting the sample mean from the real values and dividing by standard deviation (Reuter & Liebscher 2008). SRC is based on linear regression in which the value of standard regression coefficient is equal to the correlation coefficient. SRRC is similar to SRC except that it is calculated based on rank transformation data (Yildiz & Arsan 2011). Both SRC and SRRC are widely used in SA in the field of building performance evaluation (Yildiz et al. 2012; Chen, Yang & Zhang 2015; Chen, Yang & Wang 2017; Ignjatovi et al. 2016; Tian 2009; Chen, Yang & Sun 2016).

SA for identifying the effective design parameters for buildings has been applied by several studies. The results of the SA by Yildiz & Arsan (2011) showed that the building annual heating and cooling loads are mostly affected by window size, U-value, solar heat gain in hot-humid climates. In a similar study by Chen, Yang & Zhang (2015) the sensitivity index of window, solar heat gain coefficient (SHGC) is the highest among all other factors. The type of glazing i.e. single, double, triple, and the size of the window directly affect the thermal and visual comfort as well as energy consumption of the buildings (Harmathy, Magyar & Folic 2016). In another study by Wang et al. (2017), the effects of occupant behaviour were found to be significant, especially in regards to window and solar shading system operation.

The aim of this paper is to quantify the impact of different building envelope parameters on the energy use and thermal comfort of a prefabricated house in Melbourne, Australia. For this, a regression-based global SA has been conducted to investigate the effects of different building envelope parameters on energy use and thermal comfort indicators. EnergyPlus, jEPlus and Simlab have been used to conduct the energy simulation, parametric run and SA respectively.

2 Method

2.1 Baseline Building

The baseline building is a 3-bedroom single story modular house which has been selected from the existing prefabricated projects in Melbourne. This building is constructed of two prefabricated modules (dimension: 12192 x 3000 x 3100 mm, and weight: 17 t each). Figure 1 shows the plan view of the building which exemplifies the typical residential plans used by modular construction companies in Australia. The information about building details and construction materials was obtained from the website of the company.

The hourly weather data was generated by using Meteonorm software tool which provides worldwide weather data. This software tool is flexible and can generate hourly

weather data file in various formats. The data source used by the software tool is “World Meteorological Organization” (WMO) which is providing accurate scientific weather information (Bureau of Meteorology 2016). A 3D model of the building was created by using SketchUp with OpenStudio plugin. The attributes of the building such as fabric properties, air flow rates, occupancy, equipment were assigned after creating the model. The method for calculation of the heating and cooling loads in EnergyPlus was set to “ideal air loads”. The begin and end dates of heating and cooling seasons assumed for Melbourne were 1 May to 31 October, and 1 December to 28 February respectively (Lhendup, Aye & Fuller 2012). The building is in free-running mode (no space heating and cooling) during the rest of the year. The setpoint temperature for heating was 21°C during the day (6 am – 10 pm) and 18°C (setback) during the night (10 pm – 6 am) while that of cooling was 24°C. Each separate room was defined as a thermal zone. All zones except bathroom were assumed to be conditioned. The occupancy and lighting schedules were set for the building zones assuming that the building is occupied by three people. Assumptions were made about their daily activities in different spaces. The clothing schedules were set according to heating and cooling seasons in Melbourne.

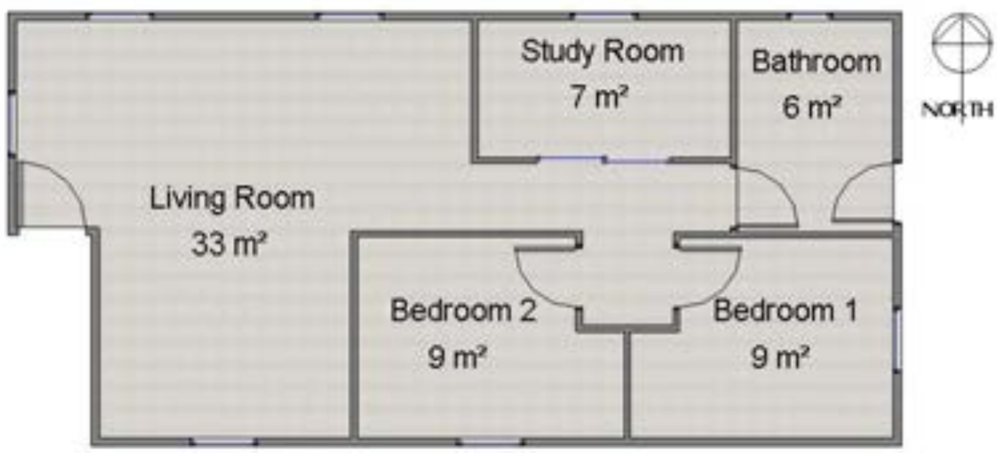

Figure 1: The plan view of the baseline building

Table 1 shows the main features of the building used in the baseline model. Table 2 shows the properties of the building materials. Some selected properties were considered as input parameters for the SA.

Table 1: Main features of the baseline building

Category	Item	Unit	Value
Location, Melbourne	Latitude	deg	–37.817
	Longitude	deg	144.967
	Time zone	h	UTC+10
	Elevation above sea level	m	38
	Site ground temperature	°C	18
Window glazing	U-factor	$W\ m^{-2}K^{-1}$	2.10
	Solar heat gain coefficient	–	0.237
Thermostat set point	Heating, day	°C	21
	Heating, night setback	°C	18
	Cooling	°C	24
Space infiltration rate	Air flow per floor area	$m\ s^{-1}$	0.0007
Design ventilation rate	Outdoor air flow per floor area	$m\ s^{-1}$	0.0003
Shading device	Orientation	–	North
	Width	m	0.5

2.2 Simulations and the SA method

In this paper, jEplus1.6.4 beta was used for the parametric analysis while Simlab4 was used for the SA. EnergyPlus was used as the building performance simulation software. jEplus is a tool that allows users to carry out parametric optimisation with using software such as EnergyPlus. It uses batch parametric simulations to explore large parametric design spaces. Several researchers have been applied this tool for parametric studies reporting the reliability of the results (Zhang & Korolija 2010; Chen, Yang & Sun 2016; Chen, Yang & Sun 2016; Delgarm et al. 2016; Carreras et al. 2015; Germán Ramos Ruiz et al. 2016; Tresidder, Zhang & Forrester 2012; German Ramos Ruiz et al. 2016; Naboni et al. 2013). It has a user-friendly interface which makes the optimisation process easier (Tokarik 2011).

Table 2: Properties of the materials used in the baseline building model

Component	Material	Thickness (mm)	Conductivity (W $m^{-1}K^{-1}$)	Density (kg m^{-3})	Specific heat (J $kg^{-1}K^{-1}$)
Exterior Wall	Wall cladding	10	0.25	1360	*900
	Airspace	60	–	–	–
	OSB board	20	0.13	640	840
	Insulation	*90	0.03	91	837
	OSB board	20	0.13	640	840
	Plasterboard	10	0.19	1300	840
Interior Wall	Plasterboard	10	0.19	1300	840
	Air space	90	–	–	–
	Plasterboard	10	0.19	1300	840
Floor	Light wt concrete	70	0.53	1280	*840
	Air space	150	–	–	–
	OSB Board	20	0.13	640	840
	Insulation	*170	0.03	265	836
	OSB board	20	0.13	640	840
	**Wood	15	0.15	608	1630
	**Ceramic tiles	15	1.30	2300	840
	**Carpet	15	0.06	288	1380
Roof	Roof cladding	1.6	54.00	7800	*418
	OSB board	25	0.13	640	840
	Insulation	*200	0.03	91	836
	Roof membrane	9	0.16	1121	1460
	Gypsum	12	0.16	784	830
Door	Wood	25	0.15	608	1630

*The property selected as input parameter for SA.
**bathroom floor: ceramic tiles; living room floor: timber; and bedrooms: carpet on timber floor.

SimLab is a tool for sensitivity and uncertainty analysis which is capable of pre-processing and post-processing. This tool has been applied for buildings by several researchers (Tr et al. 2011; Ignjatovi et al. 2016; Yildiz & Arsan 2011). SimLab provides the user with various options of SA methods including Morris, Sobol and FAST. Since this flexible tool accepts text-based inputs and outputs, the user can easily manipulate the data to be suitable for different applications.

The 3D model created with OpenStudio plugin in Sketchup was exported to EnergyPlus where other attributes of the building such as material properties, schedules for occupancy, lighting, heating and cooling setpoints were assigned. The targeted output variables were selected in EnergyPlus. Afterwards, an initial run with baseline parameters was carried out to obtain the baseline performance of the building. The model was then imported into jEPlus. jEPlus uses the EnergyPlus sample file together with weather data as input files. The input parameters and their search strings were defined in jEPlus. In parallel, input factors and their ranges were defined with uniform

distribution in SimLab. By choosing uniform distribution it is assumed that within the range given the input variables are equally probable (Ignjatovi et al. 2016). After specifying factor correlation and generation method, the sample data file can be generated in SimLab. Latin Hypercube Sampling (LHS) method was selected to be used in this SA. Regardless of sampling size, this method is reported to provide satisfactory results (Tr et al. 2011). Being popular for regression and meta-model based SA this method has been employed by many researchers for the purpose of SA in the field of building performance simulation (Chen, Yang & Zhang 2015; Chen, Yang & Wang 2017; Hu & Augenbroe 2012; Yildiz et al. 2012; Chen, Yang & Sun 2016). A sample data with 1000 population was generated and imported into jEPlus. The simulations were run through jEPlus and the combined results were imported into SimLab once again to run the SA. Figure 2 illustrates the framework for the conducted SA method.

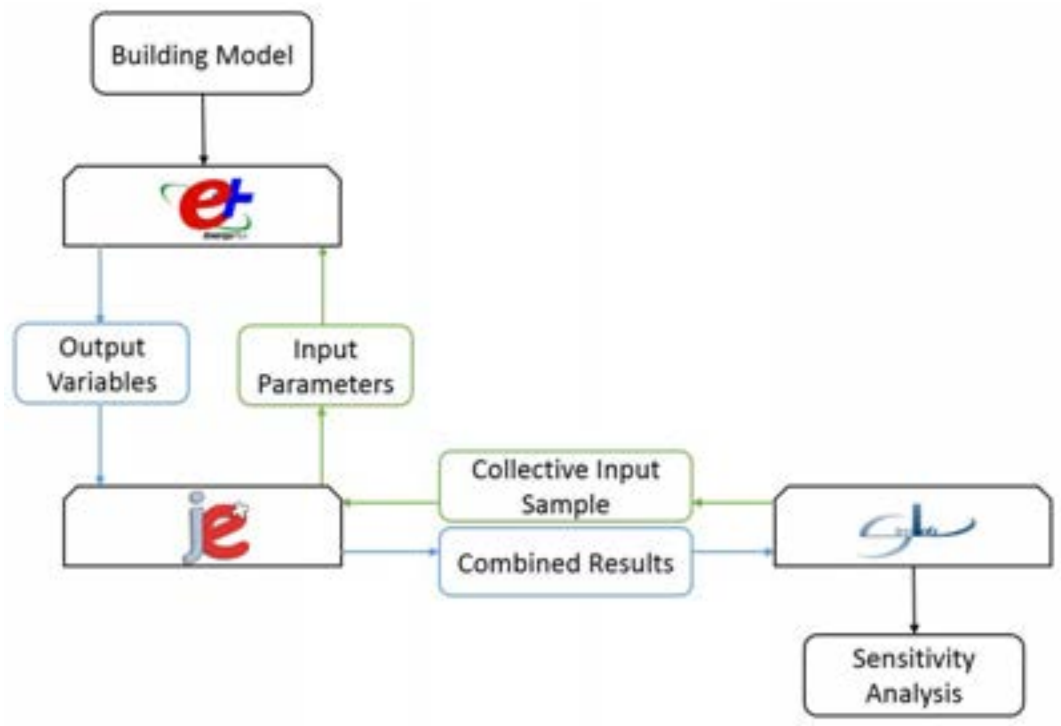

Figure 2: The framework for the conducted SA method

2.3 Input Parameters Selected

Since this paper investigates the effects of envelope parameters, the characteristics of building envelope components such as walls, roof, floor and glazing are taken into consideration. For wall, roof and floor components, input parameters represent thermal insulation and thermal inertia. Those parameters are thermal conductivity of insulation and specific heat of the exterior surfaces. For windows, the U-value and SHGC were selected as design parameters to be analysed. Furthermore, the input parameters related to walls and glazing represent separate variables on each façade direction. The ranges of design parameters were selected to meet the Australian National Construction Code (NCC) requirements as well as market availability. By running preliminary simulations, the minimum insulation thicknesses to comply with NCC requirements for floor, wall, and roof for this particular building were found to be 60, 75 and 150 mm (with 0.03 W $m^{-1}K^{-1}$ thermal conductivity) respectively. Table 3 shows the input parameters with their value ranges used in the SA.

Table 3: The input parameters with their value ranges used in SA.

No.	Input Parameter	Unit	Range
V1	North wall cladding specific heat	J kg^{-1}K^{-1}	400 – 1100
V2	South wall cladding specific heat	J kg^{-1}K^{-1}	400 – 1100
V3	East wall cladding specific heat	J kg^{-1}K^{-1}	400 – 1100
V4	West wall cladding specific heat	J kg^{-1}K^{-1}	400 – 1100
V5	North wall insulation thickness	mm	75 – 150
V6	South wall insulation thickness	mm	75 – 150
V7	East wall insulation thickness	mm	75 – 150
V8	West wall Insulation thickness	mm	75 – 150
V9	Roof cladding specific heat	J kg^{-1}K^{-1}	400 – 1100
V10	Roof insulation thickness	mm	150 – 250
V11	Floor concrete specific heat	J kg^{-1}K^{-1}	800 – 1100
V12	Floor insulation thickness	mm	60 – 200
V13	North glazing U-value	W m^{-2}K^{-1}	2.5 – 7.0
V14	South glazing U-value	W m^{-2}K^{-1}	2.5 – 7.0
V15	East glazing U-value	W m^{-2}K^{-1}	2.5 – 7.0
V16	West glazing U-value	W m^{-2}K^{-1}	2.5 – 7.0
V17	North glazing SHGC	–	0.16 – 0.81
V18	South glazing SHGC	–	0.16 – 0.81
V19	East glazing SHGC	–	0.16 – 0.81
V20	West glazing SHGC	–	0.16 – 0.81

2.4 Output Parameters Selected

Annual district heating, annual district cooling and total hours of thermal discomfort in different thermal zones are selected as output parameters from EnergPlus simulations. The selected comfort evaluation method is based on ASHRAE55 simple model criteria. These criteria can be found among EnergyPlus input options. By choosing the related output variable the software calculates the total number of hours during the year when the zone is occupied and the combination of humidity ratio and the operative temperature outside the ASHRAE 55-2004 summer or winter clothes zones. Clothing level 0.5 Clo was used for summer while 1 Clo was used for winter (U.S. Department of Energy 2012). After running simulations, the selected output variables were listed in a separate file located in the output folder. jEPlus can combine all output variables for all parametric runs in one single text-based document which can be saved as a '.txt' file and imported to SimLab for conducting the SA.

3 Results and Discussion

3.1 Baseline Performance of the Building

An initial building simulation with baseline parameters has been carried out. Figure 3 shows the monthly heating and cooling loads for the baseline building while Figure 4 shows the monthly thermal discomfort time for different rooms in the house. It is evident from Figure 3 that the heating load far outweighs cooling load for the baseline building. The justification for this lies in the climate conditions of Melbourne where the heating season is longer and more severe than the cooling season (Naji, Samarasinghe & Aye 2016; Naji et al. 2017). The maximum monthly heating load occurs in July with 39.36 MJ m^{-2} while the maximum monthly cooling load is found to be in January with 8.38 MJ m^{-2}. The annual heating load is 178 MJ m^{-2} while the annual cooling load is 18.84 MJ m^{-2}.

As discussed before, the thermal comfort is evaluated using ASHRAE 55-2004 summer or winter clothes zones. It is evident from Figure 4 that the number of discomfort hours in bedrooms are more than those in the living room. The discomfort hours for both bedrooms increase dramatically from March to July which coincides with the heating season and the increase in heating load. This could be a result of setback temperature

during the night when the setpoint temperature is 18 °C. The maximum number of discomfort hours in bedrooms occur during July and August while the minimum discomfort is during February. In Living Room and Study Room the maximum number of discomfort hours occur during April. The discomfort hours during the winter in the living room are much fewer than those in bedrooms. The increase in the discomfort hours during the winter time in bedrooms indicates that despite using air conditioning, which may not provide comfortable indoor environment. The annual thermal discomfort times are found to be 2534 and 2828 h for Bedroom 1 and Bedroom 2 respectively while this value is 1488 h for Living Room.

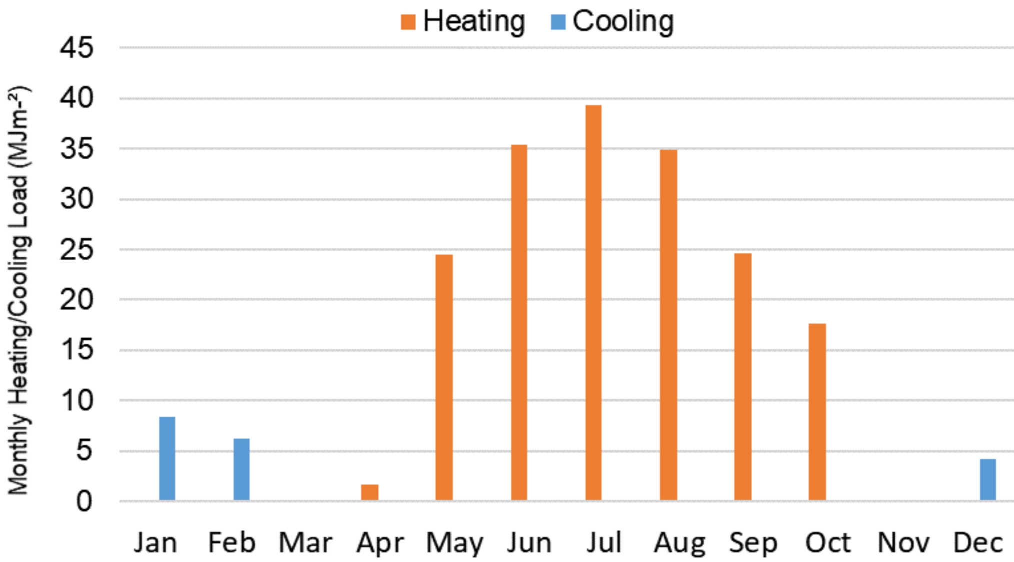

Figure 3: Monthly heating and cooling loads for the baseline building

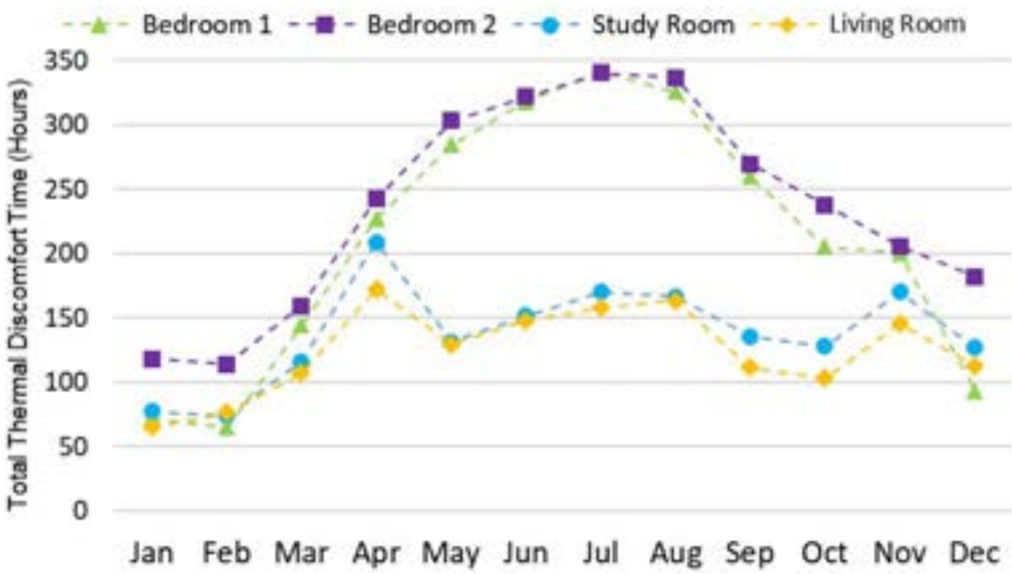

Figure 4: Monthly thermal discomfort time for different spaces in the baseline building

3.2 Sensitivity Analysis

In this section, the results of the SA are presented. The sensitivity index SRRC was used for the evaluation. The positive SRRC indicates that the increase in the building parameter will cause an increase in the corresponding value. A negative SRRC means

that the increase in the parameter will decrease the corresponding result (Yildiz et al. 2012). Figure 5 shows SRRCs of input parameters in relation to different output results.

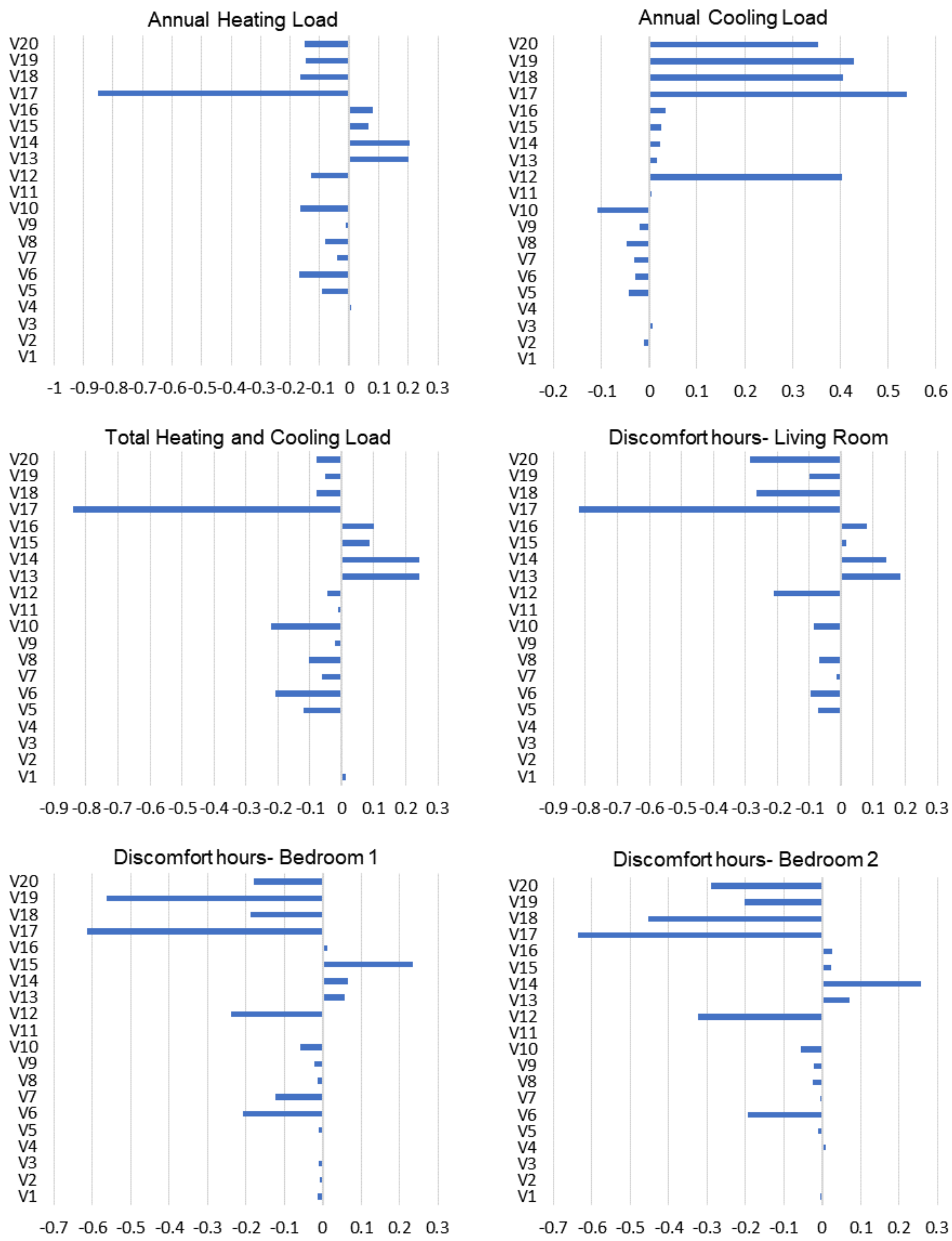

Figure 5: SRRC sensitivity indicators of input parameters on different output results

An overall evaluation of the SA results reveals that the SHGC values of the windows have higher impacts on both heating/cooling loads and discomfort hours of the building investigated. According to the results, SHGC value of north glazing (V17) is the most sensitive input parameter in relation to annual heating load and total heating and cooling

load as well as discomfort hours in living room and bedrooms. The SRRC for V17 is negative in relation to discomfort hours and total heating and cooling load, meaning that an increase in value of north glazing SHGC will decrease those outputs. In relation to cooling load, north glazing SHGC shows a positive but slightly less SRRC.

Other than glazing SHGC, north and south glazing U-value, as well as south wall, floor and roof insulation thicknesses, are other sensitive parameters regarding annual heating load. The roof and floor insulation thickness were found to be other sensitive values regarding cooling load. Also, the floor and south wall insulation thicknesses and east and south glazing U-value were found to be other more sensitive values regarding thermal discomfort hours.

The results also indicated that the specific heat of the building components have a minor effect on this building's comfort and energy consumption. This could be because of the lightweight and thin building components for which the change in material specific heat does not cause major effects on thermal mass. Figure 6 shows the scatter plot of selected output parameters in relation to SHGC value of north glazing.

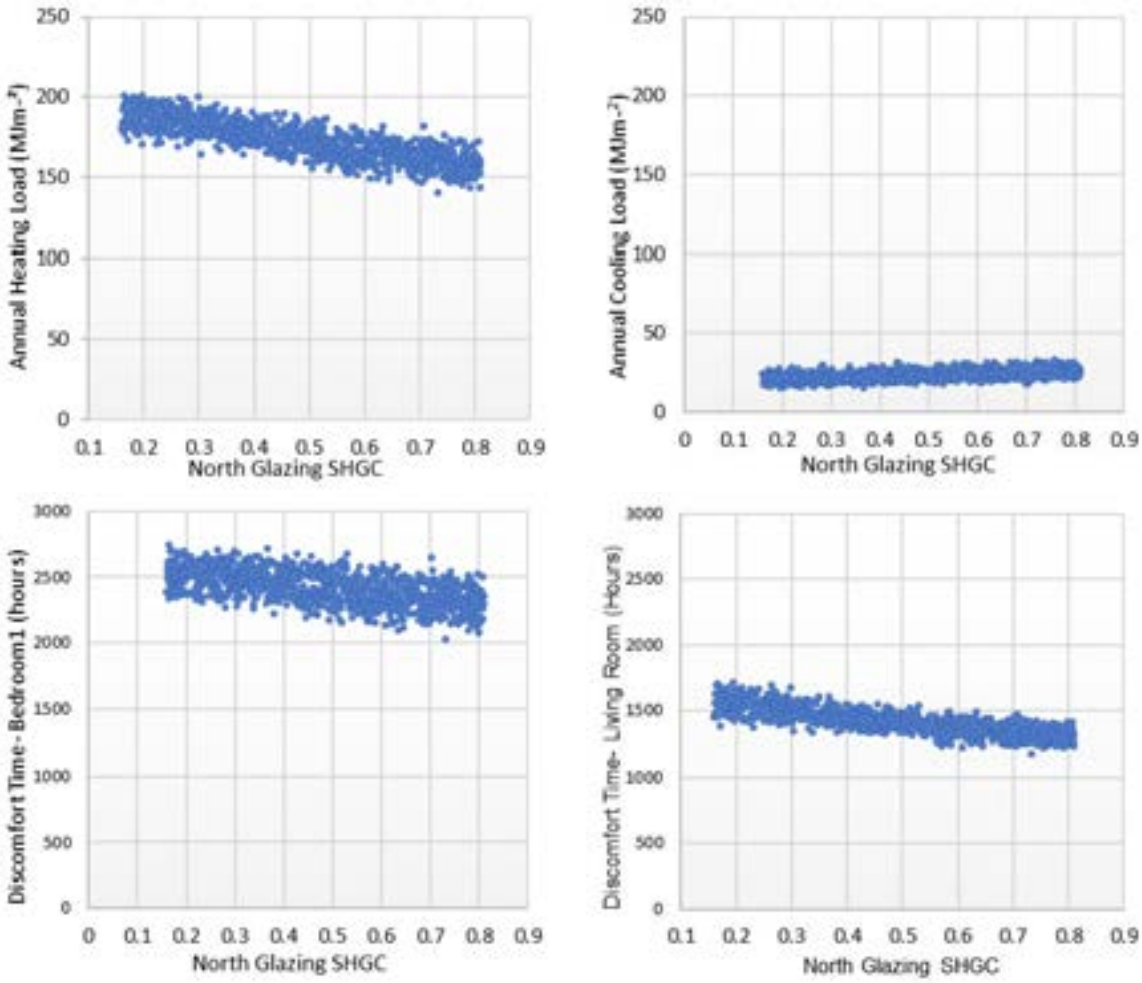

Figure 6: Scatter plot of output values in relation to north glazing SHGC

Figure 6 shows that by changing the envelope design parameters the energy performance and indoor environmental quality of building can be affected significantly. According to the scatter plots, by changing the envelope design parameters, values of

annual heating and cooling loads can differ by 30% and 52% respectively while values of the thermal discomfort time in Living Room and Bedroom 1 can differ by 26% and 30% respectively. This also indicates that improvements in the performance of the baseline building can be achieved by 20%, 17%, 20% and 20% for annual heating load, annual cooling load, discomfort time in Living Room and discomfort time in Bedroom 1 respectively.

4 Conclusions

In this paper, a regression-based global SA has been conducted to investigate the effects of different envelope design parameters on heating and cooling loads, and thermal comfort for a sample modular house in Melbourne, Australia. EnergyPlus, jEPlus and SimLab were applied to carry out the energy simulation, parametric run and SA respectively. To understand the baseline performance of the building, a baseline energy simulation has been carried out prior to the SA. According to the results of the analysis, the following conclusions can be drawn.

The results of the baseline performance simulation indicated that the building's annual heating load outweighs the annual cooling load in Melbourne. Maximum heating load occurs during July and maximum cooling load occurs during January. According to the baseline simulation results, the thermal discomfort hours in the bedrooms increase during the heating season. This could be a result of setback temperature during the night which decreases the thermostat setpoint temperature from 21 °C to 18 °C. Monthly thermal discomfort hours in the living room is maximum during April and November which are during the free-running period.

The SA results indicated that the SHGC of the glazing especially on north façade is the most sensitive parameter regarding the output parameters such as annual heating load, annual total heating and cooling load and discomfort hours. Other than glazing SHGC, north and south glazing U-value, as well as south wall and roof insulation thickness, are others more sensitive envelope design parameters regarding both heating and cooling loads, and thermal comfort.

The scatter plot of the 1000 simulations indicated that by changing the envelope parameters, values of annual heating and cooling loads can differ by 30% and 52% respectively while values of the thermal discomfort time in Living Room and Bedroom 1 can differ by 26% and 30% respectively. Results also showed that, by changing envelope properties, improvements up to 20% is possible on both energy performance and thermal comfort of the baseline building are achievable.

The baseline study and the SA in this paper was conducted based on some assumptions on the shading device, temperature setpoints, occupants' schedules and clothing. Since these factors can be influential on the perceptions of thermal comfort it is important to investigate the effects of these factors on the results of similar SA investigations. In this respect, future studies could focus on these important factors as additional design parameters.

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DIVERSE MORPHOLOGICAL PATTERNS OF URBAN VILLAGES AND INSIGHTS FOR ACHIEVING ADAPTIVE URBAN NEIGHBOURHOOD

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Abstract: *Urban village is a prevalent urban phenomenon in China's Pearl River Delta (PRD) region where thousands of former rural villages have urbanized along with the surrounding built environment during the past three decades of unprecedented rapid urbanization. Common perceptions position urban villages as to have "bad" environmental qualities amidst "chaotic" settings, and is commonly used as one of the main motivations to demolish these urban enclaves to be replaced by modern high-rise blocks. However, the urban village, as one of the most dominate residential building type and urban neighbourhoods in the cities of the PRD, has contributed significantly to the urban affordability of the megacities through providing low-rent housing and employment opportunities for the massive migrant populations. This paper argues that the environmental qualities of the urban villages are diverse in type and merits, rather than the generalized view as uniformly "bad". This research reveals the urban village to demonstrate high environmental adaptability, owing to the diverse morphological patterns of the building fabric, as well as the ecological mechanisms of self-organization and self-maintenance. Hubei is an informed case for exploration due to its unusually diverse urban morphology with distinct types of built forms of multiple generations, accumulated throughout the past century. This paper has analysed the morphological characteristics, neighbourhood dynamics, and environmental performances of seven types of built forms in the Hubei Village neighbourhood. It aims to show that lessons can be learned from the urban village to be applied toward creating and adapting urban neighbourhoods with diverse urban morphology and high environmental adaptability. This paper also reflects on the problems of the current demolition-oriented mode of urban redevelopment in the PRD and other cities of China.*

Keywords: *Urban Village, Diverse Morphological Patterns, Adaptive Urban Neighbourhood, Urban Redevelopment, Hubei Village*

1 Introduction

1.1 Urban villages and Shenzhen's challenges

As a typical urban phenomenon in China's Pearl River Delta (PRD) region, urban village means that the rural villages are gradually surrounded by the urban built environment during the rapid urbanization. Government and developers always presume that these urban enclaves are "dirty-massive-bad" and possess "poor" environmental performance. However, since the late 1980s, the urban villages have contributed significantly to urban affordability and social inclusiveness by offering adequate low-rent housing and many employment opportunities for the massive migrant workers and the newly graduated youths (Lan 2006: 146; Liu et al. 2010: 136). Known as a place originating from clusters of rural villages, the city of Shenzhen has a more prominent and typical "problem" of urban villages. Before the open reform in the late 1970s, there were about 2,000 rural villages in Shenzhen (Du 2016: 70). Large numbers of farmer houses, which were surrounded by the vast areas of farmlands, distributed randomly. Originally, these villages possessed high-density low-rise built form. With the unprecedented rapid urbanization in three decades, it had remarkably changed these villages' building form and overall morphologies (Fig. 1). These rural villages, the later so-called urban villages, have provided their farmlands for urban construction and thereby supported Shenzhen to achieve its miracles of urban development and economic growth. Nowadays, Shenzhen has 320 urban villages, including over 1,700 village units (Hao et al. 2011: 218; Zhang 2016a). As of 2011, the informal housing in the urban villages accounted for 70% of Shenzhen's rental market volume (Zhang 2011). The urban villages remain a signature of the city regarding indigenous culture, urban structure, and urban landscape. However, Shenzhen is also confronting with a conundrum, namely whether these urban villages, where over 9 million people live in the modernized farmer houses with various qualities, should be demolished and replaced by the typical high-rise and high-end urban blocks (Zhang 2016b: 16; Yan 2015).

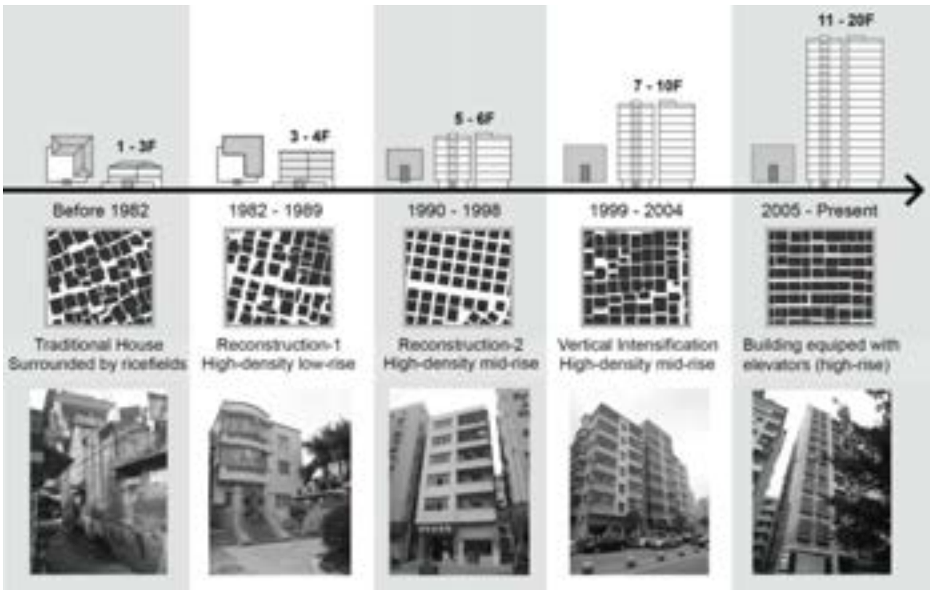

Figure 1: Morphological evolution of urban villages in Shenzhen during rapid urbanization

Nowadays, Shenzhen has been forced to enter an era of wholesale urban redevelopment. According to the international practice, the land exploitation intensity of a city should not be higher than 20%, so as to maintain a stable level of urban liveability

and ecological resilience. What is more, the international benchmark for exploitation intensity at 30% indicates a turning point of decreasing urban liveability and environmental resilience (SZUPLRRC 2015). However, a survey of land use change shows that the development intensity in Shenzhen reaches to a threshold that around 47% of the lands in the city have been covered by urban built-up areas, far exceeding the alarming international level (30%) (SZSB 2011). Consequently, those urban villages located in the urban core have become the primary target for demolition and reconstruction. As revealed by many studies, the Urban Heat Island (UHI) effect in inner-city Shenzhen has been intensified with a degree of over 1.0°C during the past decade when more and more high-rise large-scale building blocks were built in the city. This further results in poor outdoor thermal comfort during the summertime (Zhang et al. 2008: 24; Zhang et al. 2011: 484-485; Pan et al. 2014: 211-212; MBSM 2017). It can be speculated that the wholesale demolition of urban villages located in Shenzhen's urban core crucially contributes to increasing the city's UHI effect. Therefore, studying these urban villages' morphological characteristics and assessing their environmental performances can help obtain the insights for urban planning and design.

1.2 Objectives and methods

This paper argues that the environmental qualities of the urban villages are diverse in type and merits, rather than the generalized view as uniformly "bad". This research reveals the urban village to demonstrate high environmental adaptability, owing to the diverse morphological patterns of the building fabric, as well as the ecological mechanisms of self-organization and self-maintenance. Choosing Hubei Village as the case study area, this paper analyses the morphological characteristics, neighbourhood dynamics, and environmental performances of the urban villages. Through on-site survey and mapping, the characteristics of building form, spatial patterns, and occupants' behaviours were elaborated. The technique of space syntax was utilized to analyse the spatial structure and quality in Hubei, while the measurement of sky view factor (SVF) indicates the openness of each selected space. Several intelligent environmental testing instruments were employed for measuring outdoor daylighting and UHI effect. Ultimately, the potential design strategies and mechanisms for achieving adaptive urban neighbourhood were identified. Through observing the typical situation of Hubei, this paper reflects on the problems of the current demolition-oriented mode of urban redevelopment in the PRD and other cities of China.

2 Case-study Area: Hubei Village Neighbourhood

Hubei is a representative urban village in Shenzhen with distinct generations of built form at its different stages. Its history can be dated back to Chenghua Age of Ming Dynasty (A.D.1465-1487) when the Zhang Families built the village 550 years ago (Qiu 2016: 16). Hubei Village neighbourhood contains four old sections (i.e. the ancient and old villages, including southern, northern, western and eastern sections), the new village, and a few newer urban blocks (Fig. 2). The four old sections cover a land area of 45,000 m^2 with the floor areas of over 300,000 m^2, which house around 50,000 residents (Edr-lab 2016). Hubei is located in the east of Dongmen Commercial Zone in Luohu District, and also widely known as a hub of the wholesale seafood industry in the PRD region during past decades. Even today, Hubei is still the major supplier of many seafood restaurants in Shenzhen. Two metro stations (Hubei and Shaibu) and several bus stops are located nearby Hubei Village (Fig. 2). These public transport stations not only enable Hubei to act as a destination for urban transit users who work nearby commercial and official areas in Luohu but also distributes Hubei 's working population over the city. According to the authors' site observation, Hubei had a very high accessibility from the public transport system and accounted for much of its patronage in Dongmen Community.

Since 1992, Hubei has been listed in a municipal redevelopment plan. However, this plan has yet to be implemented due to the obstacles of ambiguous ownership of the buildings and lands, the housing issue of massive low-income migrants who have lived in Hubei for several decades, and the debate on balance between the inheritance of local culture and continuous economic growth of the city. It is not until mid-2016 has this redevelopment program been put on the formal agenda. However, the actual launch of this program had drawn many attentions from the society to discuss the fate of such a historical, valuable village, which has witnessed the transformation of Shenzhen and been a crucial part of the city's history. During this course, an urban public plan named *The 120 Urban Public Plan of Hubei Ancient Village* was initiated by a group of architects, urban planners, social reformers, grassroots artists, NGO workers, college teachers and students, and indigenous villagers. This plan called for preservation of Hubei Village as the city's living cultural heritage, particularly the ancient village, which remains the traditional Cantonese Style Row Houses (*Guangfushi Paiwu*). The group also concerned about the residency of the low-income migrants as they will be "expelled" to the edge of the city once their "second home", Hubei, is gentrified. These endeavours have promoted the district government and the developer to re-evaluate the pre-announced redevelopment scenario and release spaces for debate on the direction for Hubei's future with considering the social, economic and environmental consequences.

Figure 2: Location of Hubei Village Neighbourhood and the diverse morphological patterns

Two red dots show the location of metro stations near Hubei, the numbers on the map are spaces for environmental evaluation which will be discussed in the following sections.
Note: The main types of morphological pattern in Hubei: 01) high-density low-rise ancient village; 02) high-density mid-rise old village; 03) high-density mid-rise new village; 04) low density high-rise modern block; 05) medium density mid-rise residential unit; 06) open space; 07) urban park.

3 Morphological Characteristics and Neighbourhood Vitality

3.1 Plot pattern, street networks, fabric and floor area ratio

Compared to its surrounding urban blocks, Hubei has a not only heterogeneous but also organic plot pattern which has also shaped outdoor spaces with multiple functions. The plots located near the city roads are much more regularized, such as the plot of the new village (Section C in Fig. 3-a), and Dongmen Community Park (Section D in Fig. 3-a). The street networks in Hubei are complicated though, possess high connectivity to the outside urban areas through the connection from two main roads with the opposite directions in the neighbourhood (i.e. Leyuan Road with N-S orientation, and Hubei Road with W-E orientation). While those dense, small-scale alleys in the inner area of Hubei well organize the internal traffic and pedestrian flows with a very high accessibility and connectivity to the main roads and the surrounding urban areas (Fig. 3-b).

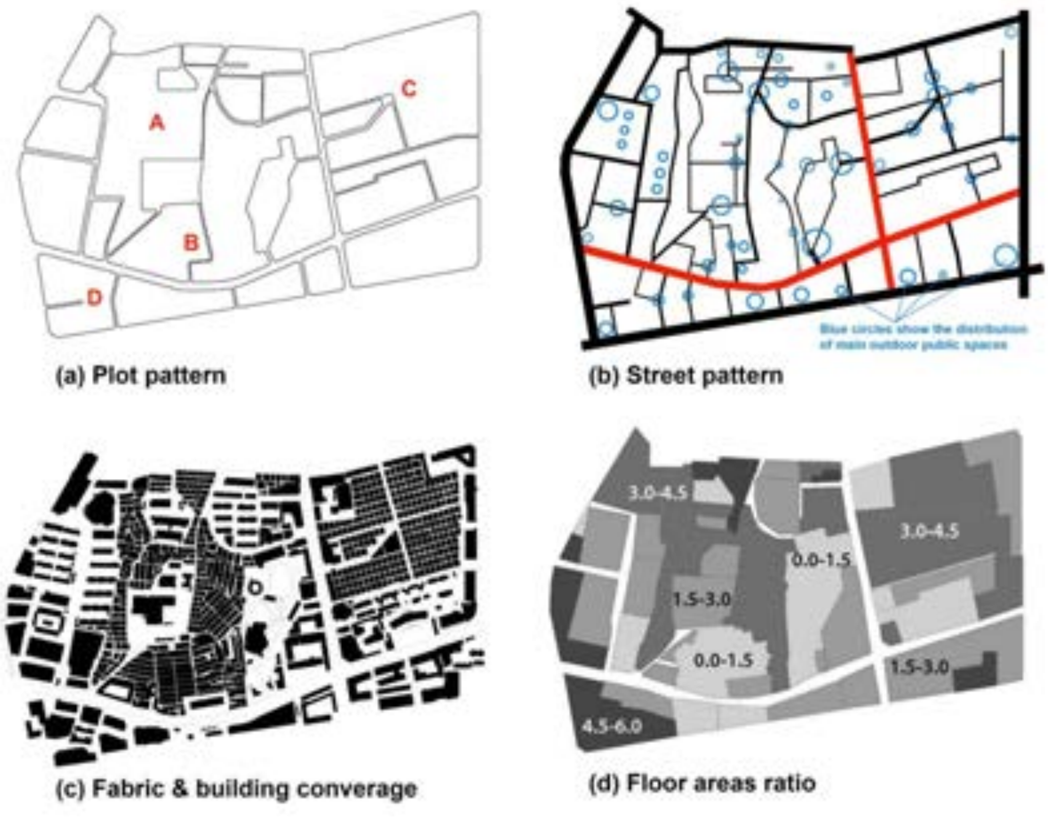

Figure 3: Morphologies and spatial patterns of Hubei Village Neighbourhood

The whole village of Hubei possesses diverse morphological patterns with multiple generations, including high-density low-rise ancient village (built in Qing Dynasty), high-density mid-rise old village (the eastern, western and northern sections, random, built in early 1980s), high-density mid-rise new village (uniform, built in 1986), low-density high-rise modern blocks (built after 2000), medium-density mid-rise newer residential units (built in 1990-2000), as well as a few open spaces and urban parks (Fig. 2 & 3-c). Its overall fabric can be portrayed as the high-density small-scale pattern mixed and combined with the low to medium density large-scale built forms. Consequently, the sections with different floor area ratios (FAR) are randomly distributed in Hubei, making a colourful landscape and diverse spatial geometries between the blocks. The ancient village possesses the lowest FAR with the value lower than 1.5, while the high-density mid-rise old and new villages possess an average FAR of 3.0-4.5. Areas with the highest

FAR (4.5-6.0) are the low-density high-rise modern blocks, which are mainly distributed in the peripheral areas of Hubei and near the main city roads (Fig. 3-d).

3.2 Spatial connectivity and integration

In May 2016, Luohu District Government and China Resources in Shenzhen released a demolition-oriented scenario for Hubei Redevelopment. All of the “handshaking buildings” in Hubei would be demolished and replaced by the large-scale shopping mall and residential towers. Only the ancient village could remain for further negotiation (Fig. 4). However, to redevelop Hubei or any other urban villages, is not just about the upgrading of the physical environment, but closely related to the ingrained social networks, sub-cultures, and economic patterns. It is noteworthy that the environmental diversity with multiple morphological patterns in the status-quo of Hubei fosters its fruitful industries and sociocultural components. Through the platform of *depthmap* and adopting the axial method, this section compares the variations of connectivity and spatial integration between the status-quo of Hubei and a design entry announced by the local government and the developer.

Figure 4: One of the versions of design entries for Hubei Redevelopment by China Resources

3.2.1 Connectivity

The value of connectivity indicates the number of nearby streets that connect to the tested space. Space syntax analysis shows that the status-quo of Hubei possesses higher connectivity than the design entry. Many small-scale, tortuous alleys are widely distributed in Hubei and well connected to the main streets (see the yellow and red lines a, b, c & d in Fig. 5-a). Such capillary-type road network, which is dominated by a few main streets, contributes to Hubei’s high accessibility and evacuation capability and then extends its residential capacity indirectly. While in the design entry, the road system has been much more regularized with a larger scale and thereby results in the decreasing connectivity of a few original main streets. Such as the situation of Line e’ (the original Leyuan Road) and Line f’ (the original Middle Dongmen Road) (Fig. 5-b & Table 1). Such shift may result from the collapse of the original long-established urban function and the shrinking of the seafood industry in Hubei after such reconstruction: from an urban neighbourhood with diverse spatial patterns and high social inclusiveness to a big-scale gated modern block. This situation will further reduce Hubei’s capability of service for the surrounding urban residential areas, making it be a featureless tower cluster in the city.

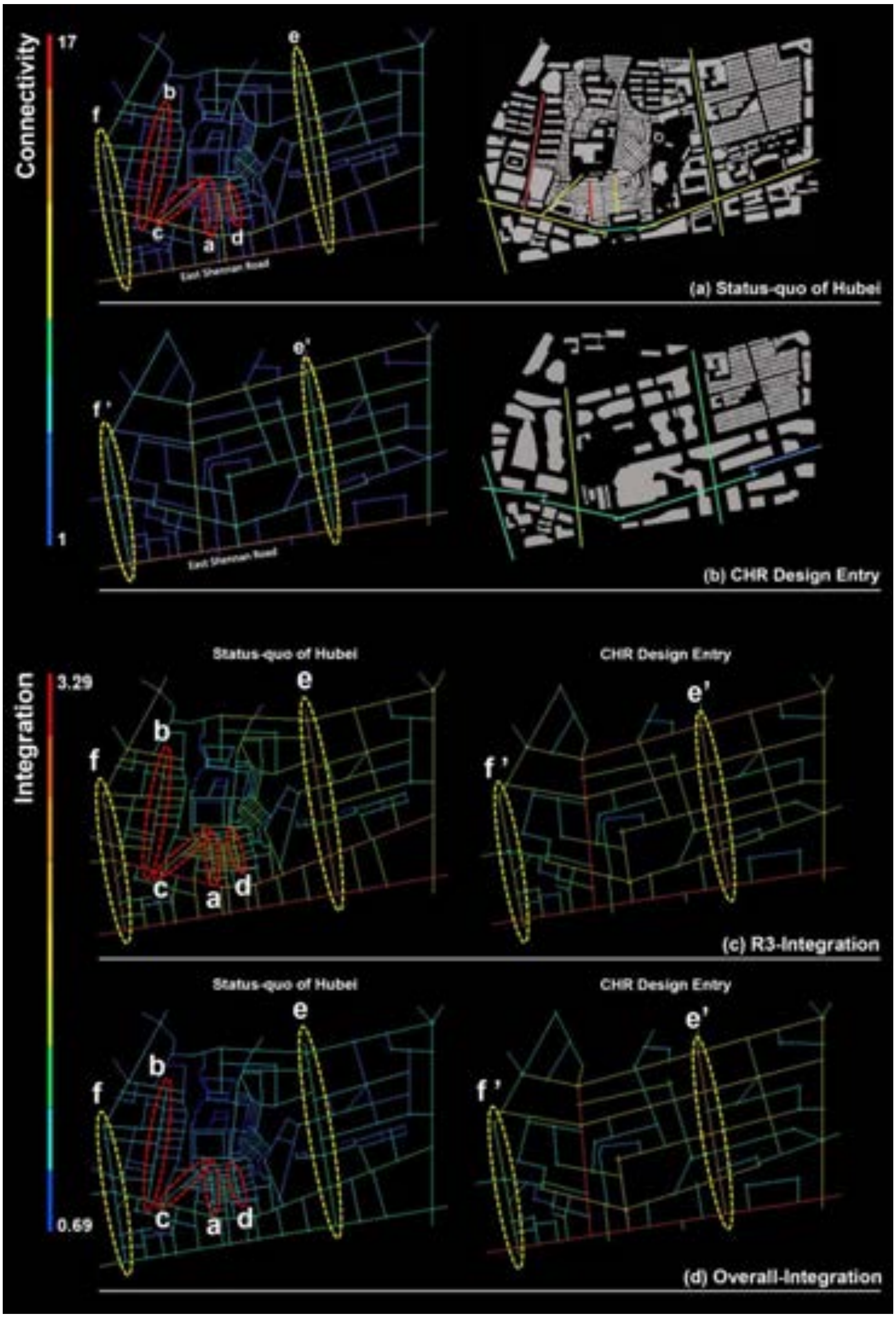

Figure 5: Analysis of Connectivity and Integration – Comparison of status-quo and design entry

Note: Line a, b, c, and d are the streets of wholesale seafood market in Hubei, which have very high connectivity to the main roads. Line e is the seafood restaurant street between the old section of Hubei and the new village of Hubei.

Table 1: Index value of Connectivity and Integration of main streets in Hubei

Codes of Analysed Streets	a	b	c	d	e / e'	f / f'
Connectivity Value	17	14	13	13	11 / 6	11 / 9
Integration Value (R3)	2.88	2.91	2.68	2.71	3.00 / 2.86	2.83 / 2.33
Integration Value (Overall)	1.33	1.34	1.55	1.30	1.72 / 2.66	1.59 / 1.96

3.2.2 Integration

On the other hand, integration indicates the discrete degree of a given space within the whole spatial network. A higher value of integration index indicates a more suitable spatial pattern with also great accessibility, which attracts more people to come and stay and contributes to forming a more dynamic urban neighbourhood (Duan 2007: 11-20). Both the status-quo of Hubei and the design entry have good spatial integration with the value of 0.69 - 3.29 (Fig. 5-c & 6-d). While at the R3 Level, the status-quo demonstrates a slightly higher degree of integration, especially for the main streets with the value of 2.68 - 2.91 (Fig. 5-c & Table 1).[1] Apparently, the status-quo of Hubei possesses much more complex road system and diverse spatial patterns than the design entry. That makes the occupants need to walk through several “sub-streets” to reach the target space even though most of the main roads have a very high connectivity (Fig. 5-a). Also, although the status-quo of Hubei has a relatively low integration value in its inner areas, the high-density mid-rise pattern mixed with other patterns can provide alternative spaces with different levels of publicity or privacy for the occupants.

3.3 Occupants’ activities and neighbourhood vitality

Tracking observation shows that the occupants in Hubei have their preferences to choose specific outdoor spaces for activities, ranging from sitting and chatting, playing cards and chess, playing ball games, singing, dancing, as well as just lying leisurely (Fig. 6). Much more occupants stayed outside in the night than the daytime. In comparison, the number of people stayed in the old and new villages was larger than the other sections in Hubei during both the day and night (Fig. 7). Obviously, the old village is more dynamic than the new village due to its more diverse building forms and outdoor spatial geometries, which can attract more people with different backgrounds. In the new village, its buildings have been regularized into a uniform shape. The tidy living condition has made a higher rental level and thereby attracted fewer low-income renters.[2] Also, it can be observed that rare people gathered in the spaces that located on the edge of urban boulevards during both the day and night even though most of these areas possess a higher degree of openness and better infrastructure. That is mainly due to the adverse impacts of traffic noise and limited convenient service points within these areas. Such as Dongmen Community Park, which is located at the intersection of East Shennan Road and Middle Dongmen Road, and actually, works as an extended zone of pass by for pedestrians other than an urban park for entertainment (see red dotted circles in Fig. 7). In contrast, those spaces with a smaller scale embedded in or located near the old village presented a higher degree of vitality. They function as buffer zones which bridge the nearby modern urban areas and the old village. Usually, these areas have fruitful spatial patterns regarding size & scale, shape & geometry, and publicity & privacy, and thus meet the multiple needs of the occupants. They can also offer low-cost services and amenities for the occupants and have more shelters and shadowed areas for preventing the direct solar radiation in summer daytime. Another striking contrast is that the medium-density mid-rise residential units (*Danwei*) are the most “deserted” part in Hubei: only 1-5 people were observed to stay there in the day and even no people stayed outside in the night (black dotted circles shown in Fig. 7). The mode of gated management has strengthened these units’ psychological boundary even though the entrances are open for all occupants in Hubei (Feng et al. 2014). While in the old village,

[1] In space syntax analysis, R3 is the scope that people can directly percept and understand space in urban context. Many previous studies have verified that R3 integration has a significant correlation with economic dynamics and people gathering.

[2] The rent for a one-room unit in the new village is around 1200-3000 RMB per month; the rent level in the old village is around 600-1500 RMB per month.

the widely distributing small stores and workshops on the ground floor make most of the spaces between the buildings maintain a high utilization and vitality for most of the time.

Figure 6: Usage patterns in various sections of Hubei during different time periods within a day

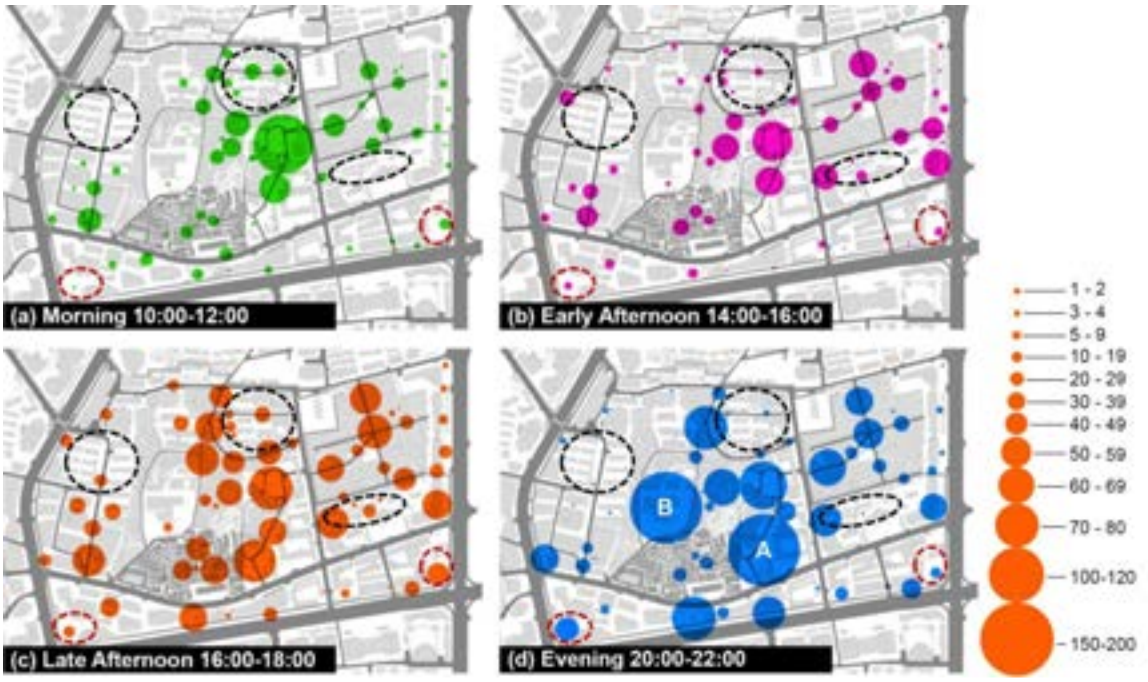

Figure 7: Map of people gathering in Hubei Village Neighbourhood during different time periods

4 Diverse Environmental Performances

The research selects 28 spaces with different morphological characteristics and high utilization in Hubei for environmental analysis. These selected areas cover seven main types of morphological patterns in Hubei, including low-density low-rise, high-density mid-rise (random), high-density mid-rise (uniform), low-density high-rise, medium-density mid-rise, open space, and urban park (Table 2). Obviously, the sections with high-

density pattern (i.e. the ancient, old, and new villages) have a higher building coverage ratio (BCR=55-93%) than other sections in Hubei. The ancient village with a high-density low-rise pattern possesses the highest BCR with the value reach over 90%, while has the lowest mean building height (MBH is around 4.0m). To compare the situations of high-density mid-rise old and new villages, they have the similar value of MBH (18.0-21.0m), while the old village has more diverse spatial patterns with multiple values of BCR (35-80%) and mean nearest neighbour distance (MNN=2.0-13.0m) than the regularized new village, and thereby presents a higher degree of spatial porosity. Notably, although the low-density high-rise modern blocks (Type-04) and the medium-density mid-rise newer residential units (Type-05) share the very close average values of BCR and MNN, the newer residential units have a lower average degree of spatial openness (Avg. $SVF_{Type-04}$=0.29; Avg. $SVF_{Type-05}$=0.13) due to the sheltering effect of vegetation coverage (Table 2 & Fig. 8).

This section examines the performances of daylighting and urban heat island intensity (UHII) in Hubei's different types of outdoor spaces. Daylighting is a vital component for visual comfort and humans' health, which contributes to killing bacteria and promoting the synthesis of vitamins in human bodies, while too strong solar radiation would hurt people's skins and lead to some skin diseases (Tregenza & Wilson 2011: 3-30). Under the background of climate change, the increasing UHII has threatened our cities' environmental quality and ecological security. It has also crucially damaged the economy ranging from the increased energy use, the increasing production of ground-level O_3 to humans' health and quality of life (Stone 2005; Estrada 2017). Therefore, consideration of both daylighting and UHI as the critical environmental indices enables a more careful and effective evaluation of urban planning and design.

Table 2: Morphological characteristics of the 28 selected outdoor spaces in Hubei

	No.	Categories	Built in	Morphological Characteristics	Orientation	BCR (%)	MBH (m)	MNN (m)	SVF
01	S-03	Ancient village	1800s	High-density low-rise (linear)	NNW-SSE	92.8	4.2	1.8	0.24
	S-04	Ancient village	1800s	High-density low-rise (linear)	WSW-ENE	92.8	4.2	1.8	0.08
	S-05	Ancient village	1800s	High-density low-rise (linear)	WSW-ENE	83.4	4.4	2.4	0.23
02	S-11	Old village	1980s	Open space in the old village	W-E	34.7	9.3	12.6	0.26
	S-13	Old village	1980s	Open space in the old village	--	41.3	20.1	6.0	0.27
	S-14	Old village	1980s	High-density mid-rise (random)	NNE-SSW	62.0	20.3	2.3	0.09
	S-15	Old village	1980s	High-density mid-rise (random)	NW-SE	73.9	18.5	1.7	0.07
	S-16	Old village	1980s	High-density mid-rise (random)	NE-SW	77.0	18.5	1.7	0.06
	S-17	Old village	1980s	High-density mid-rise (random)	WSW-ENE	54.9	17.7	4.6	0.19
03	S-21	New village	1986	Open space in the new village	--	48.9	21.1	2.7	0.29
	S-22	New village	1986	High-density mid-rise (uniform)	WSW-ENE	73.7	21.6	3.8	0.09
	S-23	New village	1986	High-density mid-rise (uniform)	WSW-ENE	79.6	21.4	1.8	0.06
	S-24	New village	1986	High-density mid-rise (uniform)	NNW-SSE	79.6	21.4	1.8	0.02
04	S-02	Modern block	2000s	Low-density high-rise	WNW-ESE	48.6	41.3	11.5	0.15
	S-10	Modern block	2000s	Low-density high-rise	NNE-WSW	48.1	22.4	15.2	0.22
	S-20	Modern block	2000s	Low-density high-rise	NNW-SSE	31.2	14.0	11.2	0.45
	S-26	Modern block	2000s	Low-density high-rise	W-E	31.0	23.8	5.6	0.32
	S-28	Modern block	2000s	Low-density high-rise	--	26.5	22.9	13.1	0.31
05	S-07	Residential unit	1990s	Mid-density mid-rise	N-S	48.1	19.5	13.4	0.22
	S-08	Residential unit	1990s	Mid-density mid-rise	W-E	35.8	21.9	12.2	0.11
	S-12	Residential unit	1990s	Mid-density mid-rise	W-E	40.7	20.4	9.5	0.07
06	S-01	Open space	2000s	Urban open space	--	7.6	3.0	24.1	0.42
	S-06	Open space	1980s	Urban open space	--	35.2	17.4	25.2	0.50
	S-19	Open space	1986	Urban open space	--	10.1	8.3	26.5	0.56
	S-27	Open space	2000s	Urban open space	--	14.5	19.5	8.4	0.45
07	S-09	Urban park	1990s	Urban vegetated park	--	18.0	11.0	12.0	0.12
	S-18	Urban park	1986	Urban vegetated park	--	16.9	8.3	26.5	0.10

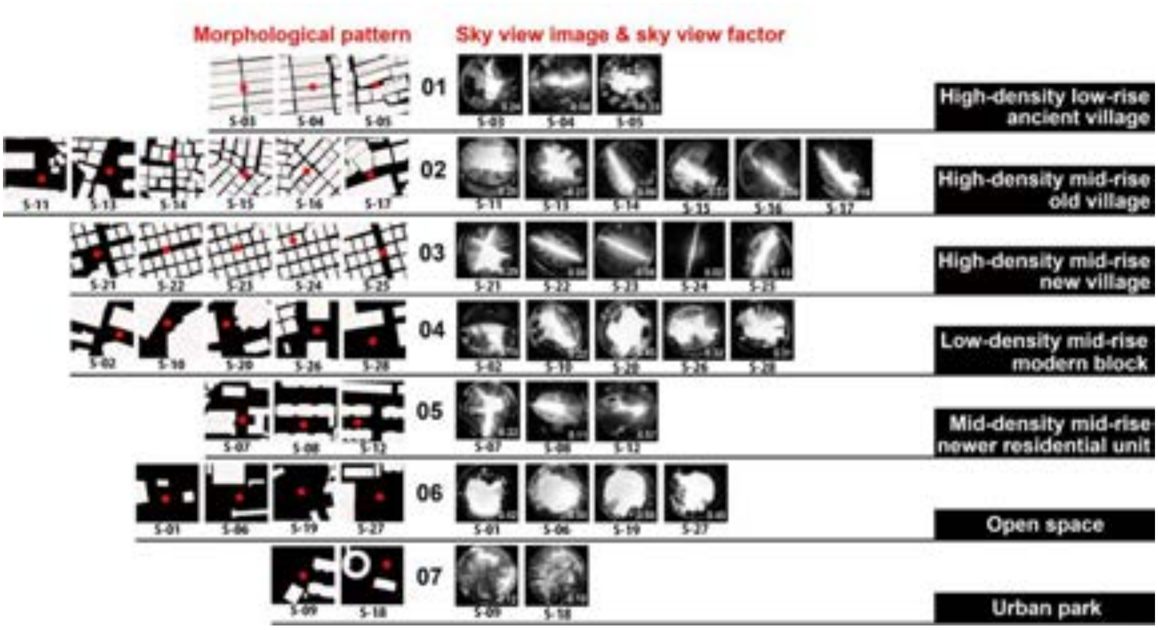

Figure 8: Seven types of morphological patterns of the selected outdoor spaces with high vitality within a day (the red dot shows the place of measuring point in each space)

4.1 Daylighting

This paper uses sky view factor (SVF) to define the degree of openness of a given space by taking account the impacts of multiple elements in and surrounded the space, such as buildings, vegetation, and related constructs. After taking sky view image (SVI) for each space through a digital camera with fisheye lens (at the geometry center of each space pointed upward at a height of 1.1 m) (Middel et al. 2017: 21), the values of SVF were measured by the system of WinSCANOPY-2016 (Fig. 8). The illuminance level (IL) of each space was monitored in the morning (10:00 am-12:00 pm) and the afternoon (14:00 pm-16:00 pm) through the illuminometer TES-1330A. In most cases, the higher the SVF value, the higher the openness of the space, thereby the higher solar admittance and IL in the daytime. Open spaces and the low-density high-rise modern blocks in Hubei presented the highest average outdoor daytime IL (Avg. IL=46,230 lux & 23,322 lux) during the test. While the high-density mid-rise old and new villages with a very low average SVF presented dramatically lower average IL (Avg. IL=6,077 lux) than other sections in Hubei (Fig. 9). It is worthy noted that the urban parks presented the lowest average IL among the seven types of morphological patterns (Avg. IL=1,513 lux) due mainly to their high vegetation coverage. However, the canyon orientation also plays a significant role in influencing the solar admittance and IL. In subtropical Shenzhen, the space with a near West-East orientation has a better agreement with the trajectory of direct solar radiation. For instance, S-14 and S-22 all possess a very low degree of openness ($SVF_{S-14}=SVF_{S-22}=0.09$), but S-22 with an orientation of WSW-ENE has a higher capacity of solar admittance and daylighting during the daytime than S-14 (Avg. IL_{S-14}=3,450 lux; Avg. IL_{S-22}=11,025 lux) (Table 2 & Fig. 9).

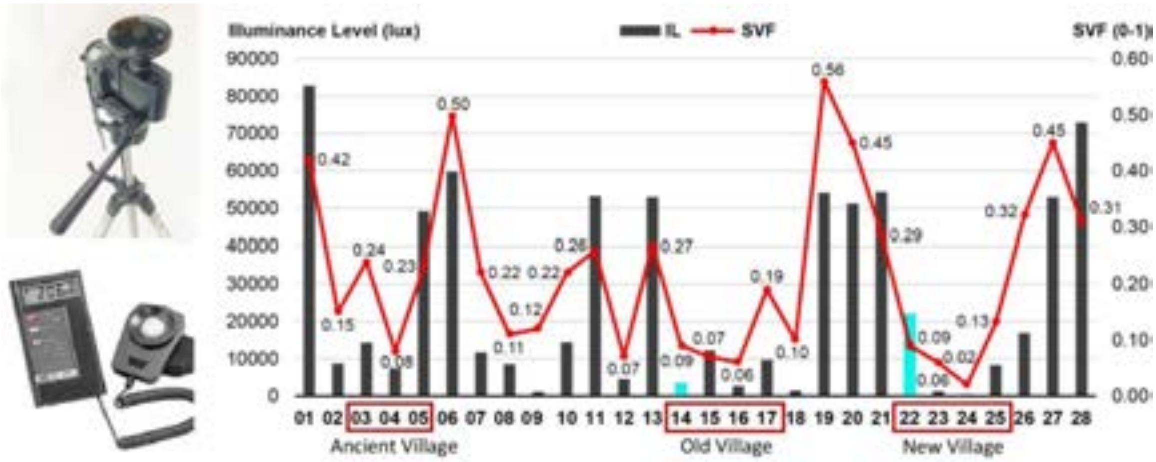

Figure 9: The average value of illuminance level of the 28 spaces in the daytime

4.2 Urban Heat Island Intensity (UHII)

Urban heat island intensity (UHII) was selected to examine the thermal environment in Hubei during Shenzhen's typical summertime.[3] Air temperature (T_a) and other microclimate parameters were automatically monitored and recorded at a pedestrian level (H=1.5m) by the weather meter of Kestrel 5500 for three days (Oct. 5-7, 2016, fairly clear and calm days, 25-32^{o}C, as shown in Fig. 10). The measurement of UHII was based on the real-time T_a of Shenzhen Reservoir, which is the nearest suburb area to Hubei (UHII = $T_a - T_{suburb}$). In general, all of the 28 tested spaces have higher T_a in the daytime than the night time. The highest average T_a was monitored in the high-density low-rise ancient village in the early afternoon (14:00 pm-16:00 pm) with the value reach 32.3^{o}C. While the lowest average T_a was observed in the urban park and low-density high-rise modern blocks during the night time with a value of 29.1^{o}C (20:00 pm-22:00 pm). Regarding the performance of each type of morphological pattern, they all presented significant diurnal air temperature difference with the difference reaching 1.1-2.2^{o}C. The open spaces presented the most dramatic diurnal T_a difference with the value of 2.2^{o}C, followed by the low-density high-rise modern blocks (1.8^{o}C), high-density low-rise ancient village (1.7^{o}C), medium-density mid-rise residential units (1.7^{o}C), urban park (1.6^{o}C), and the high-density mid-rise old and new villages (1.1 & 1.3^{o}C) (Fig. 11-a).

Figure 10: Kestrel 5500 weather meter and on-site measurement in Hubei Village Neighbourhood

[3] Shenzhen falls under subtropical monsoon climate with relatively long summer and short winter. With an annual range between 14.8°C-38.7°C, the average annual temperature is 23.0 °C. The duration of summer in Shenzhen is over 6 months (from mid-April to early November). According to the information of Shenzhen Municipal Meteorological Bureau, the summer condition should be achieved by uninterrupted 5 days with the mean temperature higher than 22°C.

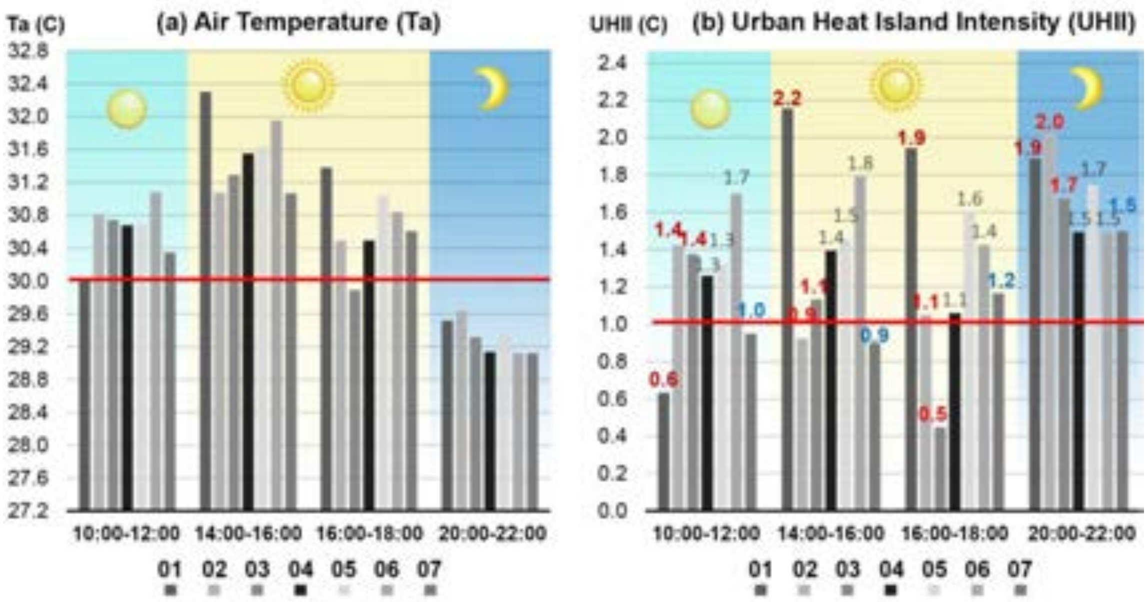

Figure 11: a) Air temperature of different types of outdoor spaces in Hubei; b) UHII of various types of outdoor spaces in Hubei

Note: 01) low density low-rise ancient village; 02) high-density mid-rise old village; 03) high-density mid-rise new village; 04) low density high-rise modern block; 05) medium density mid-rise newer residential unit; 06) open space; 07) urban park.

All of the seven types of morphological patterns occurred significant UHI effect, and each of them exhibited variations during different time-periods within a day.[4] The average UHII in Hubei in the night time (Avg. UHII=1.7^{o}C) was a little stronger than the daytime (Avg. UHII=1.4^{o}C) by 0.3^{o}C. UHII in the old village, new village, and urban parks presented lower values than other sections by 0.2-0.9^{o}C. The strongest average daytime UHII was monitored in the low-density low-rise ancient village in the early afternoon (14:00 pm-16:00 pm) with the average UHII reached to 2.2^{o}C. While the weakest daytime average UHII was observed in the high-density mid-rise new village in the late afternoon (16:00 pm-18:00 pm), which has the uniform building form and very low average degree of spatial openness (SVF=0.02-0.09; Avg.UHII=0.5^{o}C). Moreover, the low-density high-rise modern block showed a stronger UHII (Avg. UHII=1.1-1.5^{o}C) than the old and new villages of Hubei. It exhibited a higher UHII than the high-density mid-rise old and new villages in the afternoon by 0.3-0.6^{o}C, but lower in the morning and evening by 0.1^{o}C and 0.5^{o}C respectively (Fig. 11-b). Such situation reveals that the high solar admittance in the low-density high-rise modern blocks leads to high air temperature in the external spaces during the daytime and then result in a relatively uncomfortable outdoor thermal environment. While during the night, spaces embedded in these low-density high-rise modern blocks with a higher degree of openness and porosity are conducive to increase air movement, and thereby promote the release of heat gain in the daytime and the longwave radiation to the sky (Oke, 2011).

Order of daytime average UHII in different sections of Hubei (10:00 am-18:00 pm): Open space (1.6^{o}C) = high-density low-rise ancient village (1.6^{o}C) > mid-density mid-rise residential unit (1.5^{o}C) > low-density high-rise modern block (1.2^{o}C) > high-density mid-

[4] Currently, there is not a uniform standard for UHII, depends on the climatic and geographical conditions. According to Urban Heat Island Assessment Guide (2014) edited by Guangdong Climate Center (China), UHII can be divided into five levels i.e. UHII≤0.5C (no sensation), 0.5C<UHII≤1.5C (weak), 1.5C<UHII≤2.5C (medium/significant), 2.5C<UHII≤3.5C (strong), and UHII>3.5C (very strong).

rise old village (1.1°C) > high-density mid-rise new village (1.0°C) = urban park (1.0°C). Order of night time average UHII in different sections of Hubei (20:00 pm-22:00 pm): High-density mid-rise old village (2.0°C) > high-density low-rise ancient village (1.9°C) > high-density mid-rise new village (1.7°C) = mid-density mid-rise residential unit (1.7°C) > open space (1.5°C) = urban park (1.5°C).

5 Discussion

5.1 Environmental diversity and adaptive use

As analysed in the sections above, the high-density mid-rise pattern is the dominating morphological characteristic in Hubei, while there are also other patterns with different densities surrounded or embedded in this urban village neighbourhood. Governments and developers always presume that the urban villages with high-density mid-rise pattern naturally present a very "bad" environmental quality. However, there are various types of urban villages with multiple morphological patterns in the cities of the PRD, which possess different environmental qualities and degrees of urbanization. Even in the same urban village, such as Hubei, the morphological pattern in its different areas is distinct. It seems that systematic assessment of these urban villages' environmental qualities has unduly been ignored, while nearly all of the existing studies had a uniform conclusion that the urban villages presented "poor" living conditions and "intolerable" outdoor thermal environment in the summertime, such as Zhang et al. 2013, Wang et al. 2014, Li et al. 2014, Wu et al. 2015, and Liu et al. 2017. The measurement in this paper reveals that there was significant differentiation of UHI effects between different time-periods within a day in each type of morphological pattern in Hubei. Though not always, most morphological patterns exhibited relatively comfortable outdoor thermal environment in a particular time-period within a day. Such as the situation in the old and new villages with the typical high-density mid-rise pattern. In the morning, they presented a medium level of UHII ($UHII_{10:00\text{-}12:00}$=1.4 °C). During the early afternoon, they had a lower UHII than other morphological patterns while exhibited the highest UHII in the evening ($UHII_{14:00\text{-}16:00}$=0.5-1.1°C, $UHII_{20:00\text{-}22:00}$=1.7-2.0 °C, as shown in Fig. 11-b). The testing results have preliminarily questioned the uniform conclusion of the previous studies. Importantly, most of the outdoor spaces in Hubei are well connected by the organic street network. To some extent, such mixed morphological pattern shows a flexible manner and has high adaptability for the residents in Hubei and nearby neighbourhoods. Residents have many options to conduct outdoor activities refer to the locations, spatial scales and geometries, and thermal environmental performances during different time periods within a day rather than passively accept the monotonous, large-scale outdoor spaces in the modern high-rise residential areas. That makes Hubei become an adaptive urban neighbourhood and further promote community vitality in its different sections.

5.2 Self-organizing neighbourhood with mixed pattern

At present, many urban villages in the cities of PRD are still "struggling" with the fate of demolition and gentrification. This situation has set off a wave of debate on urban design and urban resilience, such as the discussion of a planned, regularized urban block and the unplanned, spontaneously developing informal neighborhood, as well as the recent debate on reevaluating the value of those older, smaller buildings for fostering and inheriting a city's identity and vitality. There are a lot of reflections and insights for urban design and management from the urban villages. Indeed, the physical space of neighborhood and functional vitality are closely related to and spontaneously formed by people's life experience. The mixed densities and multiple spatial patterns contribute to Hubei's diverse environmental performances and energetic outdoor atmosphere, which

thereby form a flexible mode of space utilization. Nonetheless, the diversity of social components, such as the differentiations of residents' daily routines, make Hubei an urban neighborhood with enduring vitality during day and night. Like Hubei, each urban village is a mature urban neighborhood complex, which includes not only multi-functions such as living, working, entertainment, and education, but also communities of various social strata. The urban villages have formed a particular niche within the urban system today. As the hubs of urban vitality, they offer adequate low-cost, convenient services to both the residents living in these urban enclaves and nearby urban residential districts. Meanwhile, the pattern of "big mixed residence and small settlement" (*Dazaju-Xiaojuju*) in these urban villages provides an excellent platform for residents from all social strata to communicate, educate, and influence each other. Such physically and socially mixed pattern has promoted a balanced neighborhood development concerning social structure, physical environment, industries, and indigenous culture. In this regard, the urban villages should not be arbitrarily deemed as the so-called "dirty-massive-bad" (*Zang-luan-cha*) settlements as the government and most of the media have reported. Instead, they need an objective and justice evaluation, especially for their role in maintaining and strengthening urban resilience and adaptability. In fact, many urban villages located in the city centers, such as Hubei and Huanggang Villages in Shenzhen, and Tangxia Village in Guangzhou, have been well operated with good living condition under their informal rules.

6 Conclusion: an ideological shift in the transforming era

To sum up, the urban villages can be characterized as an open neighbourhood with mixed morphological pattern, diverse population structures, and fruitful small-scale industries. In a context of urban villages, the morphological pattern provides the cultural medium, the diverse population structures act as the active factor, and the fruitful small-scale industries are the product of the interaction between the former two elements. What is more, the synergy of these three elements forms a mechanism to foster and maintain an environmentally and socially adaptive urban neighborhood. However, such an adaptive mechanism cannot be achieved through pre-planning because people's living experiences cannot be planned and framed in advance. In fact, its germination and evolution need time. When the neighrbourhood has already reached a mature status, government and developers should not hastily destroy it. If comparing the situation in some reconstructed urban villages, such as Dachong and Gangxia in Shenzhen, it can be found that the original high-density mid-rise built form with organic road networks and diverse spatial geometries have entirely been replaced by low-density high-rise tower blocks and large-scale, regularized street grids. Consequently, neighborhood vitality and environmental diversity in these "villages" are dramatically declined and hard to recover in a short run since most low-income populations can no longer afford such high-end housing. Even worse, such low-density, large-scale built form in China's cities not only increases the heat exposure but also possesses very high energy consumption, which further makes the new outdoor spaces thermally uncomfortable in the summer (Doherty et al. 2009: 10-13).

China has ushered in the era of urban redevelopment. Those widely distributing urban villages have become the primary target for demolition and reconstruction. The recently issued *National New Urbanization Report 2016* in China advocates a quality-based mode for urban development and redevelopment. More crucially, it prompts decision-makers and urban practitioners to carefully "diagnose" each piece of land in the cities and make the optimal "treatment." It is worth mentioning that the so-called "high-end-magnificent-classy" (*Gao-da-shang*) modern towers and big-scale malls do not always speak for economic achievement. Instead, they might be the eliminators of a city's

characteristics, the potential high energy consumers, and artificial heat emitters in most instances. Cities need multiple morphologies to build a self-adaptive and self-balanced network to respond the social and environmental changes. Instead of calling for the overall retention of the urban villages in the cities, this paper advocates a more rational attitude to excavate the distinct identity and features of each urban blocks. Such “identity” should not be limited to the physical form and image. It is of great necessity to make a holistic evaluation of our cities’ resilience regarding the environment, society, culture, and economy. Meanwhile, government and developers should not always be subjected to the "Big" and "High" ideological shackles, but need to be cautious about the impacts of those ongoing “subversive urban operations” (i.e. wholesale demolition and reconstruction) on the self-healing ability of the cities. Before making responsible, context-based decisions, people should return to the basic study of specific identities and conditions of various blocks within the city. Furthermore, local government can cultivate all residents’ master consciousness and stimulate their enthusiasm to create shared living environment and then gradually improve the life quality.

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SUSTAINABLE PREFAB HOUSES: CHALLENGING CONVENTIONS IN DESIGN, CONSTRUCTION AND OCCUPATION

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Abstract: *The Australian volume housebuilding industry has been reluctant to adopt more sustainable or innovative alternatives to well-established construction methods such as brick veneer (Dalton 2013:14). Furthermore, new dwellings have, on average, increased in size, instead of being designed to make more intelligent and effective use of space and resources (ABS 2010; Clune 2012). To date, architects and academic researchers have had little influence in this market, and instead focussed on cost-certainty with limited scope for experimentation and innovation (Dalton 2013:30&59). In order to overcome such barriers, the LP13 project was set up as a collaboration between the Applied Design Research Lab at the University of Sydney and the Industry Partner, who is a manufacturer and supplier of Structural Insulated Panels (SIPs) for large housebuilders. The project attempts to integrate a SIP system into a quality, sustainable and affordable prototype prefabricated house that would challenge conventions in design, construction and occupation of current offerings in the volume house building market. Design solutions were developed to appeal to and impact on this outwardly conservative market. The aim was to innovate by building on the existing SIP building system already on offer and to integrate it into an optimised overall solution that addresses issues of design quality, affordability and energy-efficiency holistically. The project makes improvements that address technical and construction issues (for example by optimising energy efficiency and speed of construction) as well as configuration (through layout and customisation options for the houses). The collaborative design approach of the project involved manufacturers, designers, engineers, expert consultants and house builders.*

Keywords: *Housing, Sustainable Design, Prefabrication, Energy Efficiency, Mass Customisation*

1 Introduction

This paper will describe the research process and results from the LP13 project at the Innovation in Applied Design (IAD) Lab at the University of Sydney. The LP13 project was born out of an ARC linkage grant, set up by IAD Lab director, Prof. Mathew Aitchison, in order to research the design and construction of quality, sustainable and affordable pre-made housing in Australia, using an integrated and holistic approach.[1]

The industry partner was a manufacturer of Structural Insulated Panels (SIPs) with Expanded polystyrene (EPS) core and Magnesium Oxide (MgO) boards externally. The advantages of this product are high R-values, high levels of airtightness, low levels of Volatile Organic Compounds (VOCs) from the MgO, which is also mildew resistant and highly durable. The industry partner's interest in this project was to demonstrate that their SIPs can be used to build more efficient, sustainable and affordable housing through the design and building of a pilot project house.

Working with industry on applied research projects with real building outcomes carries its own risks - the same risks faced within the commercial realities of the industry itself. These include: uncertainty around financing and partnering; complicated decision-making processes that go outside the control of the research team; tight timelines; and, complex communication issues. Cumulatively, these factors come to bear in ways that “pure” research projects are less exposed to. Nevertheless, the purpose of applied research is to test ideas and strategies, not in the rarefied conditions of the Lab or university, but the terminal environment where the final product will be designed, built and used. This process, which might appear confusing and disjointed, still holds many valuable lessons that are shared in this paper.

2 Project References

The industry partner had previously worked in areas of innovation of housing design and some of these ideas also influenced the LP13 project. One example is a collaboration of Frazer Paxton Architects on called the ‘Grow Your Own Home’ project. This was a modular house that could expand over time, so a family could add on extra modules as needed (Fig. 1). Members from the industry team had also previously been involved with disaster relief housing in Haiti where they worked with local communities on the design of prefabricated house types that would best suit their needs.

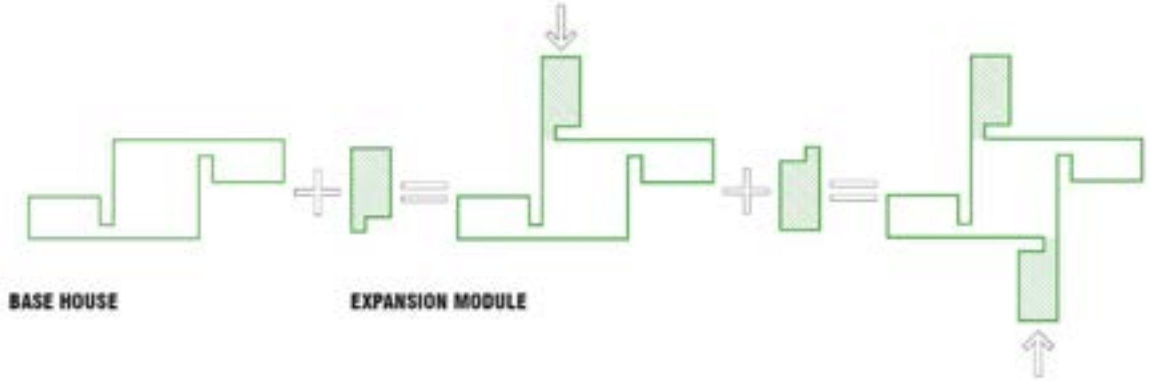

Figure 1: ‘Grow Your Own Home’ project by the Industry Partner and Fraser Paxton Architects
Source: Correspondence from the industry partner

As part of the literature and references review, other projects were studied where universities or research organizations collaborated with industry and consultants on creating sustainable prototype projects. Two examples are the sustainable retrofit project HouseZero, a collaboration between Harvard University and Snohetta (Snohetta 2017) and also the Illawarra Flame house by the Sustainable Research Building Centre at the University of Wollongong (SBRE 2017). In terms of research method, the relevance for LP13 is the holistic approach; both of these reference projects involved incremental improvements on various aspects of the building, in order to achieve the overall aims of designing and building a more sustainable home.

Another prototype house that influenced the approach taken was the Lighthouse in the UK, constructed in 2007 on the BRE Innovation Park in Watford and designed by Sheppard Robson Architects (Fig.2) (Shepard Robson 2007). This project also uses a SIP system (by Kingspan) and incorporates design and technical innovations in terms of layout, efficient building fabric, ventilation and renewable energy generation, in order to achieve the highest code for Sustainable Homes in the UK – a rating of 6.

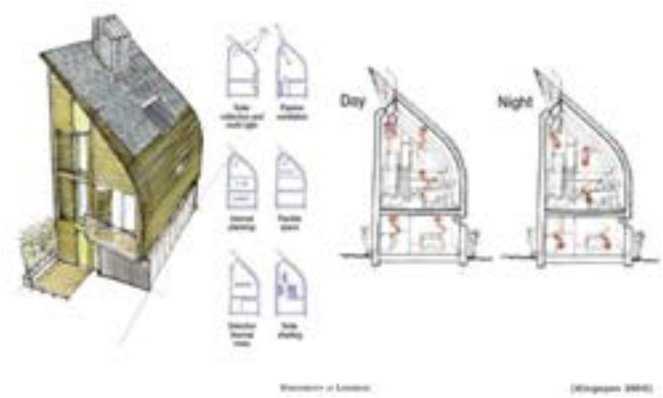

Figure 2: Lighthouse by Sheppard Robson Architects
Source: https://www.slideshare.net/WT4603/wt5912-2012-u6w7

In terms of design innovation, two reference research projects are particularly relevant: Diego Ramirez-Lovering's work on housing flexibility (Ramirez-Lovering 2012) (Fig.4), and Damian Madigan's work on infill housing in established suburbs (Madigan 2017). Both projects challenged housing design conventions by rethinking the way familiar housing typologies can be planned and used. This was particularly relevant for the floorplan layouts of the LP13 project.

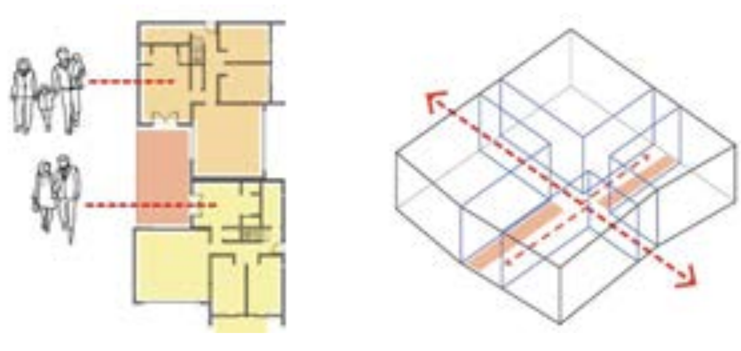

Figure 3: Diego Ramirez-Lovering 'The Space of Dwelling'
Source: Ramirez, 2012:82

3 Briefing and Problem Definition

The initial project aims were developed through collaborative briefing workshops with the industry partner to better meet their needs and business goals. The complexity of the research question and aims required an approach that addressed multifaceted aspects of the problem, which became apparent in the initial briefing meetings. Issues raised included: an integrated design approach with the engineers; understanding how this product fits into the market (specifically the affordable housing market); flexibility in architectural expression; meeting high sustainability targets; refining product engineering; and, initially, the goal of building a completed prototype house (Fig. 4).

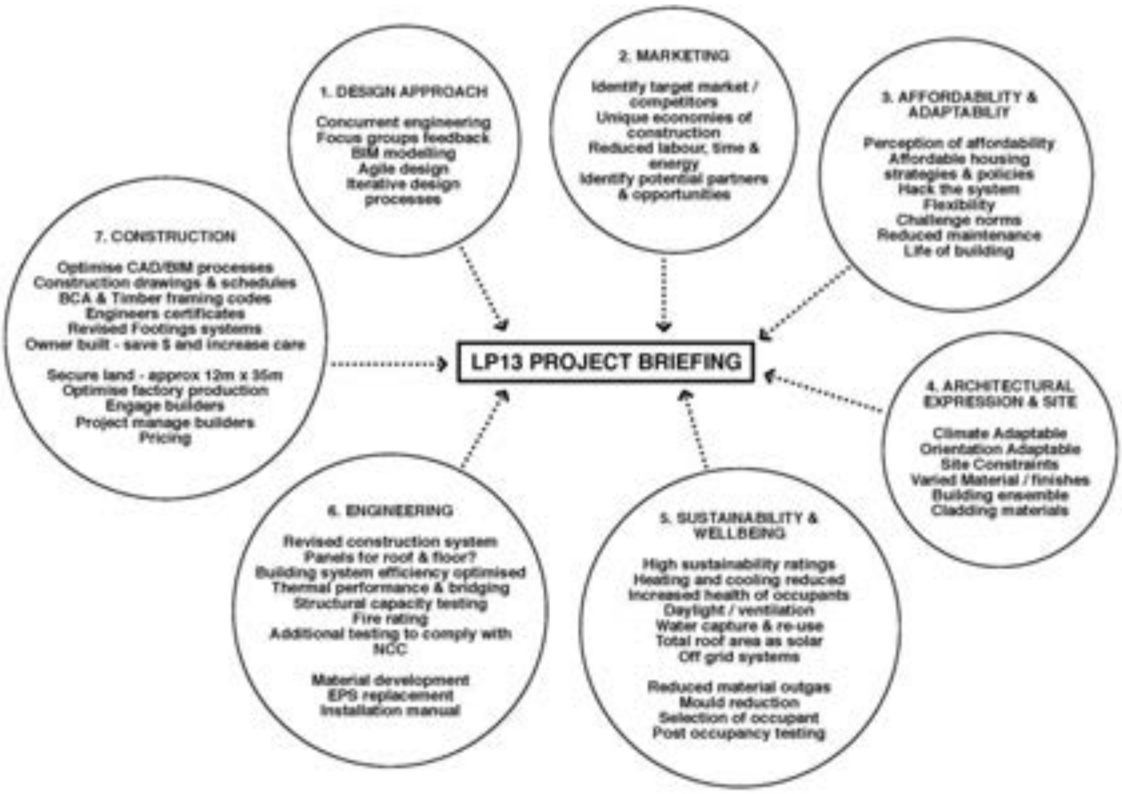

Figure 4: Mapping of project considerations from industry partner briefing

In the volume house building market, two areas in particular stood out to us with significant scope for innovation and improvement. Firstly, energy-efficiency standards in low-cost volume house building in Australia are notoriously poor (Fig.5). The example image shows a suburban house in Gawler (SA) under construction to basic specifications. Although incomplete, the construction already shows significant weak points in the thermal envelope, for example: aluminum window frames without thermal breaks, single glazing and gaps in the timber framing where it will be difficult in practice to install effective insulation.

Figure 5: House under construction near Gawler, South Australia, 2015.
Photo by David Kroll

Secondly, floorplans often prioritise quantity over quality of space and usability (McMansion syndrome) (Ramirez-Lovering 2012:45-46). Through the initial workshops and benchmarking research, the LP13 project objectives were further refined to develop a prototype house designed with the Industry Partner's SIP product at an affordable price point but without the usual trade-offs in design quality and energy efficiency. This project therefore attempted to meet higher sustainability targets and offer a smarter design and layout than typical for affordable volume house building.

The project aims were refined in more concrete financial terms by carrying out a survey of competitors in the market of volume housing, pre-fabricated and sustainable houses (Fig.6). One of the cheapest houses on the market were project homes by Statesman Homes in South Australia with a base price of $735 per m^2 (construction cost). Modular prefabricated homes from Ecoliv cost around $2500 per m^2. Highly energy-efficient prefabricated offerings from Archiblox are priced around $3500 to $5000 per m^2. While the comparison based on m^2 prices is difficult given exclusions and inclusions, which were also reviewed, this benchmarking of m^2-costs was a useful exercise to understand where the project would sit in the market. The goal in this project was to be affordable but not necessarily to develop solutions that are even cheaper to build than low-cost (but also low-quality) housing that is already on the market. Instead, the aim was to develop solutions that offer other benefits at a similar price point and that support affordability in the long run in terms of running cost and enhanced usability.

Figure 6: The breadth of the market: Homes by Statesman, Ecoliv and Archiblox.
Source: http://www.statesman-homes.com.au/, https://ecoliv.com.au/, http://www.archiblox.com.au/

In addition to assessing how the project fits into the market, a survey was undertaken of the regulatory context of affordable and social housing in Australia. This survey was useful so that potential regulatory barriers could be identified – aspects of which may need to be challenged if they contradict the project aims – and to allow the design to be compliant for as broad an application as possible. Multiple sites were under consideration at this stage of the project, so codes and regulations were mapped out that would affect the way affordable housing is designed and built across four states that were surveyed (Fig.7). This survey suggested that NSW has the most stringent design guidelines for affordable housing and was therefore used as the basis for the first design iterations.

Figure 7: Affordable housing initiatives and guidelines

The kinds of areas regulated in the surveyed design codes were: site planning, interior layout, building construction and finishes, as well as energy-efficiency and sustainability. In this cross comparison, the Livable Housing Design guidelines (LHA 2017) and the NSW FACS Design Standards provided the most concrete guidance (FACS 2017). A

design that takes these into account should therefore be as versatile as possible within the affordable housing market across Australia. The overall size of the houses and spaces was one of the key aspects in these guidelines. The challenge was to fit the larger size rooms of the houses designed to a Livable 'platinum' standard within the confines of what was considered an acceptable maximum overall dwelling size.

4 Design Development

In terms of design, the research employed an iterative process, which can be broadly outlined in four main steps: Step 1 was to develop a prototype concept design. Step 2 was to refine this design through energy-use simulation and input from our engineering research partners. Step 3 was the development of specifications, as well as external envelope detailing and design options. Step 4, the final step, was to build a full size, actual house to demonstrated these principles in built form. For reasons outside the control of the research team, this prototyping was cancelled. Nevertheless, the findings of steps 1-3 hold great value for future work.

The LP13 prototype design developed in steps 1-3 challenges volume suburban housing by providing an alternative solution that offers improvements in three areas in particular: a) increased adaptability and flexibility; b) improved thermal efficiency; and c) customization to site and user preferences. The iterative process and considerations that underpinned the development of this design solution will be discussed in the following key steps.

4.1 Step 1 – Prototype Concept Design

The site dimensions of 12.5 x 30m were based on the industry partner target market and on suburban housing that their volume house builder clients build. The first step was to test the floor area standards from the above guidelines by applying them to a three-bed house floor plan layout. Several plan options were developed: a compact option, an L-shaped plan type, as well as two long and narrow plan types (Fig. 8). All these options satisfied the functional requirements, but they did not sufficiently challenge the floor plan arrangements that can be found in other volume house building.

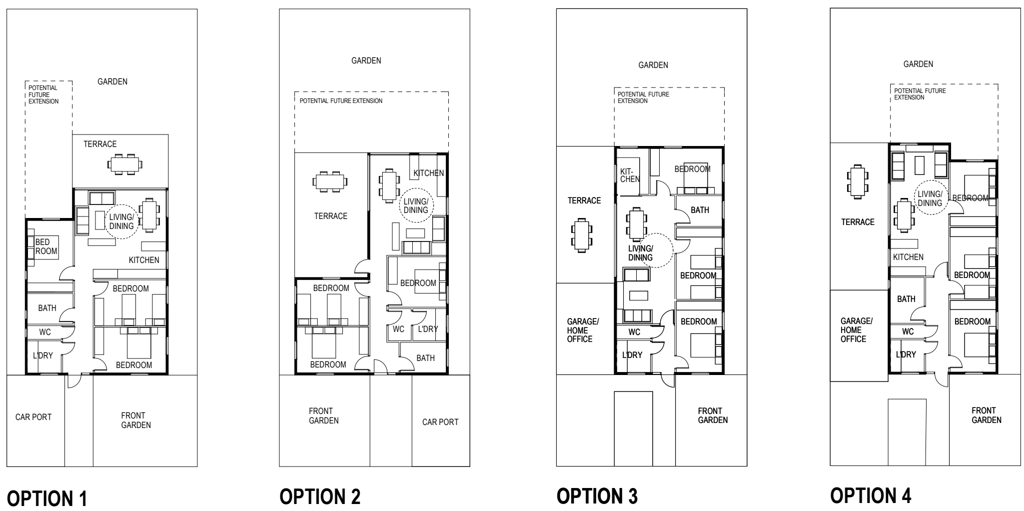

Figure 8: Initial test floor plans

In response to this first design test, strategies were introduced to challenge aspects of volume house building that had been identified as problematic earlier. In particular, adaptability and flexibility could be used as cost-effective ways to make the proposed homes more user-friendly and affordable in the long run. The comprehensive survey of flexible design tactics by Tatjana Schneider and Jeremy Till was used as a key reference (Schneider and Till 2007) (Fig.9) and three strategies were identified in particular that were useful for the LP13 project:

1.) Functionally neutral and reconfigurable spaces that could change use over time
2.) Slack space that could be appropriated, particularly outdoor space
3.) Structural design that supports flexibility

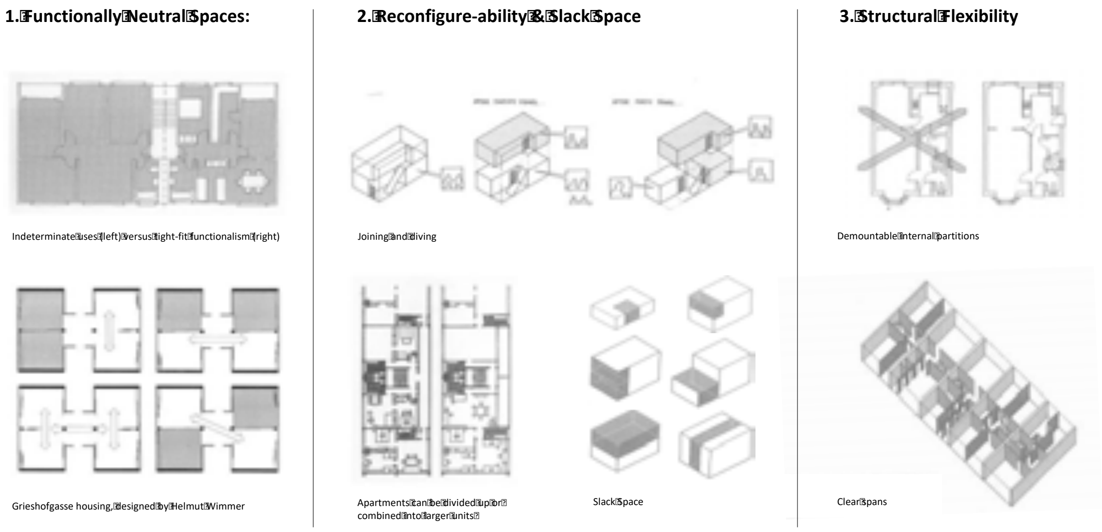

Figure 9: Strategies for achieving flexibility that influenced the LP13 design proposals
Adapted from: Schneider and Till 2007:181-200

These strategies informed a new series of concept sketches and design iterations, developed in workshops by the architectural team. These new design concepts of elastic volumes move away from an 'Existenz Minimum' (bare essentials) approach to affordable housing. The floorplan is less compact than the previous versions but it makes use of the low-cost wall system to offer an overall more generous spatial experience. This revised design concept offers a number of advantages that a basic, compact form could not provide (Fig.10):

1.) Functionally neutral and re-configurable. Each volume is large enough to accommodate either 2 bedrooms, a Living/Dining/Kitchen area, a small granny flat or a home office and kitchen.
2.) Slack space & expandability. The volumes are spaced apart to create slack space that can be used for storage, terraces or laundry, for example, which suits an 'outdoor' lifestyle, or which could be filled in by an extension at a later date if required.
3.) Structural flexibility. The external walls of each volume would be built with the Industry Partner's SIP system and would be structural. The internal walls would not be structural and could therefore be reconfigured.
4.) Thermal envelope hierarchy. This arrangement of volumes enclosed by SIP walls creates thermal zones that could potentially be heated and cooled separately.
5.) 'Elastic' volumes. The concept could be adapted to sites of different widths.

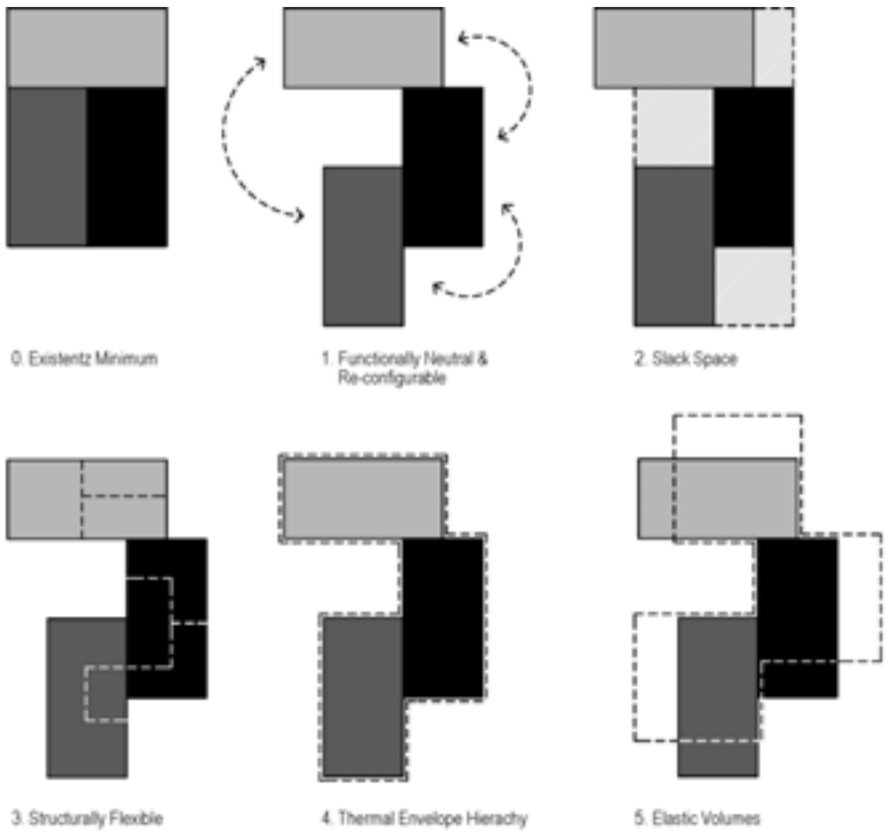

Figure 10: Diagrams of design concepts

The application and testing of these principles can be seen in a series of draft floorplans (Fig.11).

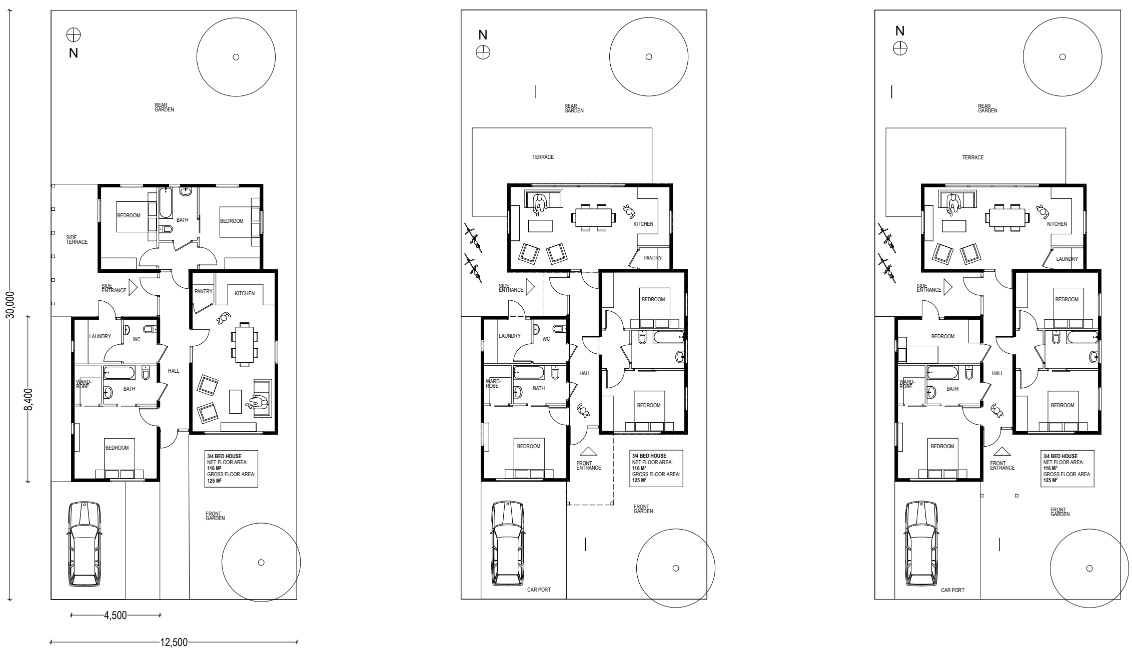

Figure 11: Floor plan options

This first sketch design was further refined to align with complying development rules within NSW, because at the time, this was the most likely location for the prototype (NSW 2008). The revised designs could achieve planning approval swiftly for a potential site in NSW and it would also be likely to be closer to the expectations in other states. Six different floor plan options emerged out of this compliance check and its potential implications on the layout (Fig.12). A key alteration was prompted by the requirement of a carport or garage to be set back 1.5m from the front façade of the building. The first option was chosen as the preferred design because the plan successfully retained the courtyard slack space and also incorporated the required garage.

Figure 12: NSW Complying development floor plans

The aforementioned Livable House Design guidelines were re-applied to this preferred floor plan layout. Option one shows the initial configuration with a garage as a 3-bedroom house (Fig.13). However, as circumstances change, the garage could be converted into an extra bedroom and bathroom (Fig.14). Eventually the eastern portion of the building could be converted into a self-contained 'granny' flat for extended family or a source of income for the main household (Fig.15). The final layout therefore incorporates the advantages of a more flexible house plan that can accommodate changes in household circumstances.

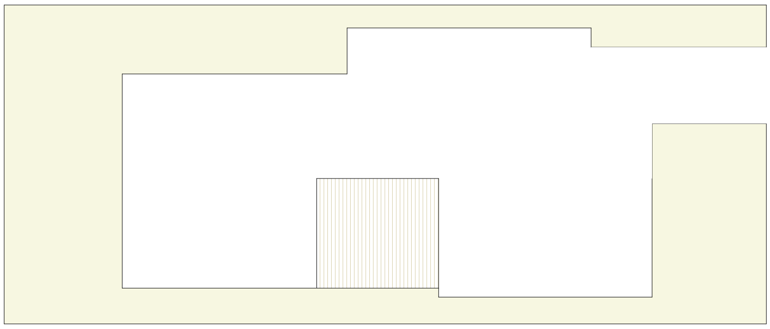

Figure 13: Option One: Three bedroom plus garage

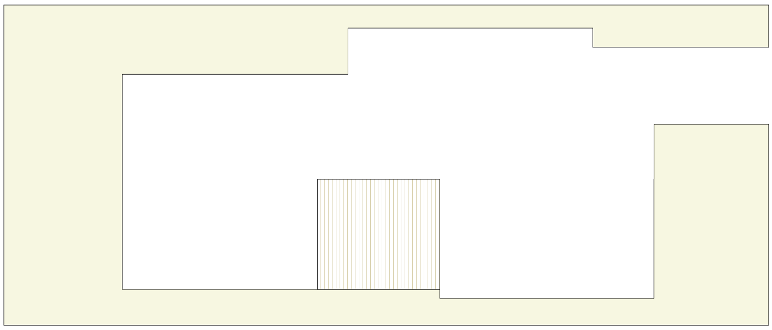

Figure 14: Option Two: four bedrooms

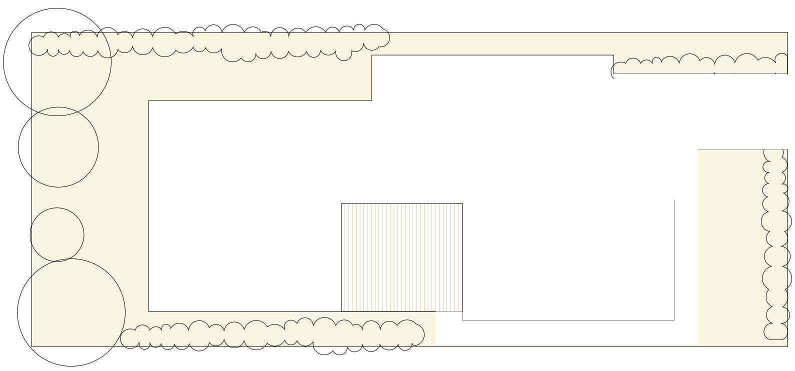

Figure 15: Option Three: Two bedroom plus granny flat

4.2 Step 2 – Energy-Use Simulation and Engineering

Apart from challenging conventions in housing floor plans, another important aspect was achievable energy-efficiency in relation to the targeted price point. A first step was to identify the standards and guidelines that were used for rating energy-efficiency for housing in Australia. The most common is the NatHERS rating. For NSW, Basix is a key rating tool also used for code compliance. Furthermore, the passive house standard was used as a more ambitious benchmark to assess the LP13 project against, taking into account aspects such as airtightness and thermal bridging that are not as relevant for these other rating tools.

To make sure that the consequences of these different standards and guidelines were translated into the construction, their impact on the specifications was documented. These would influence parts of the design including: site works, construction materials, insulation, windows, doors, power, ventilation, water, sanitary, joinery, metalwork and finishes. Some aspects of the guidelines and standards contradicted each other and also conflicted with the project aims. For example, the NSW FACS guideline explicitly states that there should be no double glazing in affordable and social housing designs, although it can improve energy efficiency (FACS 2017). In the spirit of the project, such conflicts were addressed as part of the challenge to rethink affordable housing.

In order to rate the house design and achieve the energy-efficiency target, a survey of energy assessment tools was undertaken to identify those appropriate for the LP13 project. The tools identified were the Firstrate5 tool as a quick way to evaluate design options for NatHERS. Sefaira was used as a more general tool to estimate the overall energy use of various design iterations. The PHPP package and DesignPH tool would be used for assessing building performance in relation to the passive house standard. Another energy assessment tool which was considered was Design Builder. Furthermore, one of the engineering PhD students, Gerardo Soret, supported the project by providing thermal bridging analysis, which will be further outlined below.

For the NatHERS assessment, a series of tests were run to optimize the design for a potential site in Adelaide (then, the most likely as a location for the Step 4 prototype build) and later for a site near Sydney (Fig.16). A 6-star rating would be sufficient to achieve BCA compliance. With the right orientation, however, an initial test showed that an 8-star rating could be achievable when incorporating the Industry Partner's SIPs wall system, a waffle pod ground floor slab, R4 insulation in the ceiling and double glazed UPVC windows.[1]

[1] Note for final paper presentation: we intend to calculate the added cost for these specifications over a basic NatHERS pass. These should be available for the presentation in January.

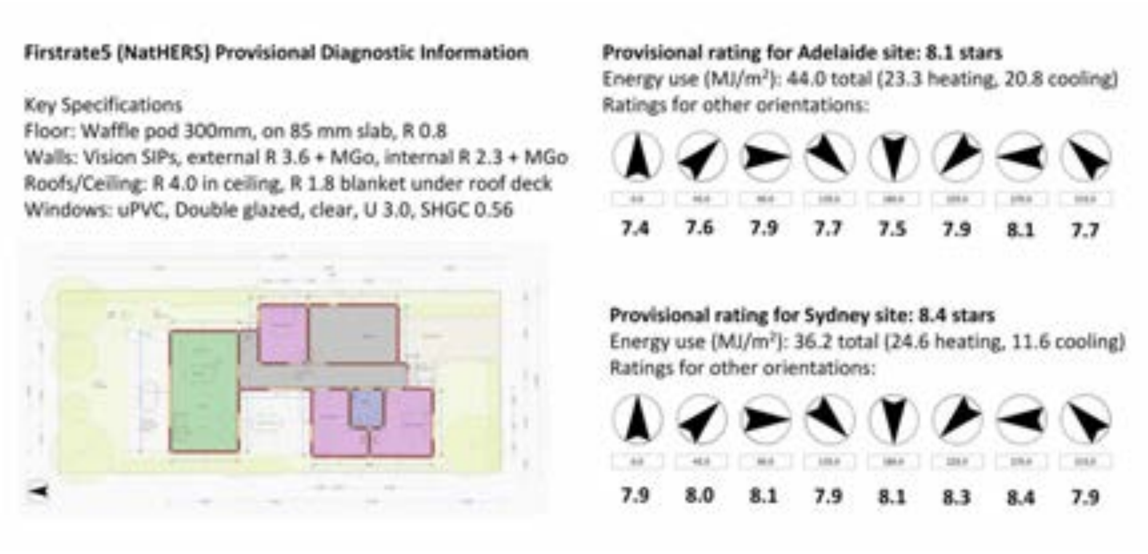

Figure 16: NatHERS testing

The Sefaira tool provided a better breakdown of where additional improvements could be achieved and where most of the heat loss happens (Fig. 17). Areas of improvement, according to this assessment, would be additional floor insulation and also increased airtightness. Sefaira was also used for an initial assessment of how much roof area for Photovoltaics (PV) would be needed to achieve a zero-energy home, as a potentially enhanced version of the low-cost house prototype. Although it exceeds the scope of this paper, a passive house assessment is underway and will be published in a forthcoming paper in collaboration with Dr. Carlos Jimenez-Bescos.

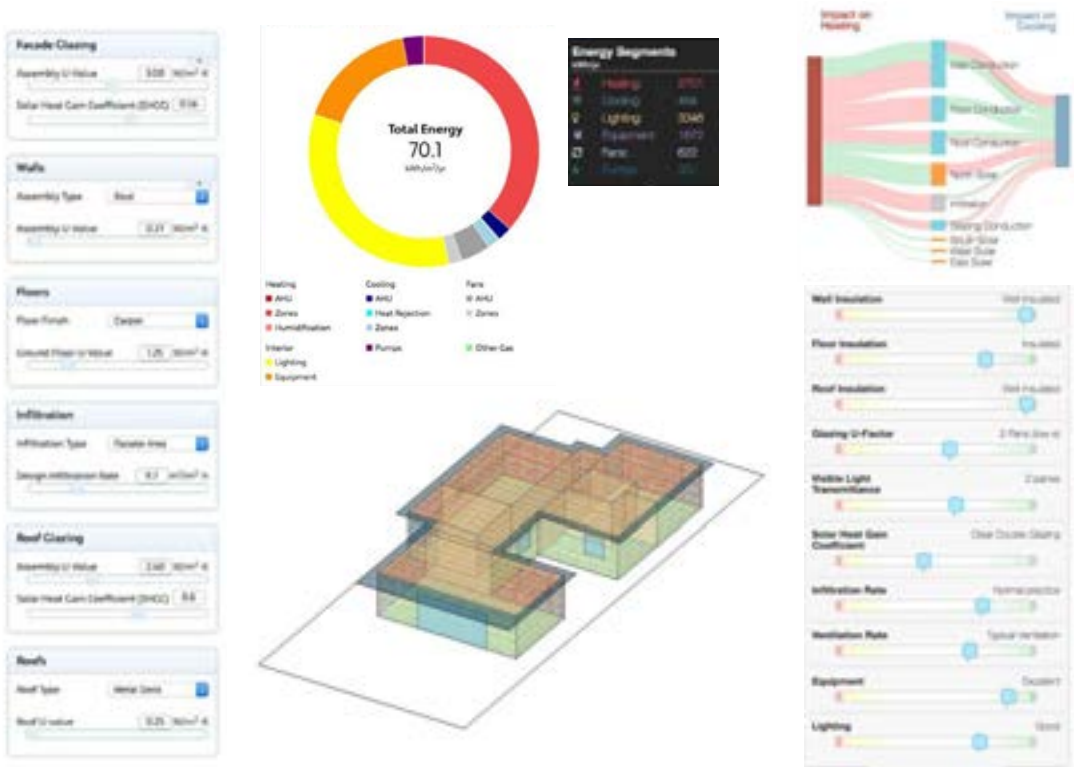

Figure 17: Sefaira testing

4.3 Step 3 – Detail Specifications and External Envelope

A key objective of the research was to improve the efficiency of the panel product (Fig.18). The cutting SIPs on site, for example, not only reduces the efficiency of construction by creating waste and adding time and Labour cost, but it also makes it harder to control the consistency of the thermal envelope and increases chances of air leakage and thermal bridging. Several solutions were investigated. To facilitate BCA compliance, a secondary timber support structure was introduced as a structural spline, which also improved fire performance. Although the panels are structurally self-supporting without the timber studs, in the event of fire, the EPS core could melt and the structure of the whole system could be compromised.

Figure 18: SIP project by the Industry Partner's - Adelaide Hills

Throughout the design development and benchmarking research, the two engineering PhD candidates at the University of Queensland, Gerardo Soret Cantero and Aaron Bolanos Cuevas, researched the thermal, fire and structural performance of the Industry Partner's SIP system. Soret calculated the thermal performance of a previous system which used laminated MgO splines between the SIPs. The system performed well in terms of thermal mass, but poorly in terms of thermal bridging and also constructability (Soret 2015, 2017). A further thermal analysis simulation of the new SIP wall system showed that the overall R-value would be markedly reduced by the introduction of timber studs versus a pure SIP system (Fig.19). The final version of the prototype structure should therefore be designed to reduce the timber framing as much as possible and replace the studs with SIP splines where possible, without compromising the structure.

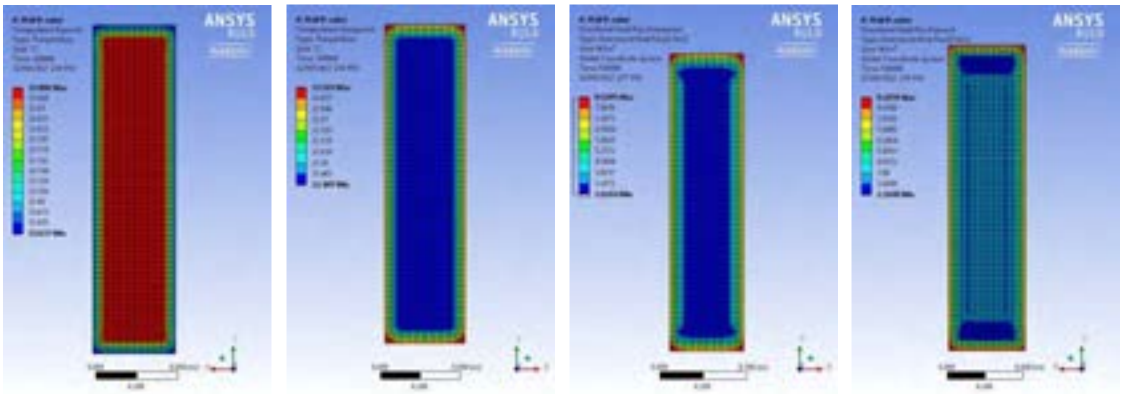

Figure 19: Industry Partner's SIP – Thermal bridging analysis

Cuevas tested how the EPS responded to various levels of heat. The main recommendation from this test was that the entire perimeter of the SIPs would need to

be encapsulated to protect the EPS core from direct exposure to fire. Fire and/or excessive heat could comprise the structure of the system once the EPS melts.[2]

As part of collaborating with engineering experts, the building's construction details were to be developed to ensure their methods of encapsulation and potentially alternative methods for framing were applied. One of the key construction details was the roof system. While the wall system had gone through various iterations of detailing, the interface with the roof and type of roof system was less well developed. These details would be crucial for energy efficiency, buildability and cost. After discussions and a survey of common roof systems used for cost-efficient housing, three potential options were identified. The first was a traditional steel roof system with rafters. The second option was a truss roof, with the main part of the insulation at ceiling level and a ventilated attic. The third option was a SIP roof with rafters below to achieve the required spans. (Fig. 20).

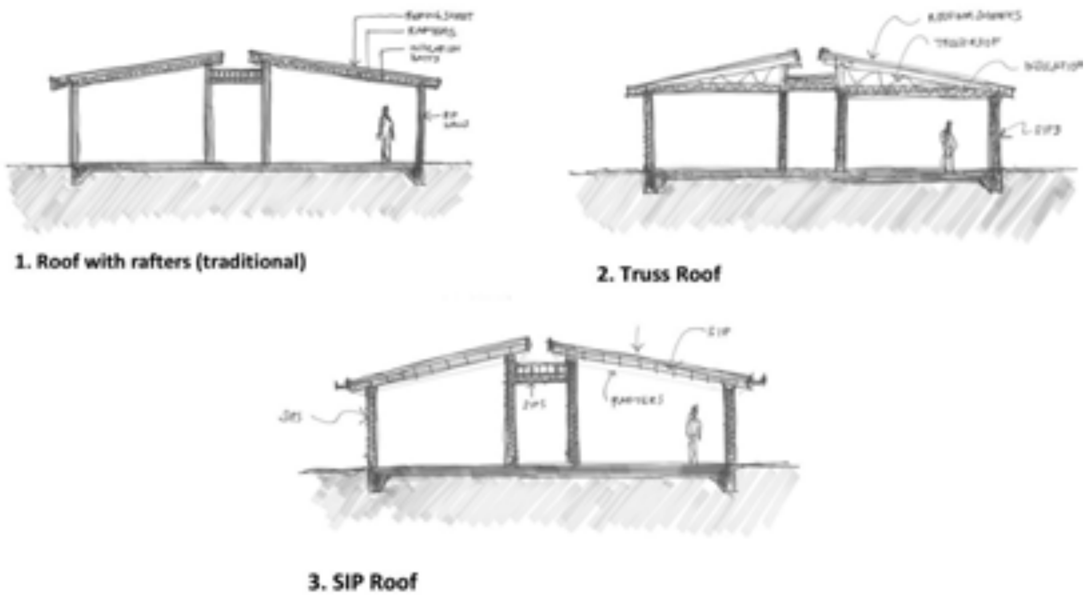

Figure 20: Roof construction system options

These roof construction system options informed an external envelope design studies matrix that was used as a design development and benchmarking tool (Fig.21). Part of the project brief was to target a volume house building market, rather than an exclusive 'high-end architecture' market. It was therefore important not to impose architectural tastes but to offer options and design flexibility to suit different user preferences. The matrix demonstrated that the same floor plan could be used with different roof types to achieve vastly different architectural expressions. The hip roof was a favoured option because of its mass-market architectural appeal and cost-certainty. Others preferred a skillion or gable roof version, with a more contemporary design appeal. By tabling the various options, it was easier to go through an evaluation process to identify the one that best meets the project aims.

[2] Cuevas currently continues his PhD research on the structural integrity of a system with a focus on achieving a system that relies on as little timber framing as possible, taking account of both fire and structural loads.

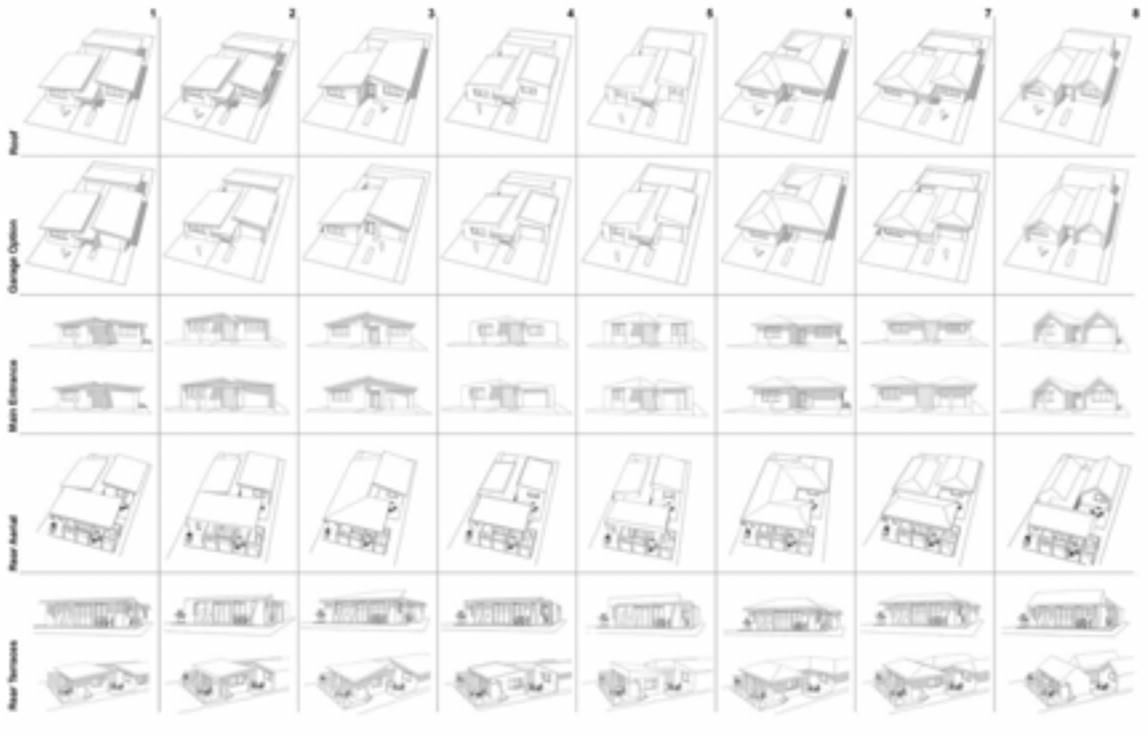

Figure 21: External Envelope - Design Studies Matrix

5 Conclusions

This industry-linked research has challenged assumptions and conventions of what could be achievable in affordable house building, in terms of energy-efficiency and design quality. Overall, this project is a promising starting point rather than an endpoint. It has also served to find leading research in the field and incorporate these lessons in new ways. These lessons, and the finding of this study, can be transferred into further work in this area and can make a contribution in transforming Australia's housing for a more sustainable future.

The designs, that were developed for an affordable housing market, demonstrated that a high level of energy efficiency can be achieved with cost-effective construction specifications. The additional measures required, such as double glazing and R4 ceiling insulation, can change the house design from a bare pass to an 8-star NatHERS rating and are not as prohibitively expensive as assumed.[3] In the design and benchmarking process, it has also become clear that achieving strict standards, like the passive house standard for our example sites in Adelaide and Sydney, has less to do with expensive specifications and is more about considered planning and construction.

Furthermore, the designs developed challenge floor plan conventions in volume house building. The project showed that innovative planning of the houses can make a significant difference for long-term usability and flexibility. These aspects are particularly important for a smart and sustainable housing future, where the mono-functional suburban house may no longer be achievable for most. The findings of this project suggest that volume house building can do more than be designed for and serve the average family model of 2 parents and 2 children. This ideal model only applies to a limited number of households and houses will need to be able to adapt to other scenarios when required throughout the householders' lifetime. The proposed prototype

design provides an alternative solution to suburban housing that is potentially adaptable to different sites and user preferences, more flexible in its long-term use, and offers improved thermal efficiency.

Future research avenues could include: cost-benefit calculations and comparisons to traditionally built volume housing offerings; comparative energy-efficiency simulations; optimised construction detailing; design studies of adapting the concepts to another site; and, the ultimate test of constructing a prototype house.

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RESILIENCE, RESIDENTIAL BUILDINGS AND RATING TOOLS IN AUSTRALIA

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Abstract: *Resilience is emerging as an important component of building and urban design. The Rockefeller Foundation has established the 100RC (Resilient Cities) to demonstrate the scope of issues and the ways in which different cities globally are addressing their issues and challenges. Sixty-eight resilience issues have been identified; some are social, economic, governance or environmental in nature. Our ability to be resilient to chronic and acute resilience issues such as overpopulation and flooding, and to cope with resilience challenges such as heatwaves or lack of affordable housing, increasingly concern city authorities. Rating tools provide benchmark and objective indications of sustainability within buildings or precincts. Since 1990 many have been launched, for example BREEAM, BASIX, and NatHERS. They are developed by government and/or private bodies and can focus on a limited issues such as energy and water, or a wide range of metrics including social and environmental criteria. Some are mandatory, imposed by government, such as the European Energy Performance Certificates (EPCs) others are voluntary. Some measure design and construction sustainability, whereas others focus on operational or in use sustainability. A number of questions arise with respect to rating tools used to evaluate building sustainability. For example, what choices are available to people in respect of new build and adaptive reuse for housing? And, given the focus here; do any of the tools, explicitly or implicitly, adopt resilience issues? This paper reviews two Australian sustainable building tools in the residential sector and evaluates their potential contribution to increasing resilience in the two 100RC cities; Melbourne and Sydney.*

Keywords: *Residential, Resilience, Housing, Sustainability, Rating tools*

1 Introduction

Many cities worldwide are developing resilience plans to address issues such as population growth, urbanisation and the impacts of climate change. The Rockefeller Foundation set up the 100 Resilient Cities (100RC, 2016) to help cities to meet the physical, social and economic challenges they face. The 100RC supports the adoption and incorporation of acute and chronic manifestations of resilience. Acute or shock events include bushfire and floods. Chronic stresses undermine and weaken the fabric of a city on a daily or cyclical basis include inefficient public transport systems; high levels of unemployment; and chronic shortages of water and food. In tackling shocks and stresses, a city becomes more able to respond to adverse events, and is better able to deliver basic functions in both good times and bad, to all citizens. Melbourne, Australia was among the first wave of 32 cities to join the 100RC network and published its resilience strategy in May 2016.

The 100RC has identified and collated 68 challenges facing a number of global cities. For example, weather related issues can include flooding or heatwave and the way buildings are designed, built and adapted can impact resilience. Residential buildings provide shelter for citizens and need to fulfil requirements of safety and have resilience built into them. Clearly different solutions suit different cities and locations, and have different degrees of importance.

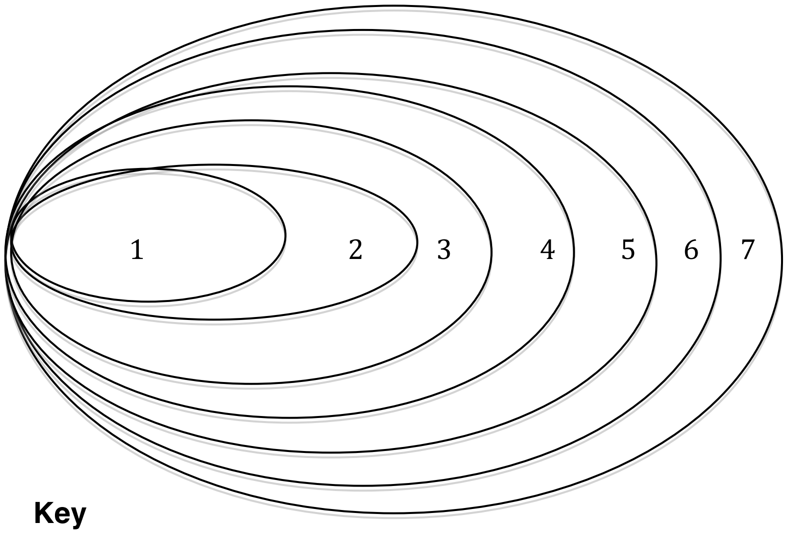
In 2016 the Australian Sustainable Built Environment Council (ASBEC) outlined a national Plan Towards 2050 Net Zero Emissions Buildings; targeting 100Mt GHG savings and A$9b savings through existing building retrofits as part of their policy solution (ASBEC, 2016). This is an encouraging development as they see building retrofit as the second highest opportunity for savings after, distributed energy which is estimated to deliver up to 300Mt GHG savings, whereas savings from appliances and equipment delivers 71Nt GHG and new builds 47Mt GHG savings to 2050 (ASBEC, 2016).

Building rating tools have been around since 1990 to enhance sustainability and include criteria relating to energy and water efficiency, embodied energy, waste and so on. Depending of the amount of measures included various rating tool points are awarded. However should resilience issues be incorporated into these tools or, are they already there implicit in existing criteria? What choices are available to people in respect of new build and adaptive reuse for housing in Australia? And, given the focus here; do any of the tools, explicitly or implicitly, adopt resilience issues?

2 Resilience issues

Our ability to be resilient to the 68 chronic and acute resilience issues such as overpopulation and flooding, and to cope with resilience challenges such as heatwaves or lack of affordable housing, increasingly concern city authorities. Resilience impacts at many scales, from building to worldwide (see figure 1) (100RC, 2016). Measures taken at the building level impact up to a global level. After building scale, there is the suburb, district or precinct scale. After the district is the city scale and the level where policy is made and executed and governance applied. After the city scale come metropolitan areas, followed by the national scale, and here national policy and governance decisions are made and executed. After national, comes the regional scale such as Europe, whereby some collective decision-making may be exercised. The final scale is worldwide or global.

Figure 1 Resilience Scales



Key
1 Building
2 District or Precinct
3 City
4 Metropolitan area
5 Country
6 Region
7 World

(Source: Adapted Rotterdam Resilience Strategy, 100RC, 2016).

3 The concept and qualities of resilience

The concept of urban resilience is used in policy and academic discourse (Meerow et al, 2016; NSW Government Planning and Environment, 2014) to explain complex socio-ecological systems and their sustainable management here; cites and buildings. Theorists claim resilience offers a framework for dealing with future uncertainties (Meerow et al, 2016).

Resilience is seen as positive action to reduce vulnerability to climate change, natural disasters and/or man-made disasters such as economic downturns or collapse. Resilience is an attractive perspective with regards to cities, which are complex adaptive systems (Batty, 2008) and have changed from 10% of the population living in urban settlements in 1990 to 50% in 2010 (UN DESA, 2010). Towns exceeding 50,000 people, use 71% of global energy related carbon emissions, though they cover only 3% of the area. In accommodating growth and expansion, cities and their buildings need resilience.

Resilience literally means to bounce back, though in the 19th century, evolved to embrace adversity (Alexander, 2013). The term is used by many disciplines, which understand and interpret it differently with five attributes emerging as shared qualities of urban resilience;

(1) Equilibrium versus non-equilibrium,
(2) Positive versus negative conceptualisations,
(3) Mechanisms of system change,
(4) Adaptation versus general adaptability and;
(5) Timescales of action (Meerow et al., 2016).

Meerow et al (2016) defined urban resilience as ability; *to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity*. The 100RC define urban resilience as *'the capacity of individuals, institutions, businesses and systems within a city to adapt, survive and thrive no matter what kind of chronic stresses and acute shocks they experience'* (100RC, 2016). In both urban resilience is dynamic and changing.

Cities and urban systems are complex networked systems (Desouza & Flanery 2013:91); conglomerations of ecological, social and technical components (Ernstson et al 2010). Cities and hinterlands are highly inter-dependent with delineation of boundaries difficult, as some systems, such as water supply, extending beyond physical city limits.

Another issue is equilibrium; with scholars debating single state, multiple-state and dynamic non-equilibrium (Davoudi et al, 2012). Single state equilibrium is the ability to return to a previous state of equilibrium post disturbance; prevailing in disaster management where post flood, buildings are reinstated. Multiple-state equilibrium recognises many states of equilibrium in any system. Systems exist in dynamic non-equilibrium, that is no constant state can exist and there is continuous flux and change. Here systems are 'safe to fail' as opposed to fail-safe, and post disturbance, cities and buildings, may not return to a prior state. A return to 'normal' may be inappropriate as it is undesirable to perpetuate vulnerability (Sanchez et al, 2016).

Resilience was seen as positive (Meerow et al 2016); able to maintain basic functions and prosper. Others question if existing states are desirable (Cote and Nightingale 2011), for example, areas with inadequate housing. Questions arise; resilience *'for whom'* and; *'to what?'* and power inequalities determine whose agenda prevails (Cote and Nightingale 2011).

Three mechanisms of change exist. The first is persistence; where efforts are made to return or maintain the built environment and systems to an existing state, e.g. after a storm buildings are reinstated (Chelleri, 2012). In this sense, retrofit is an example of persistence. Transitional is the second mechanism and implies some adaptation to a new state or incremental change. Change of use from a former land use such as warehousing to accommodate a new residential land-use as an area transitions post industrialisation is an example. The third, most extensive change is transformative, where wide-scale change occurs and areas totally transform. Change of use adaptation can be examples of transitional systems change and resilience and; collectively, transformational systems change.

The fourth aspect, adaptation, refers to the differences between specific adaptations, such as high adaptability compared to generic adaptability (Haase et al, 2014). Wu and Wu (2013) argued that too much emphasis on specified resilience undermines flexibility and ability to adapt to unexpected threats. Others perceived adaptability as synonymous with adaptive capacity and noted the importance of maintaining general resilience to unforeseen threats in addition to specified resilience to known risks. An example, here might be a known risk of pluvial flooding affecting a city or region, and taking measures in the design, construction and adaptation of buildings to reduce the risk of water damage arising and ensuring faster recovery. Equally, adopting flexible design and construction in buildings might accommodate a greater variety of alternate uses over time, thereby having adaptive capacity. The UK Tower of London has high levels of adaptive capacity; in its 900 year history, it has been a home, prison, barracks, armoury

and now a museum and tourist attraction. Warehouse buildings are a design with good adaptive capacity, and globally are used for housing, hotels, art galleries and retail.

Finally there is timescale. Some perceive immediate and rapid recovery as essential; however it depends on whether the focus is on rapid onset events such as storms or long-term gradual states such as changing climate (Wardekker et al, 2010). The measurement of timeframes is unclear and can be hours, months or years. Reinstatement of energy supply after a storm would be preferably within hours, whereas reinstatement of flood damaged buildings may take months. Then there is the question of reinstatement being a return to a prior, or an improved state that would be more resilient to the same event. Sanchez et al (2016) noted urban transformation requires engagement in setting long term goals at city or state level, however flexibility is a pre-requisite to adapt to changes that occur as unintended adverse consequences may arise. Though issues are dealt with at city level, building level is where many adaptations occur.

Resilience is complex with multiple attributes and levels of interpretation. Meerow et al (2016) proposed consideration of the '5 Ws'. These are who, what, when, where and why? When considering resilience, 'who' is determining what is desirable for an urban system, whose resilience is prioritised and who is included or excluded from the urban systems. In respect of 'what'; what should the system be resilient to, what networks /sectors are included in the urban system, and is the focus generic or specific resilience? On the question of 'when'; is the focus on rapid or slow onset disturbances, short or long term resilience, and is it the resilience of current or future generations? The fourth W covers 'where'; in respect of the boundaries of the urban system, and whether resilience of some areas is prioritised over others, and whether resilience in some areas affects the resilience in other areas. Finally the issue 'why'; what is the goal, what are underlying motivations and is the focus on process or outcome (Meerow et al, 2016)?

Other concepts distinguish between built environment resilience (referring to the physical built environment that accommodates human activities), whereas community resilience refers to the resilience of individuals or a group of inhabitants and their social constructs. This literature focuses on well-being, governance and economy. Sanchez et al (2016) give the example of stakeholders having a different focus, with built environment resilience, engineers focus on engineering infrastructure and restoration to operation as soon as possible after a disaster, whereas a community engineering resilience will focus on social and economic outcomes.

4 Resilience challenges for Sydney and Melbourne

The resilience challenges faced globally vary depending on socio-economic, technical, climate variables. Within the 100RC network, cities identify their challenges and those affecting the two Australian cities in the network, of Sydney and Melbourne are set out in Table 1. It is apparent that some challenges affect both cities (ageing infrastructure, lack of affordable housing, rising sea level and coastal erosion and terrorism) whereas others differ.

Table 1 Resilience challenges in Sydney and Melbourne

City	Resilience Challenges (100 Resilient Cities)	
Sydney	1.	Ageing infrastructure
	2.	Heat wave
	3.	Infrastructure failure
	4.	Lack of affordable housing
	5.	Overtaxed/ under developed/unreliable transportation system
	6.	Rapid growth
	7.	Rising sea level and coastal erosion
	8.	Social inequity
	9.	Terrorism
	10.	Wildfires
Melbourne	1.	Ageing infrastructure
	2.	Coastal/tidal flooding
	3.	Declining population / human capital flight
	4.	Lack of affordable housing
	5.	Disease outbreak
	6.	Drought
	7.	Coastal/tidal flooding
	8.	Sea level rise / coastal erosion
	9.	Terrorist attack
	10.	Rainfall flooding

(Source: Author).

5 Residential rating tools

Rating tools provide benchmark and objective indications of sustainability within buildings or precincts (Hurley and Horne, 2006). Since 1990 many tools of residential buildings have been launched, for example BREEAM, and is Australia BASIX, and NatHERS. They are developed by government and/or private bodies and either focus on limited issues such as energy and water or, a wide range of metrics including social and environmental criteria. Some are mandatory, such as the European Energy Performance Certificates (EPCs) others are voluntary (Wilkinson et al, 2015). Some measure design and construction sustainability, whereas others focus on operational or in use sustainability. The aim is to encourage more uptake of sustainability and in this way, could they also enhance resilience?

The residential sector accounts for around 20% of total built environment GHG emissions (Pérez-Lombard et al., 2008) and are worthy of researching as they have a significant impact on sustainability and also affect some resilience issues. In Australia the Nationwide Home Energy Rating Scheme (NatHERS) measures predicted residential building energy performance; using a star rating going from zero to ten (NatHERS, 2017). 10 stars is 'Excellent' indicating the best building performance where a 0 star rating indicates the building is 'under performing'. It can be applied to new build and renovation projects and thereby can impact in an on-going and potentially changing way.

The Building Sustainability Index (BASIX) was launched in 2004 as part of the NSW planning system to reduce water consumption and greenhouse gas emissions for new homes in NSW (BASIX, 2017). BASIX is assessed online using the BASIX assessment tool, which checks elements of a proposed design against sustainability targets. If a development application is submitted in NSW for a new home or for any adaptation or

addition of $50,000 or more to an existing home, owners need to get a BASIX certificate. The certificate shows commitments made in respect of water, energy and thermal comfort and confirms the proposed development will meet NSW Government sustainability requirements. Water and GHG reduction targets for BASIX are based on average per person residential use of potable water and average GHG emissions in NSW prior to 2004 and the introduction of BASIX (BASIX, 2017). For water, the NSW benchmark is 90,340 litres of water per person per year (or 247.5 litres per day). For energy, the NSW benchmark for residential GHG emissions and is 3,292 kg of CO2 per person per year (or 9.01 kg per day). By multiplying water and energy per-capita benchmarks by average occupancy rates, taken from the Australian Bureau of Statistics for dwelling size and location, water and greenhouse budgets for proposed dwellings can be calculated. Savings are estimated by comparing the dwelling's modelled performance to this benchmark figure. The size of NSW housing has increased in many parts of Australia (Clune et al, 2012) over this period and therefore the validity and reliability of the baseline data may be questionable, however it is the tool required by the State.

NatHERS and BASIX tools both measure residential building environmental performance in design. They are important, because in providing a measure of environmental performance; they are an effective way to promote building retrofit.

6. Evaluation and discussion

The review has shown that some resilience issues are clearly and directly related to the built environment and buildings in particular. The relationship of resilience issues faced in Sydney and Melbourne and buildings is shown in Table 2 below. In the table, X equals an indirect relationship exists and XX indicates a direct relationship exists.

Table 2 Sydney & Melbourne Resilience Challenges & Relationship To Buildings

City		Resilience Challenges (100 Resilient Cities)	Relationship of buildings to resilience
Sydney	1.	Ageing infrastructure	X
	2.	Heat wave	XX
	3.	Infrastructure failure	
	4.	Lack of affordable housing	X
	5.	Overtaxed/ under developed / unreliable transport system	
	6.	Rapid growth	X
	7.	Rising sea level and coastal erosion	
	8.	Social inequity	X
	9.	Terrorism	XX
	10.	Wildfires	XX
Melbourne	1	Ageing infrastructure	X
	2	Coastal/tidal flooding	
	3	Declining population / human capital flight	
	4	Lack of affordable housing	X
	5	Disease outbreak	
	6	Drought	XX
	7	Coastal/tidal flooding	
	8	Sea level rise / coastal erosion	
	9	Terrorist attack	XX
	10	Rainfall flooding	XX

(Source: Author)

Looking at the challenges, it is possible to determine how buildings could mitigate or reduce the resilience issue faced. For example with ageing infrastructure, the problem is

exacerbated by population growth placing greater demand on the system. Taking building partially or wholly off grid in terms of water or energy would extend the life of the existing systems. With heatwave issues, the adoption of passive haus design approaches, with high thermal mass, would make homes less prone to excessive heat gain thereby affording greater protection to occupants. Urban design and housing in vulnerable areas can be made more secure by design thereby making them and their occupants less vulnerable to terrorist attack or invasion. Similarly in areas prone to wildfires, housing design can be focussed on reducing flammability and promoting active fire fighting measures. Where rainfall flooding is an issue, measures to increase water sensitive urban design (WSUD) are available such as green roofs and soft landscaping. Conversely where drought prevails measures to maximise resilience include onsite rainwater harvesting measures, water saving devices to sinks, showers and baths and waterless closets.

The lack of affordable housing needs addressing at policy level but could be mitigated with partial or shared ownership programmes or compulsory percentages of affordable housing in developments to ensure areas are more reflective of broader society. Again rapid growth is something that can be managed at policy and government level with the establishment of new towns or promotion of urban regeneration of areas in transition. With rising sea levels action is required at all levels including, Federal level. Housing can be constructed on stilts to allow quicker recovery times post inundation, however long term governments need to assess whether major flood prevention barriers are a solution or managed retreat. These issues are not easily integrated into existing tools. Equally flood issues, security (terrorism) and wildfires are not featured in rating tools. The resilience issues of affordable housing, rapid growth, rising sea levels and coastal erosion are not within the scope of these rating tools and do need to be addressed elsewhere.

Overall there is a range of physical measures are possible to make our buildings more resilient to the challenges we face. The question is; do any feature in our sustainability rating tools? The two most popular residential rating tools in Sydney and Melbourne are NatHERS and BASIX and they are restricted to energy and energy and water efficiencies respectively. Therefore currently they indirectly can be said to contribute towards two resilience challenges in respect of heatwave impacts and drought migitation, however this is not explicit or a goal of the tool currently. As both NatHERS and BASIX cater for new build and adaptation projects, there is potential for the tools to acknowledge resilience challenges throughout a buildings lifecycle. As ASBEC note (2016) retrofit offers the second biggest opportunity for GHG emission savings. Resilience has a positive connotation and can reduce our vulnerability (Batty, 2008) however we do need to remain cognisant that, over time, the degree and type of resilience required in a geographical location will vary. This change needs to be reflected in on-going amendments to the tools and some flexibility is needed (Wu & Wu, 2013).

5 Conclusions

This paper set out the issues of chronic and acute resilience identified by the Rockefeller Foundation for the 100 Resilient Cities. Twenty two of the 68 challenges are either social, governance, political and or economic issues outside of the physical building metrics (100RC, 2017). However, 27 issues can be addressed in some way in the design and construction and operation of buildings. Some examples of how resilience issues can manifest at building level were discussed and the resilience scales figure shows how buildings affect and contribute to resilience at all other scales.

The choices of rating available to people in respect of new build and adaptive reuse for housing in Australia include NatHERS and BASIX. This initial scoping study has explored nature of extent of two Australian existing sustainable residential building rating tools and the degree to which they overlap with resilience challenges affecting Sydney and Melbourne. NatHERS and BASIX share similarities and have been in the market since the mid 2000s. These tools have also been adopted by the residential sector, though the percentage of buildings achieving the highest levels of sustainability in these tools is low and therefore their impact is limited currently.

The second question posed asked if any of the tools, explicitly or implicitly, adopt resilience issues? Currently in Australia, we do not address resilience in our sustainable residential building rating tools for adaptive reuse or conversion or, for new build or building performance. It is evident we are missing an opportunity here; firstly, to acknowledge resilience as it relates to heatwave (energy) and drought (water) challenges. Second, the question of whether to extend the scope of the tools to other building related resilience issues such as wildfire and flood events needs further investigation. This gap needs addressing; as we need to raise awareness at all levels, and within the property and construction industry and professions of resilience issues and how our new and existing residential buildings can play an important part in delivering a more resilient built environment for all.

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AN OPTIMISATION METHOD FOR MEP PLANT ROOM MODULARISATION

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Abstract: *Modularisation in mechanical, electrical and plumbing (MEP) in construction has become more prevalent along with mass customisation of buildings during the last decade. However, it is currently accomplished only for smaller systems where integrated packaged units are used in heating, ventilation and air conditioning (HVAC) and other building services installations. The term 'optimum modularity' is rarely used in the field due to extensive use of packaged systems. Packaged units are limited to external plant room installations and hardly used in building internal installations such as in basements due to difficulties in assembly and job-site delivery. In this study, an efficient method is developed which leads to the minimum total assembly and installation cost of building services systems. The method identifies the optimum sets of modules and module division points based on assembly cost and capacity weight of lifting equipment. It is shown that the optimum modularity for a system is highly dependent on the module weight and the module division point.*

Keywords: *MEP, Modularisation, Optimum Modularity, HVAC*

1 Introduction

Module and Modularity are terms used widely in the product design and engineering industry to address a set of components/elements that make up a unit also known as a module. The word 'module' originates from the Latin word 'Modulus' meaning a 'unit' (Baldwin & Clark, 2000). In engineering terms, module is a group of components/elements that carryout one or more functions which has standardized interfaces to other components/elements (Ericsson & Erixon, 1999). Baldwin and Clark (Baldwin et al. 2004), state that managing complexity, parallel work and accommodating future uncertainties as three main purposes of modularisation. When searching the literature for the definition of a module or modularity many researchers focus on either the physical structure of a product/system or the functionality of it. There are many advantages of modularisation described in the literature; however, very few researchers have addressed the core phenomenon of modularisation. Therefore, it is reasonable to assume that this poor understanding on modularisation has led to many industries not adopting this strategy although it is prevalent in the industry.

It is important to identify the purpose of modularisation before applying it to any industry. The term 'optimum modularity' is subjective and it depends mainly on the final goal of modularisation. The values of modularity can fall in the categories of functionality, manufacturing, serviceability and any other requirement of a product during its life cycle. For example, in Boothroyd and Dewhurt's (Boothroyd et al. 1985) Design for Assembly (DFA) concept, minimum number of components will lead to minimum number of assemblies and therefore cost of installation is reduced. The concepts of modularisation and integrated product development are related to DFA and in this case, the purpose of modularisation is to reduce the number of assemblies. In this study, the main goal of modularity is to achieve the minimum construction cost while meeting the onsite installation constraints.

2 Standardisation or Modularisation

Modularisation and standardisation are two terms that are well-known in the prefabrication and product development industry. Although, these two words are used together in many cases, there is a distinct difference between them when applied to product development. Börjesson (2012) has described some of the main differences of the two concepts when applied to product development.

Misjudgement of these concepts is one of the reasons for lack of prefabrication in Mechanical, Electrical and Plumbing (MEP) systems. Both these concepts can be applied to MEP systems, however, there is a strong dependency on the building functionality. For example, standardisation can be applied to data centres, where the cooling load of the building depends greatly on the data centre size. There are standard sizes for data centre and therefore, the cooling system can also be standardised to meet the cooling requirement. This is a concept of providing a standard scalable product to function another range of standard products. A set of battery-operated toys can be taken as an example. They all have the same type and size of battery; however, the number of batteries depends on the size of the toy and the operation.

In commercial buildings such as, hotels, office & shopping malls, variation in heating and cooling load due to architectural and functional aspects makes it impossible to achieve standardisation in HVAC systems. In other words, it is very difficult to provide a standardised product to function within an irregular product range. Another dominant factor that limits standardisation is the onsite limitations during construction. Due to the

late installation of MEP systems, there are number of limitations on site. In many cases MEP systems are located in the basement level of the building and when transporting equipment onsite, limitations caused by existing building structure should be taken into consideration. These structural and architectural limitations vary significantly from project to project. The variation in design restricts the use of standardised MEP systems.

Limitations during construction and variations in design makes modularisation the perfect solution for MEP systems in commercial buildings. Unlike in product modularisation, in construction industry (especially in the case of MEP systems) a constraint based approach should be considered from the initial stages of the modularisation process. This gives the MEP designer the freedom to design the optimum system for each building and the modularisation process will mainly consider the limitations during construction and easy maintenance during operations.

In modular prefabricated construction, all MEP designs shall be finalised at the initial design stage. This allows for concurrent manufacture of building services modules while structural & civil work being done onsite. Introduction of modularisation to MEP systems should take place during the preliminary concept design stage, however, major changes shall be made to the conventional design process if modularisation is to be practiced in the MEP industry. Current application of prefabrication in MEP is to develop integrated packaged systems such as plant rooms. However, onsite limitations are not taken into consideration and a clear methodology in identifying the optimum number of modules and module division points is missing in the industry.

Construction managers and MEP site engineers should have much greater influence on MEP design from the preliminary stages, where, site constraints shall be discussed with the MEP designers during the concept design stage prior to preliminary designs. These constraints shall be considered during the design stage to identify the limitations in module size, weight and assembly methods. Authors involvement in case study projects and the time spent during site visits were used to identify the typical onsite constraints that will have a major influence on modular MEP construction. Constraint details, calculations and the inputs required from onsite staff will be discussed further in methodology section.

3 Modularisation Techniques in Other Industries

Design Structure Matrix (DSM) is used mainly in product development industry to identify the interactions between the product, process and the consumer (Browning 2001). Functional decomposition of elements, element interactions and other information on each element in a product can be illustrated using DSM. These elements can vary from physical components in a product and different design teams involved in any interaction that takes place in a company during its operations. Figures 1 & 2 illustrate an example of an Un-clustered and a clustered DSM for a climate control system of cars and truck produced by Ford Motor Company (Pimmler & Eppinger 1994). These interactions can take place in the form of energy, material, information or space. Rows and Columns in the DSM is rearranged so that the elements are clustered into chunks (modules) depending on the importance of the element interaction to fulfil the system function.

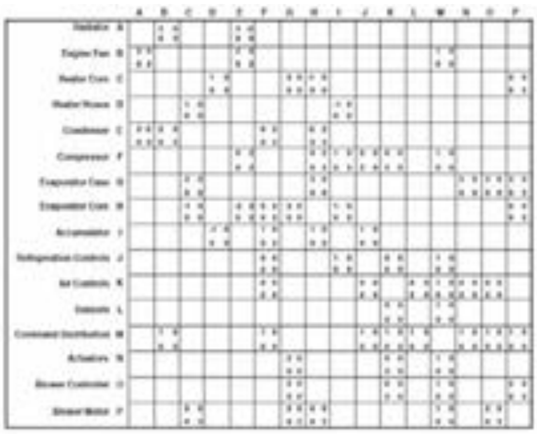

Figure 1: Un-clustered DSM for CCS (Pimmler & Eppinger 1994)

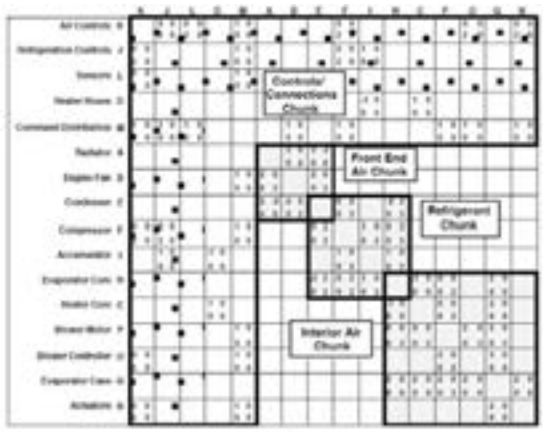

Figure 2: Clustered DSM for CCS (Pimmler & Eppinger 1994)

A methodical approach to modulation in construction is rare to find in literature. Isaac et al. (2016) is one of the few studies, which takes a graph method approach to modularising building design. The focus of this study is on developing a semi-automated method to identify modules for a given system. These modules contain both MEP & civil components in the building. Authors have taken the approach to cluster building components with similar replacement rates in order to minimise demolition during renovations. They have come up with a graph based clustering algorithm, which does a pair-wise comparison of components to identify the relative replacement rates rather than the actual replacement rates. The functional interactions of the components are not identified automatically and rather entered manually to the graph. Once the connectivity was identified, authors arranged the components according to their replacements rates so that components whose replacement rates will occur at different intervals throughout the life-cycle of the building are not clustered together. Figure (3) shows graph method to cluster building components to identify optimum modules introduced by Isaac et al (2016). This method can only be used to identify the optimum arrangement of elements into modules to suit the operational stage of building and might not be the optimum configuration for construction stage. Some modules that are identified using this method may not be practical during installation due to limitations on site. Size and weight, of each module plays an important role in prefabricated construction and it is not determined in this study.

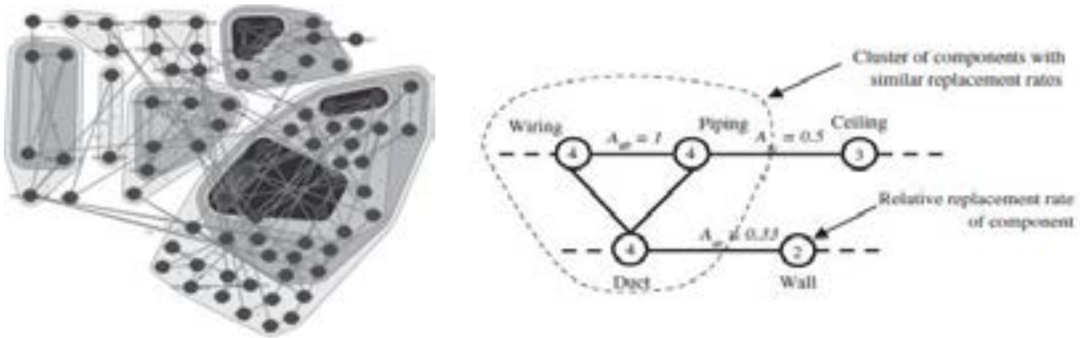

Figure 3: Graph Method for identification of components with similar replaceability rates (Isaac et al. 2016)

Analysing the complete process of MEP modularisation in the industry and identifying a valid method to establish the optimum modules for a given MEP system was not found in

the published research. Court et al. 2009 were one of the few researchers who have published papers on MEP prefabrication in terms of modularisation for assembly. Court et al. have mainly focused on the safety & productivity issues in MEP industry and identification of an assembly method to improve safety and production. However, main factors such as onsite limitations during construction and replaceability during operations is not considered in his work. This paper will focus mainly on the identification of optimum number of modules and module division points during construction stage. Future research will be undertaken in this project to look into all phases of MEP installations and propose a method to identify the optimum modules and division points that satisfy the constraints during all stages.

4 Methodology

It is evident from the literature that modularisation has played a significant role in achieving cost benefits while improving the quality in industries such as aerospace, shipbuilding, automotive and product design. There are many different methodologies suggested by researchers in the aforementioned industries to identify the optimum modularisation strategy for the relevant industry. Design structure Matrix (DSM), Graph method and GA based algorithms are the most popular strategies adopted. However, in the field of construction, requirement of an applicable modularisation strategy is indisputable due to the lack of literature and the rate of growth in prefabrication. Popularity of BIM in the construction industry plays as an advantage in developing a methodology for modularisation due to the considerable amount of information generated through BIM models. Proposed methodology shows how BIM is used to obtain necessary information to develop a workflow that can be used to identify the optimum modularisation strategy for HVAC chilled water central plant rooms. Although the method proposed in this paper is applied only to HVAC central plant rooms, this can be modified easily for other modularisation scenarios in the construction industry by defining the relevant constraints.

System modularisation workflow consists of three stages as Pre-processor stage, Configurations Generator stage & Optimiser stage. User input data and element data obtained from BIM will be used to create an element database during the pre-processor stage. Data collected during the authors' visits to case study projects will be used at this stage to create a set of rules that will govern the module configurations. The optimum module configuration for the given design is determined during the configuration generator and optimizer stages. Matrix clustering analysis combined with cost penalty method described by Lapp & Golay (1997) has been used in this study to obtain the optimum design that has the minimum assembly cost during construction. Initially elements are clustered according to the assembly cost penalties where, complicated assemblies are clustered together so that they can be done offsite leaving simpler, less time-consuming assemblies to be done onsite. Once the module division points are identified according to the connection CPs, modules are analysed under a set of site constraints to determine the practicality of installation. If any module fails to meet the constraints, it will go through the clustering process for further divisions.

Final stage of the study will introduce an Optimum modularity index (OMI) which, will indicate the design assembly cost (ACP) and the onsite handling cost (HCP) of a particular module configuration. This is useful when there are few choices of module division points. This index can also be used to compare the overall modularisation cost with the traditional construction cost.

4.1 Cost Penalties Evaluation for Chilled Water Plant room Assemblies

Onsite assembly of components is one of the biggest costs of prefabricated construction due to the safety reasons, skilled labour requirement and quality of installations. There are many different assembly types related to mechanical and electrical installations in buildings. This study will mainly focus on the connection types in chilled water plant rooms. Component assembly types were investigated to understand the resource requirements and cost allocation for a particular assembly. This will also be helpful to determine the suitability of modular design and configuration of modules. Connection type depends on the material, replicability and the function of a particular interaction. There are many types of connections in a HVAC central chilled water plant. Weld connections, flange connections, coupling and flexible connections can be named as few popular assemblies in plant room construction.

Figure 4: (a). Weld assembly, (b) Flexible assembly (source: KINETICS n.d), (c) Flange connection

Each assembly type has a different cost penalty (CP) assigned to it when assembled onsite. Assembly difficulty, time, safety and skilled and unskilled labour requirement are the factors considered when determining the CP for each assembly type. The objective of the algorithm is to cluster the assemblies with higher CP's to determine modules that can be fabricated in an offsite factory while, assemblies with lower CP's will be identified as module division points so that the cost of onsite assembly is reduced significantly. For example, weld connection is more reliable if it is done in a controlled environment such as an off-site factory. Welding is a time consuming operation and weld quality especially in the case of narrow gap welding is poor when done onsite. Therefore, it has a higher CP in this study. An unskilled labour force can easily complete simpler assemblies such as flange connections and flexible connections in a shorter time with less risk of failure. Therefore, it has a lower CP in this study.

Evaluation of assembly cost penalty is done through engineering judgement during conceptual design stage. The constraints derived from engineering judgement are described using fuzzy logic. In this study, the focus is mainly on the variation of assembly cost in different type of assemblies when done onsite instead of offsite. Therefore, the cost penalty CP will be the output of the fuzzy logic model. This judgment criterion is used as input variable for the proposed fuzzy model. Factors that contribute to the cost of assembly on site such as assembly complexity (narrow gap welding, assembly quality), Resource requirement (setup time, assembly time, labour skill level and equipment) and safety during assembly (welding in shafts and basements, ventilation required for welding) will be treated as input variables. The list of linguistic input and output variable used to measure the onsite CP index of the assemblies in the system are shown in table 1. Variables in the model are measured in a rating scale of 1-6 and they are treated as fuzzy numbers by showing three levels of measurements as 'low', 'moderate' and 'high'.

Table 1: Input and output variable with their measure levels

Performance metric	Input (cost drivers)		Output (CP)	
	Linguistic variable	Measure level	Linguistic Variable	Measure level
Assembly cost	Assembly complexity	Low, moderate, high	Onsite cost index	Low, moderate, high
	Resource requirement	Low, moderate, high		
	Safety	Low, moderate, high		

Table 2: Evaluation guideline for assembly complexity

Rating	Measure level	Description
1-2	Low	No difficulty of assembly on site due to site limitations. e.g.. flange connection in a spacious plant room
3-4	Moderate	There is some difficulty in connecting two elements (long pipe coupling)
5-6	High	Connecting the elements on site can be very complex and can cause a reduction in connection quality. e.g.. narrow gap welding

Table 3: Evaluation guidelines for resource requirement

Rating	Measure level	Description
1-2	Low	Connection can be done in less than 15 minutes by 1 unskilled labourer
3-4	Moderate	Connection can be done in less than 45 minutes by 1 skilled labourer
5-6	High	Connection will take more than 45 minutes and will need more than one skilled labourer

Table 4: Evaluation Guidelines for safety during assembly

Rating	Measure level	Description
1-2	Low	No safety problems in installation therefore no additional work required to ensure safety
3-4	Moderate	There are few safety and therefore will be few additional work needed to be done to assure safety
5-6	high	High risk to labourers during installation therefore require significant amount work to be done to assure safety

Fuzzy if then rules were introduced to the model to represent the MEP designer's knowledge on the interaction of input variables and their effect on the CP output variable. These rules can be expressed as if x is A then y is B. These rules are generally known as 'if then rules'. The 'if' part of the rule is called the antecedent or premise, while, 'then' part of the rule is called the consequent or conclusion. In this study with 3 inputs 27 different rules can be developed in order to evaluate the output CP for different assemblies. Model can be further developed by introducing new input variables which will then increase the number of rules.

Table 5: Assembly cost penalties

Assembly type	Connection Complexity CP	Assembly time & labour requirement	Safety	Cost Penalty
Weld	High	High	High	4
Flange	low	Moderate	Low	2
Coupling	High	High	Moderate	3
Flexible	Low	Low	Low	1

a. Matrix Clustering Analysis (Configuration Generator)

McCormick et al. (1969), describe three main algorithms for clustering analysis. Bond Energy Algorithm (BEA) and Moment Compression Algorithm (MCA) described in their study stands out as clear competitors for this application. The ability to describe the topological properties, denseness, connectivity and computational ease during optimisation made the authors select BEA as the clustering analysis algorithm for this study. Bond energy originates from chemical industry where every chemical bond has an energy associated to it. This same concept is used in this study to determine the connectivity between components in a system and identify locations of division where, every connection will have a Cost Penalty assigned to it. Ideal system division points are connections with lower bond energies (connections with low CPs). Connections with higher bond energies (higher CPs) will be clustered together so that they can be fabricated in an offsite factory environment.

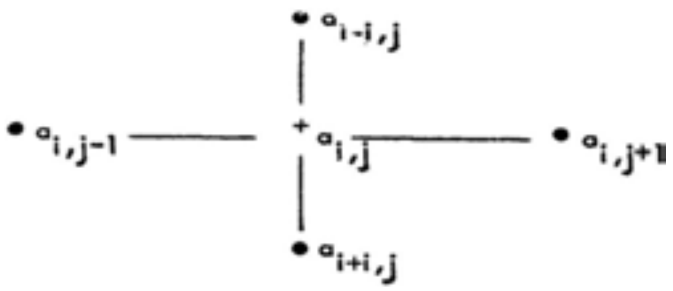

Figure 5: BEA Method (McCormick et al. 1969)

BEA is used to group the plant room components into clusters. Rows and columns of the matrix are rearranged to cluster the components until the highest bond energies are achieved. This is done by multiplying component Aij in a matrix by components surrounding it to determine the values (figure 5). Adding up these values in each column or row gives the Bond Energy. Algorithm rearranges the columns and the rows until the largest value of BEA is achieved for a particular column or a row. This process stops when all column and rows are arranged to its optimum position. McCormick et al.(1969), introduced an index called measure of effectiveness (ME) to indicate the optimum clustering or "clumpiness" in a particular matrix, where the maximum ME denotes the optimum cluster arrangement.

Measure of effectiveness can be determined from equation 1

$$ME = \sum_{i=1}^{N}\sum_{j=1}^{m} A(i,j) \times \{A(i,j-1) + A(i,j+1) + A(i-1,j) + A(i+1,j)\} \quad (1)$$

The matrix of connectivity relationships is assumed to have dimensions M by N with non-negative elements a_{ij} and the value A_{ij} can be determined from equation 2

$$A_{ij} = \frac{1}{2} \times \left[a_{i+1,j} + a_{i-1,j} + a_{i,j+1} + a_{i,j-1}\right] \quad (2)$$

Piping section of the supply side of a chilled water plant room was used to demonstrate the use of bond energy method to identify the optimum clusters. This section connects the supply side of two chillers to three chilled water supply pumps through a header. The

selected section consists of more than 30 elements (pipes, valves, etc.), however, in order to reduce the complexity and to develop a model for demonstration, these elements were grouped to four areas by authors depending on the application and a sample python code was developed to apply the clustering algorithm. In the final algorithm all these elements will be considered in the clustering analysis. Chillers to main distribution piping connection sets were identified as ‘chiller pipe set’ and pumps to header connections were identified as ‘supply pump set’. Other two elements were identified as ‘Distribution piping set’ and ‘Supply ‘Header’. Interactions between the four groups were mapped on a matrix as shown in figure 6. Assembly cost penalties identified in table 5 were assigned for each interaction depending on the assembly type. Maximum CP of 5 was assigned when an element interacts with itself. Results of the study are illustrated below.

Table 6: Supply-side components

Component	Component number	Weight (kg)
Chiller pipe set	1	536
Supply Header	2	120
Dist. Piping	3	729
Supply sump set	4	560

	Chiller pipe set	Supply Header	Dist. Pipe set	Supply Pump set
Chiller pipe set	**5**	**0**	**4**	**0**
Supply Header	**0**	**5**	**2**	**4**
Dist. Pipe set	**4**	**2**	**5**	**0**
Supply Pump set	**0**	**4**	**0**	**5**

Figure 6: Component interaction Matrix

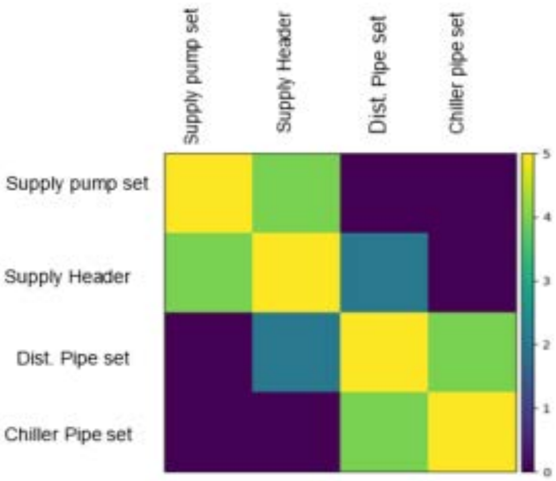

Figure 7: BEA Clustered Matrix

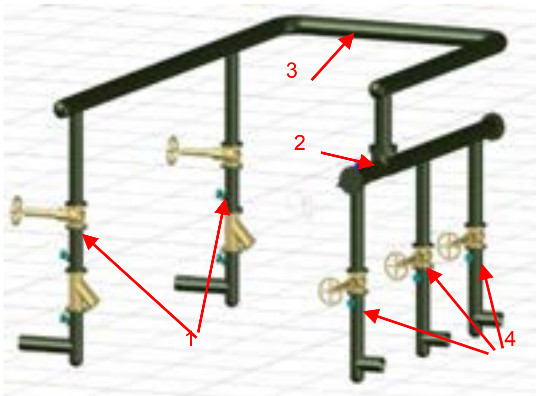

Figure 8: Supply-side piping chilled water plant

Cluster 1 Weight – 680 kg	
Cluster 2 Weight – 1265 kg	

Figure 9: Identified Clusters

The matrix clustering analyses identified two main clusters with strong interactions within them and a weak interaction between them. Strong interactions are assemblies with higher cost penalties and therefore they are clustered together and can be fabricated offsite. Connection between the supply head and the distribution piping is flange type, which has a lower cost penalty and therefore can be identified as an optimum division point. Results presented above gives the optimum configuration of elements based on the assembly cost. However, to make sure these modules can be practically installed onsite, they should be evaluated under a set of rules that govern the job-site delivery and installation process.

4.2 Optimising for Job-Site Delivery and Installation

Modularisation when applied to construction is governed mainly by the limitations on site and during transportation and installation. Handling of the modules on site is one of the main costs in prefabricated construction. Therefore, it is important to plan the onsite handling and transportation during the module design phase. Number of modules and the complexity of the module placement (i.e. installations in basements through openings and installation on higher stories in high-rise buildings) have a significant effect on the overall modular construction cost. Once the modules are transported to site, cranes and chain-blocks are used to lift and hold the modules during installation. Onsite transportation of the modules to plant room locations is generally done using forklifts and handcarts depending on the limitations on site.

Module size and weight are the main constraints in prefabrication. This study will mainly focus on the module weight constraint due to limitations on site. Size of the module (length, width & height) will be incorporated to the module assessment process in future research. Possible modules identified during the clustering process will be assessed under the set of site constraints to verify the practical application of it in the industry. In the case of module weight, the handling equipment will be divided into two weight categories as for hand-carts and forklifts. Any modules that exceed this weight category will go through the clustering process again. For demonstration purposes the following data were used for weight categories. However these weights will be significantly higher in actual plant rooms and more accurate values can be applied when the algorithm is applied for the complete plant room.

Table 8: Identified Clusters for sub-division

Category (L_i)	Equipment	Renting cost (RC)
< 500	Hand-cart	low
500<W_m<1000	Forklift	High

Weight of the module was determined as to be the sum of all element weights in that particular module. It is assumed that a material lifts (forklift, handcart) are used to transport and place the modules in respective locations inside the building. Therefore, the upper limit of the module was taken as 80% capacity of the equipment. This leaves a safety factor of 20% to address the possible weight distributions during transportation.

Equation 3 is used to determine the total weight of a module

$$W_m = \sum_i^n w_i = w_1 + w_2 + w_3 + \ldots + w_n \tag{3}$$

Weight of cluster 2 identified in section 2.2 has a higher weight than the lifting weight capacity of the equipment. Therefore, this will be further divided into sub-modules depending on the interaction of elements. The cluster was divided into four main elements; distribution piping, P1(x2), valve (x2) and Y-strainer (x2). Table 7 shows the components and respective weights. Figure 8 shows the identified clusters indicating distribution pipe and P1(x2) assemblies to be done in an offsite factory. Connection cost of valves and Y-strainers is also higher than the P1 (x2) and valve connection. Therefore, the ideal location of division is P1 (x2) and Valves. In the case of having many possible locations of division, several design configurations will be generated and will be analysed to identify the optimum design using optimum modularity index described in section 2.4.

Table 7: Components for sub-division

Component name	Weight	
Dist piping	729	
P1 (x2)	96	
Valve (x2)	224	
Y-strainer (x2)	216	

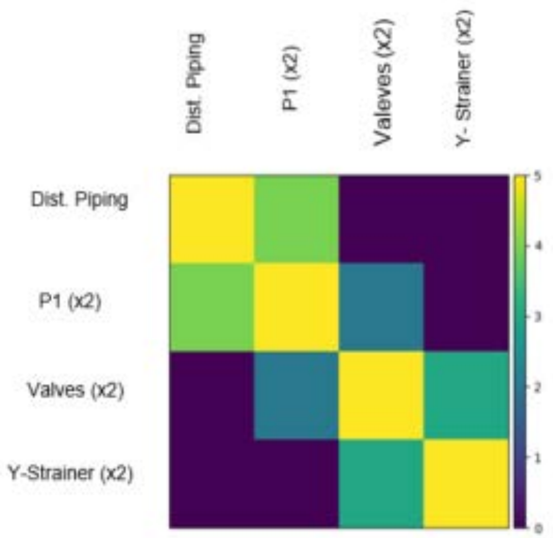

Figure 10: BEA for Sub-modules

Table 9: Identified Clusters for sub-division

Cluster number	Components	Weight
Cluster 2.1	Dist. Pipng + P1 (x2)	825
Cluster 2.2	Valves + Strainers	440

Table 10: Final Clusters for the system

Cluster number	Components	Weight
Cluster 1	Supply pump set +Supply Header	825
Cluster 2	Dist. Pipng + P1 (x2)	825
Cluster 3	Valves + Strainers	440

In order to measure the optimum modularity of a design, an index based on assembly cost (ACP) of a design and the handling cost (HCP) is introduced in the study. This index is mainly used when there are many possible division points in the design and therefore, optimum number of modules need to be determined. Equation 4 can be used to obtain the OMI.

$$OMI = ACP + HCP \tag{4}$$

As discussed in section 2.2, flange and flexible connection points are considered as optimum division points. However, these different arrangements can mean that the assembly cost changes as the number of modules varies and the handling cost varies

with the module weight. Assembly cost penalty (ACP) and handling cost Penalty (HCP) for each arrangement can be determined from equation 5 and 6.

$$ACP = \sum_{i}^{n} n_i \times CP_i \qquad (5)$$

Where
n_i = Number of assemblies of type *i*
CP_i = Cost Penalty for assembly type *i*

$$HCP = \sum_{l}^{m} m_l \times RC_l \qquad (6)$$

Where
m_l = Number of modules in the weight category *l*
RC_l = Equipment renting cost for weight category *l*

5 Concluding remarks and Future Work

This paper introduced a methodology for identification of optimum modules in MEP plant rooms considering the module assembly cost and weight constraints due to onsite handling limitations. Matrix clustering analysis based on Bond Energy Algorithm (BEA) was used to identify the clusters of elements that have strong interactions for off-site fabrication and locations with weak interactions were identified as optimum division points. Python based code was developed to perform the clustering analysis and sample analysis was presented in the study for chilled water central plant room supply-side elements. Identified clusters were assessed to verify whether they meet the site constraint for lifting of modules. One cluster identified during the analysis was found to be heavier than the capacity weight of lifting equipment and therefore further clustering was required.

The proposed methodology will be improved in the future to incorporate more onsite constraints such as module length, height and width, which will depend greatly on the location of the plant room in the building. Equipment replaceability rate will also be considered in the clustering process to identify elements with similar replaceability rates. Comparison of the proposed method to the traditional construction can be done once the methodology is applied to modularise the complete plant room with all elements to calculate the time and cost savings from the proposed methodology.

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FILLING THE GAPS: MODIFYING MODULAR HOUSING IN CHILE

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Abstract: *Standardised and mass-produced houses have attracted the interests of many teams of designers and scholars in the twentieth and twenty-first century. A significant proportion of this effort has gone into housing for the least wealthy sectors of society and is based on reducing the costs of production in terms of labour and materials. However there is evidence that significant contributions, in terms of labour and design ingenuity from the future residents, is an potent resource ignored by many designers who see the mass production process as a discreet activity that excludes the end users. This paper highlights three housing examples selected from within northern Chile to highlight roles played by the end users to help facilitate improved mass housing outcomes. Although each project has been conceived quite differently and is characterised by markedly different production processes, each has involved significant contributions from the residents themselves. Despite the end users developing their houses over a period of five to fourteen years, the houses exhibit an organic nature as they have evolved to various degrees of completeness and complexity according to the desires and capacities of the residents. However it is important to recognise that despite this organic process the houses have maintained very strong links with prefabrication frameworks of modularity and materiality and that this has been determined by the mass-produced construction technologies in evidence.*

Keywords: *Modular Housing, Housing Modification, Social Housing, Informal Settlements, Chile*

1 Introduction

The Chilean government has developed proactive policies to address the housing needs of its people and distributes significant subsidies to private developers and NGOs to deliver mass housing programs. The Chilean Ministry of Housing and Urbanism provided 2,876,325 subsidies between 1990 and 2017 to build new houses (MINVU, 2017). This represents a significant commitment by the Chilean government when we consider that from the total population, 17,789,267 (CIA, 2017), 1 in 6 people lives in a government-subsidised house. The main focus of the subsidies is to house the residents of the many informal settlements occupying public or private vacant land in urban and peri-urban areas.

Despite this significant investment in public housing residents' organisations have protested the poor quality of many of the housing projects built by housing agencies and also highlight many of the social problems that accompany these housing outcomes (Rodriguez and Sugranyes 2004:53-65). There are additional documented examples where residents have abandoned their government subsidised housing and returned to their informal settlements to live in self-built housing (Morales et al 2017:51-75).

This paper investigates two government subsidised housing projects and one informal housing settlement to investigate three types of developments and the ways they shelter the least economically stable sectors of Chilean society. Of particular interest is the role the resident might play in the housing process as well as the role that mass production plays in facilitating mass housing. Three housing paradigms are outlined with each revealing a common purpose – housing vulnerable households in an efficient framework – but with significantly different processes and outcomes.

The goal of this paper is to demonstrate that despite the obvious differences in the outcomes (which could be described as 'organic' in their process and appearance) a clearly defined 'logic' of production prevails that is both systematic and humanistic. A nuanced analysis suggests some key attributes remain as keystones to the process and demonstrate the ways that industrialisation and creative ingenuity work hand in hand in the development of housing for, and by, the people.

2 Locations and research strategy

Three housing settlements were selected within the province of Iquique in northern Chile. Iquique sits on the edge of the Pacific Ocean with the vast Atacama Desert separating it from neighbours such as Bolivia, Peru, Argentina and Brazil. The municipality of Iquique is the historical capital of the province and its port prospers today due to the free-trade zone created in 1975 to promote passing trade from central and eastern South American countries into Asia.

Iquique is constrained to the west by the Pacific Ocean and to the north, east and west by escarpments that lead to the Atacama Desert. The plateau to the city's east, half an hour's drive up the escarpment, is the location for significant tracts of low and high rise residential development as well as commercial developments known as 'Alto Hospicio'. The municipality of Alto Hospicio has developed as a counterpart of Iquique because of its explosive growth changing its original agricultural role to a residential centre. The population of Alto Hospicio has evolved from 173 people in 1970 to 20,000 people in 1995 (Guerrero 1995) and 118,413 people in 2016 (Municipalidad de Alto Hospicio 2017). Alto Hospicio has attracted migrants from different regions of Chile and from

neighbouring countries due to the cultural similarities of Aymaras ethnic group from the Andean plateau.

Figure 1: Location of sites analysed in the cities of Iquique and Alto Hospicio (Google maps modified by authors)

The first settlement studied in the paper is Quinta Monroy (see Figure 1) located approximately 4km from Iquique city centre. The second and third settlements are located in the rapidly developing Alto Hospicio city (see Figure 1). The second settlement, Parque Oriente, is a government-funded housing complex close to local markets and other city facilities. The third settlement, Toma El Boro, is an informal settlement occupying privately owned vacant land and is located adjacent to Parque Oriente.

The data for this paper was obtained through site surveys, mapping exercises, trace analysis, interviews with residents, reviews of government and NGOs' reports and photographic surveys. Site surveys were undertaken in August 2017 and the information collected was analysed using case-study research methods (Yin 2013, Zeisel 1984, Groat & Wang 2002).

3 Case studies

3.1 Quinta Monroy

'Elemental' is an award-winning Chilean architecture firm renowned for its pioneering housing projects that challenge the 'one size fits all' approach that has characterised much of the world's dominant mass housing ideologies. Although the concept of incremental housing has been promoted by the Chilean government representing almost 30% of all the funded housing projects between 1990 to 2017 (MINVU 2017), this project finally provided clear guidelines for a gradual self-help expansion and modification of the houses by its own residents based on their own changing needs and interest over time.

Elemental's project at Iquique includes ninety-three houses and has piqued the interest of architects worldwide for its innovative approach to the mass housing model. The key innovations associated with this program were borne from two parallel dilemmas. How to make mass housing affordable in inner-city areas? How might the residents of mass housing not be subsumed by the 'one size fits all' conundrum that is so often seen as the by-product of the mass housing model?

Figure 2 compares the original inner city informal settlement characterised by an irregular occupation and spatial diversity organised around communal courtyards with the Elemental designed plan. Following the death of the settlement's manager the residents were threatened with eviction and organised themselves to pressure the government for a permanent housing solution to remain in their original location. The government responded by contracting Elemental to design and facilitate the construction of the new development with the residents receiving their new homes in 2003. Elemental's solution was unusual in Chile with a modular format arranged in a complex matrix with built and 'yet to be built' modules combining horizontal and vertical patterns. Housing blocks were built around four courtyards following a traditional local typology that facilitates community activities and socialisation.

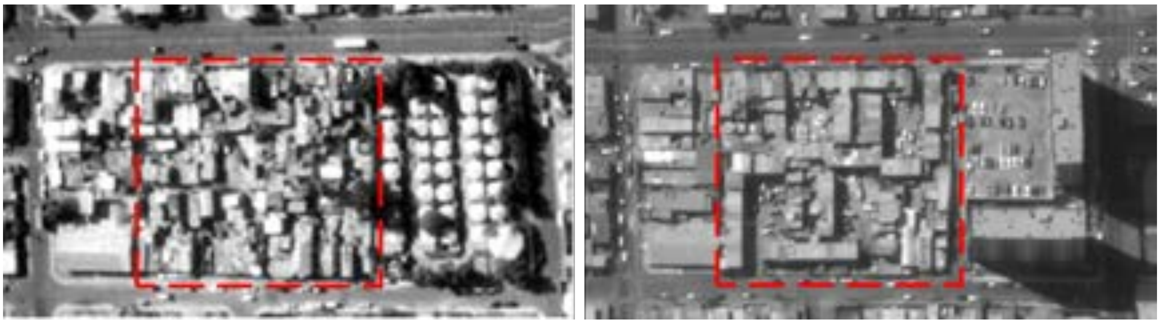

Figure 2: Quinta Monroy, original informal housing before 2003 (Aravena and Montero 2004) and the housing project built (Google maps, modified by authors)

Figure 3 demonstrates the complexity of the housing designed for future extensions to be made horizontally for some typologies and vertically for others. Typology 1 (ground floor) comprises single floor housing units of 3 modules (one of which is unfinished) of 3x6 metres with an initial area of 36 square metres. After extensions the area can be increased to 70 square metres if the backyards are incorporated. Typology 2 (upper two floors) comprises duplex units of 4 modules of 3x6 metres (two of which are unfinished). Initially 36 square metres were completed and after extensions the total area could be increased to 72 square metres.

Figure 3: The Quinta Monroy houses at the completion of the contractor's work. Soon after the residents began adding their own modifications and extensions (Elemental Architects) and the early stages of housing modification/extension (Krzykowski 2008)

However the residents' needs, motivations and creativity produced more complex housing extensions than planned. Figure 4 (left) shows houses, located on the main roads, that were extended at the front mainly due to the security concerns of the residents. Courtyard houses initially followed the expected modification patterns. However as it is seen in Figure 4 (right) residents have started to build additional floors above those designed by Elemental. Another unexpected result stems from the conflicts caused by car parking which has transformed the courtyards into parking lots and distorted their intended function as community spaces.

Figure 4: Images of modified/extended housing in Quinta Monroy (authors)

The residents have followed the architect's advice to extend with lightweight construction materials due to the structural limitations. Residents have 'filled' the empty modules gradually according to their needs and resources. Residents of the ground floor units have occupied the backyard area and some residents of the upper floor units have also extended above the backyard area after coordinating with their neighbours. Only two of the houses remain in their original condition and have not been extended while the vast majority have show additions that demonstrate both practical and aesthetic improvements.

3.2 Parque Oriente

The second example is a government-funded housing estate located in Alto Hospicio in the limits of a larger residential area, close to shopping districts and next to the main green area in the deserted plateau which doubles as the municipal sewage treatment plant. The complex has 477 houses covering an area of 67,210 square metres (see Figure 5). Completed in 2012 the houses were built to a standardised 2-storey format comprising one living room, kitchen and bathroom downstairs and two bedrooms upstairs (see Figure 6). Houses were built in blocks of four units attached to each other. There is nothing remarkable about the layout of these houses and they follow a design that is both efficient and utilitarian except for the generous dimensions of the land plot which is 3.6x20 metres, with a total of 72 square metres residents have enough space to expand their homes either in the front or at the rear.

Prior to moving to Parque Oriente the residents were living in informal settlements in Alto Hospicio for six years. They were encouraged by their community leaders to apply for subsidised housing programs through government agency SERVIU (Housing and Urbanisation Services). Residents had the opportunity to show their preference for a

house or an apartment unit in a multi-storey building. While it is unclear how much the government outlaid in land costs, professional fees, project management fees and construction costs there is no doubt that this far exceeded the US$300 cost paid by the residents for the house title.

Figure 5: Housing complex in Parque Oriente (Google Maps modified by authors)

Figure 6: Typical floor plan of a block of four houses and images of modified and unmodified housing in Parque Oriente, Alto Hospicio (authors)

The construction technologies follow the 'frame and infill' model used throughout the industrialised world. Columns, beams and floors are from reinforced concrete and the infill, in this case, is with hollow core concrete blocks. The roof is corrugated metal. The designers have been careful to work with the dimensions of the standardised construction materials - for example the room sizes have been determined by the dimensions of the concrete blocks that infill the frame. This foresight has reduced both material and labour costs and improved the efficiency of the housing program. The

construction quality has not been raised by the residents in either a positive or negative light.

After five years of occupancy the residents have undertaken a variety of changes to the original house creating a complex streetscape with some houses remaining in their original condition while others have been substantially added to and are difficult to recognise as government subsidised housing (see Figure 6). Residents have demonstrated their confidence to extend with both light and heavyweight materials and in the front and rear of their houses.

3.3 Toma El Boro

The households that have most recently settled in Alto Hospicio generally squat on land in close proximity to the houses funded by the government. Informal settlements established in illegally occupied public or private land are locally called 'tomas' which means 'taken' or 'occupied'. Toma El Boro is named for a mining company with factories in this area and is divided into two sectors. The oldest sector is called Ex-Vertedero and residents have lived here for more than five years. The newest sector is called Laguna Verde and has been settled during the last three years. Reports from a local NGO found that in 2014 there were living 900 families at Ex-Vertedero and 300 families at Laguna Verde (this figure is rapidly increasing) with a total of approximately 4,200 people living in the area (TECHO 2014). This is one of the largest informal settlements in Alto Hospicio.

Most of the residents of El Boro are migrants from southern Chile attracted by work in mining companies. A significant number of residents from neighbouring countries; Ecuador, Colombia and Venezuela are also attracted to the area seeking employment and housing in the informal settlement.

Living conditions in the settlement might appear precarious however there are both formal and informal ways to access basic services. Despite no formal power connections, no running water or sewerage, a resident's committee has successfully lobbied for government support. Government agencies tolerate informal connections to unmetered mains power supply, collect rubbish and replenish individual and collective water tanks at no charge.

Figure 7: Toma El Boro in Alto Hospicio, sectors 1 and 2 (Google Maps modified by authors)

The houses at Toma El Boro are ordered into a grid pattern divided by wide roadways and a clearly defined border (see Figure 7). The settlement includes a community building for their housing committee that organises community activities, coordinates with government and NGOs and allocates residents onto the waiting list for government subsidised social housing programs. Settlement leaders also organise security patrols to keep crime rates low because there is no formal police presence in the settlement. The problems associated with many shantytowns; discordant construction materials, muddled site planning, poor sanitation and poor rubbish removal, are not clearly evident at Toma El Boro. Even without a formal sewerage system there is no sewerage smell as most residents have installed septic tanks inside their plot.

A variety of prefabricated materials have been used to construct the housing compounds at Toma El Boro. Typically the perimeter of the plot is defined with a tall timber framed wall for security and the various rooms are located within the walls. The perimeter walls are most commonly made from panels of plywood or chipboard (1200 x 2400 x 9mm) attached to a timber frame (see Figure 8). Less commonly these walls are built with repurposed timber pallets or corrugated iron. Once this perimeter wall is completed internal walls separate living, sleeping and ablution areas according to family means and needs. Due to the extremely low levels of rainfall in this region many parts of the compound are built without a roof.

Figure 8: Modular and lightweight housing materials at Toma El Boro (authors)

Residents of Toma El Boro have shown a proactive attitude towards solving their housing needs on their terms and have been granted a two-year permit to occupy the land through a negotiation with the landowner, the local government and the neighbourhood committee. Despite the community organisation and the relatively good conditions in the settlement most residents share a long-term aspiration to purchase a subsidised house, similar to those at Parque Oriente, from the government. Between 2013 and 2014 up to 440 families in the sector received subsidised houses (TECHO 2014) with some of the cost of the purchase coming from the 'sale' of their house in Toma El Boro to incoming settlement squatters.

4 Mass production, modularity and modification

Chilean housing researchers investigating government programs observed that although the residents have been initially happy to move into their subsidised housing the satisfaction levels diminished significantly in the six months to two years after the occupation (Rodriguez and Sugranyes 2005, Arriagada and Sepulveda 2002, INVI 2002). Researchers have argued that housing finance programs create other social

problems because they are inadequate for the resident's needs and in response the residents take control of their situation and become proactive actors to address deficiencies with a series of modifications they control on their own terms (Rodriguez and Sugranyes, 2005).

The three housing examples discussed above have all been conceived under vastly different circumstances. However underlying these differences are some key similarities that reveal the role that mass production and modularity plays in enabling and encouraging residents to take control over their housing needs and aspirations.

In each of the three case studies the house has been developed with a strong respect for the materials used in its production. These materials – concrete block, reinforced columns and beams, and timber panels – are the most dominant and have driven the modularity of each project. Efficiency has been enhanced with design and construction systems that minimise both the amount of labour required to install each item and reduce any times the material needs to be cut during the installation process. It is argued that minimising material, minimising labour and minimising cutting together minimises the costs of production and maximises the opportunities to house the most numbers of people at the least cost.

Whilst mass production brings significant advantages to large numbers of people the tenet does not always sit so easily with notions of status and broader aspirations that people hold within themselves to set them apart from their neighbours. Nearly 100 years of mass-produced housing, stemming from the aftermath of the First World War, has produced evidence that the human condition has a complex issue reconciling itself with this 'one size fits all' model. This is compounded by various factors within the end user's mindset and pertaining to the end user's housing culture.

Worldwide the production of mass housing was the result of an attempt to provide quality of life to the residents, especially to the socially most vulnerable, taking an approach that mainly combined two principles paternalism and standardisation (Urban 2012). This approach does not always follow the same pathways and can be contradictory and unanticipated. This complexity can be highlighted in the work of highly respected architects. For example, housing built by the highly regarded Egyptian architect Hasan Fathy at New Gourna in Egypt was reconfigured by the residents who themselves replaced the traditional architectural styling with contemporary styling (Ozkan 1997, Curtis 2000, Hassan and Plimpton 1989). On the other hand, the famous architect Le Corbusier designed and coordinated a housing estate at Pessac in France that was subsequently heavily modified by the residents who added traditional elements and decoration to his austere Modernist aesthetic to reclaim the regional and traditional architectural elements they believed were missing (Boudon 1972).

What these historic examples reveal, especially when considered alongside the modifications and additions made to the three housing programs discussed in this paper, is that many residents have clear ideas of their own housing desires and will, where possible, make their own efforts to modify their standardised housing to suit their own aspirations. However the traditional approach for mass housing does not consider the need for the residents to play any active role – instead rendering the resident impotent and passive. This 'top down' approach was first challenged by Turner who theorised and argued that the resident must play an active role in the housing process and have some control over the outcomes (Turner 1972, 1976). At the same time Habraken argued that prefabricated, mass produced housing frameworks could be built that enabled the resident to 'fit out the infill' to suit their own needs (Habraken 1972).

The architects at Elemental, designers of the Quinta Monroy project, have followed the ideologies espoused by Turner and the processes espoused by Habraken. Their development is a modular framework, partially complete, for the residents to complete themselves in an incremental manner filling the spaces within the concrete frames. The architects of the Parque Oriente development have been somewhat more prescriptive in that their houses were ‘complete’ in that they did not specifically require further work. However the small size of the houses and the large allotments of land enabled (or perhaps even encouraged) many residents to add to their houses. Given that these houses offered little more than a ‘core dwelling’ and were exceptionally cheap (US$300) it was always likely that a significant number of residents would quickly begin modifications while others would plan incremental improvements in coming years as they accumulated more resources. Therefore in both examples the housing programs have led to a significant level of resident engagement with the housing and significant levels of modification to the original dwelling.

Our third example, the self-built houses at Toma El Boro, take this to another level where the residents are entirely responsible for their housing. Without the capacity to build permanent houses with reinforced concrete and masonry blocks their housing uses the next most available and inexpensive material – timber frames and composite timber panels. These materials offer the self-builder maximum opportunities with minimum costs. Of particular interest remains the question of resident satisfaction levels at informal settlements such as Toma El Boro. As discussed research has shown increasing levels of dissatisfaction with typical government subsidised housing in Chile (Rodriguez and Sugranyes 2005, Arriagada and Sepulveda 2002, INVI 2002). Despite the informal nature of the Toma El Boro settlement, the haphazard connection of services and the flimsy, lightweight construction there is some evidence from the discussions with residents of the community that people are proud of their houses and their resilience in the face of their difficult circumstances. Their level of control over their housing is something that gives them pride and anecdotal evidence showing that many residents in housing projects such as Parque Oriente sell their houses to return to informal settlements is an area of future research that should be undertaken by housing researchers.

5 Conclusion

There is little doubt that the size of the world’s cities is increasing rapidly and that governments have a role to play ensuring that its citizens are adequately housed to reduce risks associated with societal breakdown. Subsidised housing relieves the housing burden for many communities but comes with the question of what additional interlinked roles the government might play. Is the government’s appropriate housing system based on a ‘top down’ model or can the resident play a significant role shaping their housing in a ‘bottom up’ or ‘supporter’ model?

This paper has reviewed three types of housing in Chile all of which address the paradigm outlined above. The Chilean government has been careful to ensure that its housing programs are broad in their type and this policy has led to a variety of outcomes. Even the Parque Oriente project, the most ‘complete’ of the projects investigated in this paper, has been located on sufficient land that the residents have the space to extend the house, front and/or back, to suit their changing needs and desires. This opportunity has been taken by most of the residents of this settlement who have extended and improved their ‘core’ house in the years they have occupied it.

A more sophisticated outcome is evidenced at the Quinta Monroy housing that was specifically designed to facilitate the resident's opportunities to renovate and improve their housing. The modular system underpinning the design not only reduced the initial construction costs but also reduced the costs of modifications undertaken by the residents while also affording them the opportunity to complete their house to their specific needs and aspirations. Thus this project fulfilled government and residents expectations in terms of housing and physical environment. However community interactions and social issues must be further analysed to gain a deeper understanding of the project's longer-term values.

The third example revealed that the residents of the Toma El Boro showed proactivity and creativity in the construction of their houses taking advantage of modular elements and responding to their available resources, income and culture. The government's assistance is minimal, essentially 'turning a blind eye' to the settlement, however the settlement remains a desirable place to live with strong governance, few evident social problems and surprising levels of amenity when compared with other informal settlements around the world.

While many global examples of mass produced housing have been criticised for the costs, social outcomes, blandness and capacity to reduce the self-esteem of the inhabitants the examples here describe ways to provide opportunities for the residents to engage positively with their housing and contribute to building both their own esteem and their 'home'.

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AN OPTIMUM CONSTRUCTION STRATEGY FOR MULTI-STORY RESIDENTIAL PREFABRICATED MODULAR BUILDINGS

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Abstract: *Prefabrication is recognised as the way forward in building construction by the industry as it delivers quality yet affordable mass customisable houses faster than traditional on-site construction. The prefabrication of multi-story buildings transforms traditional construction into off-site manufacturing of repetitive components. Currently there are three main structural systems being adopted for modular multi-story buildings; 1) Building with a rigid in-situ central core to which the modules are connected, 2) A podium structure which acts as a base where modules are placed on top of it, 3) Fully modular structure with strategically placed load bearing modules. Current investigations on these systems focus on improving their benefits such as construction time, cost, safety and quality based on one variable at a time. However, there is a lack of studies with a holistic approach to identify the optimum structural system. This paper aims to define an Optimum Modular System Index (OMI) which will be based upon three main indices; Assembly cost penalty Index (ACPI), Onsite handling cost penalty Index (HCPI) and Concrete cost penalty Index (CCPI). Determination of OMI is expected to provide a framework to identify the optimum construction system for multi-story residential prefabricated modular buildings.*

Keywords: *Prefabrication, Assembly Cost, Handling Cost, Optimum Modularity Index*

1 Introduction

Innovative construction methods are being developed in order to cater the needs of the rapidly increasing urban population throughout the world. One such innovation is prefabricated modular construction, where the building is divided into parts (modules) and these volumetric modules are prefabricated in a factory under controlled conditions and then transported to the site and assembled to form the final structure. Although this has been practised in other industries such as car manufacturing, aircraft construction and ship building for few decades, this technique is relatively new to the building construction industry (Lawson et al., 2014).

Prefabricated modular structures are increasingly becoming popular as it uses fewer resources than conventional structures while allowing speedy construction. Research has shown that modular construction at present reduces onsite time by over 50% from a site-intensive building construction (Lawson et al., 2011) and site wastage up to 70% (Jaillon et al., 2009). This proves that apart from being time-efficient, modular construction is environmentally friendly as well. As the modules are manufactured within a factory environment, the quality is improved while providing safe working conditions for the workers compared to site intensive construction (Gunawardena et al., 2016).

Prefabricated modular construction is yet to make a significant impact on high rise building construction as there is lack of research and development in that field. Few examples can be identified such as nine storey “Little Hero” building, Melbourne, 44 story Latrobe Tower in Melbourne, 25 story modular building in Wolverhampton and 32 story Atlantic yards tower, Brooklyn where modular construction was effectively used to construct high rise buildings (Generalova et al., 2016). Case studies done on those buildings highlights that modular construction enabled the builder to overcome challenging site conditions, weather and time constraints which ultimately resulted in a more economical building (Lawson et al., 2014). The limitation of these studies is that it gives a more general idea of benefits of modular construction but does not critically evaluate and quantify the positive or negative impacts.

The concept of modularisation is very common in the product manufacturing industry (Erixon, 1998). There are many different approaches to modularisation suggested by researches in the product and system engineering fields. Hölttä-Otto (2005) describes three main approaches to modularisation as Design Structure Metrix (DSM), Function Structure Heuristics and Modular Function Deployment (MFD) for product architecture. The method used and degree of modularity depends on the purpose of modularisation. Modularisation when applied to the construction industry lacks in practical methods of identifying the optimum modules for Construction. This is mainly due to the limitations on site and significant variation of design in the industry. Graph method described in (Isaac et al., 2016) is one of the few modularisation approaches in construction industry where, components are clustered into modules depending on the replaceability rates. Since the construction industry is a collection of different disciplines such as structural, mechanical and electrical, difficulty in design coordination is also a reason for lack of modularisation in the construction industry. Although a method for identification of optimum modules in construction is premature in the research industry, there are different approaches taken by researches to determine the suitability of modularisation for construction projects (Salama et al., 2017).

In high-rise buildings, lateral loads such as wind loads and earthquake loads are more critical than vertical loads due to self-weight and occupants. Therefore, the lateral load

resisting system plays an important role in maintaining the stability of a high-rise building. Based on the literature, following key volumetric systems were found to be used in modular high rise buildings at present (Cartz and Crosby, 2007, Gunawardena et al., 2016) ;

1. A rigid central core which is constructed on site using concrete or steel that act as the principal lateral load resisting structure. Modules are connected to the core by means of bolts or wet concrete joints allowing the lateral load to be transferred to the rigid core. (See Figure 1).
2. A podium structure which act as a base where modules can be placed on top of it. From foundation up to podium level is constructed on site according to conventional construction methods. (See Figure).
3. Fully modular structure with strategically placed load bearing modules to improve the overall stiffness. (See Figure 3)

The paper aims to provide a scientific base to choose the best system out of the three systems, based on ease of assembly, handling and cost.

Figure 1 Multi story modular structure with a core which act as the primary lateral load resisting member (Cartz and Crosby, 2007)

Figure 2 The use of a podium structure which act as a base to place the modules (Cartz and Crosby, 2007)

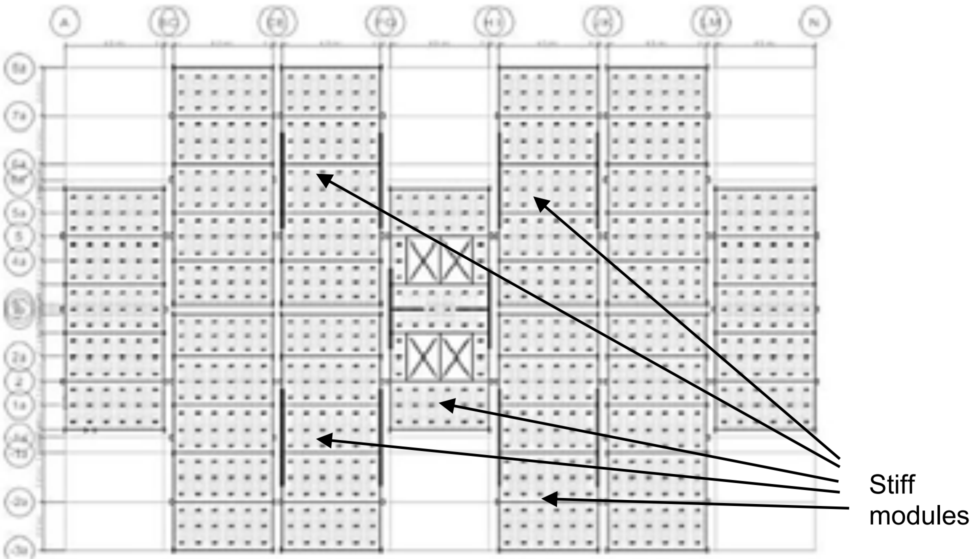

Figure 3 Fully modular construction with strategically placed stiff modules (Gunawardena et al., 2016)

2 Method

There are three main structural systems in construction of prefabricated buildings in the industry. Evaluation of these systems is presented in Section 2.1 with examples. Selection of the construction strategy for a project depends greatly on the previous prefabrication experience of the contractor and the designer. Therefore, the optimum construction strategy for a particular design is not achieved in many cases. In this paper, an index is proposed to identify the optimum construction strategy to achieve minimum construction cost while completing the project within a shorter time period. This is achieved by analysis of a particular design under each construction strategy considering the assembly cost, handling & installation cost and the in-situ concrete requirements as decision indices. Figure 4 illustrates the methodology adopted in this study.

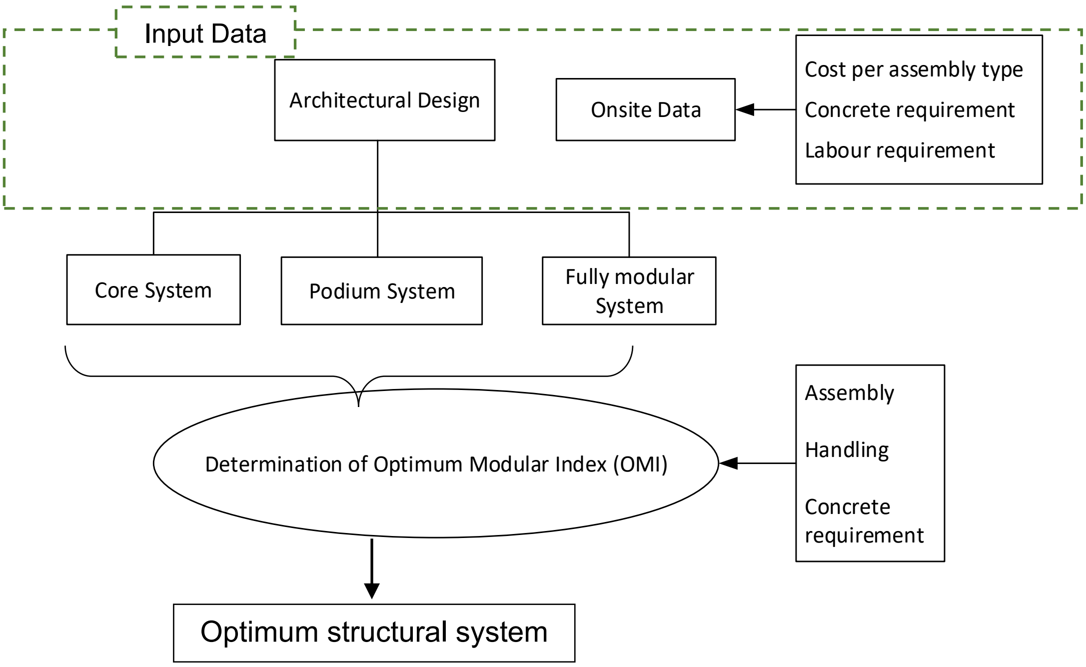

Figure 4 Method adopted to determine the optimum structural system

2.1 Assembly Cost Penalty Index

Onsite assembly of modules is one of the greatest challenges in prefabrication industry and can be costly depending on the type of assemblies. Resource requirement, complexity of the assembly and the assembly time can be named as the major factor of the assembly cost index. Steel-steel assemblies, Steel-concrete assemblies were identified as the two major types of assemblies associated with prefabricated construction. Steel-steel connections can be further categorised as horizontal and vertical. There are other assembly types within and between modules such MEP services. However, in this study only the major types of structural connections will be considered. Fuzzy logic approach was taken to assign a cost penalty (CP) for each type of assembly depending on the resource requirement, assembly complexity and assembly time. For example, steel-steel vertical connections can be particularly challenging when done onsite due to the difficulty of module alignment and therefore the labour and equipment requirement is high compared to horizontal connection between modules. Therefore steel-steel vertical connections are given a higher cost penalty. Steel-steel horizontal connection within modules are less complicated and can be easily done onsite compared to other assembly types. Therefore, a lower cost penalty is assigned for horizontal steel-steel connections. Higher CP is assigned to steel-concrete assemblies due to the high assembly time and labour requirement. Table 1 summarises the cost penalties for the structural connections used in this study.

Table 1 Cost penalties for different types of structural connections

Assembly type	Type index (*i*)	Resource Requirement	Complexity Level	Assembly time	CP
Steel - steel vertical	1	High	High	Moderate	5
Steel - steel horizontal	2	Low	Low	Moderate	3
Steel - concrete	3	High	High	High	6

Number of assemblies for each type and the assigned cost penalties can be used to determine the Assembly cost penalty (ACP) and Assembly cost penalty index ($ACPI$) for each structural system using Equation 1 and Equation 2.

$$ACP = \sum_{i}^{n} n_i \times CP_i \qquad (1)$$

Where
AI = Assembly Index
n_i = Number of assemblies of type *i*
CP_i = Cost Penalty of assembly type *i*

$$ACPI = \frac{ACP\ for\ any\ design}{least\ ACP\ for\ the\ same\ plan\ area} \qquad (2)$$

2.2 Onsite Handling Cost Penalty Index

Handling of the modules on site is one of the main costs in prefabricated construction. Therefore, it is important to plan the onsite handling and transportation during the module design phase. Number of modules and the complexity of the module placement (i.e. module installation on higher stories in high-rise buildings) have a significant effect on the overall modular construction cost. Once the modules are transported to site, cranes and chain-blocks are used to lift and hold the modules during installation.

The use of equipment and resources for module handling and module placing rate will depend on the weight and size of the module. For example, modules that are smaller in size and lighter in weight will require minimum resources for handling and therefore handcarts and chain-blocks can be used to place the modules with minimum time. Modules that are larger in size and heavier will need more resources and therefore, cranes and forklifts will be used in handling with a higher module placing rate. Module placing rate will also be affected by the limitations on site. However, in this study only the general limitations due to module weight will be considered. Increasing the number of modules will reduce the weight of an individual module and therefore the hourly equipment rental rate and the module placing rate will be less. However, this will increase the onsite assemblies which will therefore, increase the onsite assembly index.

Weight of an individual module varies with the structural system used in the design. In core structural system, concrete core itself will resist the lateral load of the building. Similarly, in the podium structural system, podium will be acting as the lateral load-resisting element. However, in the fully-modular system, strategically placed stiff modules will have to resist the lateral load using load bearing walls within modules. Therefore, the weight of those modules will be higher than the modules in the other two systems. Handling cost penalty (HCP) and Handling cost penalty index ($HCPI$) for the three structural systems can be determined using Equation 3 and Equation 4.

$$HCP = No\ of\ Modules\ (m) \times Equipment\ renting\ cost\ index (EI) \times Module\ placing\ time\ (MT) \quad (3)$$

$$HCPI = \frac{HCP\ for\ any\ design}{least\ HCP\ for\ the\ same\ plan\ area} \quad (4)$$

Equipment renting cost index was defined depending on the weight of a module. If the module weight is high, cranes and other machinery will be required to lift and place the modules. Therefore, a higher EI is assigned for heavy modules. Module weight generally falls in the range of 8000 kg – 16000kg (Lawson et al., 2014). Table 2 contains the EI values for respective module weight categories.

Table 2 Equipment renting cost index (EI) values for different module weight categories

Module Weight Category (kg)	Equipment Requirement	EI
w < 10000	Light	2
10000 < w < 13000	Moderate	4
13000 < w	Heavy	6

Module placing time (MT) varies with the weight per square meter of the module (M_z), Length of the module (M_l) and the width of the module (M_w) can be calculated using equation 5, which was derived, based on the study by Garg (2013).

$$MT = 0.108\ \left[{}^{M_z}/_{490}\right]^3 \times M_l \times M_w \quad (5)$$

2.3 Concrete Cost Penalty Index

Prefabrication is preferred over conventional construction due to the minimum use of concrete during construction. However, volume of concrete used in a prefabrication projects depends greatly on the structural system used. Concrete cost penalty (CCP) and

Concrete cost penalty index ($CCPI$) calculated using Equation 6 and 7 indicates the in-situ concrete volume for each structural system.

$$CCP = Total\ concrete\ volume\ \times cost\ per\ meter\ cube\ of\ concrete \tag{6}$$

$$CCPI = \frac{CCP\ for\ any\ design}{least\ CCP\ for\ the\ same\ plan\ area} \tag{7}$$

2.4 Optimum Modular System Index (OMI)

The methodology uses three indices, which accounts for the assembly modules onsite, handling time of modules and the Concrete volume per design, which covers the main areas of interest in prefabricated structural system selection. There three indices are integrated into one indicator (OMI) to measure the optimum modular system for a given design. This single unified index can be used as an indicator of optimum structural system during the preliminary design stages of prefabricated projects. OMI is determined using Equation 8.

$$OMI = ACPI + HCPI + CCPI \tag{8}$$

3 Case Study

To illustrate the use of the OMI, a case study was conducted for a 10 storey medium rise modular building. Following three structural systems are assessed to determine the OMI.

I. System 1(Core System) – Modules attached to a cast insitu concrete core
II. System 2 (Podium System) – Modules placed on a insitu built podium structure
III. System 3 – Fully modular System

A plan view of the building considred for the case study is shown in Figure 5. The arrangement of the modules are for a fully modular structural system with strategically placed stiff modules. For the core system (System 1), it was assumed that the area of the two center modules (highlighted in Figure 5) becomes the core having a 300 mm thick wall. For the podium system (System 2), it was assumed that the total plan area (31.5 m x 24 m) of the ground floor is constructed at site as the podium. A concrete slab having a thickness of 200 mm was assumed to be supported by 32 columns (750 mm x 750 mm) for the podium structure.

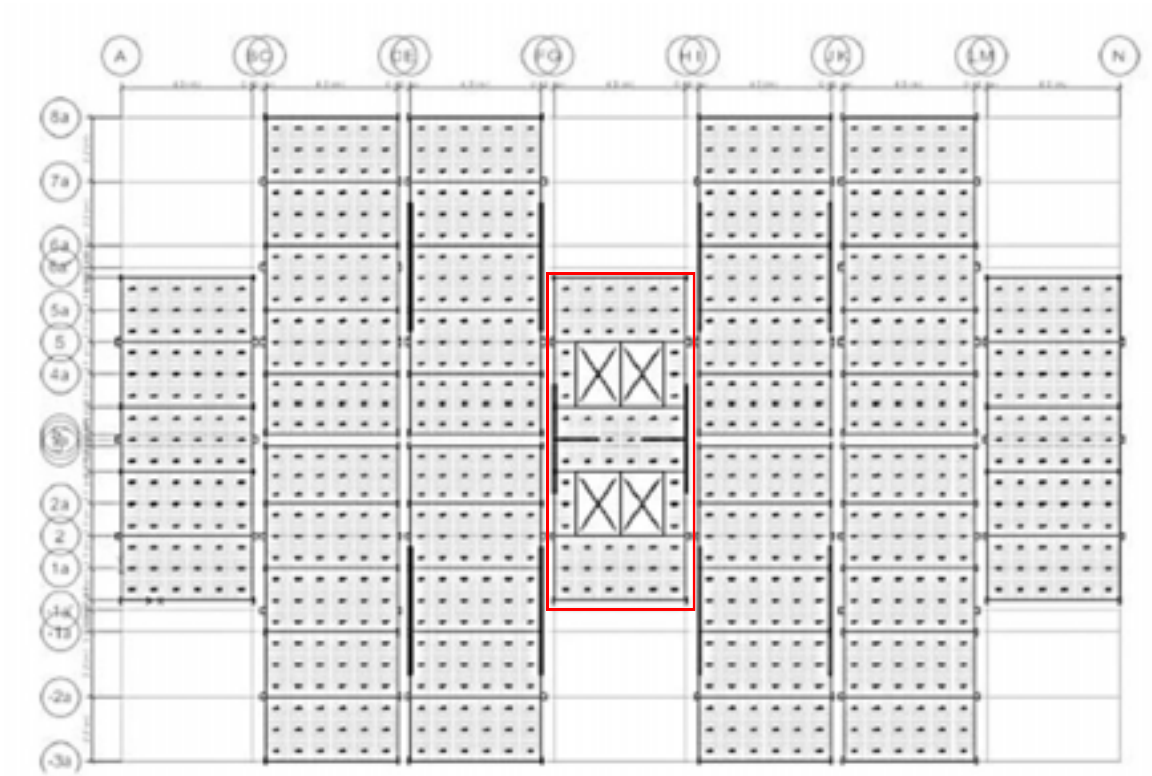

Figure 5 Floor plan of the modular multi-storey building considered for the case study

Table 3 summarises the parameters calculated for each system which will be used to determine the assembly cost penalty index (ACPI), onsite handling cost penalty index (HCPI), concrete cost penalty index (CCPI) and subsequently Optimum modular system index (OMI)

Table 3 Parameters calculated for different structural systems to determine the indices

		System 1	**System 2**	**System 3**
No. of modules		100	108	120
Steel – Steel Connection	Vertical	600	576	640
	Horizontal	120	160	160
Steel – Concrete Connection	Horizontal	40	64	-
Concrete Volume (m3)		286	205	60
Concrete cost ($/m3)		300	300	300
Module size (plan) (m x m)		12 x 4.5	12 x 4.5	12 x 4.5
Module weight (kg)		12000	12000	14000
Module placing time (hr)		0.54	0.54	0.86

Based on the values in Table 3 indices were calculated as follows (see Table 4).

Table 4 Optimum modular system index for three systems

Structural system	*ACP*	*ACPI*	*HCP*	*HCPI*	*CCP*	*CCPI*	Optimum modular system index (*OMI*)
System 1 (Core)	3600	1.00	216.0	1.00	85800	4.77	6.77
System 2 (Podium)	3744	1.04	233.3	1.08	61500	3.42	5.54
System 3 (Fully modular)	3680	1.02	720.0	3.33	18000	1.00	5.35

Fully modular system has the least OMI whereas the Core system has the highest OMI out of three systems considered. Therefore, OMI suggests that the fully modular system would be the most cost-efficient system to be used for the 10 storey modular building considered.

4 Conclusions and Future Work

This paper presented an efficient method to support the selection of optimum structural system for medium rise modular prefabricated construction projects. The proposed method was applied to a medium-rise modular building and the results were discussed in Section 3. Optimum modular system index (OMI) is a quantitative indicator for selection of the structural system for the modular building. This integrates three indices that represent the main challenges during modularisation. Assembly cost penalty index ($ACPI$) was used to determine the cost of assembly for three structural systems where, three different assembly types associated with structures were analysed considering the complexity, time and resource requirement. It was evident from the results that although the total number of assemblies is high in a fully-modular system, due to the higher assembly complexity and assembly time of steel-concrete connections, assembly cost of podium system was found to be higher compared to other two systems. Onsite module handling difficulty was implied from the Handling cost penalty index ($HCPI$) where, weight and the size of the module and the number of modules were used to calculate the module-placing rate. Additional weight due to load bearing walls within modules and higher number of modules made fully-modular strategy the costliest compared to other systems when handling on site during installation. Concrete cost penalty index ($CCPI$) was used to determine the additional cost due to concrete used in different structural systems. It was very clear that core system had a higher concrete volume compared the other system due to the centre core that extends from ground to the 10th floor.

It was evident from the case study that reducing the number of assemblies alone does not reduce the cost of installation. Level of difficulty in handling modules during installation is highly affected by the weight of the module. Volume of concrete used in the project also has a significant effect on the selection of structural strategy. When all these factors are taken into consideration it was clear from the results that the fully modular structural system achieved the highest OMI due to the less overall assembly time and the minimum use of concrete during construction.

The index and the method presented in this paper can be improved in the future to incorporate other assembly types such as mechanical and electrical assemblies between modules. Furthermore, it can be applied to mass-timber, timber-frame or steel-frame volumetric construction with some modifications and further testing is required to establish a system applicable to a range of materials. More observations in the industry and collecting more data that influence the above derived indices would improve the accuracy of the analysis. It is recommended to study the effect of mass customisation on the indices developed in this paper.

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A COMPARATIVE ANALYSIS ON THE THERMAL PERFORMANCE OF AIR-TYPE PVT COLLECTOR APPLIED BAFFLES

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Abstract: *PVT (Photovoltaic Thermal) collector is a device that produces electricity in the front, from PV cells and uses heat generated from the backside of PV for heating purposes simultaneously. The PVT system can either be a liquid or air type according to the heating medium used. In particular, air-type PVT system has the advantage of being easy to manage and can be used directly for heating in building. The thermal and electrical performance of air-type PVT collector is affected by factors such as the height and internal design of the collector. Baffles, which is an important factor, are installed in the air layer of collector to generate turbulence and a larger flow rate. Accordingly, baffle can improve the performance of the air-type PVT collector. However, depending on the shape or number of baffles, the air flow of the collector can be different, that is why design of baffle in air-type PVT collector is important.*

In this study, effect of baffle on thermal performance of air-type PVT collector is analysed. For this purpose, the air-type collectors applied with three types of baffles are designed and simulated using NX CFD program. The height of collectors was used as an additional variable for improving thermal efficiency of air-type PVT collector.

Keywords: *Air-type PVT Collector, Baffles, CFD Analysis, Renewable Energy, Thermal Efficiency*

1 Introduction

As solar radiation increases, power generation of the PV module also increases. However, the heat of PV module generated during the electric production process causes the electric efficiency of the PV module to decrease. Recently, in the BIPV (Building-Integrated Photovoltaics) system, which is applied as a building envelope, there is no natural ventilation. When the BIPV is installed at building envelope, cooling of the PV modules and heat release of PV backside should be considered. PVT systems have been developed to improve the power generation performance of PV systems. PVT system can use heat for domestic hot water and heating in building, so that the utilization rate of solar energy is higher than the efficiency of PV systems. Air-type PVT system has an advantage that there is no problem of leakage or freezing because the heat generated with power generation in the PV module backside is used as air, not liquid.

The air-type PVT systems can affect efficiency depending on the configuration of the air layer. One of the factors that can increase the efficiency of the air-type PVT collector is baffle. According to the shape of the baffle, the flow path inside the collector is lengthened and the flow rate of the air is increased. Then, the Reynolds number of the fluid increases and thus the heat transfer efficiency increases due to the Nusselt number (Yadav 2013). It is true that baffle develops efficiency of the air-type PVT collector.

This study investigates the effect of the baffle influencing the internal flow of the air-type PVT collector by installing inside the collector. The heat transfer performance of the air-type PVT collector is affected by the parameters such as the shape and, position of the baffle, and collector height (Tonui 2007, Mojumder 2016). Therefore, the thermal performance of the air-type PVT collector must be quantitatively evaluated through flow analysis using computational fluid dynamics (CFD). In this study, the shape and, position of baffle, and collector height were set as design parameters to improve the heat transfer performance of air-type PVT collector. Furthermore, the thermal performance of collectors based on the variables were compared and analysed.

2 Air type PVT collector model for simulation

2.1 Model Design

For a performance analysis of the air-type PVT collector by the variables, 8 types were designed and modelled. The shape of the baffle was designed as rectangle and triangle shapes which were discussed in the previous researches, the bent shape and reference collector without baffle was designed for comparison with three collectors with baffles (Fig.1). Also, the thermal performance by the internal height of the collector was compared.

The height of TYPE 1-4 is 66 mm, TYPE 5-8 is 42.5 mm. Rectangle baffles (TYPE 2, 6) were designed with staggered arrangement and spacing between the baffles to improve the flow velocity (Table1). Triangle baffles in the collector were arranged for the purpose of reducing the dead zone in the PV backside, the upper surface of the baffle is made streamlined so that the fluid flows smoothly. On the other hand, the collector with bent baffles were designed so that the solar radiation can reach the absorb plate directly inside the collector by arranging different array of PV cells and absorb plate with curved shape can receive the solar radiation in a larger area. This plate simultaneously acts as the baffles which interrupt the flow of the fluid.

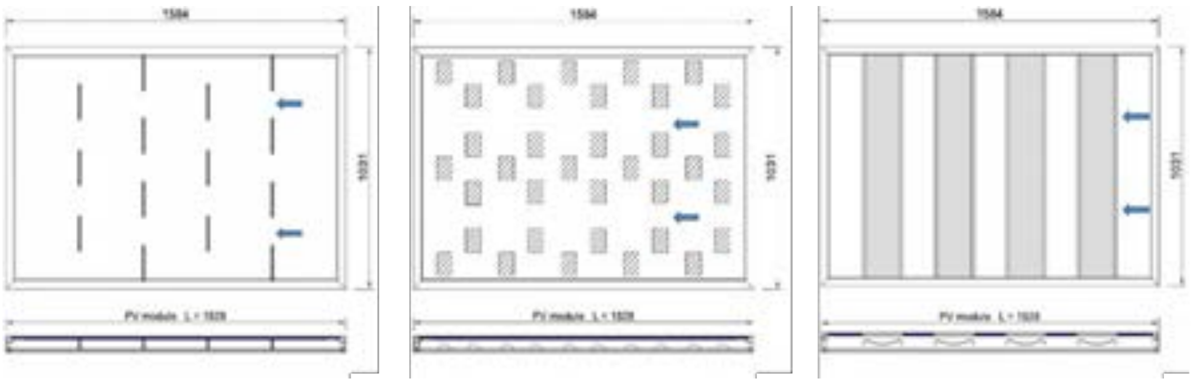


Figure 1: Air-type PVT collector with baffle (Left: Rectangle, Middle: Triangle, Right: Bent)

Table 1: Model of Air-type PVT collector according to baffle shape

	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5	TYPE 6	TYPE 7	TYPE 8
Shape of baffle	-	Rectangle	triangle	Bent	-	Rectangle	triangle	Bent
PVT collector size	1584 X 1031mm							
PVT collector height	66mm				42.5mm			

2.2 Modelling conditions and methodology

The CFD (Computational Fluid Dynamics) analysis software was used for comparing and analysing the flow and thermal performance of the collector with bent baffle. The CFD analysis was performed using the NX program.

The NX program used in this paper is a program that simulates fluid flow effects such as CFD modelling by rapidly creating complex flow regions for geometry and performing computational fluid dynamics. In addition, thermal analysis functions for conduction, convection, complex heat transfer, and radiant heat are applied in combination.

To simulate the air-type PVT collector, the PV surface area was set 1.63 m^2, and this part was supplied with 780 W/m^2 of thermal energy per unit area. In order to consider the surface heat loss, values such as the outside temperature were input, and the air density was wet to 1.225 kg/m^3 when the temperature was 25 ^OC by applying the density according to the temperature. In addition, buoyancy and acceleration due to gravity (9.81 m s-2) were applied.

The inlet/outlet and heat flux area of 8 TYPE are the same. As the input variables, the collector inlet flow rate (30, 60, 100 CMH) and the solar radiation were set, and the outlet was applied as condition of atmospheric pressure. The K-Epsilon model was selected for the turbulence model and the flow fluid inside the collector was designated as air.

3 Analysis of simulation results

3.1 Temperature and velocity characteristics of Air-type PVT collector

Figure 2 and 3 show that the temperature and the flow velocity distribution are clearly shown among the 8 types. As shown in Fig. 2, the temperature distribution of each TYPE shows a partially high temperature at the back of the rectangle baffle of TYPE 2. While the bent baffle of TYPE 4 showed the most uniformity without stagnation. Both baffle

types are collectors with rectangle baffles, but TYPE 3 and 7 have different heights of air-type PVT collectors. The temperature of TYPE 7, which is low in height, is distributed higher than TYPE 3 as the whole.

Figure 3 is a graph showing outlet temperature according to flow rate per type. The PVT outlet temperature of TYPE 4 is approximately 4 ^{O}C higher than other collectors and TYPE 8 (the low- height collector with bent baffle) is about 3 ^{O}C higher than other types. The collector temperature of the bent baffle is 3-6 ^{O}C higher than collector with baffles which have different shapes and the outlet temperature of collector with lower height is almost 3 ^{O}C higher than other types.

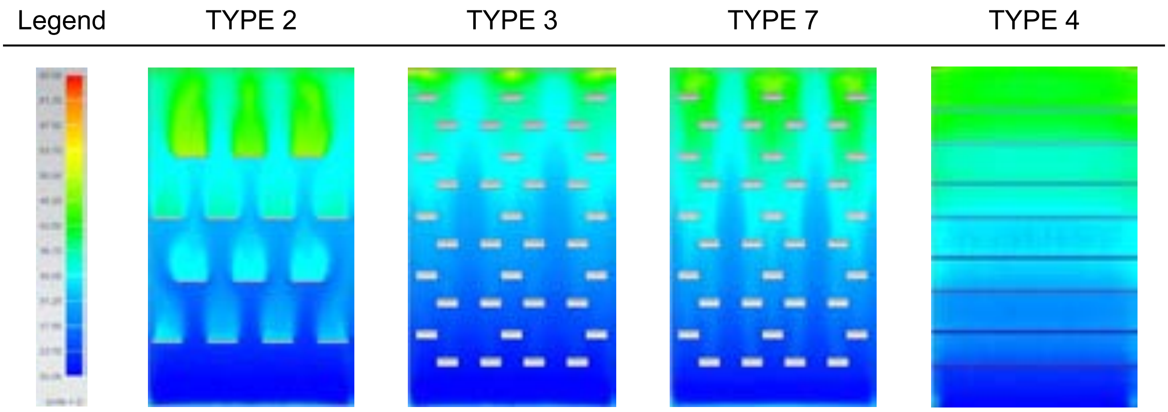


Figure 2: Temperature distribution by type (Flow rate: 60CMH)

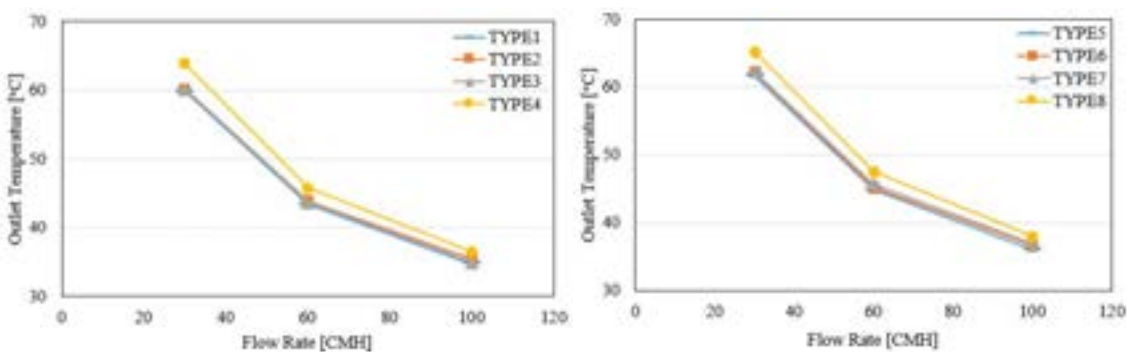


Figure 3: Outlet temperature by type (Left: TYPE 1-4, Right: TYPE 5-8)

Figure 5 is a graph showing the internal flow distribution of the collectors. Because the air layer inside the air-type PVT collector generates vortex based on the installation of the baffles, the internal flow velocity is increased as compared with the reference type without baffle. However, collector stagnation occurs by the baffle like TYPE 2, but it can be reduced as in case of types applied with triangle and bent baffles (Fig.4). Also, the collector with rectangle baffle (TYPE 2) increases flow velocity between the baffles, and the ones with triangle baffle made two linear flows, which are sections of increased flow velocity. As a result, the Bernoulli effect occurred between two lines eased the stagnant air behind the triangle baffles. In the case of bent-baffle type, the flow velocity became uniform without eddying effect and accelerating the flow velocity.

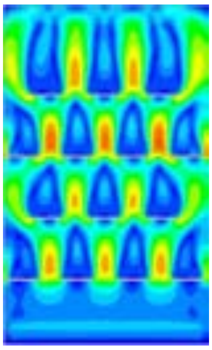
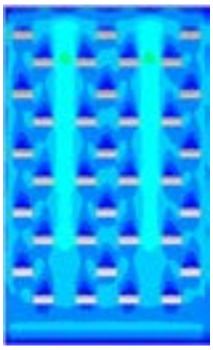
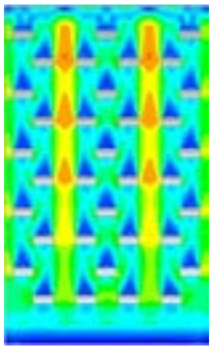
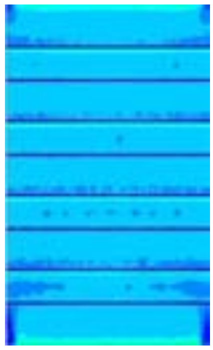
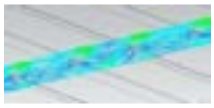
Legend	TYPE 2	TYPE 3	TYPE 7	TYPE 4
				
Detailed flow of Baffle backside				

Figure 4: Flow distribution by type (Flow rate: 60CMH)

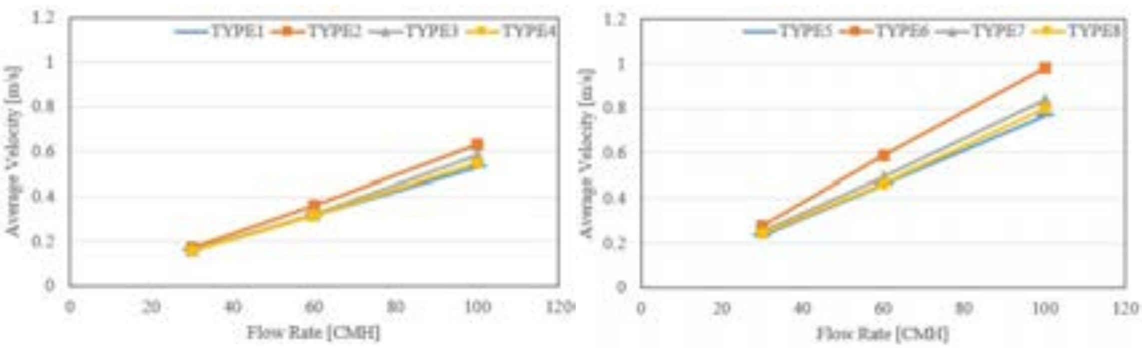


Figure 5: Average velocity by type (Left: TYPE 1-4, Right: TYPE 5-8)

3.2 Pressure drop and dead zone of Air-type PVT collector

When designing baffles, two of the most important factors are pressure drop and dead zone. If pressure loss occurs inside the collector, the power consumption of the fan and dead zone increases. Hence, it can affect the thermal performance of the air-type PVT collector. Therefore, when designing the path in which the fluid flows in the collector, it is necessary to make optimum design considering these factors.

Figure 6 is a graph showing pressure drop per type. The difference in pressure drop of collectors with various baffles was up to 50-80% relative to the collector without baffle. The pressure drop was increased by the shape of the baffle in the order of rectangle, triangle, and bent. Plus, the collectors having lower height showed a larger difference.

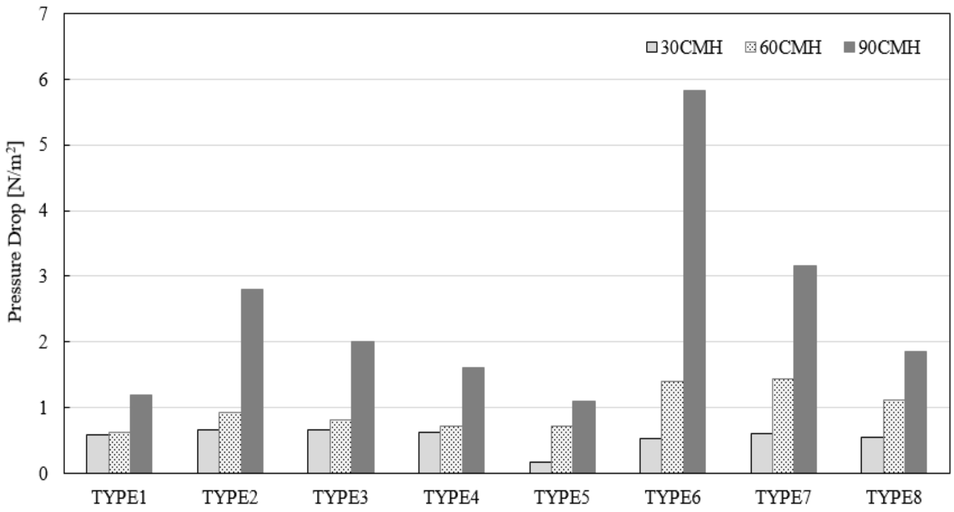


Figure 6: Pressure Drop of all types (TYPE 1-8)

Figure 7 is a graph showing the thermal efficiency according to the ratio of the dead zone. The thermal efficiency is calculated using equation 1. The dead zone of collector with various baffles was roughly 75-77% different from the collector without baffle. The dead zone was reduced by 60-70% in rectangle baffle collector.

In terms of flow, the designs of triangle and bent shape baffles are better than the rectangle baffles and the dead zone rate of the collector applied with bent baffles is the smallest. Thus, the flow through the collector is more uniform. Also the larger dead zone ratio resulted in lower thermal efficiency, as the air passes through the internal collector with the same flow. Hence, the baffle plan should be designed to gently sweep the back of the PV.

$$\eta_{th} = \frac{Q_2}{Q_1} = \frac{\dot{m}\ C_p\ (T_{outlet} - T_{inlet})}{A_{pvt} G} \qquad (1)$$

η_{th} Thermal efficiency [-]
A_{pvt} Collector area [m^2]
T_o Collector outlet air temperature [°C]
T_i Collector inlet air temperature [°C]
$\dot{m}$ Mass flow rate [kg s-1]
C_p Specific heat [J kg-1 K-1]
G Irradiance on the collector surface [W m-2]

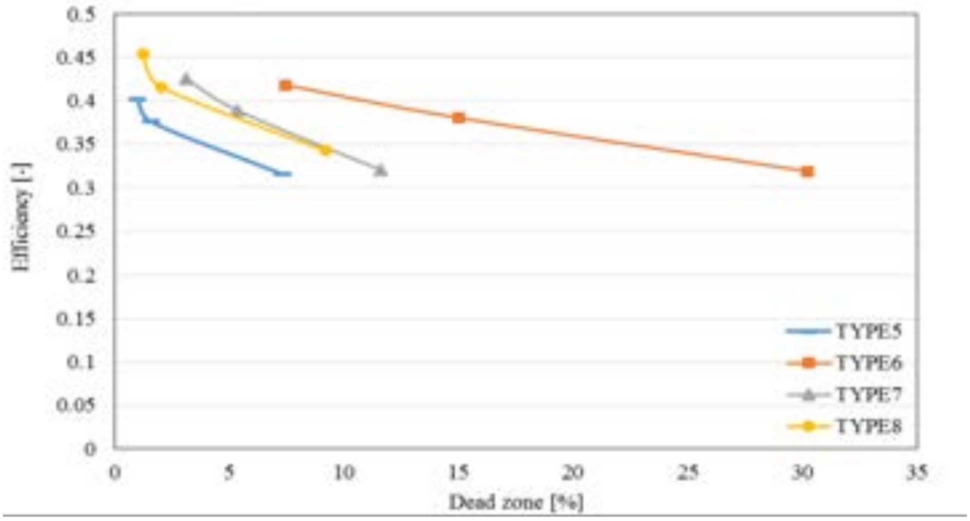


Figure 7: Thermal efficiency by Dead zone rate of TYPE 5-8

4 Conclusions

In this study, air-type PVT collector applied with different types of baffles were analysed for comparison. Especially, thermal performance of the collector was simulated with CFD program.

The CFD analysis showed that temperature distribution of bent type was uniform and had 3-6°C higher outlet air temperature than square type. The average inside air velocity was enhanced 30% and 33% respectably in rectangle type and TYPE 6 than reference type. Velocity difference was decreased with reducing air flow rate. Thus, Pressure drop, Dead zone rate and air stagnation also declined in bent type. Thermal performance of the collector applied with bent type baffles was improved 11.3% compared with reference type in higher heat transfer, and the thermal efficiency enhanced by 3.7%p as the height of the collector decreased.

In future work, optimized shape, installation location, and size of baffles are compulsory to improve the thermal and also electrical performance of air-type PVT collector.

Acknowledgements

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EFFECT OF THERMAL BRIDGE ON THE INSULATION PERFORMANCE OF VIP APPLIED WALLS

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Abstract: *To prevent environmental pollution and global warming, it is essential to reduce greenhouse gas (GHG) by saving energy. In developed countries, building energy consumption has reached almost 40% of the total energy use. In the case of Korea, 25% of total energy use is consumed in buildings; of this, energy used for space heating and cooling accounted for almost 60%. In order to reduce heating and cooling load, the insulation performance of building is very important. Thus the regulation for building insulation is being strengthened gradually. Consequently, high efficiency insulation such as vacuum insulation panel (VIP) is required. VIP is a high efficiency insulation which has 7~8 times lower effective thermal conductivity than conventional insulation materials. Applying VIP reduces insulation thickness and makes wider effective inner space. However when VIP is applied in a building, thermal bridge occur which decreases the insulation performance of the building. In this study, the thermal bridge effect which is caused when VIP is adopted is analyzed by VIP installation method in building, using heat transfer simulation program. For simulation analysis, three types of installation methods, namely wooden lath, anchor fixing and insulating joiner. were designed and simulated.*[1]

Keywords: *Vacuum Insulation Panel (VIP), Thermal Bridge effect, Installation Methods, Heat Transfer Simulation, Effective Thermal Transmittance*

[1] **Notation**

⚲	VIP area		[m²]
☺	Thickness of VIPs(heat flow direction)	[m]	
≣	Diameter		[m]
U_{823d}	One-dimensional thermal transmittance	[W/m²K]	
U_{eff}	Effective thermal transmittance		[W/m²K]
· ✓	Central thermal conductivity		[W/mK]
· ◉	Effective thermal conductivity		[W/mK]
›	Lineal thermal transmittance		[W/mK]

1 Introduction

1.1 Background of research

Economic development based on fossil fuels such as petroleum and coal is causing serious environmental problems such as global warming and abnormal climate. Global efforts to reduce GHG emissions are being made around the world in order to solve the increasing environmental problems.

In developed countries, more than 40% of the total energy consumption is used in buildings; besides building energy consumption is continuously increasing due to the development of buildings and equipment systems. In Korea, the building sector accounts for 23% of national energy consumption and 25.2% of greenhouse gas emissions. This is the second highest, next to the industrial sector. To reduce building energy use, many countries have implemented various policies such as mandatory zero energy building policies. In Korea, the zero energy certification system will be introduced for the first time from 2017, stepping up the scope of application to public buildings in 2020 and private buildings in 2025.

More than 60% of the energy consumption in the building sector is used for heating and cooling loads. In order to reduce the heating and cooling load, the insulation performance of the building envelope should be considered. For this reason, the government has continuously strengthened the building insulation regulations, reinforcing the thermal transmittance of the outer wall which was 0.36 W/m^{2}K in 2010 to 0.21 W/m^{2}K in 2016. It is expected that the insulation regulation of building will be gradually strengthened to meet zero energy building standard.

In order to satisfy the insulation criterion which is continuously strengthened, the insulation thickness of the outer wall of the building is increasing. Consequently, the indoor occupancy space is reduced. As an alternative to reduce the thickness of the wall, it is required to insulate the building using high efficiency insulation material, which has improved thermal performance compared to existing building insulation material. Due to the need for high-efficiency insulation materials, vacuum insulation panels (VIPs) which have been mainly used in electronic products such as refrigeration appliances, are being introduced in the building market.

VIP is a high-efficiency insulation material with a thermal conductivity that is about 8 to 10 times lower than the existing insulation material. Thus, it can meet the reinforced insulation regulation by thin insulation thickness. This is effective to increase the occupied space of the building and reduce the energy consumption of building due to the improved insulation performance. However, when VIPs are applied to a building wall as a thermal insulation material, thermal bridging occurs due to the different thermal conductivity of the surrounding building material. And it leads to deterioration of the insulation performance of the wall. In this paper, thermal bridge phenomena of VIPs according to the installation method and the insulation performance of the wall are analysed by the simulation program.

1.2 Purpose of research

In this paper, the insulation performance of VIP walls according to the building installation methods are analysed and compared by using a simulation program. In order to evaluate the thermal insulation performance of the VIPs, the outer walls were

designed with three types of VIP installation methods; wooden lath, anchor fixing and insulating joiner connection methods. Thermal bridge phenomenon was confirmed through modelling and simulation of the heat transfer analysis of the VIP walls according to each connection method. In addition, the linear thermal transmittance and the effective thermal conductivity of the VIP walls according to each connection method were calculated. Then the thermal insulation performance of the VIP walls was compared and analysed.

2 Vacuum Insulation Panel (VIP)

2.1 VIP specification

VIP is a non-homogenous insulation material, it is composed of materials which have different thermal conductivities (Fig. 1.). It is a high-efficiency insulation material in which a core of porous material is sealed with a moisture-proof and low-permeability sheathing material, and then the inside of the panel is kept in a low vacuum state.

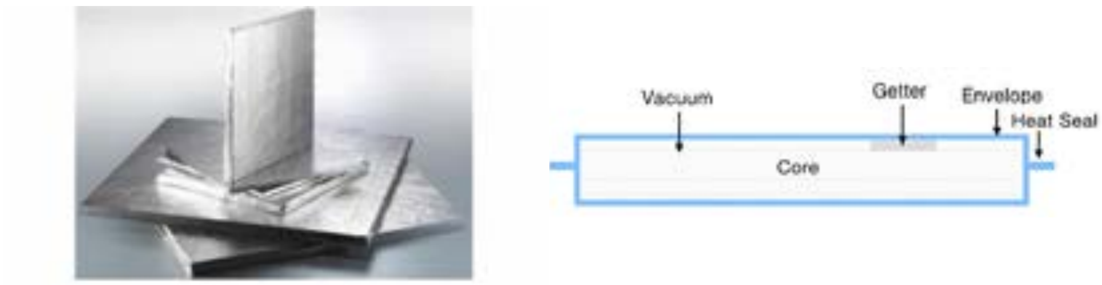


Fig. 1. Vacuum Insulation Panel Construction

The center-of-panel thermal conductivity of the initial panel is 0.004 W/mK, which is 7 ~ 8 times higher than the existing insulation. Fig. 2. is a picture comparing the thickness of VIPs and different insulation such as glass fiber, EPS, and PU to satisfy the same insulation performance. In order to meet the same insulation performance of the VIP as shown in Fig. 2. The conventional insulation such as glass fiber requires a considerable thickness of insulation. Therefore, if the VIP is applied to the building, the insulation thickness of the building wall can be reduced, which is advantageous in securing the occupied space of the building.

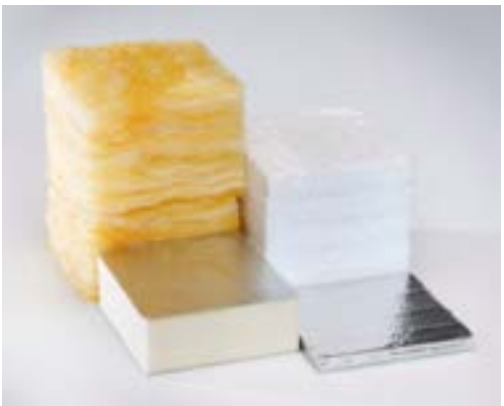


Fig. 2. Comparative thickness of different insulation materials to achieve same U-value

2.2 VIP Thermal Bridge

The thermal bridge defined in ISO 10211 of the International Organization for Standardization is a part of the building envelope with constant thermal resistance showing a significant difference in thermal performance. It is a phenomenon that occurs mainly at the portion where materials with different thermal properties come into contact with each other. When thermal bridges occur, heat loss occurs through the thermal bridges at the exterior wall of the building, which causes problems such as energy loss and condensation. Therefore, it is important to reduce heat loss by minimizing thermal bridge for the application of vacuum insulation panels.

Many studies have been carried out to minimize the thermal bridges, and the thermal bridges of the VIPs ensuing during the application of the building are divided into three categories.

(a) Thermal bridging due to the VIP system level

(b) Thermal bridging due to air gaps between two adjacent panels level;

(c) Thermal bridging effects at a building façade level

First of all, at the VIP system level, thermal bridge occurs between the materials constituting the VIP itself. VIPs consist of materials with various properties, not single materials, and each material has different thermal conductivity.
In particular, the metalized envelope of the VIP has a relatively high thermal conductivity as compared with the core material, which causes a thermal bridge in the VIP itself.
Fig. 3. is a conceptual diagram showing the thermal bridges generated by the VIP itself. As shown in the following figure, the thermal insulation of the VIP itself occurs due to the difference in thermal conductivity between the core and the envelope.
In addition, the envelope surrounds the entire VIP, which results in continuous connection from the warm side to the cold side, resulting in thermal bridges at the corners.

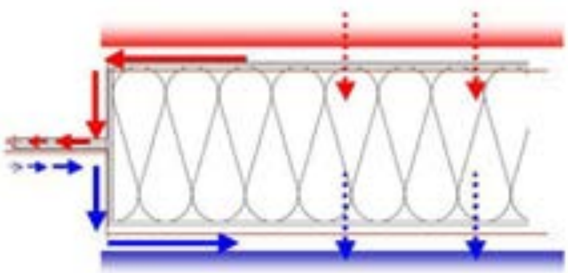


Fig. 3. Conceptual diagram of thermal bridge between core material and enveloe

Therefore, when applying VIPs to a building, it is necessary to calculate an effective thermal conductivity of the VIP which considers thermal bridge itself as well as the center-of-panel thermal conductivity. The equation of effective thermal conductivity can be calculated as shown in Equation (1). The effective thermal conductivity is a thermal conductivity considering the thermal bridging of the VIP itself, which is higher than the center-of-panel thermal conductivity that does not consider thermal bridging.

$$(1)$$

Secondly, the thermal bridge between the adjacent VIPs results in a small air gap between the two adjacent VIPs, as shown in Fig.4.
Then, thermal bridge at the component level is generated through the air gap between VIPs. Heat flows through the small air gap between the VIPs, thereby causing thermal bridge.

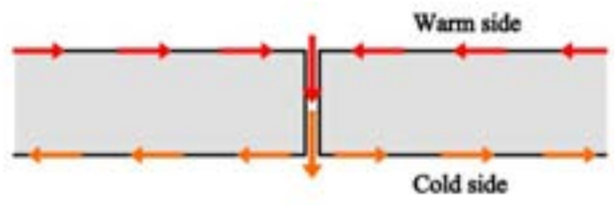


Fig. 4. Conceptual diagram of thermal bridge between two Vacuum Insulation Panels

Third, the thermal bridges of the façade level occur due to joining with building materials of different physical properties according to the installation method when the VIPs are applied to the building. The thermal bridge of the building is caused by the difference in thermal conductivity between the building material and the VIP.
Therefore, when applying VIPs to buildings, it should be considered to minimize these thermal bridges.

3 Simulation

3.1 Simulation Modelling

To evaluate the thermal performance of the VIP walls, simulation models were designed by three connection methods. The models were designed as wood lath, anchor fixing and insulating joiner installation methods. In case of insulating joiner method, it is designed to minimize the heat flow in connection area by filling the joiner inside with urethane foam.

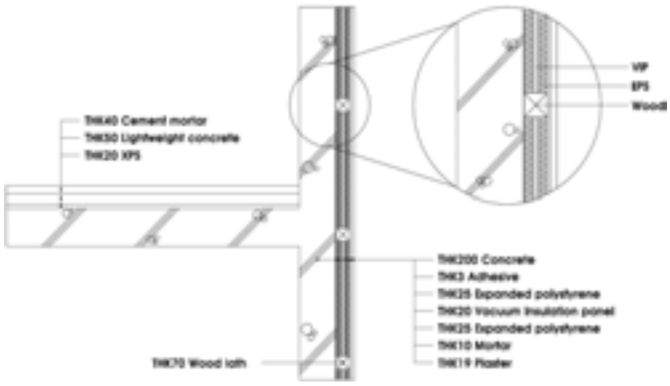


Fig. 5. Wooden lath installation method

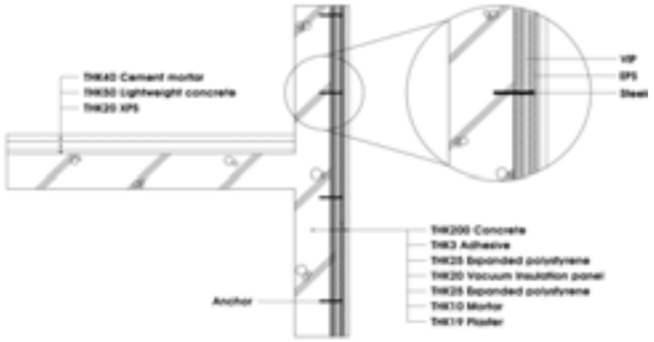


Fig. 6. Anchor fixing installation method

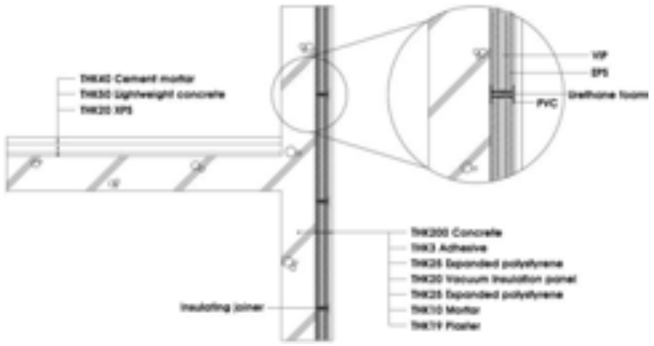


Fig. 7. Insuating joiner installation method

3.2 Simulation boundary

In this study, the simulation programs used were BISCO (v. 10.0w) and TRISCO (v. 13w) from Physibel Co. BISCO is a thermal analysis program that analyses steady-state heat transfer at different boundary conditions of two-dimensional objects made of different materials and can be used to calculate the linear thermal transmittance and the effective thermal transmittance of the wall.

TRISCO is a three-dimensional steady-state heat transfer analysis program for rectangle blocks made of different materials. It is a program used to calculate the effective thermal transmittance of walls, generated thermal bridge, condensation, and walls generated by discretizing the thermal equilibrium equation for finite difference method. The wall boundary conditions used to evaluate the thermal performance of VIP walls and the surface heat transfer resistances based on building energy conservation design criteria of Korea are shown in Table 1.

.

Table 1 Boundary condition

	Set temperature(℃)	Surface heat transfer(m2K/W)
Indoor	20.0	0.11
outdoor	-11.3	0.043

In addition, the thermal conductivity of building materials used in the simulation was applied as shown in Table 2. The dates of VIP used in the simulation was the product of

O company, which is manufacturer of VIP in Korea. Table 3 shows detailed specifications of VIP.

Table 2 Material properties

Material	Thermal conductivity(W/mK)	Material	Thermal conductivity(W/mK)
Concrete	1.600	Wood	0.170
Lightweight concrete	0.130	Steel	45.30
mortar	1.400	Adhesive	0.353
Gypsum board	0.180	Plaster	0.196
Expanded Polystyrene(EPS)	0.034	Urethane foam	0.019
Extrude Polystyrene(XPS)	0.029	PVC	0.170

Table 3 VIP specification

Classification	Content	Classification	Content
Core material	Fumed silica	Applied temperature	-200 ~ 100℃
Envelope	Aluminium film laminate	Maximum size	940mm x 1650mm
Thermal conductivity at center of panel	≤ 0.0045 W/mK	Density	210 ± 30kg/m3
Degree of vacuum	< 5 mbar	Thickness	5-40mm
Thickness tolerance	< 1,000mm ±6mm ≥1,000mm ±10mm	Thickness tolerance	< 20mm ±1.5mm ≥20mm ±2.0mm
Fire resistance	Semi-non-combustible	Compression strength	>8N/cm2

The effective thermal conductivity of the VIP considering thermal bridge was calculated as shown in Equation (2), thereby applied to the simulation. The used VIP size was 600 x 600 x 20 mm^3 for simulation.

$$[illegible] = 0.0045 + 0.00919 \text{ X } 0.02 \text{ X } 3.6/0.72 \quad (2)$$

The simulation parameter was applied as shown in Table 4.

Table 4 Simulation parameter

Parameter	Assigned value
Maximum number of iteration cycle	5
Maximum number of iterations within each iterations cycle	10,000
Maximum temperature difference between	0.0001℃

iteration cycle	
Maximum temperature difference between iterations cycle	0.001℃
Max. heat flow divergence for total object	0.001%
Max. heat flow divergence for and node	1%

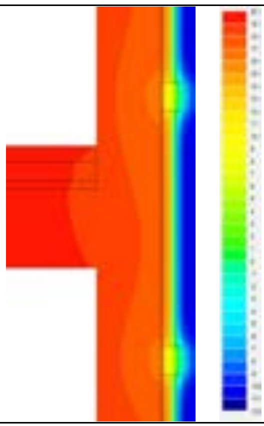
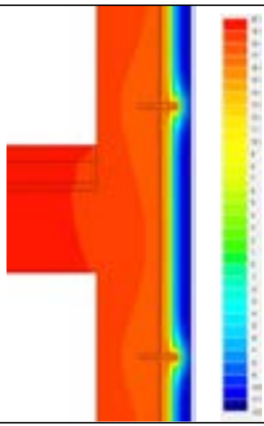
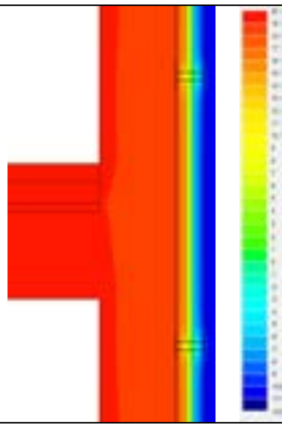
4 Simulation Result

4.1 Insulation Performance (two-dimensional)

The simulation result showed the temperature distribution of the wall in accordance with the building connection method of the VIPs. Table 5 showed the temperature distribution of the wall through the BISCO program. It could be seen that the heat loss and the thermal bridge was mainly generated at the joints between the VIPs and building materials. Results confirmed that heat transfer and thermal bridge at the joining area was significantly larger for the anchor and pin methods than the wood lath method. The reason why thermal bridge caused widely in wooden lath method was that the joining area was wide.

Also, in case of the anchor fixing method, the thermal conductivity of the metal anchor was relatively higher than that of the other materials constituting the wall, so that the heat flow was greatly increased at the connecting area and the thermal bridge was increased. In the insulating joiner method, the bonding area was smaller than wood lath method and the thermal conductivity of PVC was lower than that of metal. Also, the filled urethane foam inside of joiner prevented heat flow in connection area, thus it could reduce thermal bridge and heat loss.

Table 5. BISCO simulation result

	Wooden lath	Anchor fixing	Insulating joiner
Graphic result			
U_{1d}	0.178	0.178	0.178
>	0.078	0.223	0.027
U_{eff}	0.318	0.319	0.193

Simulation results showed the one dimensional thermal transmittance, the linear thermal transmittance and the effective thermal transmittance of VIP applied walls. The one

dimensional thermal transmittance without considering thermal bridge was 0.178W/mK in all three wall types.

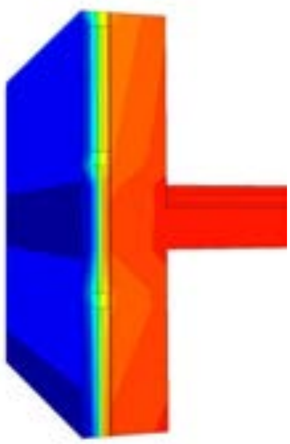
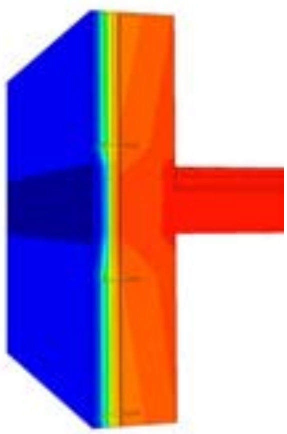
However, since the effect of thermal bridge was different depending on the VIP installation method, the linear thermal transmittance and the effective thermal transmittance considering thermal bridge showed different results. In the case of wooden lath and anchor fixing method in which the influence of thermal bridges was significant, the linear thermal transmittance was high.

Accordingly, effective thermal transmittance was 0.318 W/mK and 0.319 W/mK, which was almost two times higher than one-dimensional thermal transmittance. In the case of insulating joiner method, it was confirmed that the effective thermal transmittance considering thermal bridge was higher than the one dimensional thermal transmittance. However, since the effect of thermal bridges was less than that of wood or anchors, the increase of the effective thermal transmittance was small.

4.2 Insulation Performance (three-dimensional)

Table. 6 showed the results of simulation the outer wall of the VIP using the 3d heat transfer analysis program TRISCO. The results of TRISCO analysis showed that the effective thermal transmittance was higher than that of BISCO, which is a 2D analysis program because of it could reflect more accurate effect of thermal bridge. The effective thermal transmittance was higher in order anchor, wooden lath, and joiner type.

Table 6. TRISCO simulation result

	Wooden lath	Anchor	Joiner
Graphic result			
U_{eff}	0.377	0.407	0.197

It could be seen that the anchor fixing method having the highest effective thermal transmittance was almost twice as much as the effective thermal transmittance of the insulating joiner method. It was found that the insulation performance of the wall of the same layer significantly different depending on the installation method of the vacuum insulation panel.

5 Conclusion

In this study, the insulation performance of the VIP exterior wall was compared and analysed through heat transfer analysis program. The analytical methods of VIPs connection were wooden lath, anchor fixing and insulating joiner methods.
The effect of thermal bridges was larger in the order of anchor fixing, wooden lath and insulating joiner. The effective thermal transmittance considering thermal bridging was from 0.197W / mK to 0.407W / mK. The effect of thermal bridge affected on effective thermal transmittance almost twice.
Even if it has the same one-dimensional thermal transmittance, when the area of the VIP connection is wide or the thermal conductivity of the material used for connecting differs greatly from that of other materials constituting the wall, the effect of thermal bridge was increased. And it caused the degradation of insulation performance in VIP applied wall.

Therefore, when VIPs is applied in building, it is important to reduce the thermal bridge and minimize the deterioration of the insulation performance when vacuum insulation panel is applied to the building.

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ANALYSIS OF LIGHTING PERFORMANCE IN RESIDENTIAL UNIT CONVERTED INTO NURSERY

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Abstract: *Lighting can be used in an efficient way to maximize occupant comfort and to conserve energy. This paper studies a residential villa located in Sharjah that has been converted into a nursery. In the study, methodology includes Autodesk Revit and its lighting analysis plug-in, light-meter to validate initial results, Climate Consultant and a questionnaire-based survey to gauge occupants' and nursery students' level of comfort. The aforementioned equipment was used to generate results, results were then compared to average illuminance requirement standards of the rooms in their original intended function as part of a residential villa and the rooms in their present functions as part of a nursery. Illuminance distribution gradients were generated in four rooms of varying functions. The gradients showed poor light performance, as three out of the four rooms vastly exceeded the illuminance standards. Proposals to improve the passive solar design quality were tested; introduction of horizontal overhang shading devices onto windows proved to be the best proposal, as it met the standards for optimal light performance while also reducing solar heat gain and admitting diffused sky light for illumination, thus catering to the occupants' comfort.*

Keywords: *Lighting Analysis, Autodesk Revit, Climate Consultant, Indoor Environmental Quality, Passive Solar Design.*

1 Introduction

It is important to ensure optimal daylighting within any space because illumination is one of the parameters that influence metabolic processes (Ott Biolight Systems 1997). If occupants of a certain space do not receive enough light, the inadequate illumination will lead to inability to get a clear picture of the colour spectrums in their environment. This inevitably leads to negative effects on the occupants' mood and metabolism. Light is much more than just chromatic perception; it plays a crucial role in shaping the atmosphere needed for whatever function the space serves. Nurseries are the place where children start to bud, explore, socialize and discover the joy of learning. Which is why adequate day lighting must be ensured, as reduced metabolism and concentration will ultimately lead to a poor experience for the child in the nursery due to neglect of one of the parameters that gravely influence the child’s attentiveness and learning experience (Mayron et al. 1974).

This paper seeks to identify whether students in a villa nursery in Sharjah that originally served as a residential unit receive adequate lighting as per the average luminance required standards. The paper will not neglect the function change and, therefore, gauge the villa’s performance as a residential unit as well.

1.1 Objectives

- Analyse illuminance levels in different rooms of the nursery serving different functions and compare them to the average required illuminance standards.
- Gauge the subsequent indoor environmental quality of the space through questionnaires.
- Provide proposals to improve the light performance passive solar design quality and comfort level of the occupants.
- Analyse the proposals then compare the results to determine the best proposal.
- Provide recommendations for additional methods to ameliorate indoor environmental quality.

1.2 Methodology

Autodesk Revit and its light analysis plug-in were used to generate illuminance distribution gradients in four rooms of the nursery. Light meter was used to validate initial results and Climate Consultant was used to show the annual performance the proposed shading device. A questionnaire survey was conducted in both the nursery and the neighbouring residential villas in the same complex. The questionnaire provided us with a means to gauge occupants’ and nursery students’ level of comfort.

1.3 Site Analysis

The villa in is located in Al Sharqan area in Sharjah, United Arab Emirates. It originally served a residential function, but was later converted into a nursery. The villa is part of a complex consisting of fifteen identical villas in total.
Although the villas do not share the same orientations as shown in Figure 1, they all share the same plan with the same window sizes and distribution. This is alarming, as it indicates lack of consideration for the utilization of natural means of illumination in the design process and the comfort of occupants.

Figure 1: Location of the villa, showing neighbouring villas from the compound

Since the villa was originally intended to serve as a residential unit, analysis results will be assessed in comparison to residential and educational standards. This will stress a point that building functions should be respected and that, without significant changes in planning, the building will not optimally cater to the needs of the occupants after the function change.

Sharjah is one of the emirates in UAE, located in the northeast region, overlooking the Persian Gulf. The weather in Dubai is warm and sunny most of the year, because of its location which has the tropic of cancer passing through it. Dubai has a desert climate, has rare rainfalls that average to 5 days a year and a very humid air mostly in summer. The average temperature of the year is 26.7°C, where it reaches mid 40’s in summer as shown in Figure 2.

Figure 2: ***Temperature range***

Solar radiation is one thing that UAE has plenty of, but this energy which has much importance, when having such a hot climate reflects in a bad way on buildings. Since buildings are built to satisfy thermal comfort, the first factor that has to be considered is the solar radiation as it affects the buildings' envelope and internal spaces. The UAE has a monthly mean direct solar radiation that varies between 5000 Wh/m² to 8000 Wh/m² which results in an annual mean of about 6400 Wh/m² as shown in Figure 3. Solar radiation is the most effective factor in heat gain of buildings, especially since this region has an annual average cloud cover of 20% only as shown in Figure 4, which would need a lot of effort in order to reduce the heat gain and improve the thermal comfort of buildings.

Figure 3: ***Radiation range***

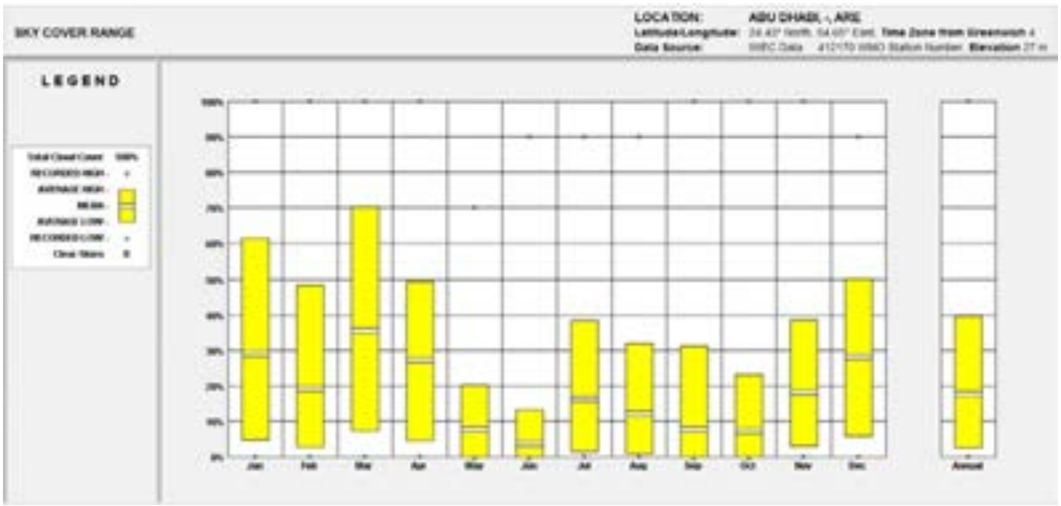
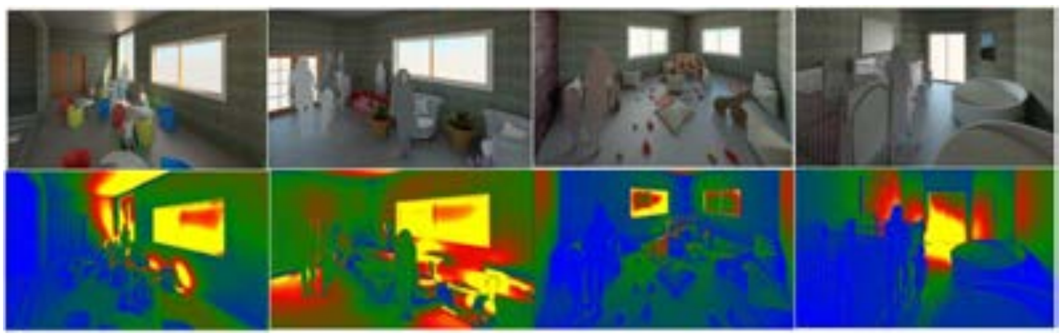


Figure 4: ***Sky cover range***

2 Analysis and Results

Analysis was conducted via Autodesk Revit, using the Solar and Lighting Analysis for Revit plug-in. Figure 5 show the ground floor and first floor plans, with the rooms of interest labelled. A total of four rooms serving different functions (reception, classroom, playroom and sleeping room) were chosen for analysis.

Figure 5: ***Ground Floor Plan (Left side), First Floor Plan (Right side), with rooms of interest labelled***



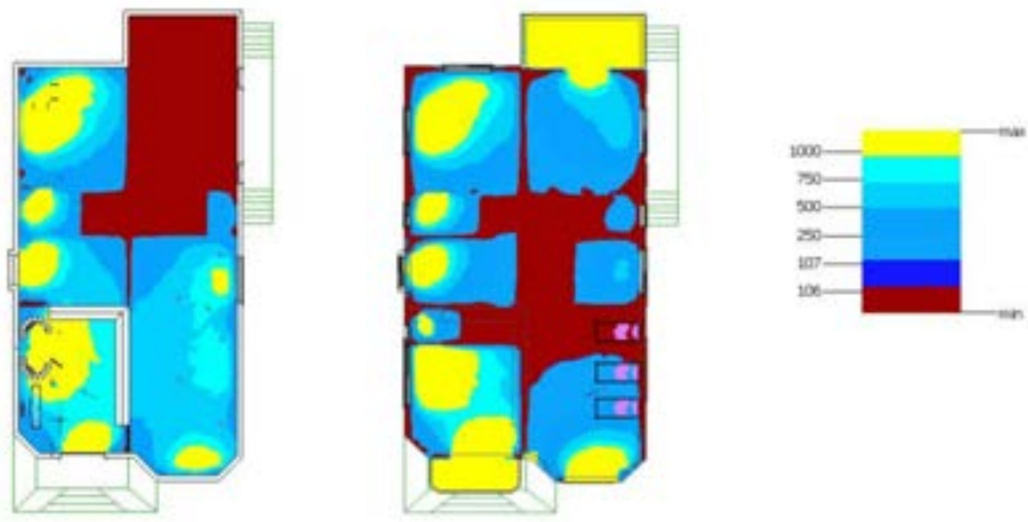
(a) Room 1: Classroom

(b) Room 2 Recepti

(c) Room 3: Play Room

(d) Room 4: Sleeping Room

Figure 6: ***Interior 3D Perspectives of the rooms (Generated by using Revit) with their illuminance gradient renderings underneath***



(a) Ground Floor (b) First Floor

Figure 7: ***Results of the analysis on the ground floor and first floor showing illuminance gradient with lux key provided***

The results demonstrated in Figure 7 were generated with the parameters of date September 21st and its respective DNI and DHI values, at times 9:00 am and 3:00 pm and using clear sky conditions. The results show very high lux levels in rooms 1, 2 and 3, whereas room 4 showed results that are more moderate. According to the standards followed in UAE shown in Figure 8, room 1, which serves as a classroom, exceeds the illuminance level allocated as standard for classrooms; 400-500 lux, and shows results in the range 500-750 lux. Room 2, which serves as reception and waiting space, suffers from very high levels of lux that are completely unwarranted and must be reduced. Room 2 does not comply with illumination standards of 100-300 lux in entrance and inquiry desk spaces. Room 3, which serves as a playing room, also suffers from high amounts of lux that will surely result in an uncomfortable educational and social experience for the children, as it shows illuminance level of 750 lux which is well above the recommended average illuminance level found in the table; 400 lux. Room 4, the sleeping room, shows illuminance level of 250 lux that is congruent with that found in the table for bedrooms. However, room 4 demonstrates very high levels of lux in the area near the window, therefore the amount of glare must be reduced.

Building Type	Space Type	Maintained Average Illuminance at working level (lux)	Measurement (working) Height (1 meter = 3.3 feet)
Barracks/Dormitories	Bedrooms	300	at 0 m
	Laundry rooms	300	at 1 m
Educational Buildings	Play room, nursery, classroom	400	at 0 m
	Lecture hall	400	at 0.8 m
	Computer practice rooms (menu driven)	30	at 0.8 m
Office buildings	Single offices	400	at 0.8 m
	Open plan offices	400	at 0.8 m
	Conference rooms	300	at 0.8 m
Educational buildings	Classrooms	300	at 0.8 m
	Classrooms for adult education	400	at 0.8 m
	Lecture hall	400	at 0.8 m
Hospitals	General ward lighting	300	at 0.8 m
	Simple examination	500	at 0.8 m
	Examination and treatment	1000	at 0.8 m
Hotels and restaurants	Self-service restaurant, dining room	100	at 0.8 m
	Kitchen	500	at 0.8 m
	Buffet	100	at 0.8 m
Sport facilities	Sports halls	300	at 0 m
Wholesale and retail sales	Sales area	500	at 0.8 m
	Till area	500	at 0.8 m
Circulation areas	Corridor	50	at 0 m
	Stairs	50	at 0 m
	Restrooms	300	at 0 m
	Cloakrooms, washrooms, bathrooms, toilets	300	at 0.8 m
Industrial	Metal working/ welding	300	at 1 m
	Simple Assembly Difficult Assembly Exacting Assembly	300 1,000 3,000-10,000	at 1 m
Central Plant	Boiler house Machine Halls Side rooms, e.g. pump rooms, condenser rooms etc. Control rooms	50 300 300 500	at 0 m
Vehicle Construction/ Maintenance	Body work and assembly Painting, spraying, polishing Painting, touch-up, inspection	500 1000 3,000-10,000	at 1 m
Wood working and processing	Saw frame Work at joiner's bench, assembly Polishing, painting, fancy joinery Work on wood working machines e.g. turning, fluting, dressing, rebating, grooving, cutting, sawing, sinking	300 300 1000 500	at 1 m

Figure 8: ***Recommended design illumination standards followed in UAE for selected building spaces (Source: IESNA 9th edition handbook 200, Illuminating Engineering Society of North America)***

The obtained results draw two consequences; the first one is that the villa, as is, is not suitable to provide a comfortable learning and social environment expected from a nursery. The high levels of incoming lux observed in the rooms indicate excessive heat radiation and glare that will irritate the occupants. This is true for the villa as both a nursery and as a residential unit, as room 1, 2 and 3 do not comply with the standards allocated for their original residential functions as well. Room 1 originally served as a dining room, which according to the table of standards requires only 100 lux. Room 2 is a lounge, and Room 3 and 4 were originally bedrooms, and so required no more than 300 lux.

The dangers of poor lighting environment must be eliminated, as the excessive lighting glare causes ocular irritation such as eyestrain and blurred vision, in addition to headaches. Glare does not only lead to ocular problems, but could also cause occupants

to suffer from stiff necks and backs due to adopting awkward positions to perform tasks under inadequate lighting. ("OSH Answers Fact Sheets", (n.d.))

The second consequence is that excessive lighting also means excessive radiation influx into the rooms, which invariably leads to increased energy consumption due to an increase in use of air conditioners to restore a comfortable indoor environment quality.

2.1 Questionnaire-based Survey

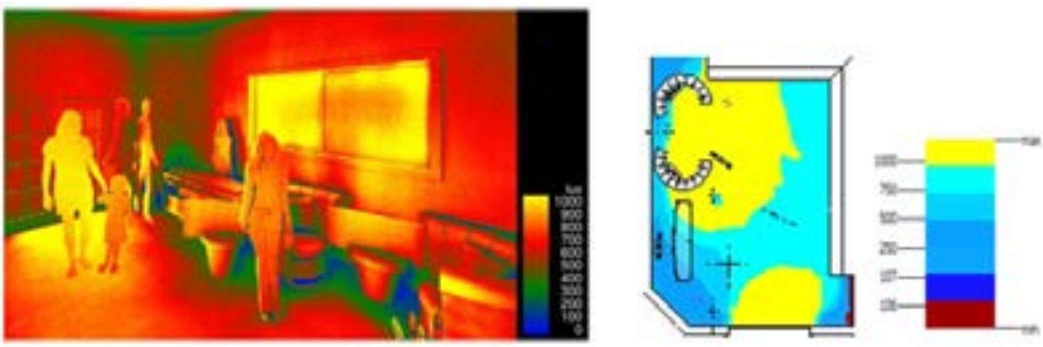
Questionnaire distributed to occupants of the villas and the principal of the nursery provided additional proof to substantiate the analysis results. Excluding the villa that has been converted into a nursery, five of the fourteen tenants of the other villas consented to performing the survey, all of whom answered "yes" when asked whether the natural daylight provided by windows made them uncomfortable from months April through October. Upon further inquiry, all four sources also stated that they tend to keep the blinds down during the aforementioned months.

The results received from surveying the nursery's principal and staff did not clash with the ones received from the other villas. The questioner was inquired about the response of children to interior daylight influx from windows and found that the staff tends to also keep thin curtains down to make the lighting less harsh.

3 Proposals to Improve Indoor Environmental Quality and Lighting Performance

3.1 Existing Case

As Figure 7 (a) demonstrates, rooms 1, 2 and 3 need improvement. Room 2 is the most extreme case among the three, bearing in mind the function it serves; a place for inquiry and waiting. The results are also incongruent with illuminance level standard for its original function as a lobby in a residential unit. This is why room 2 was picked as a specimen on which improvement proposals were tested and tried. Room 2 being the worst-case scenario will serve as an illustration for the consequences of installing shading devices and reducing window size, if proven successful, these proposals are adequate and applicable to all other rooms.



(a) Illuminance distribution in interior 3D perspective

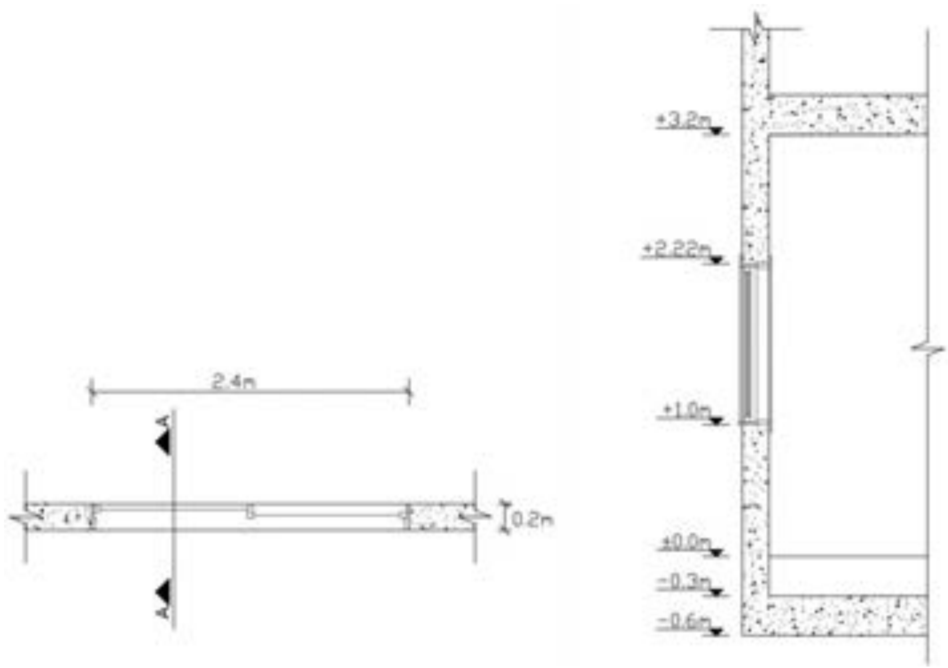
(b) Illuminance distribution in plan view

Figure 9: ***Analysis results in room 2 in a 3D perspective and plan view***

Figure 9 (a) & (b) show results of analysis performed using the following parameters: Date: September 21st, sky model: clear sky conditions, time: 9:00 am, DNI: 772 W/m^2 and DHI: 88 W/m^2. The following proposals were tested using the same input parameters to allow for comparison of results with the original.

3.1.1 Addition of Horizontal Shading Device

"The windows account for the greatest amounts of heat entering the building and therefore shading them, offers the greatest protections" (Olgay 1963, p72). Windows should be fortified with shading devices to minimize radiation in summer. An exterior shading device, as the one employed here, will shade the window from direct radiation and reduce solar heat gain. Bearing in mind the position of the sun in summer that is characterized by being higher than that of winter, the overhang-shading device would fulfil the role of shade in summer and light admitter in winter.



(b) Section view (a) Plan view

Figure 10: ***Plan and section of selected window showing the window dimensions***

The following calculations were done to find the required horizontal shading device depth:
Window dimensions: 1.22m*2.4m
Cantilever = 0.043m
Shading = 1.12m
0.043 + 1.12 = 1.2 m
$\text{Tan}^{-1}\left(\frac{0.043}{1.22}\right) = 2.0°$
$90° – 2.0° = 88°$
$\text{Tan}^{-1}\left(\frac{1.2}{1.22}\right) = 45°$
$90° – 45° = 45°$

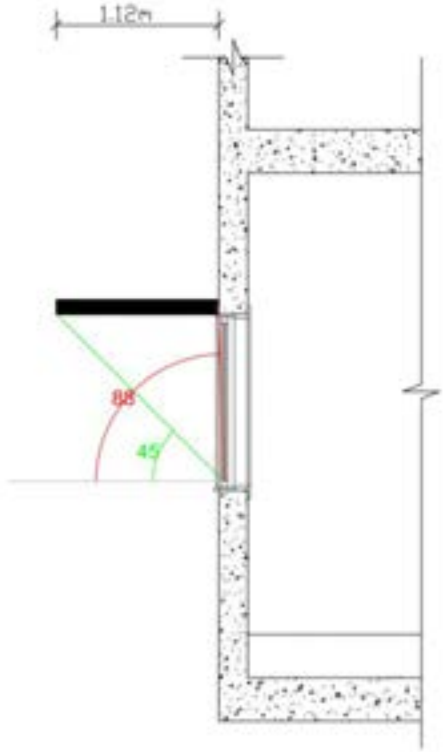


Figure 11: ***Section view after adding overhang horizontal shading device***

The shading device parameters were then entered as an input into Climate Consultant to demonstrate the effect of adding the horizontal shading device on the incoming solar light. As demonstrated in Figure 12, the shading device allows for winter sunlight admission in months December, January, February and March.

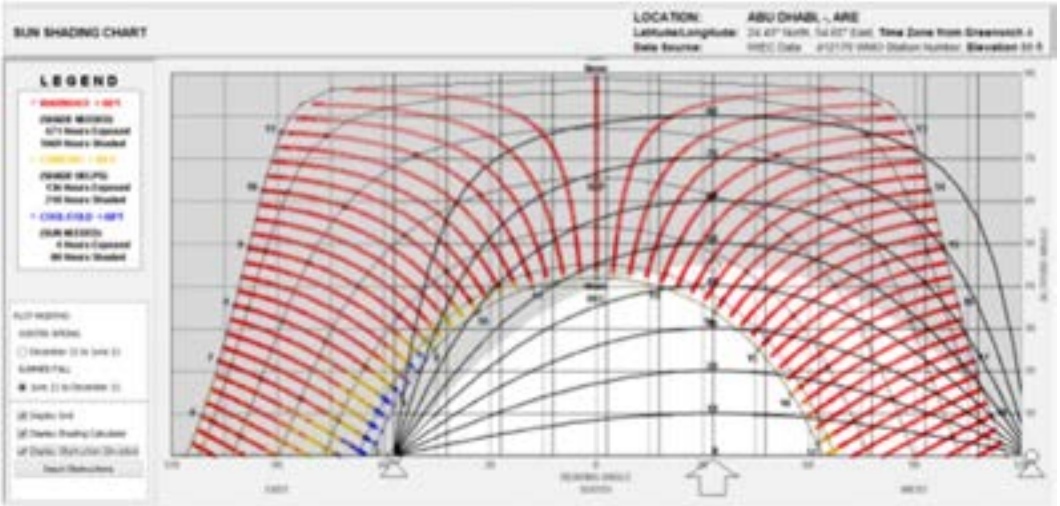


Figure 12: ***Chart obtained from Climate Consultant software demonstrating the shading device' role as a shade in summer and sunlight admitter in*** **winter**

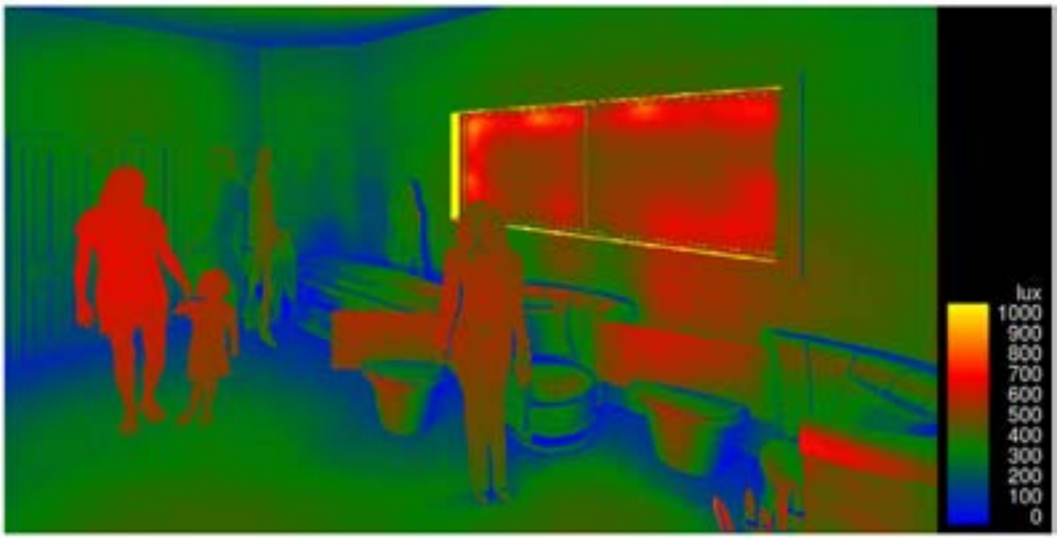
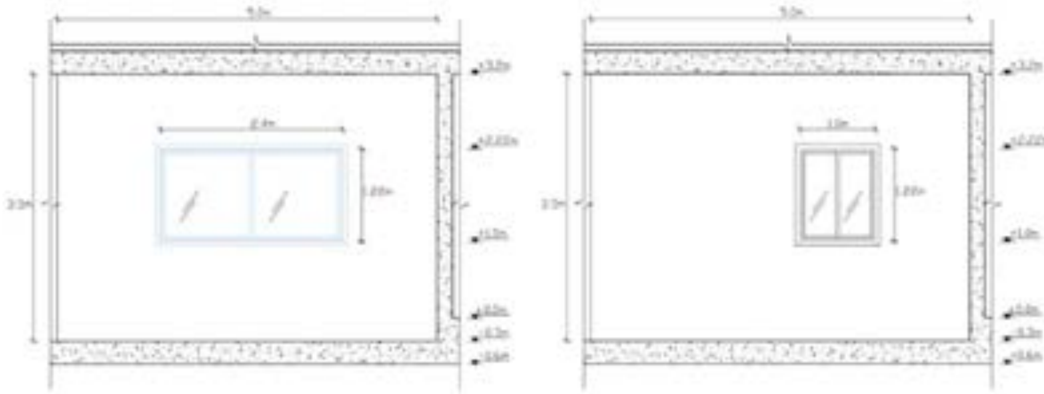


Figure 13: ***Results of light analysis in room 2 after the introduction of horizontal shading device on the window***

3.1.2 Reduction of Window Size

Window width is reduced from 2.4m to 1m. This leads to a cut down in incoming solar heat gain and radiation.



(a) Original window size *(b)* The window after width reduction

Figure 14: ***Elevation view of the window showing dimensions before and after width reduction***

Window to wall ratio (1)
Window area = 1.22m*2.4m = 2.928m^2
Wall area = 3.5m*5m = 17.5m^2
(2.928/17.5) * 100 = 16.7%

Window to wall ratio (2)
Window area = 1.22m*1.0m = 1.22m^2
Wall area = 3.5m*5m = 17.5m^2
(1.22/17.5) * 100 = 7%

The window to wall ratio in the original case illustrated in Figure 14 (a) is 16.7%, which is less than 30%. Although the ideal window to wall ratio is 30% (Arranz et al. 2014), it must be noted that the case at hand involves a small room and this space is only meant to serve as inquiry and waiting area in the nursery, and lounge in the residential unit. Therefore, a window of width 2.4m and 1.22m height allows in abundant lux levels that are not needed. According to illuminance standards, the recommended illuminance levels for an area with an inquiry desk and waiting area lie within the range 100-300 lux. As such, the window width has been reduced from 2.4m to 1m as illustrated in Figure 14 (b). The consequences of this change were tested using Revit and the lighting analysis plug-in and are shown in Figure 15.

Figure 15: ***Results of light analysis in room 2 after reducing window area***

3.2 Recommendations for Improved Indoor Light Performance and Environmental Quality

3.2.1 Utilizing Landscape Features as Shading Devices

Introduction of mature trees in the villa's landscape will help reduce solar heat gain from morning to afternoon in summer. The trees are best incorporated on the east and west sides of the villa for a more optimal passive solar design (D. Prowler et al., 2008).

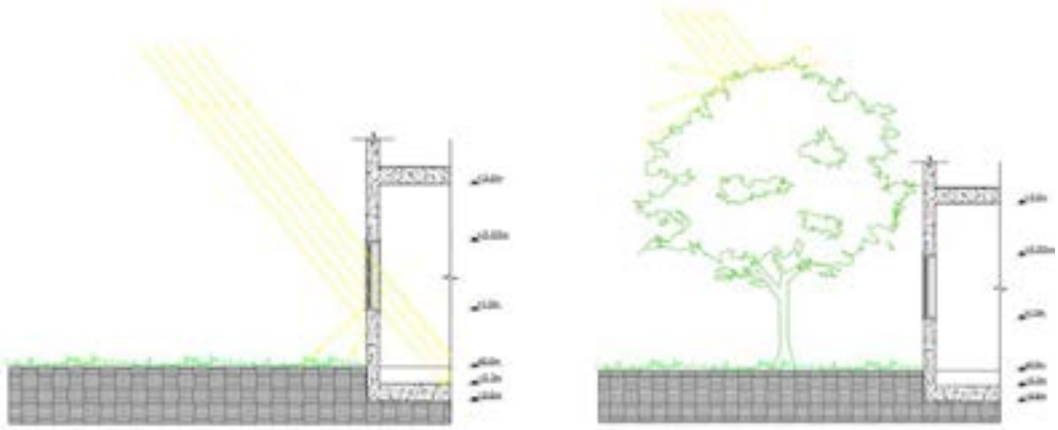


Figure 16: ***Introducing mature trees in landscape is a mean to reduce direct solar heat gain in summer***

3.2.2 Using Matte Finishing on Interior Walls

In order to minimise glare and ocular discomfort, it is best to ensure the usage of unreflective finishing on interior walls (Lewis, R. (n.d.)), like matte finishing ("OSH Answers Fact Sheets", (n.d.)), and avoid bright light colours on walls as they are more reflective and thus induce glare.

4 Discussion

As demonstrated in Figures 13 and 15, the results of the analysis performed after implementing two passive solar design improvement proposals have shown a significant decrease in the amount of lux in room 2 in both cases. Both proposals succeeded in reducing average illuminance in the room to 300 lux, which is the ideal for both lobby and inquiry desk/reception functions, therefore these proposals can be implemented in the nursery and the neighbouring residential villas.
The objective is not only to meet standards for average illuminance levels, but also to cut direct solar heat gain and depend on diffused skylight for illumination, this criterion is only met in the first proposal. Adding horizontal shading devices will provide a more comfortable indoor environmental quality, in addition to optimal lighting performance. As opposed to the second proposal which would fail in minimizing heat radiation into the interior. Therefore, the first proposal is a better and more encompassing solution to the poor lighting performance of the building.

5 Conclusions

Openings in the building envelope have a great influence on daylighting in the interior of the building space. The amount of opening area, its orientation and outside obstruction affects the inside illumination. Almost all of the energy consumption occurs during the building's operational phase for lighting, cooling & heating purposes.

There are many different reasons to control the amount of sunlight that is accepted to enter into a building. Well-designed sun control and shading devices can reduce the building top heat gain and cooling requirements and improve the natural lighting quality of building interiors. Based on the amount and location of fenestration, reductions in annual cooling energy consumption of 5% to 15% have been reported. Sun control and shading devices can also improve the user's visual comfort level by controlling glare and reducing contrast ratios. As a result, this leads to increasing the level of satisfaction and productivity. On the other hand, shading devices show the opportunity of differentiating one building facade from another.

The south direction of any building is the most side that needs consideration in providing the most suitable shading device and the best glazing in terms of heat infiltration to reduce the heat gain as much as possible, since the south area is the most area that is affected by the sun radiation. The materials used in buildings does a major influence on the heat flow through the building since each material has its own rate of heat flow (conductivity).

After performing light analysis on the existing building case, and putting forth proposals for passive solar design improvement, it has been concluded that the introduction of horizontal overhang shading devices onto windows will cater to both the lighting standard criteria and the occupants' comfort. Recommendations of utilizing landscape features to provide shading, and coating the interior walls with unreflective finishing such as matte to reduce glare have also been included to fortify the proposals in the ambition of providing a more adequate living or educational environment for both villa functions.

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EARTHQUAKE DISASTER RESPONSE: REBUILDING SUSTAINABLE MODULAR SCHOOLS IN NEPAL

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Abstract: *In April of 2015 a magnitude 7.8Mw earthquake in Nepal killed approximately 9,000 people and left around 22,300 people injured. The largest natural disaster to strike Nepal since the Nepal-Bihar earthquake in 1934, the quake left hundreds of thousands of people homeless, and much of the civic infrastructure around the epicentre of the Gorkha District at Barpak destroyed or seriously damaged. This paper outlines a kit-of-parts school design that was developed in response to the emergency infrastructure needs in the aftermath of the Gorkha earthquake. Light-weight steel frames and panelling system that incorporates contemporary seismic design principles was designed through a collaborative partnership to assist in the aid response and facilitate with the rebuild of essential infrastructure and facility needs. Able to be constructed and implemented by the local community, an open-source modular design prototype facility is in the process of being constructed in the region. This paper discusses the design process and construction methods utilised to develop a prefabricated school structure suitable for seismic areas, and the challenges that were faced to develop a novel disaster response construction process. The paper aims at providing insights into sustainable prefabrication methods that can be utilised to efficiently, quickly and cost-effectively deliver school buildings and community infrastructure needs in remote and post disaster contexts.*

Keywords*: Nepal Schools, Kit-of-parts Prefabrication, Modular Design, Post Disaster Architecture, Open Source Architectural Design*

1 Introduction

On the 25th of April, 2015, a 7.8Mw magnitude earthquake hit central Nepal. As a result of that quake and the aftershocks that followed, over 8,900 people died and approximately 22,300 were injured (Government of Nepal, 2015). Whilst Nepal is a region that is well known for large earthquakes, this was the largest natural disaster to strike Nepal since the Nepal-Bihar earthquake in 1934. Several weeks later, a second earthquake hit, causing further deaths and destruction. In total, close to 1 million homes, and over 6,000 government buildings and other infrastructure facilities in the Himalayan region were damaged or destroyed (Government of Nepal, 2015). Due to the scale of the destruction, the earthquake presented a range of challenges, as well as the opportunity to rebuild and incorporate contemporary seismic design principles in the design and delivery of new civic infrastructure.

Within the Solukhumbu district, approximately 70% of the government schools were destroyed, and more than 200 of the 300 schools supported by the Australian Himalayan Foundation (AHF) were badly damaged or levelled (Australian Himalayan Foundation, 2016; "District-wise Damage Summary," 2015). Located in the foot hills of Mount Everest, in an area that is largely inaccessible by vehicles, the village of Garma was one of worst damaged areas in the Solukhumbu district (Watt, 2015). Only 80km from the epicenter of the second earthquake, many structures that had withstood the first quake, either did not survive, or were badly damaged during the second.

Garma's special needs secondary school was no exception, with eight out of its nine classrooms destroyed during the quake and the subsequent aftershocks that ensued. This paper outlines a kit-of-parts school design that was developed in response to the emergency infrastructure needs in the aftermath of the Gorkha earthquake. Focusing on the Solukhumbu district and the Garma school as a case study for the prototype delivery, this paper discusses the design process and construction methods utilised to develop a prefabricated school structure suitable for seismic areas, and the challenges that were faced to develop a novel disaster response construction process. The paper aims at providing insights into sustainable prefabrication methods that can be utilised to efficiently, quickly and cost-effectively deliver school buildings and community infrastructure needs in remote and post disaster contexts.

2 The emergency response strategy: kit-of-parts school system

Given the increasing prevalence of disasters in recent times (both natural and made made)(DeMond S. Miller & Rivera, 2010b), there is a pressing need to "learn from past experience, address the challenges posed by disaster recovery, and embrace the opportunities to build stronger, more vibrant sustainable communities, regions and countries immediately following a disaster" (DeMond S. Miller & Rivera, 2010b, p. xxxvi). Local government agencies and NGOs face a range of immediate and conflicting challenges in trying to respond to community needs in the aftermath of a disaster. Such challenges include, but are not limited to the urgent and timely replacement of physical facilities and infrastructure; ensuring the survival and revitalization of local communities though integrated improvements in education, health and the environment; enabling community engagement in the reconstruction process; and, ensuring that the infrastructure being rebuilt builds on knowledge gained from the disaster, is reliable and robust, and better able to withstand a similar disaster.

The kit-of-parts school design outlined within this paper, was designed and developed as a collaboration between The Australian Himalayan Foundation (AHF) and its in-country partner REED (an organisation that engages in teacher training and education delivery), Taylor

Thomson Whitting (structural engineers),architecture firm HASSELL, David Francis Architects, and a range of other individuals and organisations to help provide a rapid disaster response and aid in the challenge of 'building back better'. This paper examines the design response developed by the team and some of the challenges faced in the design and delivery of a kit-of-parts of steel framed structure with component parts that were light enough to be carried on the backs of porters into remote areas, and yet strong enough to withstand future earthquakes as well as violent monsoonal storms.

In an effort to support the rebuild process and develop sustainable infrastructure suitable for the region, the Nepalese government and non-government organisations working in the area, have developed guidelines and strategic objectives for the post-earthquake reconstruction, design and delivery of schools and other infrastructure (Department of Education, 2016; Government of Nepal, 2016). The Government of Nepal National Reconstruction Authority lists the strategic recovery objectives for the reconstruction programme as:

- Restore and improve disaster resilient housing, government buildings and cultural heritage in rural areas and cities
- Strengthen the capacity of people and communities to reduce their risk and vulnerability and to enhance social cohesion
- Restore and improve access to services and improve environmental resilience
- Develop and restore economic opportunities and livelihoods and re-establish productive sectors
- Strengthen capacity and effectiveness of the state to respond to the people's needs and effectively recover from future disasters (Government of Nepal, 2016, p. 4)

With slow economic growth over recent years, a reconstruction cost estimated at approximately $10 billion dollars, the sheer logistics of a re-build programme of this scale, and difficulty in securing material and skilled labour supply to meet the reconstruction demands, the road to recovery after a disaster of this magnitude is a long one (Fickes, 2005; Government of Nepal, 2016; DeMond S. Miller & Rivera, 2010a; Yan, Wilkinson, Potangaroa, & Seville, 2011). In recognition of the need to deliver low cost, robust construction systems suitable for areas prone to seismic activity, and in support of the government's strategic objectives, the research team decided to adopt a prefabricated, modular kit-of-parts system that could use local labour and provide local community employment and up-skilling opportunities as an integral part of the reconstruction work.

A partially prefabricated system was adopted in an attempt to optimize efficiency, improve quality, reduce cost and environmental impact, and save on the construction and delivery time frame. There is a long history of the development of innovative construction systems and prefabrication processes for the design and delivery of schools and other education facilities (Andrew, 2011; Dolan, 2006; Newton, 2015). Initially fuelled by post-war building programmes, budgetary constraints, rapid project delivery requirements, and a modernist push for efficiency, over the years, manufacturers and architects have continued to develop more advanced methods of prefabrication (Andrew, 2011; Kieran & Timberlake, 2004; Mao, Shen, Shen, & Tang, 2013; Newton, 2015). Currently, factory construction is around thirty percent faster than conventional construction, and results in reduced greenhouse gas emissions (Kaufmann & Remick, 2009; Mao et al., 2013). Modular designs in recent years have reduced the number of different parts needed for on-site assembly, resulting in time and cost savings. By adopting a modular approach, in conjunction with select component parts manufactured from locally sourced materials and utilising traditional construction techniques, the design aimed to reduce the overall construction cost, and the reliance on advanced technologies for transportation and assembly, whilst providing job opportunities and skill training for local workers. Through the promotion of on-site local labour and skills

building, the project aimed not just to provide employment in a region that has high unemployment, but also to utilise the school reconstruction as a vehicle through which to "promote resilience, enhance a community's ability to bounce back from exposure to natural disaster, and help citizens build community social capital for disaster prevention and preparedness" (DeMond Shondell Miller, 2010, p. 80).

In developing the modular kit-of-parts system, a range of different proposals and approaches, such as prefabricated sinusoidal corrugated web beam-column joints, were examined to be able to develop a prefabricated steel structure system that was earthquake-resilient (Naeim, 2001; *Seismic design manual*, 2006; Zhang, Li, Jiang, Fang, & Dou, 2017). Whilst structure framing systems have become a growing area of interest in the field of structural seismic research (Grigorian & Grigorian, 2011; Naeim, 2001; *Seismic design manual*, 2006; Zhang et al., 2017), developing a system suitable for construction in remote areas with limited skilled labour, was a challenge in the design and development of the prototype system.

Following the Nepalese Department of Education spatial requirements and area entitlements scheme, four preliminary models were developed as potential configurations for the classroom kit-of-parts. The smaller prototype; RP1 is for 15-20 students, and the larger one (PR3) is for approximately 30 students. The classroom size and area entitlements are based on the number of students enrolled in schools (Department of Education, 2016). The type designs are selected to cover at least 80% of schools to be reconstructed, and the spatial class room standard design was developed in accordance with reference guidelines (Department of Education, 2016; UNESCO, 2015).

One of the challenges in designing the modular system was the difficulty in designing a system that provided spatial planning that enabled rooms and desks to be reconfigured to allow for a range of different teaching and learning modalities, from traditional didactic teaching to small group based activities, teaching and learning. Additionally, space was required for storage, and school amenities. The design of a classroom prototype suitable for Nepal presented several challenges, including, but not limited to, the requirement to house most school activities inside due to extremes in weather, and the lack of school amenities such as computer labs, library and storage space. The end design of the prototype modular system enables the several different spatial configurations within a confined space, and the increased classroom length allows for the accommodation of additional storage or lab spaces. Whilst the width of the modular class rooms is restricted by the design of the seismic structural frames (around 4800mm), the modular approach allows for flexibility in scale and the expansion of the class room along its length.

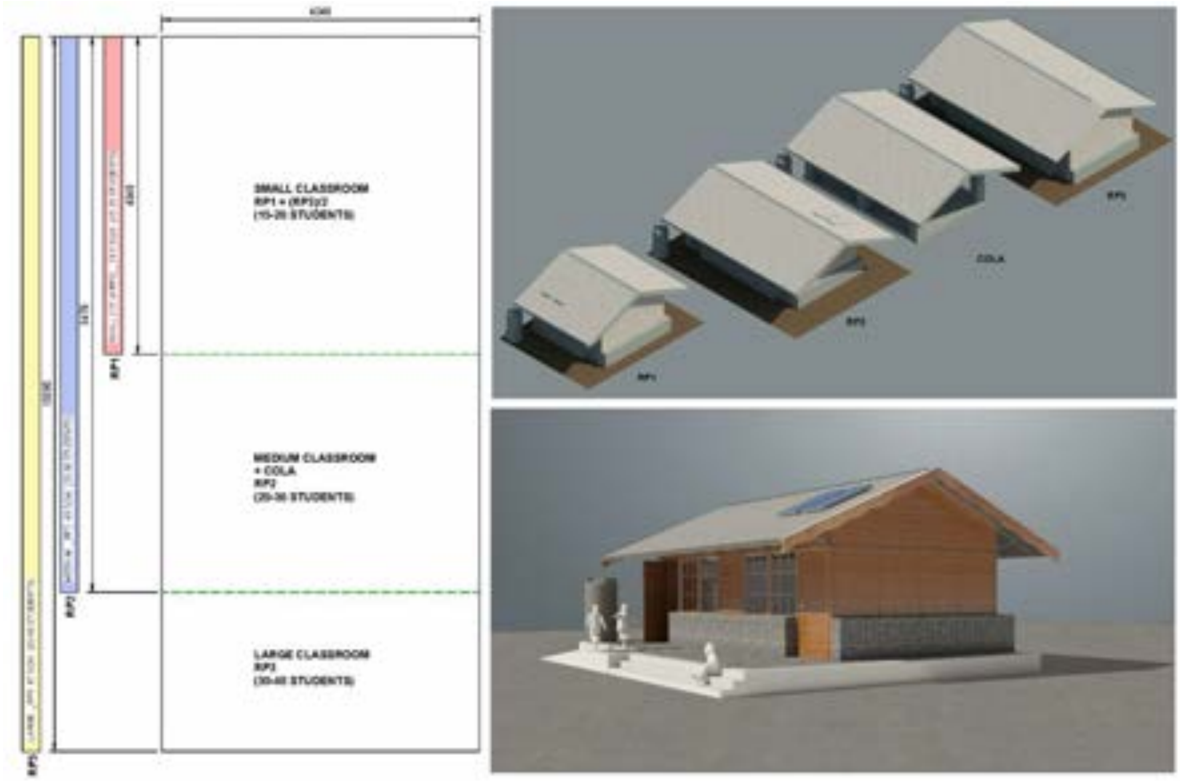

Figure 01: Special configuration of classroom sizes and the 4 categories: RP1, RP2.RP3. and COLA

2.2 Kit-of-Parts Classroom

The proposed kit-of-parts consists of 1210mm wide steel-framed wall panels (panel door, panel wall, panel window) which enable the local community to mix and match building component parts as needed. The panelised kit-of-parts system also provides the possibility create Covered Outdoor Learning Areas (COLAs) by omiting panels.

The advantage of COLAs over conventional enclosed buildings is they allow for greater natural air flow and light, and can be transformed to one of the other classroom types when needed. The open side and end structures must be specially designed to withstand wind loads and uplift without the aid of wall cladding and conventional bracing, and stiffer columns and additional lateral bracing are just a couple of the many differences which were incorporated in the original design of the solid wall panels.
The classroom design allows for on-site water collection, and in addition to the minimum government school standards provided by the Nepalese government (Department of Education, 2016), the design incorporates:
– Larger windows for deeper daylight penetration
– Lower window cells to allow the children clear sight lines to green space outside
– Large overhangs for gathering outside the classroom, and enable students to utilize the outdoor covered space for bag storage etc.
– Thermal and acoustic insulation of the prefab panels
– Acoustically tuned environments for improved voice clarity
_ Rainwater harvesting
_ Composting toilets rather than the standard septic tanks
_ Solar hot water and electricity
_ Skylights to provide natural light within classrooms

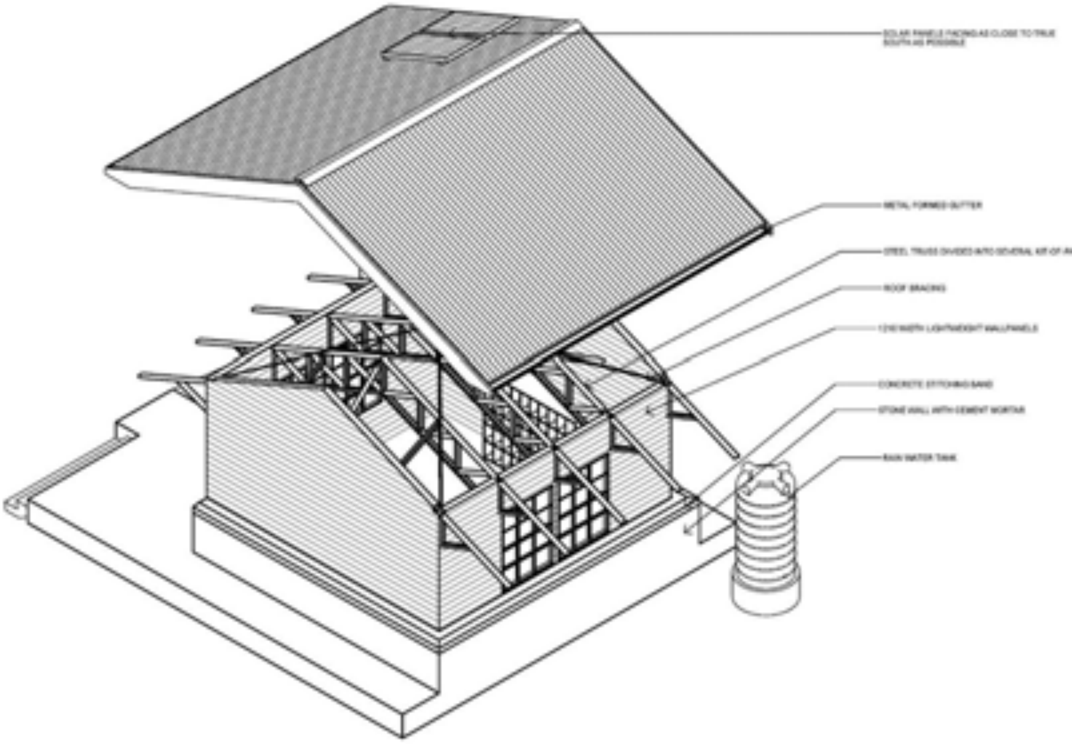

Figure 02: Classroom RP1 model components

To examine the suitability of the prototype design, the proposed kit-of-parts was first tested by TTW in a Building Information Modelling (BIM) environment. All structural frames were drawn with their assigned structural performance parameters in Autodesk Revit, and then architecture kits were also added to allow for the conceptualization of the different prototype models. The design model was formulated as a Level of Development (LOD) 4 model; that is, a production ready model. By having an accurate 3D model that incorporated a high level of building information, the team was able to utilize the model to obtain more accurate cost estimates, and to communicate directly with manufacturers across the border in India for a more streamlined fabrication process. Due to the desire to use the initial prototype to test the kit-of-parts system, and utilise the modular design for school reconstruction across a range of sites in Nepal, the scope of the initial project did not include a specific BIM plan nor further LOD 5 or LOD 6 as these are steps that are site specific and were out of the scope of the design stage.

Traditional construction in Nepal is typically based on heavy load bearing stone and mud structures, and more recently on block work construction. The poor seismic performance of many of the mass structures in Nepal was one of the factors in the high death toll and structural damage resulting from the earthquake ("District-wise Damage Summary," 2015; Government of Nepal, 2015; Watt, 2015). The school designs introduced in this paper are framed in light gauge steel and clad in lightweight materials resulting in a relatively light building which has lower seismic loads relative to a similar sized structure that utilises mass construction. Different methods used to resist the lateral loads include diagonally bracing the structure, bracing the structure with a diaphragm, or making a rigid connection point (Ambrose & Vergun, 1985; Grigorian & Grigorian, 2011; Naeim, 2001; Zhang et al., 2017).

Steel frame construction is advantageous for resisting seismic loads because of the strength and inherent material characteristics of steel. Furthermore, it is easily adaptable to different

building types. However, common problems associated with steel construction with applied seismic forces are loosening of bolts, cracks in welded connections, and torsion in areas that are intensely loaded. Optional solutions for resisting lateral forces are the inclusion of diagonal bracing and moment resistant connections. Table 1 below outlines some of the key seismic considerations for the structural engineering and design of the prototype modular system.

Table 1: Seismic considerations for the design of the prototype modular system

Earthquake Engineering Principle	Mass	Strength	Ductility
	The 'lateral load' on a building caused by an earthquake is proportional to its mass. The design earthquake loads for Nepal are about 10 times those for Australia	**A stronger building structure will resist an earthquake of higher intensity** (earthquake of higher Richter scale). Prefabricated building materials such as steel have reliable strengths compared to those made by unskilled workers on remote sites.	**Structure types and materials which can continue to support load beyond their 'yield' strength are called ductile.** For two structures of the same strength the more ductile structure will resist an earthquake of higher intensity
Traditional Nepalese school construction (Stone/masonry walls, with walls not tied to roof)	Very high mass	Low strength. Unreliable strength of materials mixed on site such as mortar and concrete.	Stone and unreinforced masonry are brittle and have no ductility
Timber framed roof with no bracing		Local timber is not graded and therefore does not have a reliable strength	
Garma - Nepal School Construction (Walls and roof framed with cold-formed steel. Steel framing fabrication and supply by a manufacturer in New Delhi, India.)	Both the cold-formed steel structure and the roof & wall cladding are lightweight. A single RP2 classroom has a total mass (excluding the low height perimeter wall) of about 2.5 tones. The same size classroom built with traditional stone or masonry walls would have a total mass of 3 to 4 times this. Because of its very low mass, the design wind load is far greater than the design earthquake load.	The cold-formed steel is high strength and of a reliable strength, manufactured to International Standards. Fabrication of the C channels undertaken by MGI Infra using a CNC machine. Assembly on site consists of joining each piece of cold formed steel with a pair of screws in holes pre-made by the CNC machine. This is a great example of coupling current technology (very precise fabrication in controlled factory conditions with a CNC machine) with assembly being carried out by unskilled workers on remote sites (every steel connection is two screws located in factory drilled holes).	Steel is a material with great ductility, able to continue to support load after it has yielded.

One of the benefits of the use of component parts that are made in factory-controlled conditions is the ability to have a structure of known and reliable strength. Furthermore, the construction time is dramatically shorter than traditional techniques as there is less on site assembly. Frames are assembled by joining each piece of framing to the next with two screws. The building's frame can be easily assembled with a screw gun by local labour, and the low stone structure built around a rammed earth base absorbs seismic forces and relies on the provision of local stone, local labour and traditional building techniques. The portability and lightweight structure means that the designs can be used across a range of earthquake prone areas in Nepal and the surrounding Himalaya region. Importantly, the design is low cost with building costs around A$15,000-20,000 per classroom.

3 Open-source Design and Community Engagement

Due to the scale of the damage in the 2015 Nepal earthquake, the post-disaster reconstruction process involves a vast range of government agencies, NGOs and design professionals. To facilitate the reconstruction process, the team involved in the design of the modular kit-of-parts system presented in this paper decided to provide the systems as an open-source design, free of charge to anyone interested in utilizing it and adapting it to other reconstruction projects. By making the design accessible as an open-source design, it enables further development and enhancement of the design, and modification of the system for application across a wider range of school buildings, sites and other facilities.

As part of the repair and reconstruction work, the AHF has also focussed on the upskilling of members of the communities in which these schools are being constructed, funding masonry and school building retrofit skills training courses for over 60 local people from the Solukhumbu district. This training was conducted by experienced staff/engineers from the National Society for Earthquake Technology (NSET), and from this training programme, the AHF has employed over 10 masons picked from across these training groups to complete the repair and retrofit of damaged classrooms at the Garma Secondary School. Working with in-country partner REED, this training scheme has helped to build a skilled labour force that, in support of the key government strategic redevelopment goals, aims to boost the local construction capacity and economy, and promote resilience and empowerment within the region (Government of Nepal, 2016).

Figure 02: classroom prototype onsite construction

4 Case Study: From an open-source design to construction on site

To enable further development of the open source prototype, David Francis was appointed AHF Project Coordinator in November 2016. One of the challenges faced in the implementation of the base open source modular system is incorporating the ability for design development and modification in construction detailing to provide design flexibility and adaptability for differing needs, conditions and material availability. The requirement to rapidly develop and incorporate changes, in some cases while the structure was being constructed, has been one of the many challenges in the development and delivery of the modular system.

Like many schools in the district, the Garma school had no power, no artificial lighting, no running water and small windows. Given the extremes in climate in the region, one of the challenges was to design a prototype that provided good natural light, access to water, and insulation from the very hot temperatures and torrential down pours in summer, and very cold temperatures and heavy snow in winter.

The prototype system relies on light weight cold rolled galvanized steel stud and truss construction, and is designed to be insulated and clad inside and out with light weight panelised materials. The developed prototype at the Garma school allows for a robust plywood cladding internally, and either a sustainable yield timber, corrugated zincalume or compressed fibre cement exterior cladding (selected by the community based on material availability and local preference). At the Garma site, the local community has been involved in the laying of the traditional low height stone walls around the base of the buildings. These stone walls serve to hold the light weight schools down in high wind conditions, and the height of the walls have been designed so that they do not represent a safety risk in the advent of an earthquake.

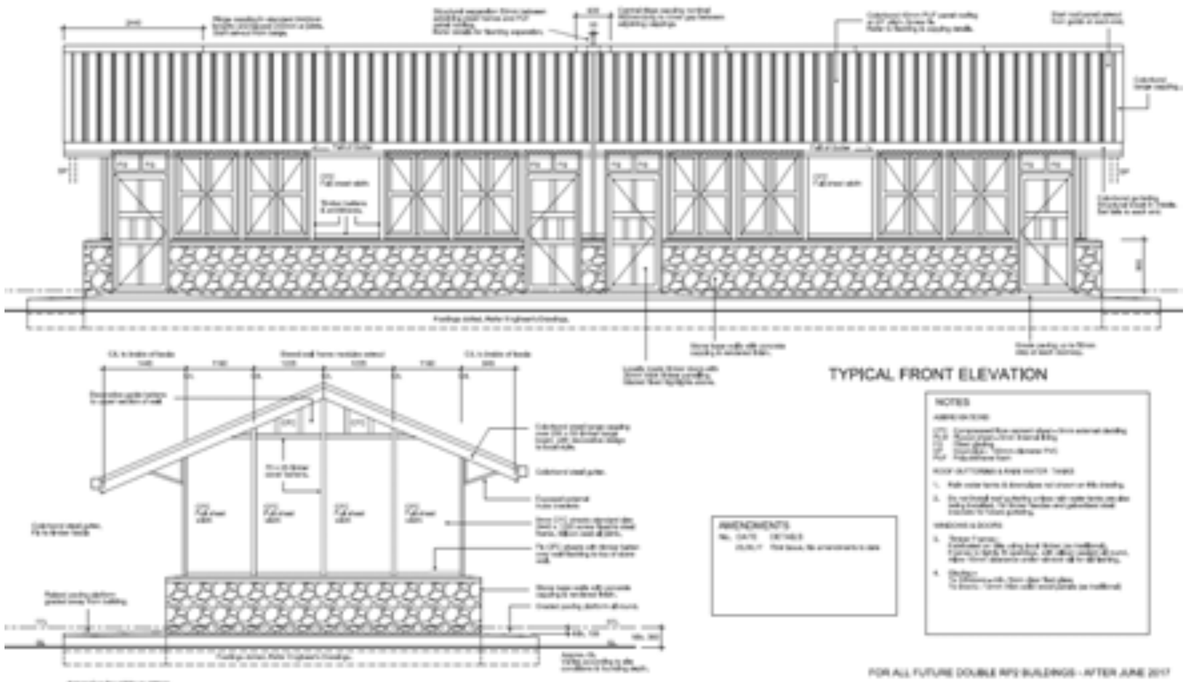

Figure 03: one prototype developed by architect David Francis from the open source design

An important final touch is the installation roof barge boards which will be designed and crafted by the local community. This decoration is a typical feature of Nepalese vernacular architecture, and helps provide individuation and a sense of local identity to each classroom. With around 300 students, the school at Garma is one of the main schools in the area.

Figure 04: work in progress at Garma School, Solukhumbu district, Nepal

A further consideration at the Garma site has been the sourcing of windows and doors. Whilst locally sourced timber framed windows and doors cost about the same as aluminium units fabricated in India, local sourcing allows for reduced transportation costs, provides local employment, and facilitates any need for ongoing maintenance.

5 Reflections from the lower Solukhumbu coalface

Whilst the modular prototype presented in this paper should theoretically be simple to implement, the reality of on-site implementation is far more complex. In Nepal, the centuries-old traditional method of solid stone construction bears little resemblance to the lightweight steel framed earthquake resistant structures designed as part of the reconstruction process. The unfamiliarity of the construction process presented additional communication difficulties in ensuring correct on-site assembly of the structural frames. In addition to the technical challenges of implementing a new type of construction system and the concomitant communication difficulties, there are a myriad of challenges that arise in the design and delivery of post-disaster reconstruction work in remote areas, and consideration needs to be given to:

- Cultural differences
- Differences in material availability, and standard dimensions and unit sizes
- Issues around site accessibility and transport to and from remote locations
- Language barriers
- Political issues - strikes, bunds, elections
- Departmental inertia and official reluctance to embrace new technologies
- The potential for deviations from fabrication and assembly instructions

- Post-disaster economic instability
- The condition of infrastructure - power supply, roads, internet, communications
- Construction difficulties due to variable site topography and site instability, and the resultant requirement for excavation, retaining walls, and other site works – all of which result in construction cost and time add-ons
- The potential for damage to large prefabricated elements during transport to remote and difficult sites
- Transportation limitations that may impact on and dictate a size limit on prefabricated components. Whilst prefabricated pre-insulated modular wall panels ready for erection are feasible, any prefabricated elements larger than 2,400mm long would be impracticable in Nepal. Within this region the ideal transportable wall panel size is around 1,200mm.

In an ideal scenario, it would have been good to be able to first build a single prototype RP2 classroom as a means by which to test the modular system and then make further modifications to the kit-of-parts design. However, due to the urgency of the reconstruction process, 20 classrooms are being built simultaneously. Whilst the learnings from these initial builds will be implemented in the next round of construction, it has resulted in an initial build process that has been more complex than anticipated.

Figure 05: Early stage artist impression by HASSELL

6 Conclusion and further work

The open-source modular system presented within this paper aimed to address the post-disaster education facility reconstruction needs within Nepal by providing a kit-of-parts system that is light-weight, incorporates contemporary seismic design principles, is low cost and has a reduced environmental footprint relative to other construction methods for similar sized buildings. In addition to seismic performance, consideration was given to passive environmental performance through careful building orientation, the provision of cross ventilation, highly insulated walls and roofing, and the utilization of local materials for the low-lying mass base wall. The modular design reduced the need for high skill level construction labour, whilst still enabling vital input and contribution from the local communities. The incorporation of local labour in the construction of the classrooms has helped to foster a sense of ownership, empowerment and has provided employment to local residents as an integral part of the disaster recovery and rebuild process.

Still in the process of construction, once the first round of school builds is complete, further research is needed to assess the building performance, the suitability of the modular design for Nepalese educational contexts, and the suitability of the design for modification and use

in a range of other post-disaster relief contexts. In addition, a post construction evaluation of the design delivery is needed to evaluate mechanisms and processes that might enable a more streamlined fabrication process and facilitate on-site assembly, construction and labour skills training.

The provision of disaster relief infrastructure designs as free 'open-source' designs is a novel approach to disaster recovery reconstruction needs, and it is hoped that with further research, that this approach may be used as a collaborative mechanism by which to help other communities in need.

Acknowledgment

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ZEMCH NETWORK

IMPORTANCE OF REGIONAL STRATEGIC PLANNING IN DEVELOPING THE REGION (CASE STUDY: EGYPTIAN REGIONS)

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Abstract:
Regional plans are considered an important first step toward reaching a national future vision for the state. Respecting the different identities of the cities & governorates, for each one of them in the Arab Republic of Egypt has its own character, potential & issues. In line with the orientations of the state towards comprehensive development of the Arab Republic of Egypt, came the importance of the strategic plans for the development of the regions of Egypt, especially regions with great fortunes & potential to be developed. Due to the importance of the global experiences that emerged which was based on development theories and plans at the regional and national levels in the European, Asian as well as in the Americas, it was necessary to use these experiences to develop a successful methodology for strategic planning at the regional level in Egypt. This research deals with 3 different experiences of regional plans and future visions in Egypt by studying & analyzing goals, aimed at developing these regions. The Suez Canal region, Western development corridor (Toshka / Al-Alamein Axis) & finally the Golden triangle are merely an example of good regional Plans put in the right place, in order to develop their regions in line with the current developing policies of the state.

Keywords: *Regional Plans, Suez Canal Region, Development Corridor, Future Vision, The Golden Triangle*

1. Introduction:

This paper displays the analytical survey of different planning theories as they differ across various aspects. Stating some general definitions regarding the scale of planning in which the thesis is concerned, proceeding with further explanation of different planning levels & scales, then stating some international experiences trying to know their goals & implementation system, finally moving on to review some Egyptian regional plans to analyse their objectives as well in order to prove how a regional plan is complementary with the development of the of the governorate or city.

1.1 Methodology

The research is conducted by first finding the factors affecting urban development on regional level, second analysing different international examples for regional plans. Then analysing different regional projects in Egypt (which was based on data collection) investigate the different objectives of those projects to emphasise the importance of regional planning in the planning system of the state.

1.2 Planning

The definition of *planning* as stated by the GOPP "General organization of Physical planning" is (A continuous operation that follows the ways and scientific methodologies to accommodate the evolution of the natural, urban, social and economic aspects with the purpose of achieving a desirable future and progress by identification of goals and the formulation of policies by scientifically.

It also defines the *Strategic plan* as (The plan that determines the future vision of socio-economic & urban development using participatory approaches, that plan could serve & be implemented on different levels of planning such as national, regional, governorate, Markaz, city or village level. Also, strategic plan illustrates the goals, polices, socio-economic development plans & the urban plan needed to achieve continuous development. It also identifies future requirements for urban expansion, development projects, various land use, priorities, implementation mechanism programs & funding recourses.(GOPP, 2015)

Some planners believe that the modern view of the planning process is "an ongoing process not related to a period of time on the basis that different planning patterns each constitute a distinct type of human activity that regulates or develops its production sector or its own region in accordance with accurate regulations and rules on a continuous and comprehensive basis"

From previous definitions, it is concluded that planning is linked to all sciences related to natural and human resources, with a view to determine the extent to which they can be exploited to achieve maximum development.(El-Deen, 2012).

Planning methods has improved & changed through the years, the physical & architectural understanding of the city was supplemented with social science & geography. Every sophisticated society has an institutionalized planning system determining the roles, rights & obligations of different stakeholders such as the public sector, private businesspersons, organizations, and individual citizens. No general planning theory has been developed due to the local & national variations in planning practice & legislation, only different schools have emphasised various aspects of the planning practice.

Planning theories are often divided into substantive & procedural theories. Substantive theories address the planning object (e.g., the city or the community), whereas procedural theories address the planning process. Planning theories can also be divided

into four categories according to whether they are descriptive or normative and substantive or procedural (Table 1). Because planning itself is a normative discipline, it is meant to create a better environment for citizens, so both the object of planning and the planning process is exposed to description, and to further development, which means that there are often implicit normative assumptions. In recent decades, normative and procedural theories have overpowered other types of planning theories, nevertheless there has been a renewed interest in substantive issues as well (such as the sustainable city) semi related to cultural role in planning. (Abdel-wahab, 2012)

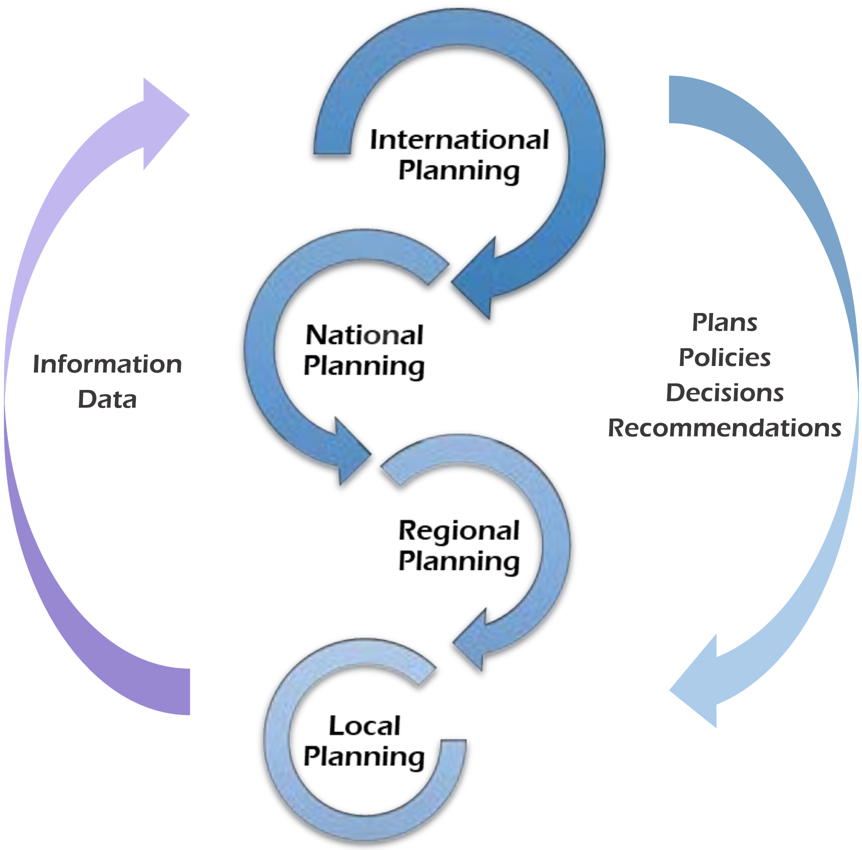
Table 1: Dimensions of Planning Theory

Dimension of planning theory	Substantive	Procedural
Descriptive	Describing the planning object (city, community, etc.)	Describing the planning process in various local and national contexts
Normative	Developing norms and ideals for planning objects (ideal cities, functional regions, etc.)	Developing the planning process (managing the process, including stakeholders, making convincing argumentation, etc.)

Source: (Hutchison, 2010)

1.3 Levels of planning

Planning in general can be presented by 4 main levels shown in the following diagram which state the relationship between them:



Two relations together link planning levels:

1) Bottom up relationship represented in information & data of the different levels that in turn forms the basic ground in which planning can achieve its goals.
2) Top bottom relation represented in plans, policies, decisions & recommendations that help implement the plan.

The pyramid starts from the top to the bottom by international planning, followed by national planning, then regional planning & local planning at the base of the pyramid.

2. Factors Affecting Urban development on the regional level:

There are numerous factors that affect the urban development in the regions positively or negatively to determine the relationship between the Region's components through its various activities, where each of these factors is individually addressed in detail also in this chapter identifying the strength of those factors to determine the extent of their impact on the regional level.

2.1 Geographical location

The geographical location is considered one of the most influencing factors as the seas, lakes and rivers are the determinants of the region affect & strengthen the relationship between the components of the region.

It also exposes the positive and negative aspects, that work on population attraction and developing the site an urban development or people turning away from those negative geographical locations to escape the devastating effects of those sites.

One of the main aspects is *Water bodies* (Water edges, Canals, Rivers & Lakes). Despite the separation made by those factors between the areas of the region, but it also plays an important role connecting them areas to share the same activity (tourism, recreation, fishing and so on)

Topography: It can insure the unification of the region components or separate them if it varies from place to another, region forms varies according to the location topography such as (Flat land, Mountainous Areas & Valleys).

Natural Hazards: There are some geographical locations with the negative impact that threaten communities with natural hazards, some of those natural phenomena are (Floods, Volcanos, Tornadoes & Earthquakes).

2.2 The effect of economic features & its distribution on the regional level

It is intended to identify the locations of economic activities in order to take advantage of their positions and linking the elements of the region to take advantage of them, where economic studies is considered one of the most important studies examining the development of the region based on the constituents & available properties represented in the tourist sites, industrial zones, mineral recourses as well as human resources & agricultural areas.

2.3 Availability of surface network & infrastructure on a regional level

the identification of features of the infrastructure at the regional level to strengthen the infrastructure aspects & the surface networks of the region which helps promoting regional development process significantly.

The infrastructure is live dependent networks that is basically difficult to live without such as Road, transit & transportation network, feeding fresh water, sewage network, Electricity grid & energy network.

2.4 Services geographical distribution & its impact on urban development regionally:

It is concerned with the impact magnitude or the availability of all the therapeutic & health services, educational, sports, recreational and cultural services on the region components, as it is based on the recognition of these services' location, their reflection on the current situation & the future of the regional strategic plan framework.

3. International Examples for strategic plans on regional level:

The allocation of this section of the paper is to address various experiences in the domain of strategic plans at the regional level and the magnitude of the success for those schemes to push urban development process of those regions. Reading the experiences of the world's countries enables us to identify the systems they follow in the planning of the regions and thus we can deduce whether the current situation in the Egyptian regions and the problems faced by are general, similar, and countries face them too or do these problems result from using unsuccessful planning methods. This section presents four international experiences

3.1 Il De France Region- France

Il De France is one of the 26 regions of France. With 12.012km2 area. 12 million inhabitant & over 30% of France's GDP it is now one of the world's largest metropolitan areas. The determination to keep the growth of the Paris agglomeration under control led to the enactment of a "development plan for the Paris Region" by a law dated 14th May 1932. Since then, the development of the Paris Region has always been governed by a regional plan. It is the second largest region in Europe in terms of foreign direct investment inflows and the world's number one tourist destination. Sustaining this dynamic and organizing the associated flows while protecting people's day-to-day quality of life and preserving the environment means setting out a vision and mobilizing the resources to reconcile, priorities and coordinate the relevant public policies. Most of the world's largest metropolitan areas either already have or are re-establishing a planning system, of which the SDRIF (Le Schéma directeur de la région Île-de-France) is a famous example

Figure 1: MAP OF THE 26 FRENCH REGIONS & IL DE FRANCE IN THE CENTRE
Source: Made by researcher based on (Bertrand and Larrue, 2005)

3.1.1 The Project Objectives

In terms of improving the day-to-day lives of people in the Paris Region, the SDRIF plans to:

Build 70,000 homes a year and renovate the existing stock to resolve the housing crisis.
Create 28,000 jobs a year and place more emphasis on mixed housing/employment areas.
Guarantee access to high-quality amenities and public services.
Design transport systems to reduce dependence on the car.
Improve the urban space and its natural environment.

3.1.2 The Future Vision & Project Implementation

Where will Ile -de- France in 2030? A logical tree was developed to break down the objectives of the plan, to priorities and to retrace the coherence of an action. The logical tree is organized according to three axes.

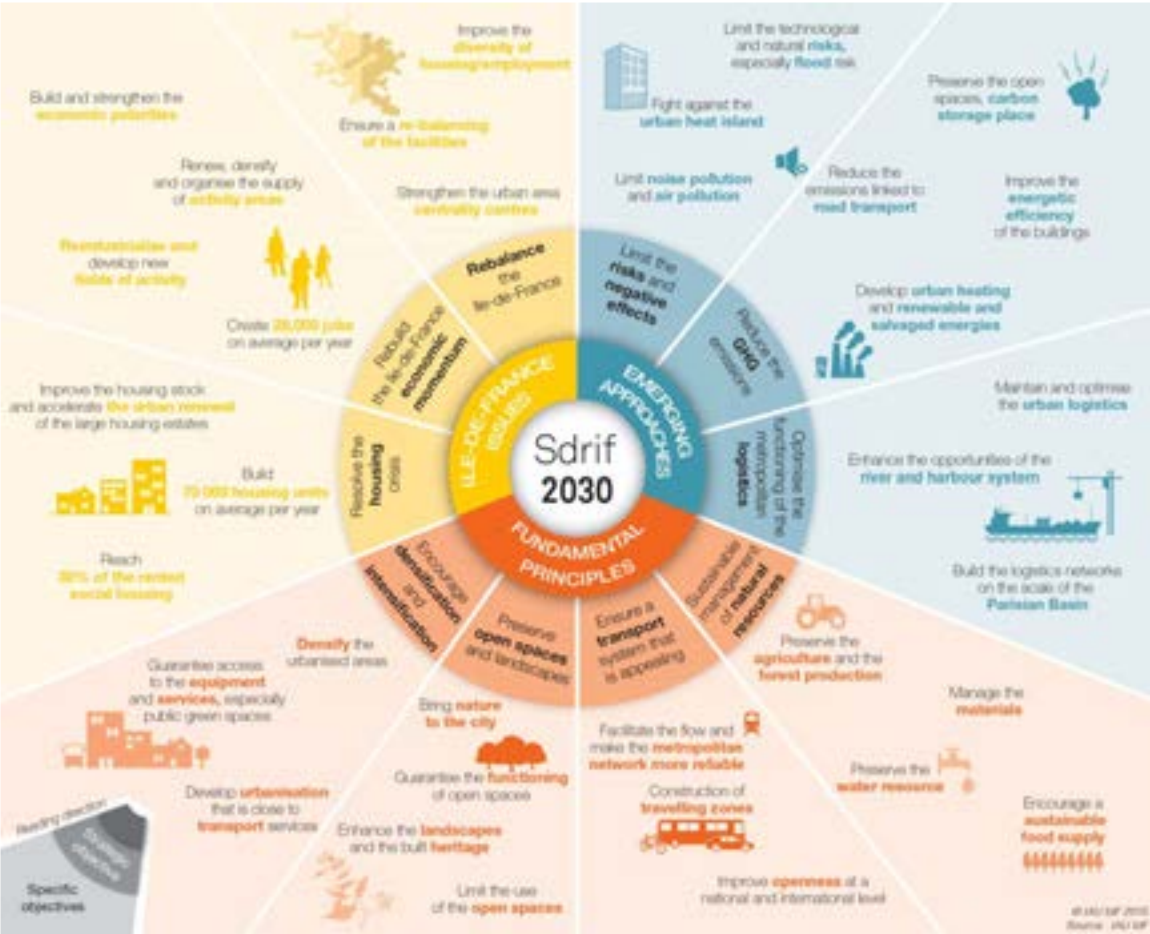


FIGURE 2: THE LOGICAL TREE OF THE OBJECTIVES OF THE GREAT PARIS REGION MASTER PLAN (SDRIF 2030) Source:(Massonneau, 2016)

1.3.3 Review & Evaluation

3.1.4 2019 First assessment

2024 Second assessment
2030 Completion date of the objectives of the great Paris Region master plan (SDRIF2030)

3.2 Calgary Metropolitan Plan – Canada

Calgary Metropolitan area is one of the 2 census metropolitan areas in Alberta which is one of 13 regions of Canada. The Calgary region is a home for 1.4 million inhabitants (based on Statistics Canada, 2016 population census) & a forecasted GDP value of $67 billion in 2012 and the highest concentration of head offices in Canada. With an area of 5,107.55 km2 containing 3 cities, 12 towns, 5 villages, 2 summer villages, 2 municipal districts, and 2 counties within the Calgary region. (The Calgary Regional Partnership, 2016).

Figure 3: POLITICAL CANADA - LOCATION OF CALGARY METROPOLITAN IN ALBERTA REGION
Source: Made by researcher based on (https://en.wikipedia.org/wiki/List_of_regions_of_Canada)

Most of the world's largest metropolitan areas either already have or are re-establishing a planning system, such as Calgary Metropolitan Plan (CMP). This Plan is the Calgary Regional Partnership's guide to what they aspire to achieve as a Region over the next 60 years. To achieve this vision, the CRP develops a Strategic Plan every four year to provide direction and ensure movement towards CMP implementation.

The most persist challenges to the Calgary metropolitan area is water, growth & expansion

3.2.1 The CMP Principles:

Protecting the natural environment and watershed.
Fostering the region's economic vitality.
Accommodating growth in more compact settlement patterns.
Integrating efficient regional infrastructure systems.
Supported through a regional governance approach.(Calgary Regional Partnership, 2014)

3.2.2 The Future Vision & Project Implementation

The following diagram shows the time line of the three phases (Emerging, planning & implementation phase), also shows that the vision depends on 4 years strategic plan to evaluate & implement the Calgary Metropolitan plan. The Calgary metropolitan Plan contains policies designed to accommodate long-term growth in the region to 3 million people in a sustainable & fiscally efficient settlement pattern. It will help guide how to manage that growth to protect & preserve that most valuable – the natural environment, the communities, fresh air, clean & plentiful water and economic prosperity

Figure 4: CALGARY METROPOLITAN PLAN IMPLEMNTATION (TIME LINE)
Source: (the Calgary Regional and Partnership, 2015)

3.2.3 Review & Evaluation

2015-2019 4-year Strategic Plan to position the Region & its members for implementation of the Calgary Metropolitan Plan

3.3 Bangalore Metropolitan Region – India

Bangalore Metropolitan region is sometimes referred to as the "Silicon Valley of India" (or "IT capital of India") because of its role as the nation's leading information technology (IT) exporter. The Bangalore is a home for 11.66 million inhabitants (based on India Statistics, 2011 population census). With an area of 8005 km2 located in the Karnataka Region, containing 3 districts namely Bangalore Urban, Bangalore Rural & Raman-garam. Topographically, it is an ecologically sensitive region with respect to water resources. It is one of a handful of urban agglomerations in the world to be situated above the 1000-meter mark. There are numerous water and environmental related sensitive issues which are vital to be addressed for the sustainable development of Bangalore region.(Bangalore Metropolitan Region Development Authority, 2011)

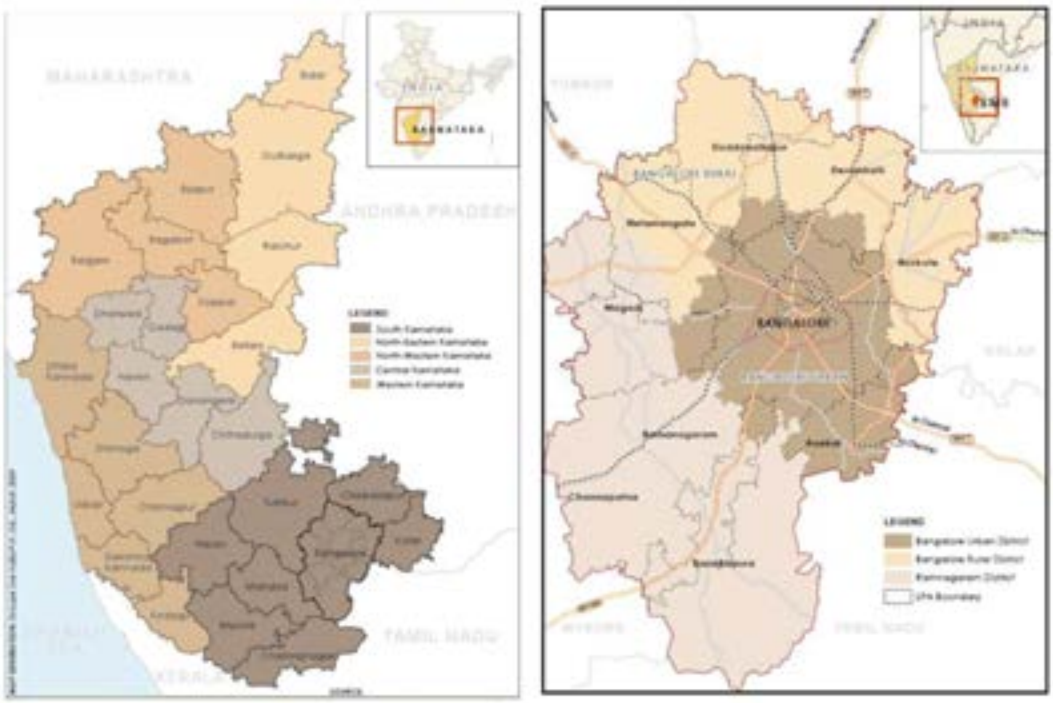


Figure 5: SOUTH KARNATAKA REGION INDICATING THE BMR (LEFT) – THE BANGALORE METROPOLITAN REGION INDICATING ITS THREE DISTRICTS (RIGHT)
Source: (Bangalore Metropolitan Region Development Authority, 2011)

3.3.1 The BMR Principles:

Ecology.
Governance
Economic Growth & Equity.

3.3.2 The Future Vision & Project Implementation

By 2031 the BMR is expected to accommodate 18m population with 75% concentrated within the core and 25% outside it (within the region). This suggests that balanced population and employment distribution will need to be supported by a strong public transport network, concentrating on social convergence and adequate physical infrastructure.

The BMR RSP 2031(Bangalore Metropolitan Region Revised Structure Plan 2031) intends to achieve a balanced growth in the region through concerted action to bring about a strong economic interdependence across the region while avoiding an over centralization which seems to accompany economic development.

In this context, BMR RSP 2031 defines the following as its vision.
'To promote the region's ecological and cultural values, while seeking optimum land utilization suited to its capability for sustained balanced economic production and inclusive growth by inducing agglomeration economies and clustered development through a decentralized planning and governance system.(Bangalore Metropolitan Region Development Authority, 2011)

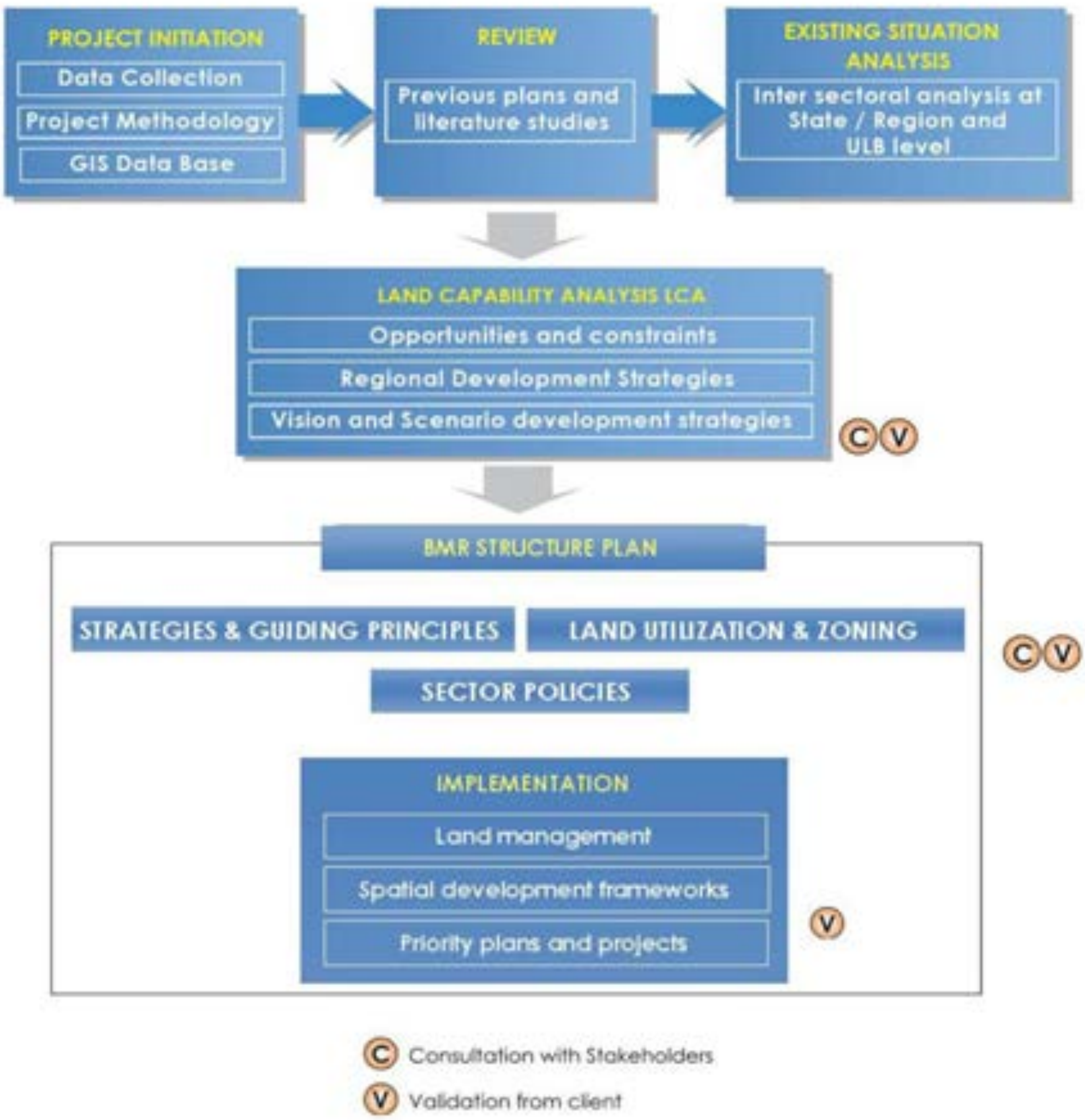


Figure 6: THE BMR STRUCTURE PLAN REVISION PROCESS
Source:(Bangalore Metropolitan Region Development Authority, 2011)

3.3.3 Review & Evaluation

A 5-year Development Programme Plan based on annual budgets (and which enables the perspective plan to be upgraded every 5 years as a rolling plan)

3.4 Wheatbelt Region – Australia

One of the Nine regions of Western Australia state. Wheatbelt is a home for 75,000 inhabitants (2013 population census). This population is highly dispersed with over 200 towns and settlements spread over an area of 155,256 km2.
The region has five distinct sub-regions, 43 local governments govern it, with no single dominant regional center. With (10-year AAGR) average annual compound economic growth rate of 8.2% (GDP $ 6.4b) and diverse economic base, the Wheatbelt is well positioned to make significant contribution to the State & Nation's growth. **the persisting challenge is to fulfil the 2050 targets.**

Figure 7: WHEATBELT - WESTERN AUSTRALIA
Source: (Wheatbelt Development Commission, 2015)

3.4.1 The Wheatbelt 2050 Vision and Aspiration:

The wheatbelt is a key contributor to Western Australia's prosperity. The Region's prime location, diverse economy, clever people, vibrant communities, and unique natural environment offer a high quality of life and will attract global innovators and investors.

The aspirations underpinning this vision are:
Vibrant Economy
Clever people
Liveable Communities
Valued Natural Amenity
The Wheatbelt value proposition
Effective Partnerships

3.4.2 The Future Vision & Project Implementation

Effective Blueprint implementation will work at many levels. The first is at the 'macro level' which requires imbedding the Blueprint into decision processes to ensure alignment of effort and resources achieve maximum results. The second is in terms of implementing the priority actions outlined within the Road Map for Growth.

Figure 8: ELEMENTS OF IMPLEMENTATION
Source: (Wheatbelt Development Commission, 2015)

3.4.3 Review & Evaluation

With over 40 priority actions within the six pillars for growth, rigorous process is required to determine which priority actions (or projects) would deliver growth in population, economic diversification, and private investment.

4 Analytical Survey of regional development axes in Egypt:

Analytical survey of different types of strategic regional plans. Going through the history of evolution of regional administrative division in Egypt till the present days, identifying the different regional development plans in Egypt. Based on data collection of the most important regional experiences in Egypt nowadays.

4.1 The current regional distribution of Egypt:

Under presidential amended decree 181 of 1986, Egypt is divided into seven economic regions as follows:
1-Cairo region, which includes the governorates of Cairo, Giza, and Qalubiya.
2-Alexandria region, which includes the governorates of Alexandria, Beheira, Matruh and the Noubariya district.
3-The Delta region, which includes the governorates of Monufiya, Gharbiya, Kafr El Sheikh, Damietta and Dakahliya
4-The Suez Canal region, which includes the governorates of Sinai, Port Said, Ismailia,Sharkiya and part of the northern Red Sea governorate
5-Northern Upper Egypt region, which includes the governorates of Beni Suef, Menia, Fayyoum and part of the northern Red Sea governorate
6-Assiut region, which includes the governorates of Assiut and the New Valley
7-The Southern Upper Egypt region, which includes the governorates of Sohag, Qena,Aswan and the southern part of the Red Sea governorate.

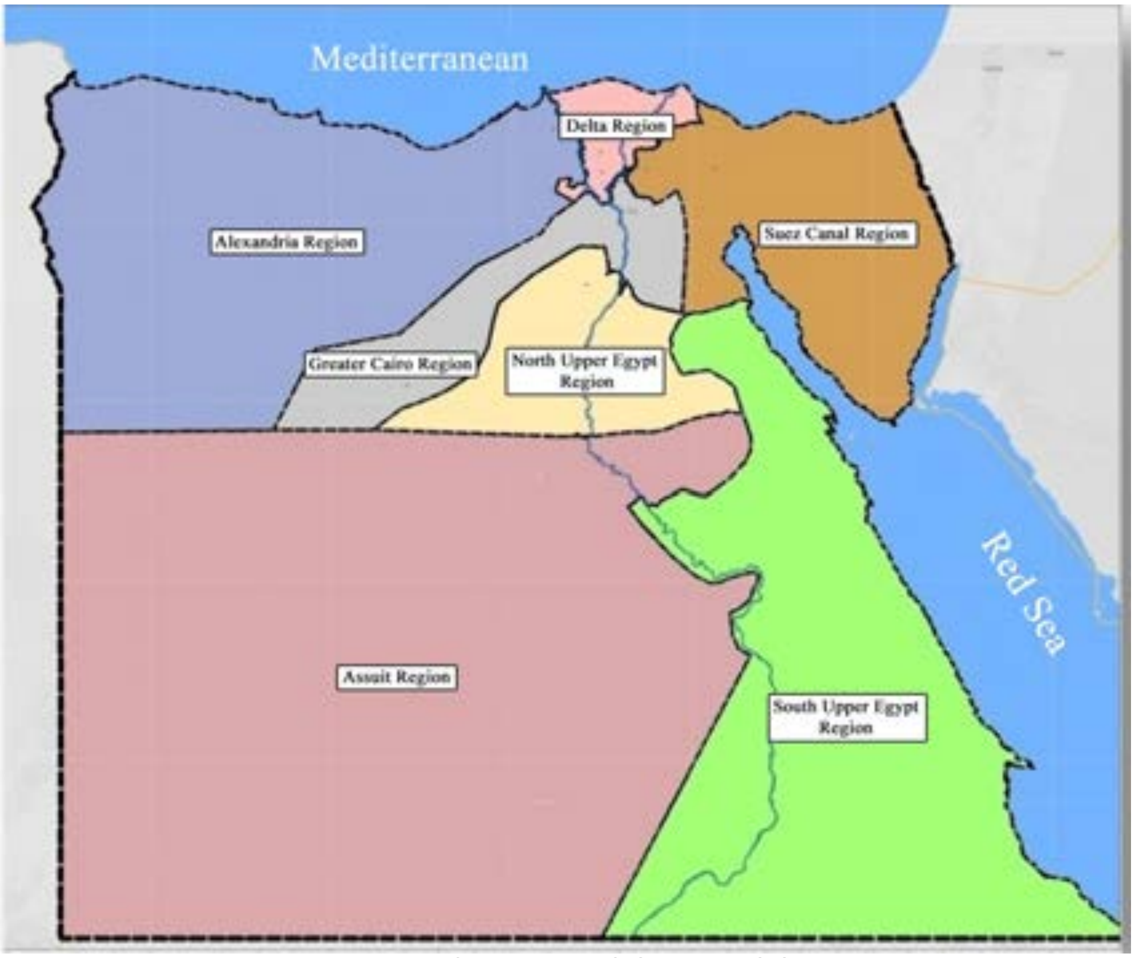


Figure 9: CURRENT REGIONAL DIVISION
Source: Made by researcher based on (GOPP - Ministry of Housing Utilities and Urban Communities, 2013)

4.2 The Suez Canal influence on urban development of the region:

This part of the study deals with an important regional axis one of the strategic axes with a historical depth, namely the Suez Canal region, first it states historical background of the Suez Canal digging, which had a great effect not only at the regional or national level but also at the global level, where it had also an excessive influence on the economic boom between all parties of the world by passing through that channel, it will also shed light on the concentration of economic and residential activities, the existence and extent of that channel.

The Suez Canal Region represents the third of the seven regions of Egypt where it occupies the North-east part of the Republic, representing the entrance of East Egypt. The area of the region is about 80.6 km 2, that's 8% of the total area of the Republic and its area is distributed among 6 governorates in the following proportions:
• Port Said by 1.7% - Ismailia by 6.3%
• Suez by 11.2% - North Sinai by 36%.
• South Sinai by 38.8% - ElSharqia by 6% (GOPP - Ministry of Housing Utilities and Urban Communities, 2012a)

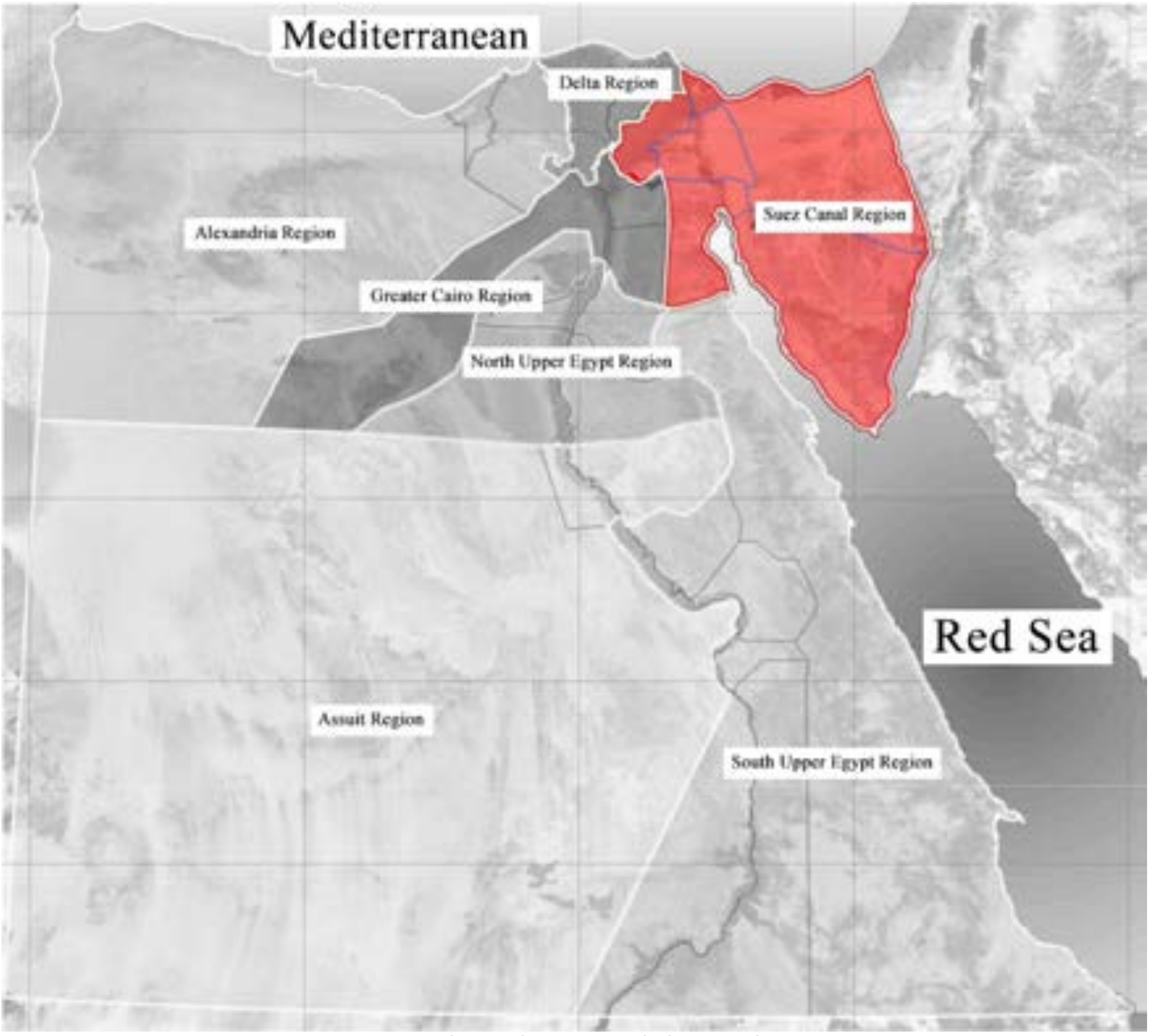


Figure 10: SUEZ CANAL REGION IN EGYPT
Source: Made by researcher based on (GOPP - Ministry of Housing Utilities and Urban Communities, 2012)

4.2.1. Development strategy of the Canal Region governorates: The main objectives to be achieved in the Region National Framework

• Preserve the existing agricultural land from urban creeping and encourage growth on lands
• Raise the efficiency and productivity of industrial services and infrastructure
• Enhancing production capacity through the development of existing facilities, industries and services that complement major production / economic activities
• Raise the efficiency and level of basic services provided to the people of the region
• Provide incentives to the private sector to participate in the development process
• Successful integration of different activities
• Ensure efficient use of resources available in the Region
• Development of projects for the purpose of reclamation and cultivation of desert lands
•Take the necessary preventive measures with regard to sanitary, industrial and agricultural sanitation because of their significant impact on lakes and waterways.

4.3 western Development Corridor for sustainable Growth in Egypt (Toshka / Al-Alamein)

An important project first proposed in 1985 by professor Farouk El-Baz director of the remote sensing centre in Boston university to address some very important Egyptian pressing issues like overpopulation, unemployment, water supply & food security.
About 95% of Egyptians live around the fertile Nile River making less than 5% of Egypt's land. The 2000 persons per square kilometre population density is among the highest in the world.

A Vast country whose population remained confined along the Nile River & Delta. Its cities & villages are severely overcrowded, and its education & health systems cannot cope with the dense population. In addition, over the past 20 years, fertile land has been lost to urban growth at the rate of 30,000 feddans per year. At that rate, all Egypt's fertile land of 5.5 million feddans would disappear in 183 years. Thus, there is a dire need for major changes, including the opening of new land for living, not only for the present 80 million people, but also for the expected addition of 60 million by the year 2050, Which Professor El-Baz predicted, so we need to expand the area we inhabit & add more agriculture, industry & create new potential jobs.

A team lead by professor El-Baz used remote sensing & satellite imagery to study landscape & geography of Sahara Desert in detail.
So, the proposed project includes the establish of:

1) A superhighway built using the highest international standards, 1,200 Km in length, from west of Alexandria at a new port near Al-Alamein along the Mediterranean coastline. This superhighway would run parallel to the Nile Delta until the latitude of Cairo then southward parallel to the Nile Valley to the border of Sudan southern of Egypt, its width varies from 10 to 80 Kilometers based on the nature of the crossed land. It would include an eight-lane highway.
2) 12 east west branches, with approximately total length 800 Km to connect high density population centers along the way.
3) A rail road parallel to the superhighway for fast transport.
4) A water pipeline to supply fresh water from Toshka Canal (Lake Nasser) for human consumption & services, & an electricity line to supply energy during the

early phases of the project to be connected to the main grid for future production of solar energy.

5) An electricity line to be available for large scale generation of solar (and wind) power in the future.

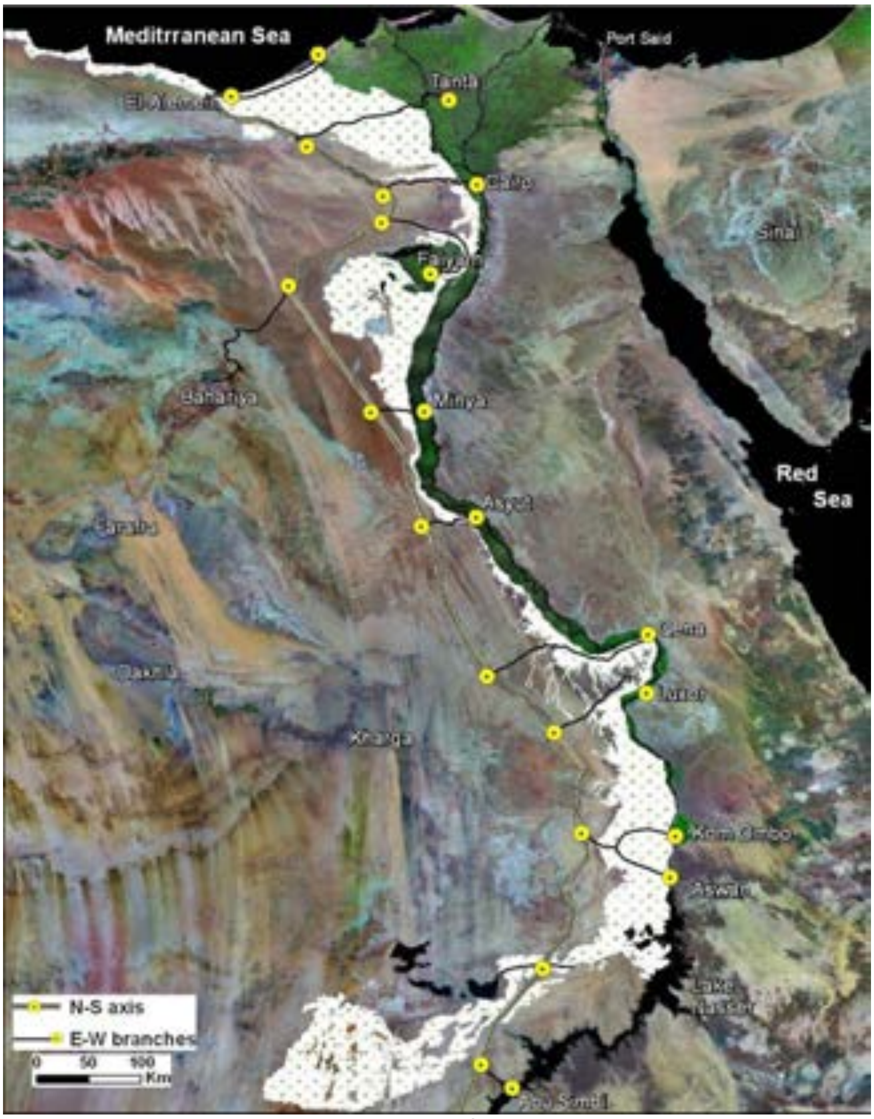


Figure 11: Trace of the proposed Development Corridor on a satellite image map of Egypt
Source: (EL-BAZ, no date)

4.3.1. PROJECT BENEFITS

The evaluation of the pros and cons of the proposed Development Corridor is naturally left to others. The only question that comes to mind that I could not answer is "how long it would take to secure a return on the investment of such an elaborate infrastructure?" This question can only be answered by the experts based on a detailed economic feasibility study. In the meantime, it is possible to list the benefits of the proposed Development Corridor for the social and economic development of Egypt. These benefits may be enumerated under the following headings:

- Utilizing New Land
- Upgrading transportation
- Countrywide Development
- New Urban Communities

- Ground water Resources
- Utilizing Solar Energy
- Public Financing
- Southward Extension

4.4 Development of The Golden Triangle area in Upper Egypt: Idea of creating a Mining Triangle

The development of the Mining Golden Triangle (Qena / Qeft-Safaga-Qusair) comes as one of the major national projects within the framework of the national plans which seeks to alleviate the population pressure in the existing urban areas and achieve the optimal use of the natural resources spread over the land of Egypt. Especially South of the valley because it is known to be less developed and with poorer areas. Taking into account the greatest equitable distribution of the benefits of development throughout the Republic.

The idea of founding the International Mining City in the area between the Qena / Safaga axis to the north and the Qift / Qusair axis to the south, which was later called the "Golden Triangle" area. The area of the Golden Triangle (Qena/ Qeft-Safaga- Qusair). When the trends and interests of the state converged to accelerate and stimulate the entire national economy and the Upper region in particular through the establishment of economic projects packages driving with quick and direct financial return, perhaps the most important is taking out and mining industries. Hence, the decision to maximize the utilization of resources and mineral wealth in the governorates of Upper Egypt to achieve comprehensive sustainable development.

5

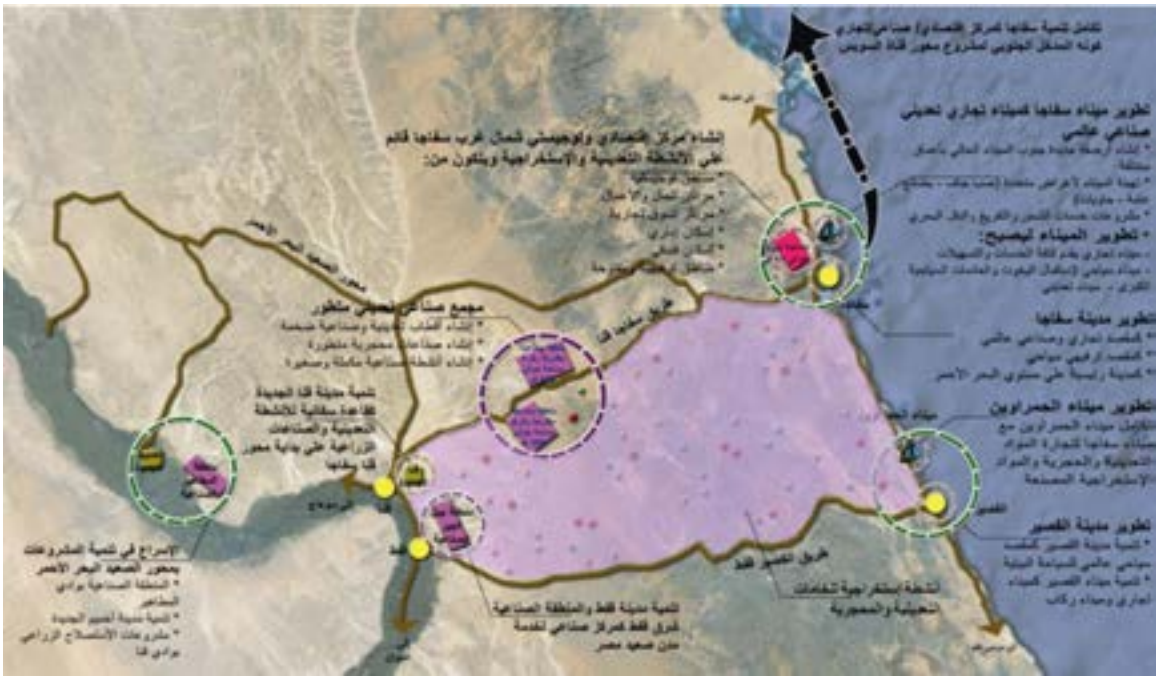


Figure 12: The Planning Idea for the Development of the Golden Triangle in the Context of the National Strategic Planning of the Urban Development of Egypt
Source: (GOPP - Ministry of Housing Utilities and Urban Communities, 2014)

4.4.1. Project Objectives:

The project aims to establish a new economic zone in Upper Egypt that will drive the development movement in various cities, in the area between the governorates of Qena

from the western side, the Red Sea Governorate from eastern side, the cities of Safaga north and El Qusair south.

5 Conclusion

Whether it's a systematic process to develop a region every certain decades (Il de france – Wheatbelt - Western Australia, or it's a long term problem that will throw its shadows later in the future – water resources problem- (in Calgary/Canada -Bangalore/India), due to the natural increase in population (96 million based on 2017 census) & decrease in resources or developing the region for its fortunes & great potential like (the Golden triangle – Suez Canal region) or creating new communities & reclaiming new desert land (Toshka / Al-Alamein axis) regional planning is an important step that connect both the National plans with local ones forming A bridge between them trying to personalize the national objectives, & putting them into action, Also the governorate's potential could be used to benefit the whole region & vice versa.

The housing section is an important axis in any regional plan, relaying on new ideas for housing development especially those of low cost, economizer & high efficient in all its aspects, whether while its being built (custom made homes) or after (using zero-energy Homes) but that would be another research that can be conducted in the future.

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A STUDY ON THE IMPROVEMENT DIRECTION OF URBAN PUBLIC SENIOR HOUSING

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Abstract: *As the issue of an aging society has been raised consistently as a social problem, the Ministry of Land of South Korea, Infrastructure and Transport announced in 2017 that 'public senior housing' that would supply housing service customized for the elderly would be planned for a long term, and they would supply from 1,000 homes up to over 5,000 homes per year by 2022. Thus, for the residential welfare of the elderly, the government is promoting the home remodeling guidelines, housing allowances for recipients of basic living allowances and the supply of residential facilities for the elderly. However, their substantial effect is very little. Therefore, the purpose of this study is to analyze the cases of the government-supported welfare housing for the elderly, and based on the analysis, to suggest guidelines for welfare housing for the elderly in Korea. For analysis, previous studies were reviewed for comprehensive understanding of public housing, and one-on-one interview and a survey were conducted with residents through on-site visit upon approval and cooperation of the administration of corresponding. The policy of the welfare housing for the elderly should be prepared by reflecting the opinions of all relevant parties including not only the elderly, medical professionals and policy makers, but also residents living with the elderly, facility managers and personnel helping with the care. Particularly, an adequate level of care and integrated medical care housing facilities in consideration of the general conditions of the elderly such as society economy, and culture should be provided. Above all, it should be ensured that care at home and local communities is mainly promoted through the remodeling of existing homes in which the elderly resided, rather than increasing the number of nursing facilities that provide care for the elderly as a group.*

Keywords: *Elderly, Residential Welfare, Public Rental Housing, Neighborhood Regeneration, Senior Housing*

1 Introduction

1.1 Backgrounds and Purpose

According to future population projections of the Statistics Korea, the population ratio of the elderly over the age of 65 have increased from 7.2% in 2000 and 13.8% in 2017, and is expected to increase to 14.1% in 2019. Thus, Korea has entered an aged society, and particularly, in Seoul, the elderly over 65 years of age already accounted for 7.1% of the entire population in 2005. The speed of aging is much faster in Seoul than nationwide average, and subsequently, it is expected to become a super-aged society where the elderly will account for 20.6% of the entire population by 2027.

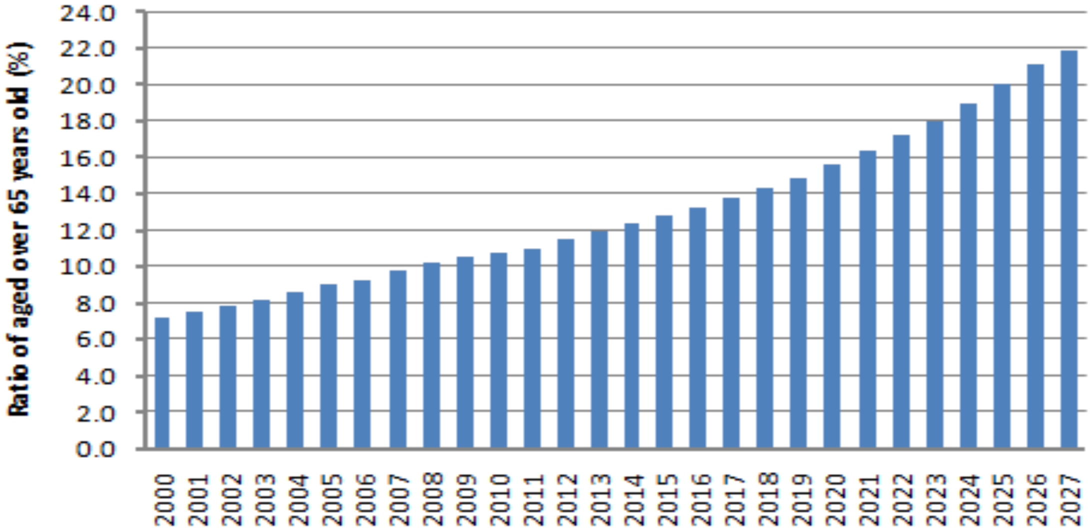

Figure 1: Expected Increasing of Aged Population in South Korea
(Source : Statistics of South Korea(2017), Key population indicators)

In addition, '2017 statistics of the elderly' of the Statistics Korea shows that the ratio of the elderly single-person household will increase from 33.4% in 2018 up to 34.9% in 2045. During this period, the ratios of single households of the elderly in 65 - 69 and in 70 - 79 years of age will slightly decrease while that of those over 80 years of age will increase considerably from 28% to 38.2%.

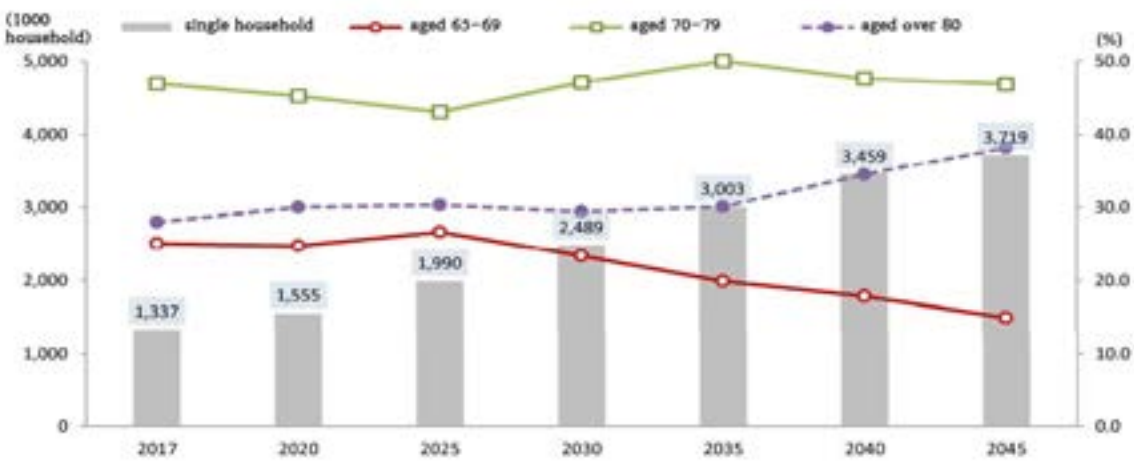

Figure 2: Statistics of Single Elderly Households
(Source : Statistics of South Korea(2017), Elderly people statistics)

Figure 3: Wirye Urban Senior Housing / Milmaru Welfare Town / Seongnam Magnolia
(Source : http://m.todaysn.com, https://blog.naver.com/hooohoooo, http://snvision.seongnam.go.kr)

As the issue of an aging society has been raised consistently as a social problem, the Ministry of Land, Infrastructure and Transport announced in 2017 that 'public senior housing' that would supply housing service customized for the elderly would be planned for a long term, and they would supply from 1,000 homes up to over 5,000 homes per year by 2022.

Thus, for the residential welfare of the elderly, the government is promoting the home remodeling guidelines, housing allowances for recipients of basic living allowances and the supply of residential facilities for the elderly. However, their substantial effect is very little. Therefore, the purpose of this study is to analyze the cases of the government-supported welfare housing for the elderly, and based on the analysis, to suggest guidelines for welfare housing for the elderly in Korea.

1.2 Research Methods

This study was conducted mainly as the case analysis of the Sinnae Integrated Medical Care Housing, the 1st block of the Daechi district, and the 3rd block of the Junggye district, all in Seoul. Since the Sinnae Integrated Medical Care Housing was the first case of such type of housing built in Korea, and the latter two were the cases of pilot programs for the first and second floor barrier-free design of public housing, they were selected for analysis.

Figure 4: Interview with Residents of Cases (16. Aug. 2017)

For analysis, previous studies were reviewed for comprehensive understanding of public housing, and one-on-one interview and a survey were conducted with residents through on-site visit upon approval and cooperation of the administration of corresponding.

2 Emergence of public senior housing and analysis of its current status

2.1 Backgrounds of the emergence of public senior housing and its status

Compared to advanced countries for the elderly welfare such as Australia and Japan where the concept and system for public senior housing have been settled relatively early, South Korea is somewhat slow in preparing measures for population aging. This might be attributed to the traditional family form in which the elderly is cared for within family, but it is more likely because it has not been long since its need has been recognized.

Figure 5: Welfare facilities for the Aged of South Korea
(Source : Ministry of Land, Infrastructure and Transport, http://english.molit.go.kr/)

Although public senior housing is a type of housing that still requires more studies in Korea, Seoul Housing and Communities Corporation (SH) and Korea Land and Housing Corporation (LH) are planning the supply of a considerable amount of relevant housing under the government's lead.

In addition, public senior housing actually under construction is developing into the form where a welfare centre and a residence are located together in a single building of permanent rental housing so that the elderly can use various services for welfare and rest. In other words, private donations and the governmental finance are commonly used to build mainly a combined form of residential and welfare facilities for the elderly including senior citizens who live alone. Planning features in consideration of the elderly are also included, such as removal of thresholds, safety handles in corridors and bathrooms, emergency call in bathrooms and bedrooms and height adjustable washbasin.

In 2017, the Ministry of Land, Infrastructure and Transport announced that they have selected 11 locations additionally for public senior housing projects, and thereby would promote the supply of public senior housing with a housing concept that combined residential and welfare services. Selected locations were Siheung in Gyeonggi (190 homes), Ongjin in Incheon (70 homes), Boryeong in Chungnam (100 homes), Jecheon in Chungbuk (70 homes), Hwacheon in Gangwon (80 homes), Jindo in Jeonnam (100 homes), Jeongeup in Jeonbuk (80 homes), Gwangyang in Jeonnam (100 homes),

Yeongdeok in Gyeongbuk (100 homes), Goseong in Gyeongnam (100 homes) and Jeju (80 homes). In these 11 sites for the second project, construction will begin in 2018 and residents will move in homes gradually from 2019. On the other hand, among 11 locations for the first project, Wirye and Mockryeon in Seongnam have been already occupied by residents, and the remaining 9 locations such as Gwanggyo in Suwon, Ulsan in Gyeongnam, Busan, Andong in Gyeongbuk, Boeun in Chungbuk, Sejong City, Jangseong in Jeonnam, Muan in Jeonbuk, Yeongwol in Gangwon are being prepared for construction in 2017.

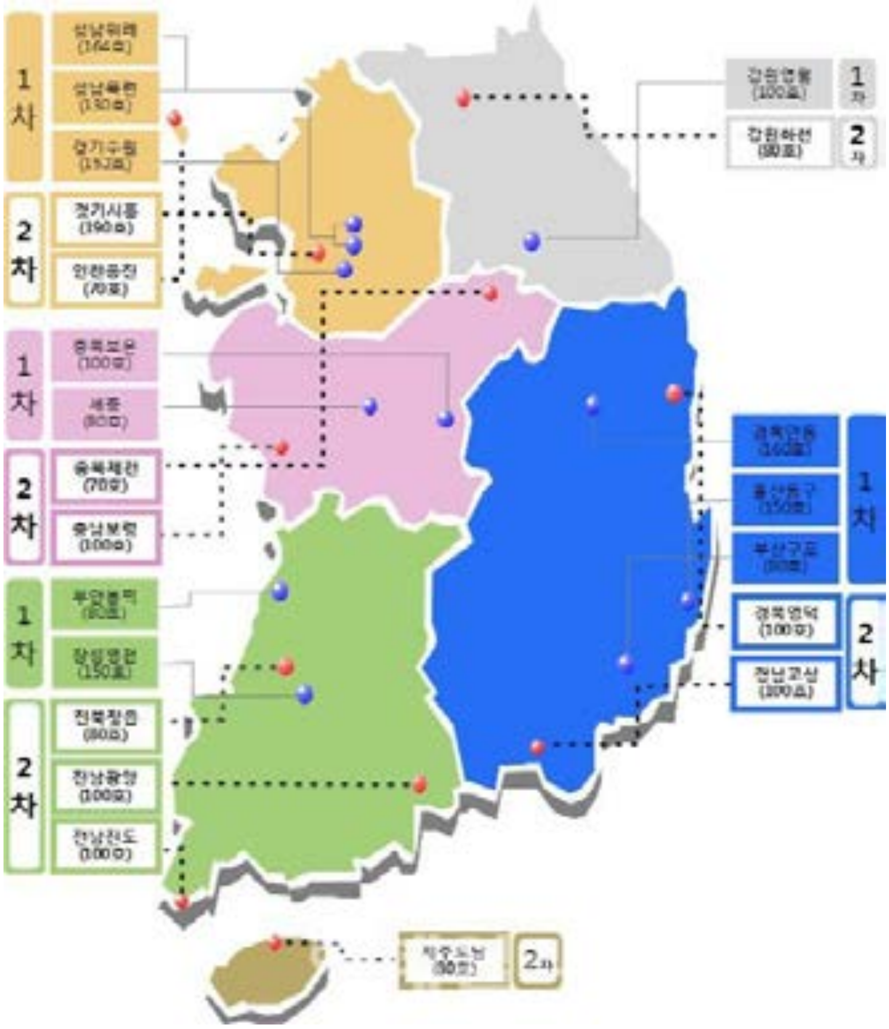

Figure 8: Public Senior Housing Projects
(Source : Ministry of Land, Infrastructure, and Transport press release March. 2016)

2.2 Analysis of previous studies

For this study, previous studies related to welfare housing for the elderly in Korea have been surveyed, which showed three major areas of domestic studies. First, there were studies on the supply policy of senior housing (S. H. Bae, et al., 2016; S. H. Kim, 2003; Y. J. Shin, 2012). Second, there were studies on barrier-free factors necessary for senior housing (O. J. Kwon, et al., 2016; T. H. Park, 1996; E. K. Hwang, et al., 2006; D. H. Park, et al., 2006; J. S. Lee, 2005). Third, there were studies on the design standard of senior housing (E. K. Hwang, 2008). Although previous studies were mainly focused on the limitations of senior housing and the differentiation between plans, studies on public senior housing do not exist.

Table 1: Analysis of Advanced researches

Division	Authors (year)	Main Content
Supply policy	Bae, Su-Hyun, Kim, So-Young (2016)	A study on the housing type for the elderly focus on the comparative analysis of domestic and foreign cases
	Kim, Sin-Ho(2003)	A study on the current status of the elderly housing demand and policy direction
	Shin, Yong-Joo(2012)	Critical Analysis of Housing Welfare Policies for the Elderly
Barrier-free	Kwon, Oh-Jung, Kim, Jin-Young, Lee, Ok-Kyung(2016)	Analysis of the disturbance factor through elderly questionnaire and remodeling demand
	Park, Tae-Hwan(1996)	Analysis of satisfaction and suggestion of improvement through survey of residents of the elderly
	Hwang, Eun-Kyung, Moon, Soo-Young(2006)	A study on survey of the elderly welfare housing
	Bak, Da-Hye, Kim, Young-Hwa, Lee, Sang-Hong (2017)	Analysis of satisfaction and suggestion of improvement through survey of residents of the elderly
	Rhee, Ji-Sook(2005)	The inconvenient detail in houses pointes out by the elderly
Design basis	Hwang, Eun-Kyung(2008)	Analysis of facilities and facilities standards and suggestions for improvement of elderly housing
Australian Elderly Housing Space	Chung, Mi-Ryum(2015)	Characteristics of australian elderly welfare houses space
	Kim, Chang-Kook(2003)	A Study on the Design Guidelines of the Private Zone for the Aged Care Residential Services in Australia
Australian Senior Housing Policy	Park, So-yeon,Jung, Seung-woo, Na, In-su,Lee. Kyung-hoon(2016)	The process and characteristics of public rental housing policy in australia

3 Characteristics of urban public senior housing

In Seoul where the downtown sites for new public senior housing is absolutely insufficient, remodeling of existing houses into the type suitable for the elderly residence has been actively promoted since 2010. The Seoul government announced the 'comprehensive housing welfare implementation plan', which included freezing of the rent of public housing for two years, and the supply of 30,000 small affordable houses each year, totaling 300,000 houses in 10 years.

This also included a plan that the first and second floors of all public rental housing would be constructed as 'senior housing' for the elderly, and the budget of 300 billion won spent to remodel the first and second floors of all permanent rental housing (6,272 homes) in Seoul as barrier-free housing by 2014.

Figure 9 : Barrier-free Housing
(Source : http://news.joins.com/article/3474395)

As the pilot program, barrier-free housing was created in the 11th block in the Banghwa distirct, and 7 homes in the 1st block in the Daechi district and the 3rd block in the Junggye district in 2010. The remodeled homes were equipped with threshold-free floor for easy wheelchair use and the height adjustable sink and washbasin indoors, and folding chairs for sitting and safety handles in the corridor. However, as of 2017, the remodeling plan for public rental housing is no longer promoted and remains in the situation of 2010.

Unlike this, the Sinnae Integrated Medical Care Housing, an example of new senior housing, is the first 'integrated medical care housing' equipped with barrier-free facilities in all homes, providing easy access to medical services as medical facilities have been built nearby. Particularly, the Seoul Medical Center located on the opposite side is a great advantage for the elderly who have difficulty in moving a long distance.

Figure 9 : Barrier-free Housing
(Source : http://news.joins.com/article/3474395)

4 Characteristics of welfare housing for the elderly in Korea

The following conclusions were drawn from the on-site interviews and questionnaire surveys of the public welfare housing for the elderly.

Table 2: Current Status of Public rental housing remodeling household and Sinnae medical safe house in Seoul

Name (Location)	Plans	Type of residents	Design Characteristics		
			Environments	Community Facilities	Units
the Sinnae Integrated Medical Care Housing Medical Treatment House (SH) 33, Sinnae-ro 16-gil, Jungnang-gu, Seoul, Republic of Korea	B1-7F, Total 222 household 	Senior Citizen Wheelchair Users Chronic patient	Seoul Medical Center 	Health Care Center, welfare facilities, family garden , physiotherapy clinic, fitness center, community facilities	18A_4 18B_28 18C_60 29A_27 29A_29 29B_65 29C_9
102, Daechi Apts (the 1st block of the Daechi district) Public Rental Housing Remodeling (SH) 102, 5, Gaepo-ro 109-gil, Gangnam-gu, Seoul, Republic of Korea	7 household 	Permanent Rental Housing Resident	Samsung Medical Center 	None 	11 11A 14 18

1102, Banghwa Apts Public Rental Housing Remodeling (SH) 1102, 4, Gaehwadong-ro 21-gil, Gangseo-gu, Seoul, Republic of Korea	3 household 	Permanent Rental Housing Resident	Ewha Womans University Medical Center 	None 	11A1 11A2 14A 18A
307, Junggye Apts (the 3rd block of the Junggye district) Public Rental Housing Remodeling (SH) 307, 333, Nowon-ro, Nowon-gu, Seoul, Republic of Korea	7 household 	Permanent Rental Housing Resident	InJe University Paik Hospital, Eulji University Hospital 	None 	11 14 18A 18B

The policy for the elderly welfare can be largely divided into three main items. The first is the housing allowances paid to the recipient of basic living allowances, the second the home remodeling guidelines, and the third the supply of residential facilities for the elderly.

As the Sinnae Integrated Medical Care Housing provides residents with a variety of spatial supports such as basic barrier-free facilities for residents, and the reception room, the rooftop garden and the senior hall for communication between residents, the residents generally expressed satisfaction with the housing environment in the interview.

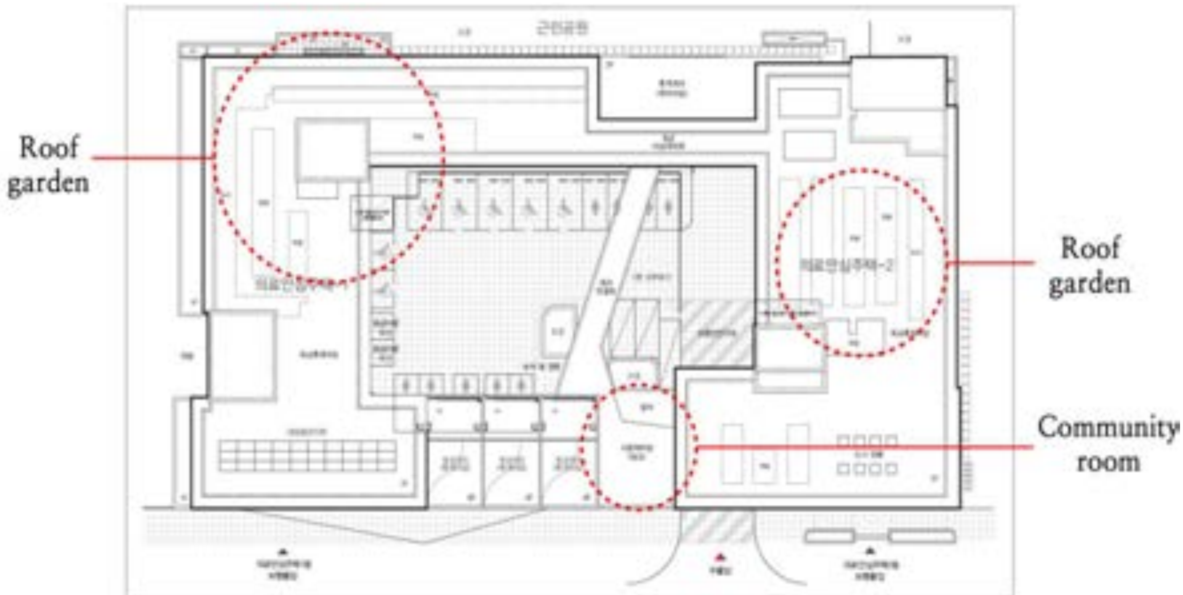

Figure 10 : Roofgarden and Community Facilities
(Source : http://www.i-sh.co.kr/)

However, limitations in practical operations have been found in the interview with housing manager. There were opinions that physical and system policies were in place, but problems of a shortage of manpower to perfectly operate and manage them, and housing management costs existed.

In cases of remodeling in the Banghwa, Junggye and Daechi districts, there was a limitation that the policy implementation was stopped at the early stage, not proceeding according to the original plan of remodeling of the first and second floors of all public rental housing, and some residents also gave opinions that some barrier-free facilities were inconvenient to use in the interview.

5 Conclusion

This study investigated the status of public senior housing in Seoul through the on-site surveys and literature review.

The results show that although the policy of supplying welfare housing for the elderly in Korea has been actively implemented by the government, its concept has only recently been specified, and thus studies in various aspects are required. Particularly, in case of the policy of public rental housing remodeling, although it was announced that a large amount of budget would be spent to carry out a large scale remodeling, the policy was implemented only for a much smaller number of homes.

In addition, in the interview, residents expressed their discomfort in certain remodeled areas for living at home. This showed a limitation that the intention of the government to provide a better housing environment for the elderly and the disabled did not necessarily satisfy what they actually needed.

Particularly, while the Sinnae Integrated Medical Care Housing appeared to satisfy many residents in terms of the physical environment, it lacked in an internal system to maintain and manage the environment.

The results also show more limitations generally in the housing welfare for the elderly including the supply policy and housing design in Korea compared to the advanced countries in this area. The policy of the welfare housing for the elderly should be prepared by reflecting the opinions of all relevant parties including not only the elderly, medical professionals and policy makers, but also residents living with the elderly, facility managers and personnel helping with the care. Particularly, an adequate level of care and integrated medical care housing facilities in consideration of the general conditions of the elderly such as society economy, and culture should be provided.

Above all, it should be ensured that care at home and local communities is mainly promoted through the remodeling of existing homes in which the elderly resided, rather than increasing the number of nursing facilities that provide care for the elderly as a group. As seen in the recent Australian policy, various types of housing should be provided depending on the characteristics, living standards and requirements of the elderly.

Acknowledgements

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A NEW CONCEPT FOR SUSTAINABLE HOUSING, A SUSTAINABLE CHANGING HOME

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Abstract: *The challenge is to create a sustainable changing house in Quito with usage characteristics that satisfy users´ needs during at least 40 years of their life; which implies that a family will stay in that house during the growth of their children or at least during mortgage term. Ecuadorian mortgage loans are given for lapses of up to 25 years with interest rates of 10.78% per years, and just these years the private banks are offering a special rate of 4.87% for 20 years.*

Nowadays, houses or apartments are built under a rigid model for a family in a contextual and temporary status; this new proposal for a model of house or apartment consists of a sustainable design with internal mobility distribution that could change according to the evolution of the family. Therefore, if a mortgage is made to buy a sustainable house, it is linked to the planning of both the family evolution and the physical space in the house. The idea of a sustainable changing home was never proposed before. This new concept used my own experience of living in Japan in 2004, comparing the environment of my country and Japanese culture, and the most important fact was the desire to developed heritage for my children by the effort of buying a property.

In order to achieve a robust sustainable housing design, the proposed design put in practice energy efficiency by natural light, exterior curtains, external walls with vegetation and internal prefabrication mobility walls. The internal facilities design allows changes. First the design is an apartment of 194 m2, which can be separated as two apartments (83 m2 each one), 3 apartments (83m2, 41m2 and 41m2) or 4 mini apartments (41m2 each one).

The central idea is that future owners´ property must be able to acquire according to their budget, and that their property could be useful during the time of the mortgage and beyond. As the family and incomes commonly become shorter during the time; then, if the initial apartment or house can be divided in mini apartments. Those could be rented and ward deliver an extra income to owners, which redound in better quality of life for retirement. On the other hand, the government could support the idea of wealth for population and look for bank agreements to allow credits for designs like this. On the long run, this idea is economically sustainable because buyers would receive a surplus for rent of apartments in the last years of mortgage. Moreover, this ensures more confidence in the purchase and repayment of the property to future owners as well as for banks.

Keywords: *Sustainable House/Apartment, Housing, Sustainable Development, Prefabrication, Energy Efficiency*

1 Introduction

A mortgage is considered when a person or heads of family are young; this means that when children leave home for good, parents will be bordered of their retirement age. This is why they have a lower chance of acquiring a new home. This situation has an issue of responsibility with the education of children at University, so parents have limited resources to purchase a new home. Then, comes a proposal house that can be comfortable at each stage of the growth of the family, which supports the changes a family has in the long run.

Economic factors are formed by the income of people, expenditure and Micro economic environment. According to a survey for this research (figure1), 88.24% of people spend 21% to 60% of their family incomes on a mortgage. This data matches with BIESS Bank requirements for loans. BIESS is one of the most important banks in Ecuador for hypothecates and it limits monthly payments up to 40% of family incomes. According to a survey see Figure 1. 33,33% of people has a mortgage term of 10 years and 26,67% has a term of 25 years. Consequently, so high is the interest rate of a mortgage that customers are paying an average of 10.10% interest rate in a long term.

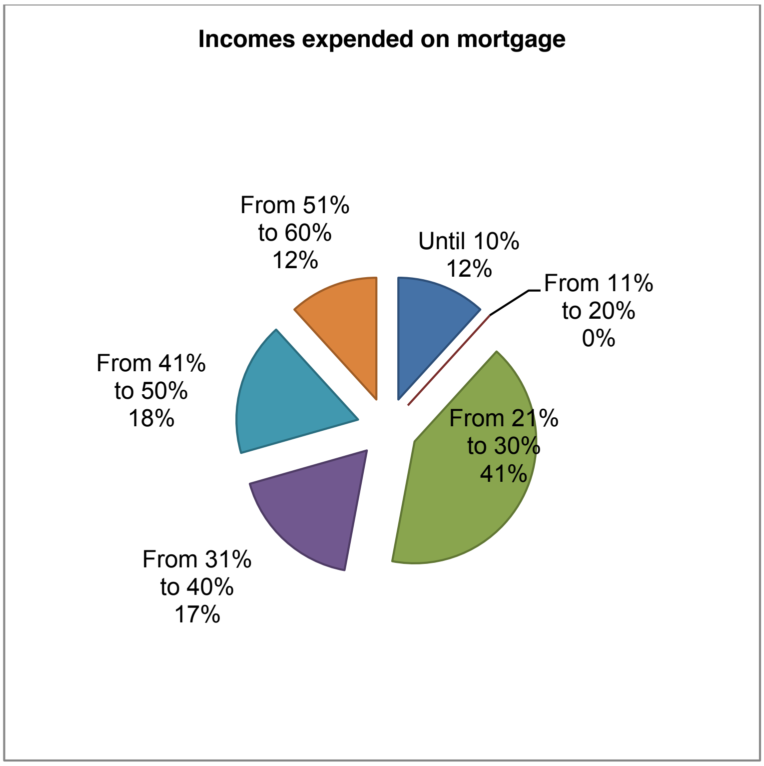

Figure 1: Incomes expended on mortgage in Quito

High and middle class incomes in Ecuador has not grown in the last 10 years and several sources correlate this information. In 2007, Gestión, a recognized local magazine published a research about people´s salaries in Ecuador. According to this source the 82% of the population have monthly incomes between 100 USD up to 1500 USD. The rest 18% of the population is dispersed (3% earns between 1500 to 3000 USDs, 14% has a negotiable salary and 1% earns monthly between 3000 to 6000 USDs).

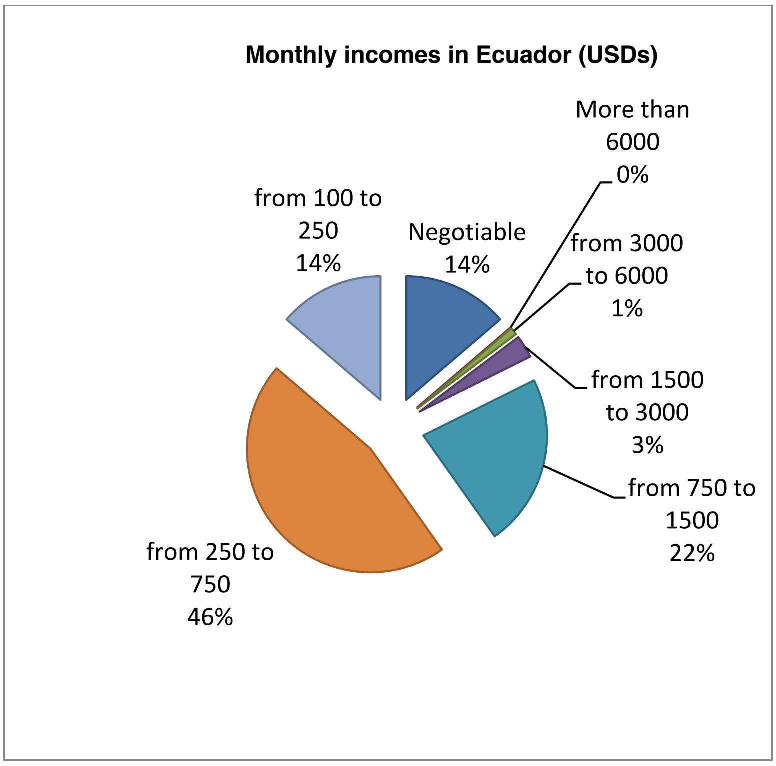

Figure 2: Monthly incomes at Ecuador (Gestión magazine 2007)

In addition, a recognized newspaper named "El Telegrafo" has published a common salary scale in Ecuador in 2017 (El Telegrafo 2017), which defines 80 percent with a maximum monthly salary of $5450 USDs and a minimum salary of $250 USDs. Therefore, comparing information from 2007 to 2017, we can conclude that salaries in Ecuador had no increment over the last ten years. Moreover, a public recognized source "Ecuador en cifras" (Ecuador en cifras 2017) notes that Ecuadorian strata is defined by five socio-economic levels (figure 3) which can be correlated with monthly income published by Gestión magazine (Magazine Gestión 2007). In conclusion medium class in Ecuador represents 72,1% of families (Ecuador en cifras 2017) represented by C+ and C- in figure 3.

Figure 3: Strata of the socioeconomic level at Ecuador (Ecuador en cifras 2017)

Incomes in Ecuador did not change during the last 10 years since continual political decisions were taken in 2007, 2014, 2015 and 2017 (El Comercio 2017), these decisions have been passed on to citizens and documented by reputable local official sources that have been taken for this study. So, salary scales on workers of the upper hierarchical level

of all the functions of the state had been reduced, as well as private telecommunication sector; finally, but not less important, it affected private sector too.

If each adult in Ecuador use 40% of it´s salary for mortgages; moreover, considering 82% Ecuadorian population has monthly salaries flowing between 100 and 1500 USDs. In addition, if medium class in Ecuador represents 72,1% of families in Ecuador, then a family would achieve to pay a 25 years mortgage house. After that they realize the house is too spacious for a couple after children leave home. Don't you think a sustainable changing home couldn't be a good idea for those families? In conclusion, the customer segment for this proposal will be 68% of Ecuadorian population composed by 46% with monthly incomes between $250 to $750 USDs; and 22% population with monthly salaries between $750 to $1500 USDs. On the other hand, cultural f and psychological facts support this idea, so important is the heritage for Ecuadorian families that they are used to taking care of children until they get married or even after. Therefore, parents support children economically during college and until they can support themselves. Besides, it is common that children leave parent´s home after getting married because of cultural and economic factors.

So important is the evolutionary cycles of the family from a physiologist point of view that each family stage needs a house with different limits and space. The cycles are defined as follows; marriage, birth of the first child, adolescence, child detachment, retirement and death (Ares 2016:17). My opinion is that there are six stages of life that require different areas in a house, figure 4 explain cycles of family applied to this proposal. Stage 1 refers to a single young person. Stage 2 is a couple wishing to share time together. Stage 3 is defined by a couple with a child. Stage 4 refers to a couple with two or three children. Stage 5 is a senior couple and finally Stage 6 is an older adult alone. Furthermore, if housing represents safety and security needs according to Maslow's hierarchy of needs theory, a sustainable changing house should satisfy these needs and maybe self esteem in the long run, because property owners could possible feel that goals will be accomplished by financial freedom or help for their children because this sustainable changing house and its versatility to become four apartments. On the other hand, so extremely is the deficit of housing in Ecuador, that the President of Chamber of construction underlines the problem that our country has a deficit of 800 thousand homes and each year it increases to 100 thousand more new homes because of the new families (Duran 2017). Therefore, this proposal could help to satisfy the demand of housing in Quito as well as mobility and social environment in the long run. As a conclusion this model of sustainable changing house/apartment can be comfortable in each stage of the growth of the family, linked to the planning of both the family evolution, and the physical space in the house because its versatility to become apartments.

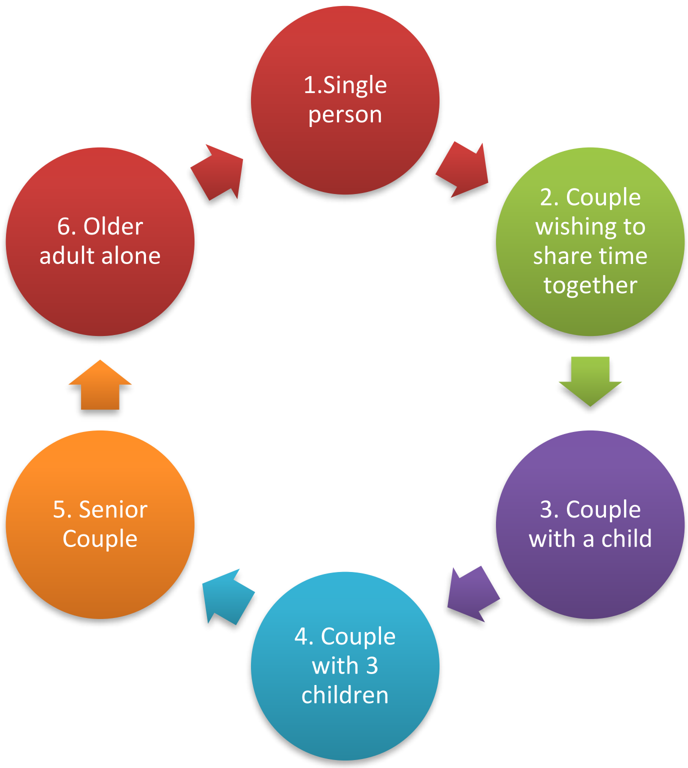

Figure 4: States of a Family

Traditional housing has little or no options to divide the asset in the long term; because Quito City Council has no regulation that allows it easily (Calderon 2017). Instead, it is hard for a department to be divided, that the hundred per cent of owners of the building have to approve the requirement before it is sent to Quito City Council. The same happens with a house if it has been built in a condominium. On the other hand, an independent house can be divided if structural regulations allow it, and if minimum space regulations accept the application at the moment it is asked for.

Quito was the headquarter of Habitat III in 2016, which is developed by United Nations; then Quito could demonstrate its commitment with sustainable buildings by taking attention of this proposal, which could contribute on housing solution, quality of life of people and family sustainability in the long run.

The proposed design has been assessed by qualitative research, specifically on action qualitative research. Interviews with banks, City Council and builders, were used for this research. It was also useful data from national statistics system, journals, radio, and a survey. Finally, as there were diversity aspects on the problem, Management point of view has been chosen a as a Green Star rating requires, in order to explain the possible solutions. Those solutions have been placed at a Business Model Canvas to develop the results and conclusions of the investigation. Finally, 4PLs method was used to describe the innovation requirements on the implementation process.

This document develops a sustainable changing model of house or apartment, a value proposition for the model, defines the customer segments for this idea, identifies revenue streams of the model, customer relationships required, channels, key partners, key activities, key resources, cost structure and the conclusions.

2 Sustainable Changing Model

The next is an apartment of 193m2, which is part of a robust sustainable building designed with energy efficiency by natural light, exterior curtains, external walls with vegetation and internal prefabrication mobility walls. Figure 6 shows the initial and easiest model apartment for a family with two or three children with lots of space. If you would like to use the design for a house, the upper part of the model would be the first floor in a house and the lower part could be the second floor; being aware that the house stairs have to be placed at a side of the house. This type of model can be transformed in 2 apartments of 83 m2 each one; into 3 apartments of 83m2, 41m2 and 41m2; or in 4 mini apartments of 41m2 each one; which are common and very comfortable in a Japanese culture.

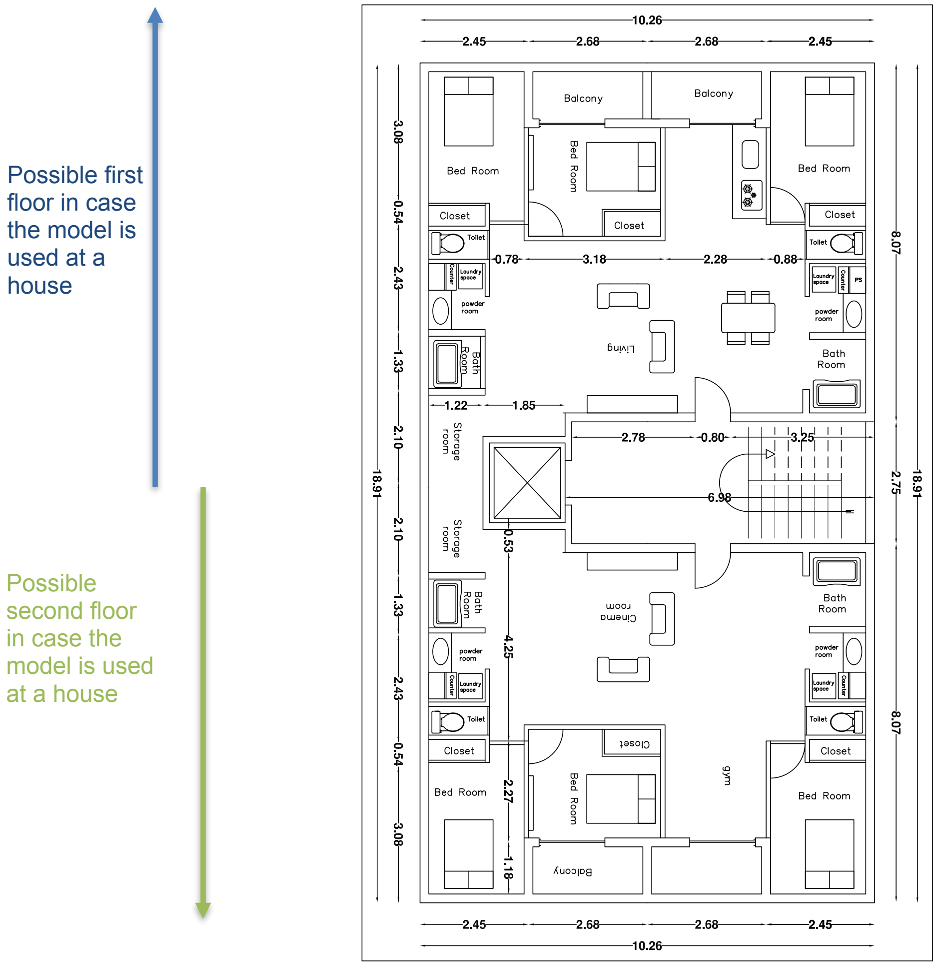

Figure 6: Full state house for a State 4 of a family composed by a couple with 2 or 3 children

Figure 7 is the division of the original department in two apartments of 83 m2. Considering the evolution of the family, this option could be useful for a couple with a child or a senior couple and a couple with up to three children.

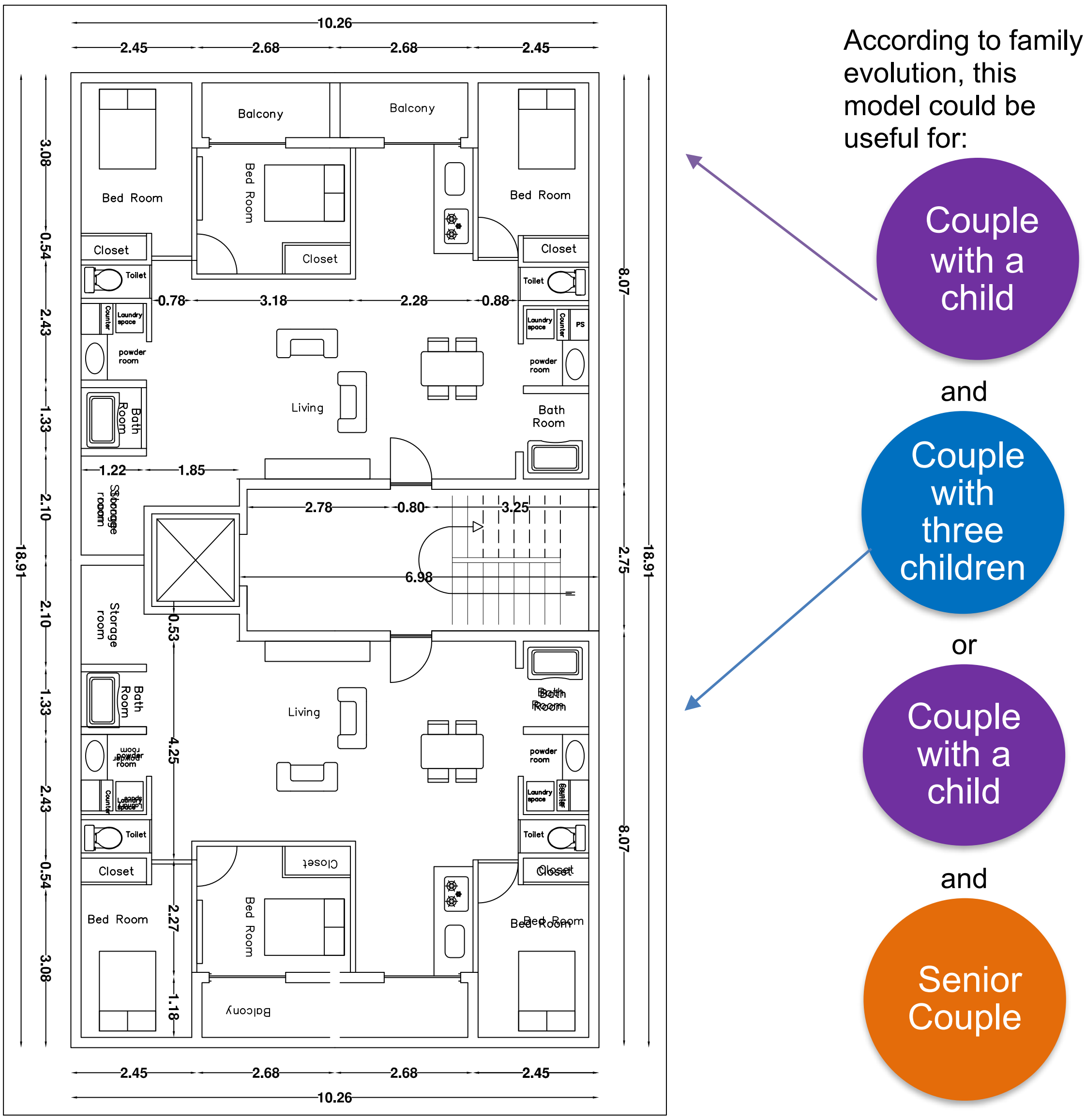

Figure 7: Full state house for two Families:
Couple with a child and senior couple; or
Couple with a child and couple with 3 children

Figure 8 shows a possible third division of the original department; which are three departments, one of 83m2, and two of 41m2. So comfortable is a 41m2 apartment that Japanese culture has adapted to them. Wouldn't it be easy to use luxury furniture, clean and relax in an apartment like this?

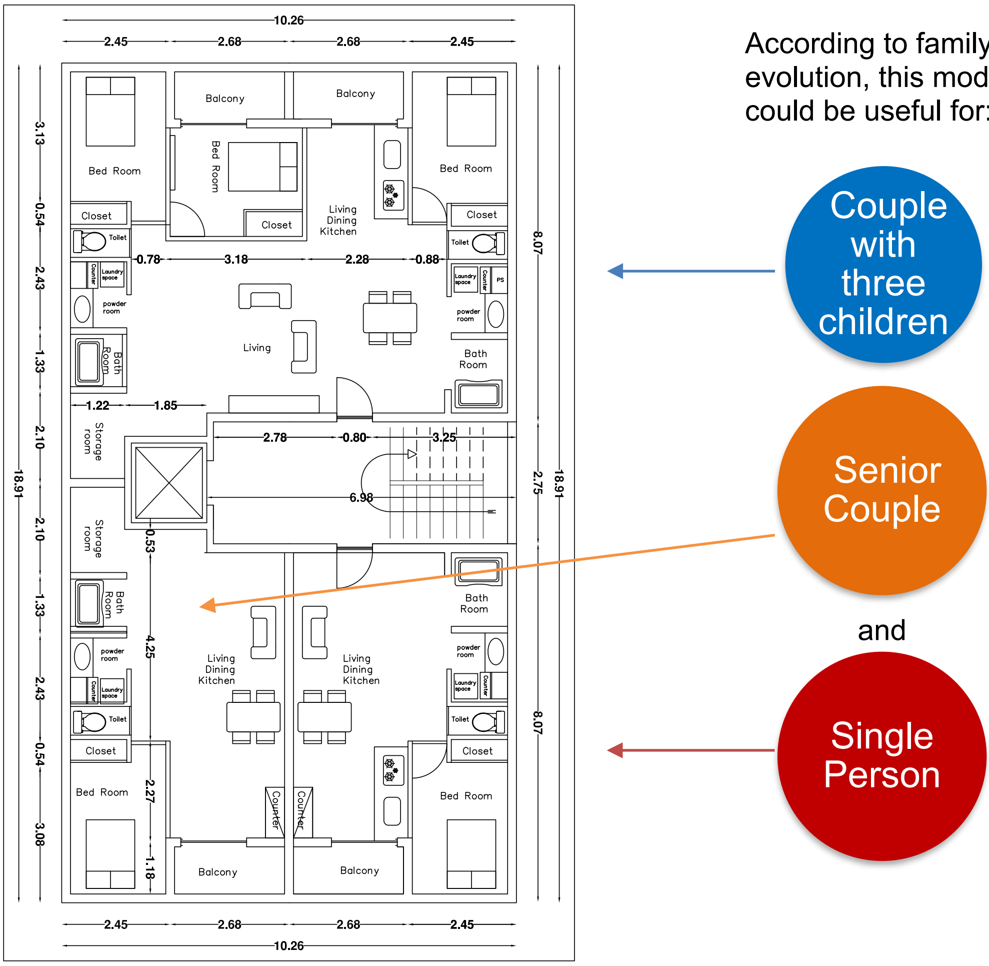

Figure 8: Full state house for three families: a single person, senior couple, and couple with three children

The final model corresponds to the last division to obtain four mini departments, which is developed in figure 9, each apartment has 41 m2 that could be useful for a senior couple, an adult alone, a single person or just a couple wishing to share time together.

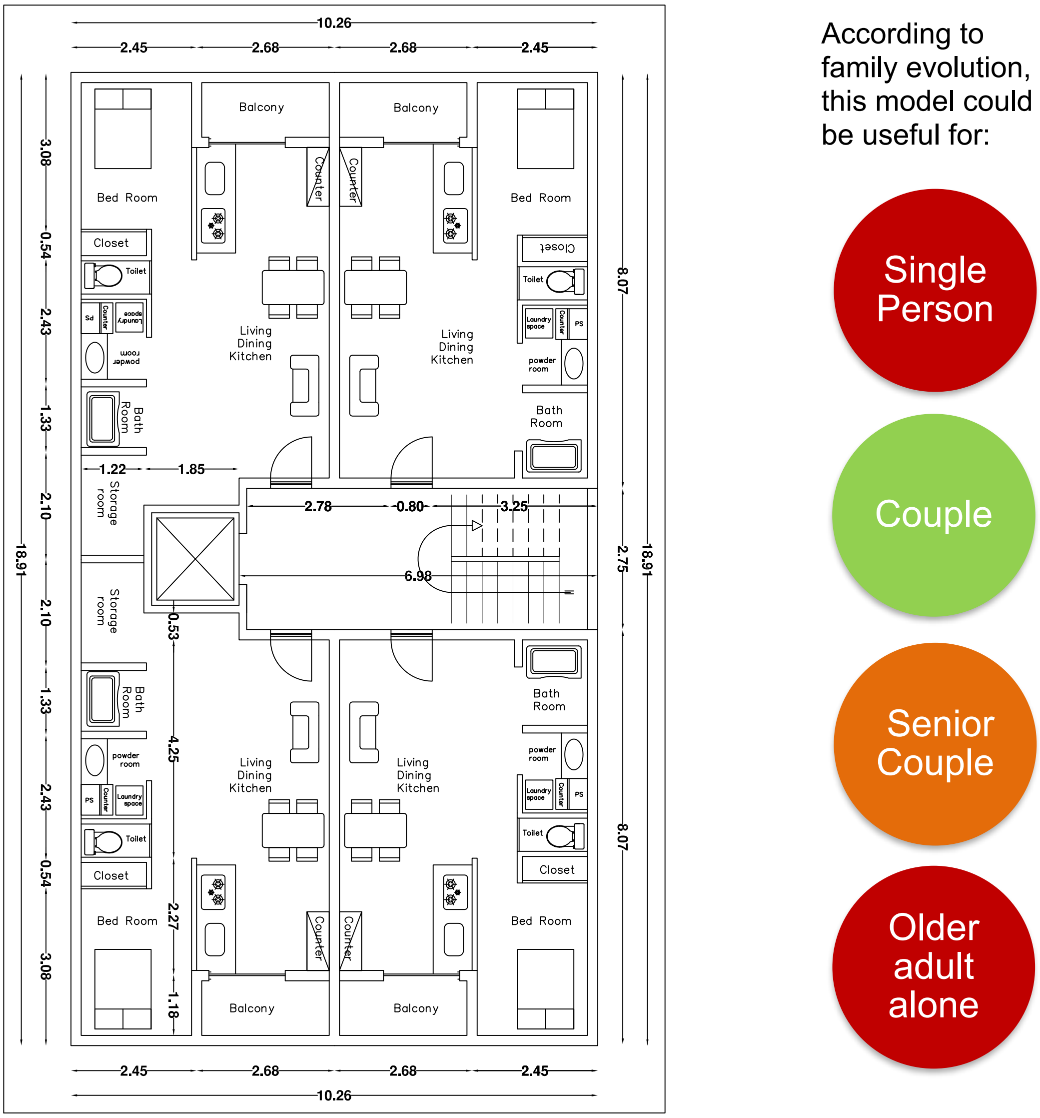

Figure 9: Full house State for four different families:
Single person, couple wishing to share time together, senior couple and older adult alone.

3 Business Model Canvas

3.1 Value Proposition:

You should ask, what value do we deliver to the customer by a Sustainable Changing Home? Well, a sustainable house in Quito could have usage characteristics that satisfy the needs of users during at least 40 years of their lives, because of economic factors, as well as cultural and psychological factors too. So helpful is an apartment as heritage that was the beginning of thinking how to change my house in to apartments, furthermore, in the future help take care of my grand children and be independent at home.

The bundle of a sustainable changing house depends on internal changes that can be done according to the evolution of the family, offering the customer to segment a long term

useful facility. As a result, the customer will require one mortgage for the purchase of a house that could be modified in the long run, instead of having several purchases according to each family stage; consequently, one mortgage in their life will be useful even for heritage.

3.2 Customer Segments:

This proposal creates value to medium class population, willing to achieve their first home that could be useful ultimately. This represents 72.1% of National Population. The most important customers are the ones between the ages of 30 and 45 years old. Specifically, the customer segment is 72,1% of the population in Quito, regarding the Strata of the socio-economic level in Ecuador, showed on figure 3 which is represented by C+ and C-.

3.3 Revenue Streams:

According to a survey for this research, 59% of customers are really willing to pay a useful home that could be divided in mini apartments in the future, which could represent revenues in the long term.

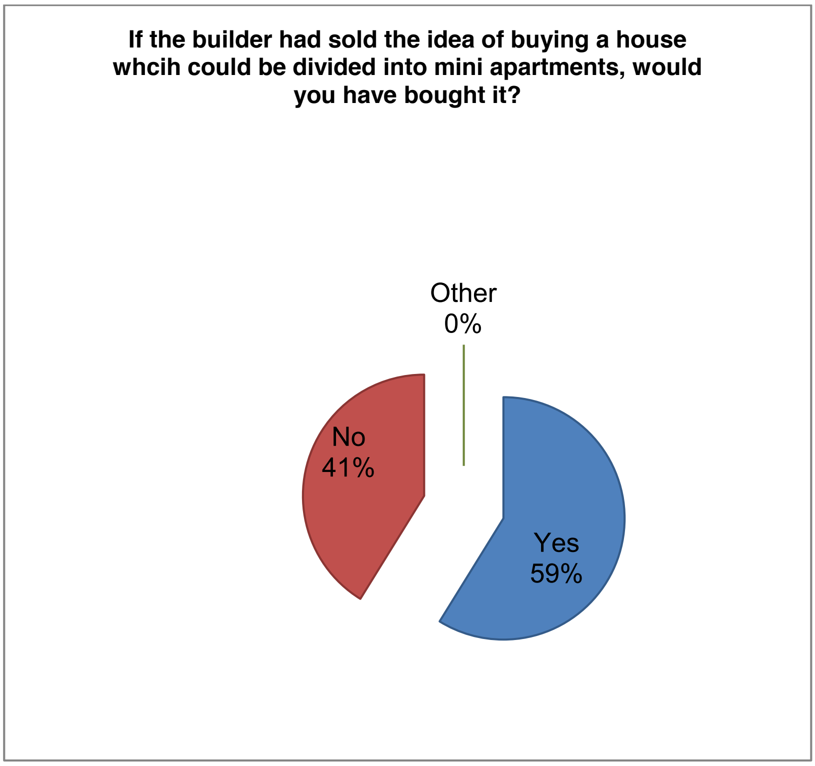

Figure 5. Percentage of people willing to buy a sustainable changing home.

A sustainable building or house could be constructed with materials that do not need maintenance for almost 80 years, so it will be important to know what to do in the long run with this type of buildings since the planning of it. Hence, the Council should be prepared to receive the initial design of the building and the possible potential internal changes that it could have in the future in order to approve of it before the construction is done; from now on these designs will be named double designs, since it will be the initial one plus several modifications that could be done in the long run; in consequence, instead of the owners requesting authorization from their co-owners in order to achieve permission to split an apartment, it could be approved since the design is done and presented to the

Municipality. Currently, Quito City Council has no regulations to accept designs like this; moreover, a mortgage is approved just for a single property with no apartments or retail areas, then regulations have to be reviewed and changed to support the construction of sustainable buildings with this new concept.

Based on a survey in which we interviewed; 80% of customers are willing to buy a home by a mortgage with a minimum length of 8 years and a maximum of 35 years. Since a sustainable house is a long term asset, which requires no maintenance for a long term but the initial cost is slightly higher than a traditional house. This should be advertised talking in consideration the benefits and the costs in comparison with the average cost of maintaining a traditional house which is $1117 per year.

As a revenue stream, there is owner's revenue because if the house is new and useful for a big family, the mortgage is paid. Furthermore, if the owner divides the house into mini apartments, it could be translated to extra incomes by renting of those mini apartments.

3.4 Customer Relationships:

Customer segments expect to establish and maintain a trustful relationship, especially, the property would have technical support for the possibility of change internally by the design of the home.

Actually, there are no customer relations between City Council and future home owners, internal processes are slow and bureaucratic. Moreover, Quito City council does not have the regulations that allow Builders to have sustainable changing homes options for customers.

Customer relations have to be integrated between builders, City Council and buyers by new regulations that allow internal changes in a sustainable house, which is one of the main conclusion of this paper. This requirement is an administrative regulation that has to be examined, published and approved.

3.5 Channels:

Customer Segments would be reached by banks, City Council, and builders. Some integrated channels are builders and banks which work good. The most cost-efficient channel are builders, therefore integrating channels with customer routines could be efficiently done by banks´ websites and all kind of information would be delivered to their customers.

3.6 Key Partners:

Key Partners for this proposal are Banks, Escrows, Builders which develop this concept and City Council.

Key Suppliers are Builders and City Council because builders will define sustainable designs with principles that benefits users with productivity. On the other hand, City Council needs to provide regulations for double designs and construction that allow future changes in a sustainable house or apartment.

Banks and escrows have to be involved in the process because they have to create and accept regulations for a home mortgage which could be internally changed to achieve more than one home unit.

Partners do perform key activities as communicating to the population about sustainable buildings and their benefits; or regulations approved by Quito City Council for sustainable buildings with characteristics of a sustainable changing home.

3.7 Key Activities:

Our Value Propositions require adaptable designs with mobile walls.

Our Distribution Channels like Banks and credit institutions need new construction projects with these principles.

Customer relationships would be supported by communicating through videos on social media how the projects are developing, triptychs; all with the support of City Council with a long term relationship with customers and builders.

Revenue streams would require communication of the projects, presale after construction, escrow and bank supports with special interest rates.

3.8 Key Resources:

Value Propositions required a Key Resource City Council Regulations approved, or initially the construction will be done as mini apartments and would be used as a complete home.

It would be very valuable that our distribution channels spread information about the benefits of sustainable buildings in the long term.

Customer Relationships would be definitely successful when citizens achieve economic stability and a better future plan with certainty of some revenue streams.

3.9 Cost Structure:

The most important costs inherent in this business model are the communication of this idea to the City Council and customer segments.
The most expensive Key Resources is creating a building as a prototype of this system, which costs approximately 2.7 million dollars.

The Business Model Canvas[1]

A SUSTAINABLE CHANGING HOME

Date:
07/17/17

<table>
<tr>
<td rowspan="2">Key Partners
Who are our Key Partners?
Banks and Escrows, Builders and City Council

Who are our Key Suppliers?
Builders and City Council

Which Key Resources are we acquiring from partners?
Regulations for construction and future changes in a sustainable house or apartment.

Regulations for home loans which could be internally changed to achieve more than one unit.

Which Key Activities do partners perform?
Communicating to the population about sustainable buildings and their benefits.

The City Council has to approve regulations for sustainable buildings like these.</td>
<td>Key Activities
What Key Activities do our Value Propositions require?
Adaptable design with mobile walls

Our Distribution Channels?
New construction projects
Banks and credit institutions

Customer Relationships?
Communication of the projects by videos through social media and triptychs.
Long term relationship with customers.

Revenue streams?
Pre-sale after construction.
Escrow</td>
<td rowspan="2">Value Proposition
What value do we deliver to the customer?

A sustainable house in Quito could have usage characteristics that satisfy the needs of users during at least 40 years of their life.

Which one of our customer's problems are we helping to solve?

A model of house/apartment that can be comfortable in each stage of the growth of the relatives, linked to the planning of both the family evolution and the physical space in the house.

What bundles of products and services are we offering to each Customer Segment?

A sustainable design that changes internally according to the evolution of the family.

One loan for the purchase, instead of one purchase of each family change of stage, therefore more than a loan.

Which customer needs are we satisfying?</td>
<td>Customer Relationships
What type of relationship does each of our Customer Segments expect us to establish and maintain with them?
Trustful relationship, especially with the possibility of change internally the design of home.

Which ones have we established?
City council does not have regulations yet that allow builders to have this options for customers.

How are they integrated with the rest of our business model?
The conclusion of this paper refers to the possibility to have regulations that allow internal changes in a sustainable house.

How costly are they?
It has no cost really, it is an administrative regulation that has to be examined, published and approved.</td>
<td rowspan="2">Customer Segments
For whom are we creating value?

Medium class population, willing to achieve their first home and thinking on giving a heritage to their children.

72.1% of National Population,

Who are our most important customers?

People with age range of 30 and 45 years old.

12,5 % of new families at Quito
22,8% of Population at Quito</td>
</tr>
<tr>
<td>Key Resources
What Key Resources do our Value Propositions require?
City Council Regulations approved
Our Distribution Channels?
Information about the benefits of sustainable buildings in the long term.
Customer Relationships?</td>
<td>Channels
Through which Channels do our Customer Segments want to be reached?
Banks, City Council, Builders
How are we reaching them now?
Builders
How are our Channels integrated? Which ones work best?
Builders and banks</td>
</tr>
</table>

[1] "http://www.businessmodelgeneration.com Bplan: The UC Berkeley Startup Competition" *(2017) Available from: Open Source Repository* <http://www.slidesshare.net/FiddiniNurvitaNurvita/business-model-canvas-template-76885401> (accessed 7 July 2017).

<table>
<tr><td></td><td>Citizens with economic stability and future planed
Revenue Streams?</td><td>Housing represents safety and security needs according to Maslow's hierarchy of needs theory.</td><td>Which ones are most cost-efficient? Builders
How are we integrating them with customer routines? By Banks information</td><td></td></tr>
<tr><td colspan="2">Cost Structure
What are the most important costs inherent in our business model?
Communication of this idea to me City Council
Which Key Resources are most expensive?
Create a building as a prototype of the system
Which Key Activities are most expensive?
Build the prototype (2.7 million dollars)</td><td colspan="3">Revenue Streams
For what value are our customers really willing to pay?
A useful home with revenues in the long term
Economic revenues
For what do they currently pay?
A mortgage for a house or an apartment
How are they currently paying?
88,24% of families invest from 21% to 60% of their entire incomes paying mortgage
How would they prefer to pay?
The most preferred term to pay a mortgage is 10 years
How much does each Revenue Stream contribute to overall revenues?
A sustainable house is a long term asset which requires no maintenance for a long term. Meanwhile the house is new and useful for a big family the mortgage is paid. If the owner divides the house into mini apartments, it could be translated to extra incomes by the rent of mini apartments.</td></tr>
</table>

Figure 10. Development of the analysis of Business Model Canvas for a Sustainable Changing Home

4 Conclusions

Customer relations have to be integrated between builders, City Council and future home owners by new regulations to have the concept of a sustainable changing home applied in future constructions. The regulation is easy to apply, with an unsuspected benefit for the population. The core of the new regulation is based on a double design acceptance for a home, which will be the base of future internal changes as a photography of the building in the long run.

The customer segment for this this proposal will be 71,1% of the population that have a range incomes of $250 to $1500 USDs per month. The most important future customers are people with a range age of 30 and 45 years old. Moreover, this proposal benefits the well being of families in the long run by accessible housing; and, financial well been for people who buy a property by mortgage. In addition, the Mayor could drive this change and work with the Central Government to support changes on rules of privates banks in order to create a real solution for housing.

Acknowledgements

My acknowledgment goes to my children, Victoria and David Sebastian who deserve happiness and heritage.

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CASE STUDY: DO DATABASE SOURCES AFFECT ENVIRONMENTAL PERFORMANCE OF ROOF COVERINGS?

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Abstract: *Because of usage of finite and limited sources unconsciously, especially after industrial revolution and increase in industrial and chemical facilities, there are environmental issues such as global warming, water pollution and ozone depletion. When the construction sector and its environmental impact are concerned, first of all, the building itself creates a negative effect by vanishing the vegetation and flora where it settles. Building destroys as much the soil and the ecosystem as the area of the settlement. Nevertheless, during the construction period, environmental impacts continue as the energy used and the process during production of construction materials. During the production processes of construction materials, there are emissions to air, to soil and to water. For designers and architects, and actors in construction sector, selection of construction materials is an important issue. Recently many construction materials manufacturers have been announcing their Environmental Product Declaration (EPD) in which the environmental impacts are measured. Construction materials that have an EPD can be compared to each other in seven categories in terms of environmental performance. However, these seven categories measured by different units; for instance, Global Warming Potential (GWP) measured in [kgCO_2-Eq], while ODP (Depletion potential of the stratospheric ozone layer) in [kg CFC11-Eq.]. Since comparing construction materials with seven indicators is difficult, some institutions developed databases for researchers to unify the results by determining the shadow cost for each category. Institutions such as Institut Bauen und Umwelt (IBU), Nederlands Instituut voor Bouwbiologie and Ecologie (NIBE), SBRCURnet (SBR: Referentiedetails voor op de bouwplaats) are examples used in this study. This study questions whether the source of data where the shadow costs are taken influences the results or not? While conducting this study, first of all, values stated in EPDs are used to make calculations and comparisons to evaluate the environmental performances. Then, shadow costs are applied to impact categories to unite the results and to make comparison in terms of one indicator; i.e. costs. Finally, a comparison carried out to analyze the effects of different shadow cost data sets on environmental performances of construction materials. As a conclusion, it is observed that the environmental impact costs vary from region to region, from culture to culture, from country to country. Therefore, in this paper, it is aimed to study whether there is an effect of choosing different database on environmental performance of construction materials or not.*

Keywords: *Life Cycle Assessment (LCA), Environmental Product Declaration (EPD), Environmental Impact Cost, Construction Materials, Shadow Cost*

1. Introduction

Construction sector, while providing social and economical growth and development, is one of the biggest industry that uses natural sources mostly together with construction material manufacturer sectors. According to studies in Europe, construction sector is claimed to be responsible for the natural source consumption and environmental damages such as highest energy consumption, green house gas emissions, waste production (Ortiz and al, 2009). Studies in USA show that construction sector uses 40% of materials in global economy, consumes 3 billion tones of materials and 25% of world forests and responsible for the %40-50 of GHG and acid rains (California Integrated Waste Management Board, 2000).

With the climate change and increased environmental damages, the importance of environmental awareness is increasing. After international standards such as Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) are introduced, construction material manufacturers have started to publish EPDs (Environmental Product Declarations) to express the environmental effects of construction materials; EPDs state environmental aspects in three sections; environmental impact, resource use, output flows and waste categories. In environmental impact section impact categories are as follows:

- GWP (Global Warming Potential) is measured in [kg CO_2-Eq.],
- ODP (Depletion potential of the stratospheric ozone layer) in [kg CFC11-Eq.]
- AP (Acidification potential of land and water) in [kg SO_2-Eq.]
- EP (Eutrophication potential) in [kg PO_4^{3}-Eq.]
- POCP (Formation potential of tropospheric ozone photochemical oxidants) in [kg Ethen Eq.]
- ADPE (Abiotic depletion potential for non fossil resources) in [kg Sb Eq.]
- ADPF (Abiotic depletion potential for fossil resources) in [MJ]

Since it is a milestone for environmental aspect, for architects and designer, environmental impact categories provide a comparison among construction materials that are to be used during implementation. However, every impact category has its own unit, the comparisons become complex and confusing. These 7 different aspects are added among comparison criteria; such as service life, maintenance frequency, initial costs.

Thanks to the certification programs such as LEED and BREEAM, credits are being given to green constructions and green construction materials by architects and designer.

But still, while comparing, there are several aspects of construction materials, measured in different units as mentioned above.

In literature, there are several studies to unite the comparison criteria into one criterion. Chevaerias (2015) studies environmental impact of building materials. In the study, to make a comparison “shadow cost” is used to unite criteria. For each of these selected environmental impact categories, a shadow cost is assigned to each unit that can then add up to a single environmental indicator resulting in the total shadow cost of the building (Chevaerias 2015).

2. Aim of the study

This study aims to question "shadow cost" database that are used to make a concrete comparison of environmental performances of construction materials. The question arises after the thesis "Life Cycle Cost Analyses of Construction Materials Including Environmental Impact Costs". While studying on environmental costs; in literature more than one database / data sets have been found. In the thesis, average costs are calculated since there is no database in Turkey where the study is carried out.
Therefore, after the study, it is questioned that what would be the results if different database/ data set were used.
The aim of this study is, hereby, to see whether there is a difference or any deflection in results by using different shadow cost data sets for roof covering materials.

3. Scope and Limitation

The scope of this study is roof covering materials. However, the study is limited to 12 roof covering materials of which have an EPD that is open to public, i.e., published online.
In the study, as in the EPDs, 1 sqm of 12 roof covering materials are analyzed and compared.
In EPDs, system boundaries vary from cradle-to-gate to cradle-to-cradle. In order to compare accordingly, cradle-to-gate is preferred in this study; since there is no cradle-to-cradle measurements for all 12 roof covering materials.
EPDs can be downloaded from internet sites "epdturkey.org", "envriondec.com" and "bau-umwelt.de".

4. Method

EPDs are being prepared in accordance with ISO 14025: Environmental labels and declarations. The measurements and calculations are being carried out third parties externally.

Table 1: List of Roof Covering Materials Used in this Study

No	EPD No	ROOF COVERING MATERIAL
1	EPD-MAR-20140216-CCD1-EN	Coated Fibre Cement Slates
2	EPD-OND-2013111-E	Onduline Classic
3	EPD-CRE-2012221-D	Tondachziegel
4	EPD-ETE-20130224-IAA1-DE	Eternit Dachstein HVGK
5	EPD-CRE-2012211-D	Tondachziegel
6	EPD-MET-20140068-IAC1-EN	Mahaphant Fibre cement roof covering
7	EPD-ERL-20140214-IAC1-DE	Tondachziegel inkl. Zubehör
8	EPD-FCH-2013211-E	Fibre-Cement Roof Slates
9	EPD-IFBS-2013111-EN (Eco-00000009)	35/207 Profile
10	EPD-IFBS-2013111-EN (Eco-00000009)	135/310 Profile
11	EPD-IFBS-2013111-EN (Eco-00000009)	130/600 Liner-tray Profile
12	EPD-IFBS-2013111-EN (Eco-00000009)	65/400 Folded Profile

Therefore, from raw material acquisition to final construction product, all production processes are observed and measured in terms of emission to air, soil, water. Moreover, energy and natural source consumptions are measured. All measurements and calculations are stated as seven categories of environmental impact.
In this study, the data is directly taken from EPD measurements held by third parties.
First, list roof covering materials and EPD numbers are provided for further controls. 12 Roof covering materials are compared in terms of seven environmental impact categories that are measured in Environmental Impact sections of EPDs. Since the numbers vary, the overall order of 12 roofing materials in terms of seven environmental impact categories are given in table 3 to express the minimum and maximum impact order vary from material to material, from environmental impact category to environmental impact category.
Since the Table 2 and Table 3 are not enough to choose the most environmental friendly material among 12 roof covering materials, it is argued to unite the seven categories into one indicator; i.e. shadow cost.
Therefore, in Table 4, shadow costs found in literature are listed.
In further steps, these shadow costs, which can be expressed as environmental costs, are multiplied by environmental impact results accordingly. The results are summed up for each roof covering materials and compared according to one single indicator; i.e. overall cost.
According to environmental impact costs, 12 roof covering materials are compared and discussed in final section of this study.

Table 2: Environmental Impact Results; 7 Impact Categories

No	GWP [kgCO2-Eq.]	ODP [kgCFC11-Eq]	AP [kgSO2Eq]	EP [kg(PO4)3-Eq.]	POCP [kgEthenEq]	ADPE [kgSbEq]	ADPF [MJ]
1	19,40	3E-10	4E-02	6E-03	6E-03	2E-05	182,00
2	1,10	2E-08	9,61E-03	1E-03	1E-03	2E-06	109,30
3	1,27E+01	1,73E-08	1,49E-02	1,98E-03	1,74E-03	1,24E-06	2,03E+02
4	1,24E+01	1,22E-09	1,73E-02	2,40E-03	3,45E-03	1,51E-05	1,08E+02
5	1,68E+01	9,61E-09	1,64E-02	2,40E-03	1,95E-03	1,37E-06	2,69E+02
6	3,56E+00	9,69E-08	3,49E-02	8,46E-03	7,77E-04	6,42E-08	1,50E+01
7	1,34E+01	2,34E-10	2,12E-02	2,25E-03	1,80E-03	2,34E-06	2,11E+02
8	6,70E+00	4,04E-07	1,54E-02	5,11E-03	1,07E-03	8,03E-06	5,77E+01
9	2,52E+01	6,55E-07	1,30E-01	6,00E-03	7,00E-03	1,07E-05	2,61E+02
10	2,65E+01	1,36E-09	9,50E-02	8,43E-03	1,21E-02	2,16E-03	3,07E+02
11	2,65E+01	1,44E-09	9,50E-02	8,50E-03	1,21E-02	2,16E-03	3,07E+02
12	2,17E+01	1,37E-09	8,00E-02	7,01E-03	1,03E-02	1,80E-03	2,58E+02

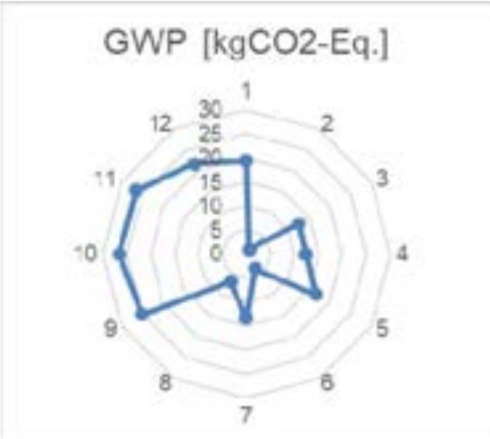
5. Case Study: Roof Covering Materials

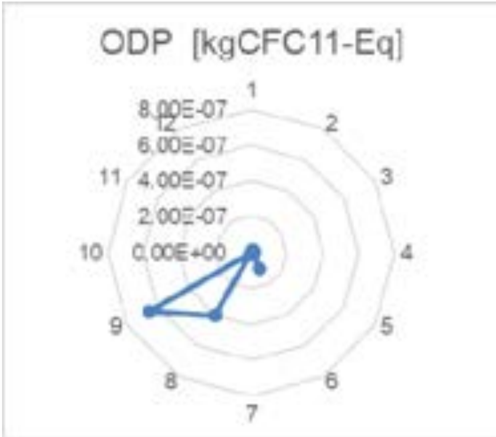
In the study, environmental impacts of 12 roof covering materials are collected from EPDs and compared in Table 2 given below:

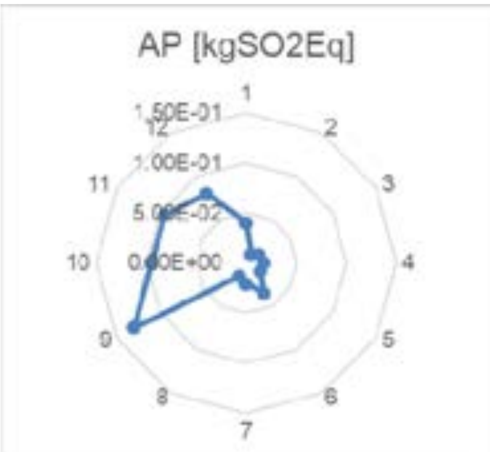
5.1. Environmental Impacts

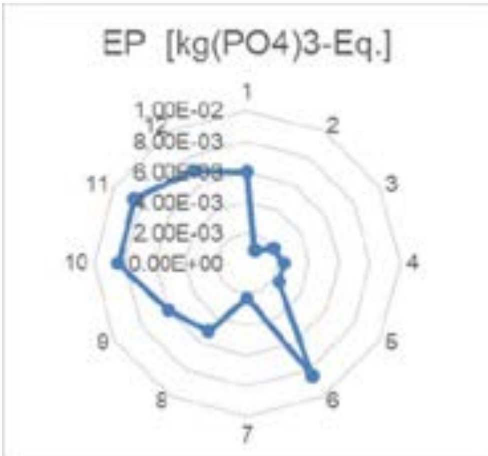
The first section of LCA results in EPDs is Environmental Impacts which has 7 sub categories; GWP, ODP, AP, EP, POCP, ADPE, ADPF.

Spider Graphs, given below, show that 12 roof covering materials have different performances in terms of environmental impacts; GWP, ODP, AP, EP, POCP, ADPE, ADPF.









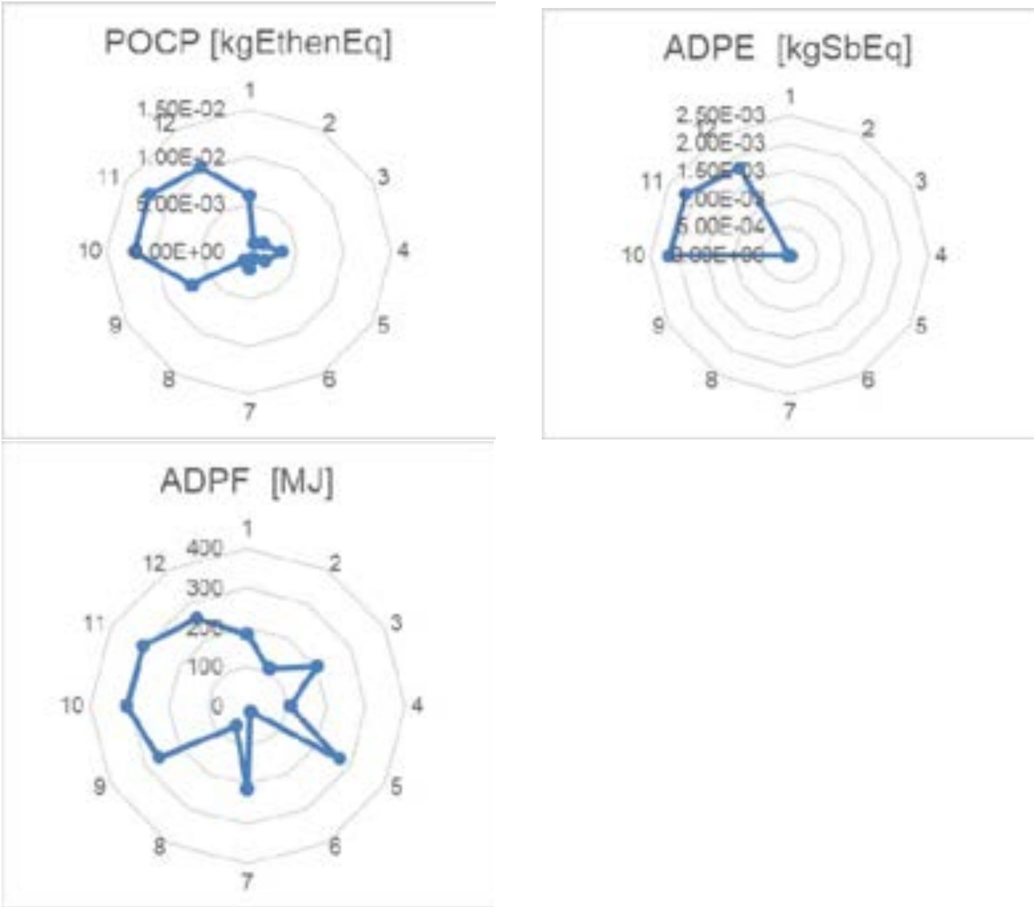


Figure 1: Spider Graphs of 12 Roof Covering Materials in terms of 7 impact categories

According to these performances to make a choice for roof covering among these 12 roof covering materials is not possible. To simplify the numbers, performance of 12 roof covering materials are ordered from the highest impact to lowest one in table 3.
As shown in table 3, metal roof covering materials have the first 4 highest order in terms of CO_2 emissions, AP and POCP.

When ODP is concerned, the order is given above (Table.3), no.7 roof tile product is listed as having less environmental impact when compared to other roof covering materials.
When EP is concerned, metal roof coverings and fibre cement roof coverings have the most negative environmental impact.
In terms of ADPE, together with metal roof coverings, fibre cement slates have the highest negative impact on environment.
When ADPF is concerned, roof tile no.5 and metal roof coverings have the highest environmental impact.

As seen from tables, to make a concrete comparison among construction materials in terms of environmental impact performance is not easy and simple.

To sum up, it is seen that metal roof coverings damage environment more when compared to others. However, it is interpreted from the results that, among 12 construction materials, it could not be stated that one of the materials ranks as first, giving the least damage to environment. Among 12 roof covering materials, for instance

Table 3 : Overall Order of 12 Roof Covering Materials

No	EPD No	Order						
		GWP	ODP	AP	EP	POCP	ADPE	ADPF
1	EPD-MAR-20140216-CCD1-EN	4	11	4	5	4	**3**	7
2	EPD-OND-2013111-E	11	**4**	11	11	9	8	8
3	EPD-CRE-2012221-D	7	5	10	10	8	10	6
4	EPD-ETE-20130224-IAA1-DE	8	10	7	8	5	4	9
5	EPD-CRE-2012211-D	5	6	8	8	6	9	**2**
6	EPD-MET-20140068-IAC1-EN	10	**3**	5	**2**	11	11	11
7	EPD-ERL-20140214-IAC1-DE	6	12	6	9	7	7	5
8	EPD-FCH-2013211-E	9	**2**	9	7	10	6	10
9	EPD-IFBS-2013111-EN (Eco-00000009)	**2**	**1**	**1**	6	**3**	5	**3**
10	EPD-IFBS-2013111-EN (Eco-00000009)	**1**	9	**2**	**3**	**1**	**1**	**1**
11	EPD-IFBS-2013111-EN (Eco-00000009)	**1**	7	**2**	**1**	**1**	**1**	**1**
12	EPD-IFBS-2013111-EN (Eco-00000009)	**3**	8	**3**	**4**	**2**	**2**	4

fibre cement covering (no.6) ranks in first three in terms of ODP and EP, while order last three in terms of POCP, ADPE, ADPF. In this case how can an architect compare and select the material is a question. Therefore, a holistic approach is needed to unite the orders and different units into one scale. In the next section of the study, shadow costs are introduced and included as the next part of the study.

5.2. Shadow Costs

In order to evaluate these impacts concretely, there is a need to have a single indicator.; which, in this case, cost. With the light of researches, shadow costs are calculated in inventories / databases to serve researchers.

Shadow cost are defined as “monetary value of something that does not have a market. In this study, the shadow represents the cost that society is willing to pay to ensure environmental quality” (Chevaerias 2015). Chevaerias (2015). In the thesis, shadow costs are taken from SBRCURnet (Cindy Vissering, 2015), as weighting factor to achieve a single value indicator. Chevaerias also mentions that there are four methods for weighting:

* Panel
* Target-to-distance
* Technology method
* Monetization

However, in this study, weighting methods are not to be discussed, since the aim of the study to compare the effects and results of using different shadow costs. Weighting methods and their effects can be discussed in further studies.

Beside IBU and NIBE, there are free online databases such as EcoCOST that provide data for students and researches. The shadow cost for GWP, ODP, AP, EP, POCP, ADPE and ADPF are listed below:

Table 4: Shadow Costs in Different Sources

Source	Shadow Cost of GWP €/(kg CO_2 equiv.)	Shadow Cost of ODP €/(kg CFC11 equiv.)	Shadow Cost of AP €/(kg SO_2 equiv.)	Shadow Cost of EP €/(kg $(PO_4)^{3-}$ equiv.)	Shadow Cost of POCP €/(kg C_2H_4 equiv.)	Shadow Cost of ADPE €/(kg Sb equiv.)	Shadow Cost of ADPF €/(kg Sb equiv.)
EcoCOST	0,116	100	8,83	4,17	10,38	7,81	7,81
IBU	0,135	30	8,25	3,90	9,70	2	2
NIBE	0,050	30	4	9	2	2	2
SBRCURnet	0,05	30	4	9	2	0,16	0,16

In the next step of the study, seven impact category results are multiplied by their shadow costs accordingly. According to data set of Table.4, the costs of impact categories are calculated in terms of the source of the data and given in separate tables category by category as follows:

Table 5: Cost of GWP

No	EPD No	GWP [kgCO2-Eq.]	EcoCOST	IBU	NIBE	SBRCURnet
			0,116	0,135	0,050	0,05
1	EPD-MAR-20140216-CCD1-EN	19,40	€2,25040	€2,61900	€0,97000	€0,97000
2	EPD-OND-2013111-E	1,10	€0,12760	€0,14850	€0,05500	€0,05500
3	EPD-CRE-2012221-D	1,27E+01	€1,47320	€1,71450	€0,63500	€0,63500
4	EPD-ETE-20130224-IAA1-DE	1,24E+01	€1,43840	€1,67400	€0,62000	€0,62000
5	EPD-CRE-2012211-D	1,68E+01	€1,94880	€2,26800	€0,84000	€0,84000
6	EPD-MET-20140068-IAC1-EN	3,56E+00	€0,41296	€0,48060	€0,17800	€0,17800
7	EPD-ERL-20140214-IAC1-DE	1,34E+01	€1,55440	€1,80900	€0,67000	€0,67000
8	EPD-FCH-2013211-E	6,70E+00	€0,77720	€0,90450	€0,33500	€0,33500
9	EPD-IFBS-2013111-EN (Eco-00000009)	2,52E+01	€2,92320	€3,40200	€1,26000	€1,26000
10	EPD-IFBS-2013111-EN (Eco-00000009)	2,65E+01	€3,07400	€3,57750	€1,32500	€1,32500
11	EPD-IFBS-2013111-EN (Eco-00000009)	2,65E+01	€3,07400	€3,57750	€1,32500	€1,32500
12	EPD-IFBS-2013111-EN (Eco-00000009)	2,17E+01	€2,51720	€2,92950	€1,08500	€1,08500

Table 6 : Cost of ODP

No	EPD No	ODP [kgCFC11-Eq]	EcoCOST	IBU	NIBE	SBRCURnet
			100 €	30 €	30 €	30 €
1	EPD-MAR-20140216-CCD1-EN	3E-10	0,000000	0,000000	0,000000	0,000000
2	EPD-OND-2013111-E	2E-08	0,000002	0,000001	0,000001	0,000001
3	EPD-CRE-2012221-D	1,73E-08	0,000002	0,000001	0,000001	0,000001
4	EPD-ETE-20130224-IAA1-DE	1,22E-09	0,000000	0,000000	0,000000	0,000000
5	EPD-CRE-2012211-D	9,61E-09	0,000001	0,000000	0,000000	0,000000
6	EPD-MET-20140068-IAC1-EN	9,69E-08	0,000010	0,000003	0,000003	0,000003
7	EPD-ERL-20140214-IAC1-DE	2,34E-10	0,000000	0,000000	0,000000	0,000000
8	EPD-FCH-2013211-E	4,04E-07	0,000040	0,000012	0,000012	0,000012
9	EPD-IFBS-2013111-EN	6,55E-07	0,000066	0,000020	0,000020	0,000020
10	EPD-IFBS-2013111-EN	1,36E-09	0,000000	0,000000	0,000000	0,000000
11	EPD-IFBS-2013111-EN	1,44E-09	0,000000	0,000000	0,000000	0,000000
12	EPD-IFBS-2013111-EN	1,37E-09	0,000000	0,000000	0,000000	0,000000

Table 7 : Cost of AP

No	EPD No	AP [kgSO2Eq]	EcoCOST	IBU	NIBE	SBRCURnet
			8,83 €	8,25 €	4 €	4 €
1	EPD-MAR-20140216-CCD1-EN	4E-02	€0,35320	€0,33000	€0,16000	€0,16000
2	EPD-OND-2013111-E	9,61E-03	€0,08486	€0,07928	€0,03844	€0,03844
3	EPD-CRE-2012221-D	1,49E-02	€0,13157	€0,12293	€0,05960	€0,05960
4	EPD-ETE-20130224-IAA1-DE	1,73E-02	€0,15276	€0,14273	€0,06920	€0,06920
5	EPD-CRE-2012211-D	1,64E-02	€0,14481	€0,13530	€0,06560	€0,06560
6	EPD-MET-20140068-IAC1-EN	3,49E-02	€0,30817	€0,28793	€0,13960	€0,13960
7	EPD-ERL-20140214-IAC1-DE	2,12E-02	€0,18720	€0,17490	€0,08480	€0,08480
8	EPD-FCH-2013211-E	1,54E-02	€0,13598	€0,12705	€0,06160	€0,06160
9	EPD-IFBS-2013111-EN (Eco-00000009)	1,30E-01	€1,14790	€1,07250	€0,52000	€0,52000
10	EPD-IFBS-2013111-EN (Eco-00000009)	9,50E-02	€0,83885	€0,78375	€0,38000	€0,38000
11	EPD-IFBS-2013111-EN (Eco-00000009)	9,50E-02	€0,83885	€0,78375	€0,38000	€0,38000
12	EPD-IFBS-2013111-EN (Eco-00000009)	8,00E-02	€0,70640	€0,66000	€0,32000	€0,32000

Table 8: Cost of EP

No	EPD No	EP [kg(PO4)3-Eq.]	EcoCOST	IBU	NIBE	SBRCURnet
			x4,17 €	x3,9 €	x9 €	x9 €
1	EPD-MAR-20140216-CCD1-EN	6E-03	0,025020	0,023400	0,054000	0,054000
2	EPD-OND-2013111-E	1E-03	0,004170	0,003900	0,009000	0,009000
3	EPD-CRE-2012221-D	1,98E-03	0,008257	0,007722	0,017820	0,017820
4	EPD-ETE-20130224-IAA1-DE	2,40E-03	0,010008	0,009360	0,021600	0,021600
5	EPD-CRE-2012211-D	2,40E-03	0,010008	0,009360	0,021600	0,021600
6	EPD-MET-20140068-IAC1-EN	8,46E-03	0,035278	0,032994	0,076140	0,076140
7	EPD-ERL-20140214-IAC1-DE	2,25E-03	0,009383	0,008775	0,020250	0,020250
8	EPD-FCH-2013211-E	5,11E-03	0,021309	0,019929	0,045990	0,045990
9	EPD-IFBS-2013111-EN (Eco-00000009)	6,00E-03	0,025020	0,023400	0,054000	0,054000
10	EPD-IFBS-2013111-EN (Eco-00000009)	8,43E-03	0,035153	0,032877	0,075870	0,075870
11	EPD-IFBS-2013111-EN (Eco-00000009)	8,50E-03	0,035445	0,033150	0,076500	0,076500
12	EPD-IFBS-2013111-EN (Eco-00000009)	7,01E-03	0,029232	0,027339	0,063090	0,063090

Table 9 : Cost of POCP

No	EPD No	POCP [kgEthenEq]	EcoCOST	IBU	NIBE	SBRCURnet
			10,38 €	9,7 €	2 €	2 €
1	EPD-MAR-20140216-CCD1-EN	6E-03	0,062280	0,058200	0,012000	0,012000
2	EPD-OND-2013111-E	1E-03	0,010380	0,009700	0,002000	0,002000
3	EPD-CRE-2012221-D	1,98E-03	0,020552	0,019206	0,003960	0,003960
4	EPD-ETE-20130224-IAA1-DE	2,40E-03	0,024912	0,023280	0,004800	0,004800
5	EPD-CRE-2012211-D	2,40E-03	0,024912	0,023280	0,004800	0,004800
6	EPD-MET-20140068-IAC1-EN	8,46E-03	0,087815	0,082062	0,016920	0,016920
7	EPD-ERL-20140214-IAC1-DE	2,25E-03	0,023355	0,021825	0,004500	0,004500
8	EPD-FCH-2013211-E	5,11E-03	0,053042	0,049567	0,010220	0,010220
9	EPD-IFBS-2013111-EN (Eco-00000009)	6,00E-03	0,062280	0,058200	0,012000	0,012000
10	EPD-IFBS-2013111-EN (Eco-00000009)	8,43E-03	0,087503	0,081771	0,016860	0,016860
11	EPD-IFBS-2013111-EN (Eco-00000009)	8,50E-03	0,088230	0,082450	0,017000	0,017000
12	EPD-IFBS-2013111-EN (Eco-00000009)	7,01E-03	0,072764	0,067997	0,014020	0,014020

Table 10 : Cost of ADPE

No	EPD No	ADPE [kgSbEq]	EcoCOST	IBU	NIBE	SBRCURnet
			7,81 €	2 €	2 €	0,16 €
1	EPD-MAR-20140216-CCD1-EN	2E-05	0,000156	0,000040	0,000040	0,000003
2	EPD-OND-2013111-E	2E-06	0,000016	0,000004	0,000004	0,000000
3	EPD-CRE-2012221-D	1,24E-06	0,000010	0,000002	0,000002	0,000000
4	EPD-ETE-20130224-IAA1-DE	1,51E-05	0,000118	0,000030	0,000030	0,000002
5	EPD-CRE-2012211-D	1,37E-06	0,000011	0,000003	0,000003	0,000000
6	EPD-MET-20140068-IAC1-EN	6,42E-08	0,000001	0,000000	0,000000	0,000000
7	EPD-ERL-20140214-IAC1-DE	2,34E-06	0,000018	0,000005	0,000005	0,000000
8	EPD-FCH-2013211-E	8,03E-06	0,000063	0,000016	0,000016	0,000001
9	EPD-IFBS-2013111-EN (Eco-00000009)	1,07E-05	0,000084	0,000021	0,000021	0,000002
10	EPD-IFBS-2013111-EN (Eco-00000009)	2,16E-03	0,016870	0,004320	0,004320	0,000346
11	EPD-IFBS-2013111-EN (Eco-00000009)	2,16E-03	0,016870	0,004320	0,004320	0,000346
12	EPD-IFBS-2013111-EN (Eco-00000009)	1,80E-03	0,014058	0,003600	0,003600	0,000288

Table 11 : Cost of ADPF

No	EPD No	ADPF [MJ]	EcoCOST	IBU	NIBE	SBRCURnet
			7,81	2	2	0,16
1	EPD-MAR-20140216-CCD1-EN	182,00	€1.421,42	€364,00	€364,00	€29,12
2	EPD-OND-2013111-E	109,30	€853,63	€218,60	€218,60	€17,49
3	EPD-CRE-2012221-D	2,03E+02	€1.585,43	€406,00	€406,00	€32,48
4	EPD-ETE-20130224-IAA1-DE	1,08E+02	€843,48	€216,00	€216,00	€17,28
5	EPD-CRE-2012211-D	2,69E+02	€2.100,89	€538,00	€538,00	€43,04
6	EPD-MET-20140068-IAC1-EN	1,50E+01	€117,15	€30,00	€30,00	€2,40
7	EPD-ERL-20140214-IAC1-DE	2,11E+02	€1.647,91	€422,00	€422,00	€33,76
8	EPD-FCH-2013211-E	5,77E+01	€450,64	€115,40	€115,40	€9,23
9	EPD-IFBS-2013111-EN (Eco-00000009)	2,61E+02	€2.038,41	€522,00	€522,00	€41,76
10	EPD-IFBS-2013111-EN (Eco-00000009)	3,07E+02	€2.397,67	€614,00	€614,00	€49,12
11	EPD-IFBS-2013111-EN (Eco-00000009)	3,07E+02	€2.397,67	€614,00	€614,00	€49,12
12	EPD-IFBS-2013111-EN (Eco-00000009)	2,58E+02	€2.014,98	€516,00	€516,00	€41,28

5.3. Comparison and Evaluation

As seen above (from Table.5 to Table.11) environmental impacts are calculated in terms of one single unit/indicator. By the help of weighting factors and method, using shadow cost enables the environmental impacts expressed in one single table as one indicator, i.e. cost.

Table.12 shows the total cost of seven environmental impact categories among 12 roofing materials.

After producing this result, it is questioned that whether the differences/deflection among the shadow cost data sets can cause a deviation or not. Also, it is questioned that whether using different source of shadow cost can affect the result by changing order of environmental performance.

In order to understand that, another column is added to Table.12 in order to see the deviations among 12 roofing materials in terms of choosing different database.

Table 12 : Total Cost of Impact Categories

No	EPD No	EcoCOST	IBU	NIBE	SBRCURnet
1	EPD-MAR-20140216-CCD1-EN	€1.891,85	€1.768,43	€365,20	€365,20
2	EPD-OND-2013111-E	€1.134,76	€1.060,45	€218,70	€218,70
3	EPD-CRE-2012221-D	€2.108,77	€1.970,96	€406,72	€406,72
4	EPD-ETE-20130224-IAA1-DE	€1.122,67	€1.049,45	€216,72	€216,72
5	EPD-CRE-2012211-D	€2.794,35	€2.611,74	€538,93	€538,93
6	EPD-MET-20140068-IAC1-EN	€156,54	€146,38	€30,41	€30,41
7	EPD-ERL-20140214-IAC1-DE	€2.191,95	€2.048,71	€422,78	€422,78
8	EPD-FCH-2013211-E	€599,91	€560,79	€115,85	€115,85
9	EPD-IFBS-2013111-EN (Eco-00000009)	€2.713,34	€2.536,26	€523,85	€523,85
10	EPD-IFBS-2013111-EN (Eco-00000009)	€3.190,72	€2.982,40	€615,80	€615,80
11	EPD-IFBS-2013111-EN (Eco-00000009)	€3.190,72	€2.982,40	€615,80	€615,80
12	EPD-IFBS-2013111-EN (Eco-00000009)	€2.681,38	€2.506,30	€517,49	€517,49

Table.13 below shows that there is no change in orders even the shadow costs differ from source to source.

As conclusion, it can be stated that to make a comparison in terms of environmental performance of roof covering materials, different data sets of shadow costs are applicable even the cost results are different.

Unfortunately, due to the limitations of the study mention above in the scope and limitation chapter, shadow cost data set should be used for other construction materials also to prove the results.

Table 13 : Total Cost and Order of Impact Categories (€)

No		EcoCOST	EcoCOST Order	IBU	IBU Order	NIBE	NIBE Order	SBRCURnet	SBRCURnet Order
1	EPD-MAR-20140216-CCD1-EN	1.424,11	**8**	367,03	**8**	365,20	**8**	30,32	**8**
2	EPD-OND-2013111-E	853,86	**9**	218,84	**9**	218,70	**9**	17,59	**9**
3	EPD-CRE-2012221-D	1.587,06	**7**	407,86	**7**	406,72	**7**	33,20	**7**
4	EPD-ETE-20130224-IAA1-DE	845,11	**10**	217,85	**10**	216,72	**10**	18,00	**10**
5	EPD-CRE-2012211-D	2.103,02	**3**	540,44	**3**	538,93	**3**	43,97	**3**
6	EPD-MET-20140068-IAC1-EN	117,99	**12**	30,88	**12**	30,41	**12**	2,81	**12**
7	EPD-ERL-20140214-IAC1-DE	1.649,68	**6**	424,01	**6**	422,78	**6**	34,54	**6**
8	EPD-FCH-2013211-E	451,62	**11**	116,50	**11**	115,85	**11**	9,68	**11**
9	EPD-IFBS-2013111-EN (Eco-00000009)	2.042,57	**4**	526,56	**4**	523,85	**4**	43,61	**4**
10	EPD-IFBS-2013111-EN (Eco-00000009)	2.401,72	**1**	618,48	**1**	615,80	**1**	50,92	**1**
11	EPD-IFBS-2013111-EN (Eco-00000009)	2.401,72	**1**	618,48	**1**	615,80	**1**	50,92	**1**
12	EPD-IFBS-2013111-EN (Eco-00000009)	2.018,32	**5**	519,69	**5**	517,49	**5**	42,76	**5**

5.4. Conclusion

By the help of weighting factor and method, using shadow cost enables to compare the performance of materials in one single parameter.

The study shows that, shadow costs are applicable to unite the impact category results to order the construction materials from the highest negative environmental effect to the lowest.

Also, study shows that, even in countries that do not have shadow cost data, in researches shadow cost data set can be chosen regardless to the source. Any data set results order will be the same, even the total cost amount differ.

On the other hand, considering the study limitations and scope, further studies need to be carried out such as:

* Database / data sets should be used for other construction materials to see whether there is a deviation in results or not.
* Life expectancy of construction materials should be considered and included during the further studies.
* Also in countries where study will be carried out, database should be developed and then results should be compared after local database introduced.

To sum up, with limitations of the study, it can be derived from that until the database is developed in the country, for researches any database could be applicable to conduct similar studies.

Acknowledgement

This study is carried out as one of further studies of master thesis "Life Cycle Cost Analyses of Construction Materials Including Environmental Impact Costs" (Bayazit 2016).

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APPENDIX I

List of Papers according to Titles in Alphabetical Order

APPENDIX II

List of Papers according to First Author Names in Alphabetical Order

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