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Energising Green Building

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EDITORIAL PREFACE

GREEN BUILDING MOVEMENT IN MALAYSIA: PAST, PRESENT AND FUTURE

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The sustainable development movement has been evolving worldwide for almost three decades, causing significant changes in building delivery systems in a relatively short period of time. A subset of sustainable development, sustainable construction, addresses the role of the built environment in contributing to the overarching vision of sustainability (Kibert, 2008). It contributes to the achievement of urban sustainability and as one of the integral processes of sustainable development. Sustainable building, on the other hand, is the subset of sustainable construction, as described by Du Plessis (2001, p.10):

"Urban sustainability is the wider processes of creating human settlements and includes areas such as governance. Sustainable building concerns itself solely with the process of creating buildings, while construction includes infrastructure such as roads and bridges".

Green building has been used as a term interchangeable with sustainable building and high-performance building. Its core message is to improve current design and construction practices and standards so that the buildings we build today will last longer, be more efficient, cost less to operate and contribute to healthier living and working environments for occupants, thereby helping to increase productivity. Green building is also about increasing the efficiency with which buildings and their sites utilise energy, water, and materials; protect natural resources; and improve the built environment so that ecosystems, people, and communities can thrive and prosper. There are numerous definitions for green building, for example, "…healthy facilities designed and built in a resource-efficient manner, using ecologically-based principles" (Kibert, 2008, p.5). Robichaud and Anantatmula (2010) described that there are four pillars of green buildings, i.e. minimising impacts on the environment, enhancing the health conditions of occupants, ensuring the return on investment to developers and the local community, and considering the life cycle during the planning and development process. Common elements of these definitions are life cycle perspective, environmental sustainability, health issues and impacts on the community.

Today's high-performance green buildings in Malaysia are a significant improvement over the conventional buildings of the past. They consume significantly less energy, water, and materials; provide healthy living and working environments; significantly improve the quality of the built environment. The concept of green building materials may have been defined and the methods for their evaluation have been developed. However, addressing the issue of closing materials loops by designing buildings for deconstruction and developing disassemblable building products with recycled materials is still considered rare in the context of today's green buildings in Malaysia. The role of nature in buildings is another one of the critical areas needing development for the future of green buildings in the country. Natural systems can provide cooling, wastewater processing, stormwater uptake, food production, and a range of other services for the built environment. To dramatically lowering energy consumption and increasing the use of renewable energy systems, green buildings need to be integrated with advanced energy strategies, such as radiant cooling and photovoltaic systems. Besides improved efficiency and better conservation of natural resources, adjustments of social expectations (comfort, amount of space, mobility, and access) are an essential factor in the development of a more sustainable built environment. In short, progress has been made, but the problematic problems remain unsolved.

There have of course been plenty written on green, sustainable and resilient buildings in Malaysia, in this journal and many others. The theories and practices have been explored by, for example, Hellwig (2015), Shari and Soebarto (2012), and Salam and Nik Ibrahim (2018). Urban and site planning and management have been addressed by, for example, Ghazali et al. (2009), Abdul Shukor et al. (2012), Arabi et al. (2015), Lim et al. (2016), Mat Raschid et al. (2015), Rakhshandehroo et al. (2017), and Raja Yahya *et al*. (2019). Studies on different aspects of indoor environmental quality have been conducted by various researchers; for instance, thermal comfort by Neama (2013), Mohammad Yusoff et al. (2012), Gital et al. (2015), Ibiyeye et al. (2015), and Maarof and Jones (2019); visual comfort by Mathalamuthu and Nik Ibrahim (2014), and Atan and Nik Ibrahim (2019); and acoustic by Dahlan (2009). The potential system to improve a building's energy efficiency and the potential of integrating renewable energy in tropical architecture have been investigated by, for example, Alavijeh and Zeinali (2015) and Long and Tazilan (2015), respectively. Furthermore, improved wastewater treatment and green material have been proposed by, for example, Mazandarani et al. (2015), and Karsan and Hoseini (2015), respectively. Comparisons of international and local green building rating tools have been well-covered by Shari and Soebarto (2015). More is and will be written about these subjects in the future, and at the end of this Editorial, the trajectory of green building in Malaysia from its more recent origins in the late 2000s to the present and future will be discussed.

Overview of this special issue

This special issue of Alam Cipta contains a collection of nine extended papers from the 2nd Malaysia University-Industry Green Building Collaboration Symposium (MU-IGBC 2018), hosted by the Malaysia Green Building Council (malaysiaGBC), in collaboration with Universiti Putra Malaysia, Universiti Kebangsaan Malaysia, Universiti Teknikal Malaysia Melaka, and University of Reading Malaysia. The MU-IGBC 2018 aimed at high-quality research and offered the platform for advancing and progressing efforts in green building-related topics. The objective is to share and exchange research findings, ideas, experience, and techniques that gave impacts to the green building industry. With the central theme "Energising Green Buildings", the MU-IGBC 2018 is programmed to invigorate the green building design, research and practice among local researchers, academics, professionals, and government officials. The MU-IGBC 2018 was held in Bangi, Selangor, Malaysia, and attracted a total of 77 full paper submissions, spanning over numerous active and emerging topic areas. The conference program committee selected 56 full papers to be presented at the conference.

The nine extended papers for this special issue were selected from among all the accepted papers by the special issue guest editor based on the relevance to the journal and the reviews of the conference version of the papers. The authors were asked to revise the conference paper for journal publication and in accordance with customary practice to add 30% new materials. The revised papers again went through the normal journal-style review process and are finally presented to the readers in the present form.

The papers in this special issue cover a wide range of the scope of green building in the Malaysian context. Two papers in this special issue address the passive design strategies to optimise indoor environmental quality. In 'Assessment of the indoor thermal condition of a low-cost single-storey detached house: a case study in Malaysia', Amir et al. argue that the issue of thermal comfort in the design of low-cost housing in Malaysia has always been neglected, leading to the unliveable indoor thermal environment. They suggest that adding bubble foil roof insulation is one of the solutions to reducing the indoor air temperature of this type of housing.

The second paper addressing the passive design strategies is 'Preliminary evaluation of airflow in the atrium of building in hot and humid climate' by Mohammad Yusoff, Mat Sulaiman and Muhsin. It calls for greater awareness on the importance of providing sufficient airflow paths (i.e. access corridors that connect inside to outside) at appropriate locations to achieve adequate air velocities inside a naturally ventilated atrium.

Another two papers address building energy efficiency issue and recommend measures to reduce energy consumption. The first paper is by Ahmad Ludin et al. titled 'Energy efficiency action plan for a public hospital in Malaysia'. The authors address the electricity consumption issue of a public hospital in Kuala Lumpur. Their preliminary energy audit suggests that the hospital could save up to 3.82% of electricity consumption, equivalent to a cost saving of about RM150,000 per year if the hospital conducts an unplugging campaign; replace all existing desktops to laptops; carries out regular maintenance; replace its old refrigerators with energy-efficient ones.

The second paper related to energy efficiency, 'Air conditioning energy profile and intensity index for retrofitted mosque building: case study in Malaysia' by Hussin et al., argues that most of the existing mosques retrofitted with air-conditioning in the country have much higher energy indices than the recommended value in the Malaysian standard. Based on a field study results of five selected retrofitted mosques, the authors recommend a few energy conservation measures, namely synchronisation of air-conditioning operation according to prayer times; set up of new comfort temperature; implementation of scheduled maintenance of the air-conditioning system; and application of appropriate air-conditioning zoning system.

Khrit et al. 's paper, 'Comparison of measured and modelled mean radiant temperature in the tropical urban environment', argues that the validation studies of RayMan1.2 simulation software in estimating the mean radiant temperature of an urban setting have mostly been conducted in moderate to high latitude locations. The paper fills the research gap by comparing the measured, and simulated mean radiant temperature of a Malaysian urban setting and the results suggest that the software needs to be improved for simple and complex urban settings in the tropical climates.

In 'The impact of air gaps on the performance of reflective insulations', Lim et al. describe that the thermal performance of reflective insulation depends on the thermal resistance (R-value) of its materials and assemblies as building components. Through some experimental tests, the authors rank different types of reflective insulation materials with various enclosed air gaps based on their R-values. The result is that big bubble foil with 50mm top air gap and 75mm bottom air gap has the highest R-value or is the most effective insulation method in a hot and humid climate like Malaysia.

The review paper included for this special issue, 'Review article: skewed wind flows energy exploitation in the built environment', is by Abdullah et al. When it comes to building-integrated renewable energy using wind power, particularly in an urban environment, the paper argues that vertical is more durable and efficient than horizontal axis wind turbine. In supporting this argument, the paper critically reviews previous studies on the skewed wind flow phenomena in an urban setting, the aerodynamics of wind turbines in skewed flow, and wind turbines on building rooftops.

Yusof and Osmadi's paper, 'Assessing green practices and their impact on the environmental and financial performances of construction projects', highlights the current debates on whether green construction practices lead to a better environment and economic profits. This paper provides a better understanding of this issue through results from quantitative research involving a questionnaire survey among different groups of Malaysian construction industry stakeholders. The result is that green project integrated practice and waste management practice are the two areas of green practices that have a significant and positive relationship with the project's environmental and financial performance. The authors then propose different actions to be taken by different groups of stakeholders to ensure the environmental and economic goals of the project are met.

The last paper, 'Building Information Modelling (BIM) for sustainable industry: the Malaysian architect's perspectives' by Ahmad Jamal et al. addresses the issue of slow uptake of Building Information Modelling (BIM) in the Malaysian construction industry, especially among architects. For green buildings, BIM can be used in the design development phase to conduct modelling and simulation to improve the building's environmental performance. Through quantitative research, the authors describe several measures that should be addressed to improve the current situation. Most of these measures are related to "people", such as support from professional bodies, better education, enforcement from authorities, as well as improvement in research and development.

Trajectory of green building in Malaysia

It must be admitted that the green building concept is still relatively new in Malaysia, about a decade in duration. Before 2009, there was no rating system and very few products, tools, or publications supporting the local sustainable construction and green building practices. Now, there are more than five green building rating tools being implemented in the country and an abundance of resources that provide services, information, and execution support for green projects. A decade ago, there was scant knowledge about this new field. Today, general knowledge about it is relatively commonplace, but strategies for resolving the major problems of buildings and their impacts remain difficult.

This special issue does not address a wide range of issues, e.g. water, materials, waste, indoor environmental quality, etc. due to the constraints of time and complexity. However, there is an emerging body of literature on these topics (for example, Lachimpadi et al., 2012; Lim et al., 2017; Mirrahimi et al., 2016; Janet Yip et al., 2018; Marsono and Balasbaneh, 2015). The future of the sustainable built environment is currently being impacted in an unprecedented manner by the issue of climate change (Santamouris, 2019). The central economic, environmental, and social issue of the next several decades will be energy, both its cost and its impacts. Malaysians will likely be forced to consider shifting to a different energy source that is likely to be more diverse and far more costly. For the built environment, the emphasis on energy as an arbiter of directions and value will increase and accelerate in the future. The dominant measuring stick for all aspects of green building will be energy. Green building rating tools developed and implemented in Malaysia, such as Green Building Index (GBI), GreenRE, Ph JKR and MyCREST have started to reflect this shift in priorities by allocating the highest total number of points to energy assessment category. Currently, the most important driver for adopting green building practices in Malaysia is energy conservation (Niroumand et al., 2013). These tools will soon reflect a future of higher cost, more diverse energy systems based mostly on renewable resources. The increased use of renewable energy will further facilitate the growth of green buildings in Malaysia.

Materials and products for construction remain primarily the traditional materials with which we are familiar. The environmental impacts of materials extraction and waste disposal are rising. These impacts include long-term effects on land, air and water quality as well as the biodiversity that lead to erosion and other local and global consequences. Although the Malaysian government has put an effort to prioritise the importance of managing construction and demolition wastes to mitigate environmental impacts, the recycling rate is still as low as 15% (Esa et al., 2017). Local architectural design practices have started to design with Industrialised Building System (IBS) to reduce wastages of building materials, but the move needs to shift from conventional IBS that still needs substantial manpower, to digital IBS. For example, instead of using precast products that only results in dull and standardised high-rise units, architects can design with the Building Information Modelling (BIM)-integrated digital design system to provide clients with customised solutions. Hopefully, BIM will one day be applied to facilitate the green building certification process as well. The advanced information and communication technologies will play a crucial role to assist the future development of green building in the country. Therefore, more studies are required to explore the best practice of integrating BIM into the various life cycle stages of the green building delivery that is suitable to the local context. In parallel, themes such as deconstruction, durability, adaptability, design for deconstruction, closed materials loops, Factors 4 and 10, and dematerialization, which are almost non-existent in the local green building sector, will slowly be practised. Certainly, these green strategies are imperative for the sector to achieve true sustainability in the future.

One of the outcomes of green building has been better communication and collaboration among stakeholders to enhance the quality of their decision-making in the building and construction processes to incorporate the principles of sustainable development. Theoretically, the knowledge of sustainable development is multidisciplinary in its nature and is covered by various bodies of sciences. That is why the key success factor of a green building design is the application of an integrated design process where multiple stakeholders (planners, architects, engineers, landscape architects, facility managers, and etc.) collaborate early in the design stage. This approach emphasises the development of a holistic design where all design requirements are considered simultaneously rather than sequentially. The tendency for these professionals to function in 'silos', each optimising the outcome for their own benefit, is in turn reflected in the curricula of the educational institutions. Malaysia needs to implement significant changes in how building industry professionals are educated and trained. Universities can take a leadership role by revamping curricula to support sustainable construction, including substantially more cross-disciplinary instruction and collaboration. Developers and building owners can help motivate this change by insisting on the implementation of a system of performance-based fees that incentivizes collaboration and performance.

Although the pace of high-performance green building has been increasing, the rate of change has been far too slow to offset the depletion of resources, local, and global environmental degradation, and other negative consequences of transforming land and materials into infrastructure and buildings. Although GBI has resulted in noticeable change after its introduction, it is time for a significant shift in government policy, from voluntary to mandatory measures, coupled with incentives, that will dramatically accelerate the transformation of the Malaysian construction industry and its products. It is now time for the environmental measures advocated by rating tools to be made as standard practices. This, in turn, would then permit the development of next-generation tools that are more ambitious and innovative and move well beyond current green building practices to notions of restoration and regeneration, as advocated by Attia (2018).

The cost factor remains the most significant barrier that leads to a low level of green home development in Malaysia (Samari et al., 2013; Mohd Nordin et al., 2017). Green housing development increases the housing costs as they involve higher capital upfront. Additionally, it is difficult to obtain green materials in the country, and most of these products are priced higher. Extra expenses are also incurred for appointing environmental consultants, green rating assessment fees, and procurement of new technology. Most speculative developers aim to maximise their profits rather than investing money in the sustainable development concept. Therefore, more robust studies are required in Malaysia to enable evidence-based decision by the client and project team. Some local green building advocates claim that green building does not necessarily cost more if done right. Without any detailed studies on local case studies to validate such claim, the perception of "building green costs too much and is economically non-viable" would persist.

Lack of awareness and understanding of sustainable development is also a crucial barrier to the implementation of green building in Malaysia (Shari and Soebarto, 2012). Many industry stakeholders are not aware of the model of sustainable development. Many building professionals are not informed about the associated benefits of green buildings. Due to limited understanding and budget constraint, many developers are unwilling to incorporate sustainable development principles in their projects. Besides, low awareness of societies in sustainable development and green building has led to low demand for green homes. Hence, more robust studies are required to validate real performance of green building through Post-occupancy Evaluation (POE). Similarly, vast majority of these studies focus on commercial building stock, the residential buildings and industrial buildings deserve further studies in terms of their real performance. Green building movement in Malaysia is still new, and the changes may be challenging to detect. Hopefully, a future special issue on this subject will be able to point to remarkable changes supporting the shift toward sustainability in this sector.

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ASSESSING GREEN PRACTICES AND THEIR IMPACT ON THE ENVIRONMENTAL AND FINANCIAL PERFORMANCES OF CONSTRUCTION PROJECTS

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ABSTRACT

Industry players are urged to adopt green practices in their projects to address the environmental problems caused by construction activities. Despite an increasing adoption of green practices by construction players, it is still unclear whether such practices have improved projects' environmental and financial performances. The aim of this study was to investigate the relationship between green practices implemented in construction projects and their impact on the projects' environmental and financial performances. A structured questionnaire survey was distributed to members of a project team to gather information on the impact of green practices on construction projects' performances. The results revealed two areas of green practices: green project integrated practice and waste management practice, which had a significant and positive relationship with the project's environmental and financial performances. The results rebut the previous findings regarding the negative impact of green practices on a project's performances. The results imply that different types of green practices will have a varying degree of effect on the project's environmental and financial performances. It is important for project managers to focus on green project integrated practices and waste management to boost the project's environmental and financial performances.

Keywords: : Construction project; environmental performance; financial performance; green practice

1. INTRODUCTION

Construction activities have been blamed as one of the environmental polluters. Industry players are urged to adopt green practices in their projects to address this problem. Construction projects in Greece and China have begun to employ measures to minimise carbon emissions (Lai et al., 2017; Yu et al., 2018), and there is a rising awareness of ISO 140001 amongst the construction firms (Manoliadis et al., 2006). In 2016, MyCREST (Malaysian Carbon Reduction and Environmental Sustainability Tool) was adopted in all federal government projects and 20 private projects in Malaysia (Ministry of Work, 2015). Also in that year, the Low Carbon Cities Framework and Assessment System (LCCF) was adopted to evaluate carbon emissions from the cities and towns of Malaysia (Chin, 2016). Despite an increasing adoption of green practices by construction players, it is still unclear whether such practices have improved the projects' environmental and financial performances.

The green practice in construction refers to environmentally friendly or environmental practice that aims to reduce the negative impact of construction activities on the environment (Liu and Lin, 2016; Yusof et al., 2017). The green practice is reflected in the form of the 3Rs (reduce, reuse and recycle), the efficient use of resources or resource minimisation, and the reduction of waste (Zhang et al., 2015; Chang, 2016). Previous studies are not unified on whether green practices will yield a cleaner environment and better financial outcome. In the case of the link between green practice and environmental performance, the adoption of ISO14001 in a country where environmental regulations are indirect but costly will lead to a higher environmental performance (Arimura et al., 2016). Effective green practice in construction projects will result in less pollution and lower carbon emissions (Shen et al., 2011). In contrast, it was argued that green practices will not necessarily result in better environmental performance; thus, a cleaner environment (Ferrón-Vílchez, 2016). Similarly, it was found that ISO14001 adoption did not necessarily result in improved environmental performance (Yin and Schmeidler, 2009). In the case of the link between green practice and financial performance, green practices were revealed to be implemented in supply chain management in manufacturing, utilities, and transportation industries, which led to a firm's higher financial performance (Miroshnychenko et al., 2017). Higher financial performance is evident if there is an increase in profits through better prices of green products or services, the reduction in operational costs through measures of optimising the use of resources such as reduce, reuse and recycle practices, and cost savings being achieved from complying with environmental regulation (Olubunmi et al., 2016). However, the firm's profit was reduced by the adoption of ISO 14001 (Miroshnychenko et al., 2017). Studies in the construction sector have shown an insignificant relationship between green practices and financial performance (Kusuma and Koesrindartoto, 2014; Renard et al., 2013).

The need for another study to shed light on the relationships between green practices implemented in construction projects and their impact on the projects' environmental and financial performances was established from the above disagreement among scholars. Although the main intention of adopting green practices is to reduce the negative impact of construction activities on the environment or improve environmental performance (Shen et al., 2011; Lai et al., 2017), it was argued by scholars that most firms are profit-oriented and they will only be motivated to adopt green practices if such effort can increase their financial performance (Zhang et al., 2015; Olubunmi et al., 2016). To provide a better understanding on this issue, the aim of this paper is to investigate the impact of green practices on the environmental and financial performance of construction projects. Theoretically, the results will identify whether the green practice leads to a cleaner environment and a better profit; providing a better understanding to the on-going debate on the relationship between green practices and environmental and financial performances. Practically, the results will help project managers and clients to be selective and invest more in green practices that yield better environmental performance and higher profits.

2. MATERIALS AND METHODS

Two aspects of project performance; environmental and financial performances, were investigated as dependent variables in the present study. Generally, environmental performance can be defined as the consequence of doing construction in a responsible manner, such as with less pollution or with a cleaner environment (Bhattacharyya and Cummings, 2015). The improvement in compliance with environmental standards, minimising waste, and reduction of pollution are conceptualised as a project's environmental performance (Li et al., 2017; Shen et al., 2011). In the wake of the increasing stakeholder demand for a cleaner environment, construction organisations with higher environmental performance will be ahead of their competitors, able to gain public trust, and secure goodwill (Yadav et al., 2017). On the other hand, the reduction in project costs, high profits, and improved investment yield are indicators of the project's financial performance (Olubunmi et al., 2016; Rao and Holt, 2005). An argument arose on a seminal work that leaders of green practices enjoyed better prices for green products and services, which could lead towards higher profits (Porter and Van der Linde, 1995). It was found in a global study that pollution prevention practices, such as waste management and the use of non-toxic materials through internal organisational efforts or engaging environmental-friendly suppliers or contractors, could lead to better financial performance (Miroshnychenko et al., 2017). Although the financial performance of green practices takes a longer time before it can be observed (Li et al., 2017); at the very least, projects that adopt green practices can avoid fines due to non-compliance (Tan et al., 2011). Acknowledging the importance of economic measures, it was argued that the financial benefits of green practices could help to motivate environmental polluters to adopt green practices (Zhang et al., 2015). Supporting this point of view, emphasis was laid on the need to overcome cost barriers of green practices to motivate construction firms to adopt green practices (Chan et al., 2018).

Regarding the independent variables, three dimensions were used to conceptualise green practices in construction projects: green project integrated practice (Lam et al., 2011; Silvius et al., 2017), resource minimization (Oyedele et al., 2014; Pero et al., 2017), and waste management (Silvius et al., 2017). In the first dimension, the green project integrated practice can be defined as a desegregation of the disjointed phases of the project cycle, from the beginning to its completion, in line with the environmental mission (Lam et al., 2011; Yusof et al., 2017). In project integrated practices, the participation of the project key members is at the beginning of the project (Yusof et al., 2016). In such an arrangement, the green practice agenda is conveyed by the client and the project manager prior to project implementation (Banihashemi et al., 2017; Silvius et al., 2017). A major role will be played by client in providing the necessary support to ensure that the environmental needs of all stakeholders are identified and considered at the earliest stage, and that green practices are implemented throughout the project cycle (Banihashemi et al., 2017). Clients insisting on green design features such as balconies, sky gardens, solar chimneys and wind catchers reduce the need for artificial ventilation and reduce carbon emissions (Zhang et al., 2015). The effective green practice adoption is shown when such practices result in low carbon emissions, as well as less air, water, and soil pollution; or in other words, a better environmental performance (Shen et al., 2011). Therefore, the study's first hypothesis is:

H1: Green practices in project integrated practices significantly influence the project's environmental performance.

Likewise, the effective adoption of green practices in each project phase will also mean less wastage, avoidance of charges due to non-compliance, and result in higher profits (Rao and Holt, 2005). In Hong Kong, buildings with green design features, such as balconies and funnels, which are less than 8% of the gross floor area, enjoyed a tax reduction, attracted more users due to the building's pleasant indoor environment, thereby increasing the marketability of the building (Zhang et al., 2015). In addition, there have been improvements in government regulations and policies (Zhong and Wu, 2015), which include assessment methods (Ding, 2008; Kneifel, 2010) to promote and support green practice. In project integrated practice, the participation of all project team members at the earliest project phase can ensure that changes or amendments to environmental regulations are considered throughout the project cycle, resulting in cost saving due to compliance and better revenue (Tan et al., 2011). Therefore, the study's second hypothesis is:

H2: Green practices in project integrated practices significantly influence the project's financial performance.

The second dimension is resource minimisation, which refers to the optimisation of the use of resources that also covers the 3Rs – reduce, reuse, and recycle activities throughout the project cycle (Oyedele et al., 2014; Yusof et al., 2016). A vital challenge in resource minimisation during project implementation is to minimise the use of water and energy (Martens and Carvalho, 2017). In terms of purchases, there have been green criteria in the selection of suppliers, where suppliers are selected based on environmental and social criteria (Pero et al., 2017). The purchase of recycled materials has been promoted by several companies as green materials, which is aimed at optimizing the use of resources (Ofori, 2000). Furthermore, the adoption of sensor technology to monitor energy and water consumptions are said to be able to improve environmental performance (Abuzeinab et al., 2016). Technical support and training to green suppliers are also provided by companies to increase their capabilities, as well as awareness towards sustainability (Ofori, 2000). The awareness and practices of resource minimisation can lead towards a cleaner environment (Pero et al., 2017). Thus, the third hypothesis is:

H3: Resource minimisation significantly influences the project's environmental performance.

In relation to resource minimization, the fact that some firms are reluctant to avoid overuse and wasting of resources was highlighted due to lack of evidence about its financial advantage (Li et al., 2017). On the contrary, the adoption of LEED or Leadership in Energy and Environmental Design rating system in the project management practice is suggested to ensure efficient use of resources and reduce wastage (Tabassi et al., 2016). As an example, investment in energy-efficient technology during housing development has resulted in better sale prices for low energy houses (Chegut et al., 2016). The use of local suppliers for building materials can avoid costly imported resources and reduce logistics cost (Pero et al., 2017). Aside from that, it was emphasized by Cheng et al. (2013) that effective resource management will optimise the use of resources, subsequently reducing project costs and thereby increasing profits. Therefore, the fourth hypothesis is:

H4: Resource minimisation significantly influences the project's financial performance.

The third and final dimension is waste management, which includes the monitoring of waste production during project implementation and ensuring that construction waste from landfills is minimised and properly destroyed (Silvius et al., 2017; Freitas and Magrini, 2017). Waste minimisation through effective waste management has become an important issue, as evidenced by many governments setting goals to reduce construction waste (Kern et al., 2015). In Malaysia, it was reported that 30% of the total waste came from construction and only 15% of this waste was collected by the waste management contractor (Chen, 2015). The industry players were urged to reduce this percentage through proper waste management, such as waste categorisation, reuse, and recycling to achieve zero waste at the construction site by 2030 (Ministry of Work, 2015). According to Ng et al. (2017), a framework that includes important elements, such as laws and regulations, scheme and incentives, consciousness and information on 3R, participation of contractors, and obtainable technology with a top-down approach and code of good governance, is required to be established in order to have an effective construction waste reduction through 3R among contractors. It was simulated by Wang et al. (2015) that, although offsite construction technology produces the better result in reducing construction waste, the synergy of multi-design strategies provides the highest waste reduction; thus, a better environmental performance. The practice of industrial symbiosis in the waste management system can help increase environmental performance by extending the construction waste destination to be used by another sector, such as manufacturing, and prevent it from ending up in the landfill (Freitas and Magrini, 2017). It is argued that waste management in a construction project can help reduce or eliminate waste; thus, resulting in a cleaner environment. Therefore, the fifth hypothesis of the study is:

H5: Waste management significantly influences the project's environmental performance.

Similarly, it was argued by Begum et al. (2006) that waste management could result in a 2.5% cost savings of the overall project costs if implemented properly. To promote the reuse and recycling of resources during project execution, a total index score was proposed by Cha et al. (2009) to manage and monitor construction waste. The proper on-site waste management by construction workers can ease up the need for waste disposal and transportation to landfills, leading to greater cost savings for contractors (Li et al., 2018). Since waste signifies cost, it is argued that stricter implementation of waste management during construction operations, such as waste prevention and avoiding the use of expired materials, entails cost savings and a better project's financial performance (Silvius and Schipper, 2016). In addition, it is argued that zero waste and circular economy practices in demolition projects provide financial benefits (Abuzeinab et al., 2016). Therefore, the sixth hypothesis of the study is:

H6: Waste management significantly influences the project's financial performance.

3. RESULTS

A structured questionnaire survey was used to gather information on the impact of green practices on construction projects' performances. All the items were measured using a five-point Likert scale, ranging from "strongly disagree: 1" to "strongly agree: 5". The unit of analysis is the construction firms; consisting of contractors, property developers and consulting firms (architecture and engineering) that are involved in construction projects in Peninsular Malaysia. The targeted respondents are architects, engineers, and project managers working in these construction firms and participating in the decision-making of the projects, whether in the planning, design or construction phase, and have knowledge about the project's performance. A total of 210 usable responses were received, exceeding the minimum required sample size of 146, which was calculated using the gamma-exponential method. Majority of the firms were contractors, followed by property developers and consulting firms. Most firms were established between 11 and 20 years old, small in size and operating at the state level. Since the respondents were of different background and types of construction firms, the ANOVA (one-way analysis of variance) test was performed to check if these differences influenced their responses. The test indicates that p value = 0.458 (no significant difference), signifying that the respondents have similar knowledge about the project activities and performances. Table 1 presents the profile of the respondents.

Table 1: Profile of respondents

Respondents	Number	Percentage (%)
Type of firm		
Property developer	62	30
Contractor	93	44
Consulting firm	55	26
Establishment		
< 6 years	22	10
6 -10 years	64	30
11 - 20 years	86	41
> 20 years	38	18
Size of firm		
Small	92	44
Medium	59	28
Large	59	28
Geographical location		
State	103	49
Regional	61	29
National	38	18
International	8	4

Two stages of analysis were performed to analyse the data using the Warp partial least squares technique (WarpPLS) Version 6.0. In stage 1, where the measurement model was evaluated, indicator reliability was performed, alongside with convergent validity, internal consistency, and discriminate validity tests for the reflective latent variables, as well as the variance inflated factor (VIF), significant outer weights, and full collinearity VIF tests for the formative latent variables.

The loadings for all items were higher than 0.5 with the P values significant at <0.001, fulfilling Kock's (2014) rules for indicator reliability. The convergent validity of the latent variable was evaluated using the average variance extracted (AVE), and the AVE of all of the latent variables exceeded 0.5, in accordance with Fornell and Larcker's (1981) criteria; suggesting the measurement model's convergent validity. Composite reliability (CR) was used to evaluate the internal reliability of the reflective latent variables. All latent variables showed a CR of above 0.8 fulfilling the minimum criteria of Kock (2011) and Hair et al. (2011). Table 2 presents the results of the indicator reliability, convergent validity, and internal consistency tests for the reflective latent variables.

Table 2: Reliability and validity of the reflective latent variables

Latent variable/item	Loading	P values	AVE	CR
Project integrated practice			0.705	0.877
P1	0.878	<0.001		
P2	0.874	<0.001		
P3	0.761	<0.001		
Resource minimisation			0.673	0.911
R1	0.786	<0.001		
R2	0.854	<0.001		
R3	0.852	<0.001		
R4	0.820	<0.001		
R5	0.788	<0.001		
Waste management			0.649	0.881
W1	0.758	<0.001		
W2	0.829	<0.001		
W3	0.818	<0.001		
W4	0.816	<0.001		

Next, the discriminant validity of the reflective latent variables was evaluated using the cross-loadings and inter-correlation indicators. The measurement model revealed that the indicator loads were greater than each opposing latent variable, in accordance with the rules of Hair et al. (2012). Also, the square root of the AVE of a single latent variable was less than the value of the inter-correlations between the latent variable and other latent variables of the model (Table 3). These tests confirmed the discriminant validity of the reflective latent variables.

Table 3: Discriminant validity

Latent variables	PIP	RS	WM	EnvP	FP
Project integrated practice	0.839*				
Resource minimisation	0.570	0.820*			
Waste management	0.474	0.448	0.806*		
Environmental performance	0.499	0.345	0.521	0.832*	
Financial performance	0.580	0.392	0.420	0.487	0.861*

*Square root of the AVE values is on the diagonal

The present study has two formative latent variables: environmental performance and financial performance variables. The variance inflated factor (VIF) or collinearity between the indicators, significant outer weights, and full collinearity VIFs were used to evaluate these formative latent variables. Both formative latent variables showed VIFs of less than 5 and all items had significant outer weights, fulfilling Chin (2010) and Hair et al. (2011) rules. The full collinearity VIFs of the environmental performance and the financial performance variables were much lower than 3.3, which fulfilled the threshold of Kock and Lynn (2012). Thus, the formative latent variables presented a satisfactory level of the measurement model. Table 4 depicts the measurement model evaluation for the formative latent variables.

Table 4: Measurement model evaluation for formative latent variables

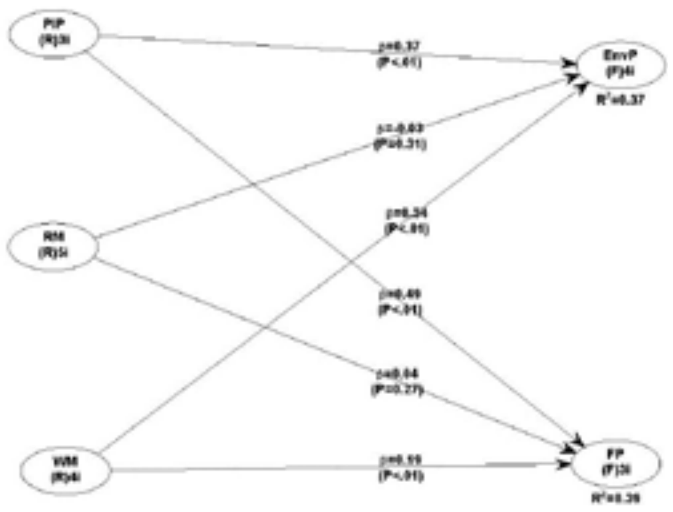
Formative latent variables	Weights	P-Value	VIF	Full collinearity VIFs
Environmental performance				1.630
Env1	0.249	<0.001	1.970	
Env2	0.265	<0.001	2.170	
Env3	0.248	<0.001	1.908	
Env4	0.237	<0.001	1.799	
Financial Performance				1.657
FP1	0.352	<0.001	2.403	
FP2	0.373	<0.001	2.658	
FP3	0.275	<0.001	1.496	

In stage 2, the structural model and the hypotheses were evaluated using the R2 measurements for the endogenous constructs and the path coefficients. The model of the study showed 37% and 39% of the variances in the project's environmental and financial performances, respectively, suggesting a moderate relationship between green practices and the project's environmental and financial performances. Also, the Stone–Geisser's Q2 (cross-validated redundancy) for the project's environmental (Q2=0.406) and financial performances (Q2=0.389) was greater than zero, displaying the model's satisfactory predictive relevance and its explanatory power; thus, complying with Hair et al. (2011). Table 5 presents the result of the test hypotheses.

Table 5: Results of hypothesis testing

Hypothesis		Path coefficient	p-value	Effect size (f^2)	Supported
H1	PIP → EnvP	0.371	<0.001	0.201	Yes
H2	PIP → FP	0.488	<0.001	0.290	Yes
H3	RM → EnvP	-0.034	0.312	0.013	No
H4	RM → FP	0.041	0.275	0.017	No
H5	WM → EnvP	0.341	<0.001	0.178	Yes
H6	WM → FP	0.186	0.003	0.079	Yes

The results reveal that the two areas of green practices: green project integrated practice and waste management practice, have a significant and positive relationship with the project's environmental and financial performances; this supports the **H1, H2, H5,** and **H6** hypotheses. Compared with the other green practices, the present study reveals that the green project integrated practice has the greatest effect on the project's financial performance (f2 = 0.290) and environmental performance (f2 = 0.201). However, the study showed insufficient evidence on the relationship between resource minimisation and the project's environmental and financial performances. One possible reason is that resource minimisation measures such as the 3Rs – reduce, reuse, and recycle activities or resource management are not widespread in Malaysian construction projects. Figure 1 shows the results of the structural model assessment.



4. DISCUSSION

The present study revealed the positive and significant effect of green project integrated practice and waste management practice on project's environmental and financial performances. The results have provided empirical evidence on the benefit of green practices in a project's environmental and financial performances. The construction projects that integrate their planning-design-construction phases with green practices and the local ecosystem, and implement waste management practices such as waste monitoring, sorting, reuse, and recycling, will benefit in terms of a better environmental outcome, such as low carbon emission; less air, water, and soil pollution; and enhanced financial performance, such as reduction in project costs, greater profits, and improved investment yield. The results support the work of Banihashemi et al. (2017) and Zhang et al. (2015) on the positive impact of green project integrated practice on project's environmental performance. The results also support the work of Tan et al. (2011) on the positive influence of green project integrated practice on project's financial performance. Furthermore, the results support the work of Freitas and Magrini (2017) on the positive effect of waste management on project's environmental performance and finally it support the work of Begum et al. (2006) on the positive effect of waste management on a project's financial performance. At the same time, the results rebut the previous findings on the negative impact of the general green practices on performances advocated by Ferrón-Vílchez (2017), Kusuma and Koesrindartoto (2014), and Renard et al. (2013).

However, the present study provides insufficient evidence on the relationship between resource minimisation and project's environmental and financial performances, indicating that the link between the two remains vague and warrants further investigation. Optimising the use of water, materials and energy is a great challenge for construction managers. The unskilled labour and the traditional construction management that are widely used in the construction projects of developing countries may be the reasons for the insubstantial link between resource minimisation and project's environmental and financial performances.

The aforementioned results imply that not all types of green practices will have a similar impact on project's environmental and financial performances. In other words, the different types of green practices will have a varying degree of effect on the project's environmental and financial performances. Construction projects should be organized to allow key players in the project; architects, engineers, contractors and suppliers, along with the client, to be involved at the earliest stage to ensure that environmental goals are understood and considered throughout the project. The implementation of integrated project management rather than the traditional project organization mode or as suggested by Zhang et al. (2015); an appointment of the environmental specialist in a project team, together with a clear understanding of project's environmental values and measures (Tan et al., 2011) and supported by the necessary environmental regulations for construction projects (Banihashemi et al., 2017) are examples of green project integrated practices that can improve project's environmental and financial performances. In addition, waste management practices such as waste sorting, reuse and recycling, the use of offsite construction technology or prefabrication, and innovative waste recovering through industrial symbiosis, are suggested to increase project's environmental and financial performance. Clients and project managers should focus on these two aspects of green practices: green project integrated practices and waste management to boost the project's environmental and financial performances.

5. CONCLUSION

As a measure to address the negative impact of construction activities on the environment, construction firms are required to adopt green practices. The relationship between green practices implemented in construction projects and project's environmental and financial performances were investigated in this study. The results revealed two areas of green practices: green project integrated practice and waste management practice, which had a significant and positive relationship with the project's environmental and financial performances. Theoretically, the results provide support to Shen et al. (2011) and Miroshnychenko et al. (2017) earlier postulation on the impact of green practices on environmental and financial performances. Practically, the results are useful to clients, project managers and policy makers. To achieve better environmental performance and higher profit, they must ensure that environmental values and measures are considered in the planning, design and construction phases, and focus on waste management practices. The professional bodies of architecture, engineering and project management practice, together with the CIDB, can provide training to its members and construction players on the best practices for project integration and waste management. The results also guide policy makers to focus on green project integrated practice and waste management to boost the project's environmental and financial performances. Proper guidance and monitoring should be in place on how green project integrated practice and waste management can be implemented. Local authorities should provide the necessary facilities for waste sorting, reduce, reuse and recycling. An example of monetary incentives is tax reduction, while that of non-monetary incentives is faster approval.

A few constraints can be found in the study. First, insufficient evidence on the relationship between resource minimisation and the project's environmental and financial performances was shown in the study. How resource minimisation was implemented should be investigated in future studies and ways to encourage such practice in Malaysian construction projects should be found. Secondly, the study's model explains 37% and 39% of the variances in environmental and financial performances, respectively. Although such predictive levels are adequate, future studies should embark into other research methods, such as the mixed method or semi-structured interviews in qualitative research to identify other green practices that may affect project's environmental and financial performance. Thirdly, the effect of project size that may influence the relationship between green practices and project's environmental and financial performance is not considered in the present study.

Project size is usually measured based on the economic value of a project, the duration or the number of people involved (Kärnä and Junnonen, 2017; Vachon and Klassen, 2006). In Malaysia, G8 contractor firms are expected to have ISO EMS 14001 certification and lead low-carbon projects for residential and commercial buildings and large infrastructure projects (CIDB, 2015). Future studies should investigate whether the project size can strengthen or weaken the relationship between green practices and the project's environmental and financial performance. Last but not least, although the results can be generalised to other developing countries similar in context to Malaysia, comparative studies between developing and developed countries will enrich the current understanding of the relationship between green practice and project performance.

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AIR CONDITIONING ENERGY PROFILE AND INTENSITY INDEX FOR RETROFITTED MOSQUE BUILDING: A CASE STUDY IN MALAYSIA

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ABSTRACT

Mosques generally consume far lesser energy than other types of buildings owing to their functional and operational characteristics. Since an effective energy management with a proper handling of the air-conditioning system can offer benefits such as the reduction of energy consumption as well as contributing to a sustainable development of the mosque, this paper has therefore presented a field case study on the energy usage and optimization strategies from a few selected retrofitted air-conditioned mosques in Penang, Malaysia. The results derived from the mosque samples (n=5) had not only shown a high energy consumption of the current air-conditioning system, the field evaluation at the Penang State Mosque (G5) was also revealed to have demonstrated a very high Energy Intensity Index (323 kWh/m2/yr.) and non-compliance to the MS Standards. As such, this study had proposed a few short and long term energy savings strategies, which can be implemented by the management committee of the mosque in not only in providing optimum thermal comfort for the worshippers but also without incurring the high energy costs.

Keywords: : Mosque, air conditioning, comfort, energy and cost.

1. INTRODUCTION

The mounting energy use in developing countries that seek to meet the world's growing energy needs has now become a social and economic concern. As a result of economic development and a higher standard of living, Saudi Arabia had shown an annual average increase of 13% in the energy consumption of the building sectors (Fasiudin and Budaiwi, 2011), while in Malaysia, the surging economic growth has led to a dramatic increase of energy consumption in the recent years. Generally, commercial buildings consume almost 32% of total generated energy with the office buildings making up the other 18.5% of total energy consumption (Saidur, 2009). The percentage is almost similar to the office buildings in Thailand, where energy consumption had been about 21% of the total energy usage (Chirarattananon and Taweekun, 2003).

According to Pérez-Lombard et al., (2008), Heating, Ventilating and Air-Conditioning (HVAC) systems make up the largest building energy demands in the non-domestic sector, which can be influenced by the adjacent buildings and its surrounding environment (Ascione, 2017). For that reason, a few strategies and measures had been proposed in the reduction of energy consumption such as by improving the energy efficiency and conversion process through passive cooling techniques as well as the application of renewable energy resources. In one of their studies, Lin and Hong (2013) had included the indoor temperature (thermostat set-point), window type, air infiltration and internal loads in a detailed description of the HVAC's energy consumption. Although numerous studies had provided different strategies in the optimization of the HVAC, the focus of the research had always been the same, where the energy efficiency of the HVAC system could be further enhanced in providing a better level of thermal comfort. In one of their studies, Teke and Timur (2014) had evaluated the energy efficiency, energy savings and energy management of the HVAC system in the hospitals, while Afram and Janabi-Sharifi (2014) had studied the potential control methods with an emphasis on the theoretical and practical of model predictive control (MPC) for HVAC systems. Apart from Shaikh et al. (2014) who had reviewed the combination analysis of control systems, optimization methods and the simulation tools used in the building of energy and comfort management, Alfroz et al., (2018) had also conducted research on the strengths and weaknesses of the current modelling techniques used in the HVAC systems in terms of their applicability and ease of practice acceptance. With that in mind, this study had aimed to evaluate the air-conditioning usage from the mosque's energy systems. Essentially, mosque not only represents the central location in which people gather for their daily and weekly prayers, but is also regarded as a social centre for Muslims to congregate during the annual Eidul Fitri (fasting month) and Eidul Adha (Haj season) celebrations as well as for other religious matters. For this reason, the thermal design and operation of a mosque are seen as crucial in providing visiting Muslims with a comfortable ambience for performing their prayers and religious rituals. Terrill & Rasmussen, (2016) had studied the energy efficient practices on the heating, ventilation, and air conditioning (HVAC) usage and comfort of two religious facilities. The study found that common, low-cost energy efficiency measures (EEMs) in commercial buildings had equivalent or increased applicability to the studied church buildings. The finding had created a possibility in development of an efficient energy model for mosque that are located in a hot and humid climate such as those in Malaysia.

In Malaysia, most of the old and traditional mosques with excellent air ventilation (Ibrahim et al., 2014) rarely receive energy assessments because of its low average operational energy intensity as most of the load had only consisted of lightings and small fans. On the contrary, the newer mosques that were retrofitted with mechanical ventilated devices such as the air-conditioning systems (Hussin et al., 2015), are required to undergo energy audits because of its high energy intensity. With commercial buildings showing a tendency of consuming up to 57% of energy usage from an air-conditioning system (Saidur, 2009), the mosque's unique operation schedule can thus be regarded as a means for potentially reducing its energy consumption.

Most of the recent studies had focused on permanently occupied buildings such as schools and offices with very few energy monitoring studies documented for intermittent operations like those of the mosques. From a field measurement conducted on the energy used and indoor environment conditions of three mosques with different sizes and shapes during its occupancy periods with intermittent operation in Dammam and Al-Khobar, Saudi Arabia, Al-homoud et al., (2009) had concluded the energy consumption from the air-conditioning system of these mosques forming the bulk of the annual energy usage. In their study, the researchers had suggested that the air-conditioning with intermittent operation can somewhat reduce energy usage while maintaining an acceptable level of thermal comfort. In addition to energy savings strategy, they had also indicated the strong dependency of the mosque's energy use on the weather conditions and the importance of building envelope designs as a way of reducing electricity consumption. In 2010, Al-ajmi had conducted a field study on six air-conditioned town mosques in Kuwait provinces. The study had recommended increasing the indoor temperature setting to a neutral temperature, which shown to have saved up to 20% of energy consumption. As for Budaiwi and Abdou (2013), they had revealed the potential of HVAC system operational strategies in reducing the energy consumption of the mosque in the Eastern Province of Saudi Arabia by up to 23% reduction in its annual cooling energy. Apart from the recommended use of an appropriate operational zoning system in a large scale mosque, where it was shown to have contributed to about 30% reduction in its energy utilization, another study conducted by Hussin et al., (2014) had also discovered the synchronization of the operation time of an air-conditioned mosque with the daily activities and prayer times having an influence on the costs and energy usage reduction of the cooling system. The above studies had thus prompted the importance of investigating the energy performance, problems and the operational practices of the air-conditioning system in a Malaysian mosque. Since gaps had been revealed in the literature review on the monitoring of energy profile and the intensity index for retrofitted air-conditioned mosques, this study had therefore attempted to evaluate the air-conditioning energy use and intensity index through a field measurement study of a few selected mosques located in the Penang State of Malaysia. The findings together with the optimization strategies proposed in the enhancement of air-conditioning systems usage at the retrofitted mosques are summarized in the following subsections of the paper.

2. METHODS

2.1 Mosque characteristics

Generally, the design geometry of a mosque is based on a simple rectangular shape that is made up of various sizes (Budaiwi and Abdou, 2013). The design geometry usually consists of wall enclosures that are complemented with a

roofed prayer hall, where one of the walls (usually described as a qibla wall) is oriented towards the direction of the holy mosque in the Makkah city, Saudi Arabia, and a niche wall or the mihrab that is located in the inner qibla wall. The mihrab also contains pulpits known as a mimbar, which is usually located on the right side of the mihrab but on an elevated floor and serves as a place for the Imam of the mosque to deliver his Friday sermons (or qutba). The floor of the main prayer hall is usually well-furnished with saf carpets that are placed in parallel and 1.2 m distance away from each other. Over the years, the characteristics of the mosque architecture, shape, space of the prayer hall, construction materials as well as its size had been subjected to modifications as a result of geographical and architectural design factors.

2.2 Energy profile and intensity case study

Based on the previous research study that was carried out from January until March 2017, an energy profile was created based on 15% of the 273 registered mosques located in the entire state of Penang (Hussin et al., 2018). The work flow of this study is shown in Figure 1. During the first stage, a total of 44 mosques had been evaluated by using standard questionnaires that were collected based on its current information and operational processes. Figure 2 shows the geometrical mosques configuration that is commonly built in the Penang State. As shown in Figure 3, these mosques were subsequently divided according to its cooling area namely G1, G2, G3, G4 to G5.

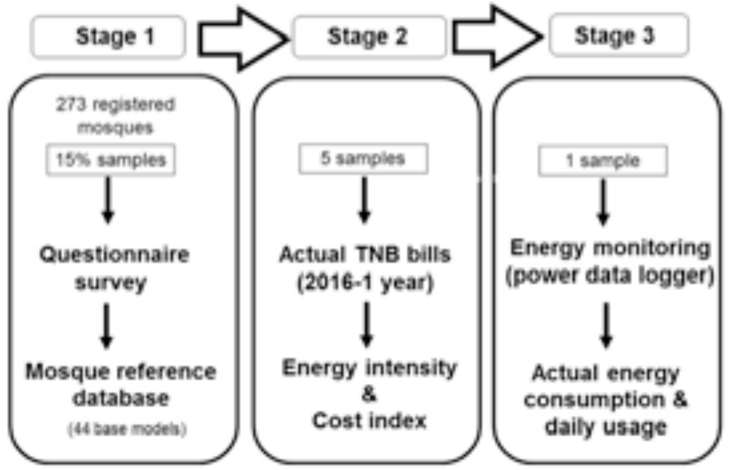
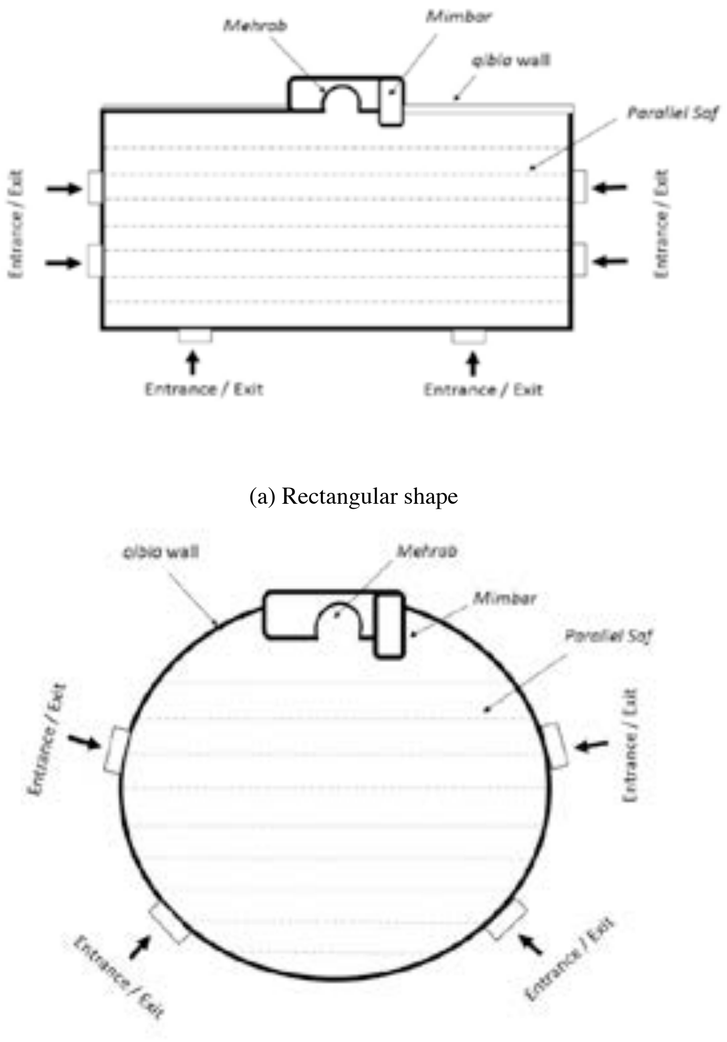


Figure 1: Workflow



(a) Rectangular shape

(b) Circular shape

Figure 2: Geometrical configuration of a commonly built Penang State mosque

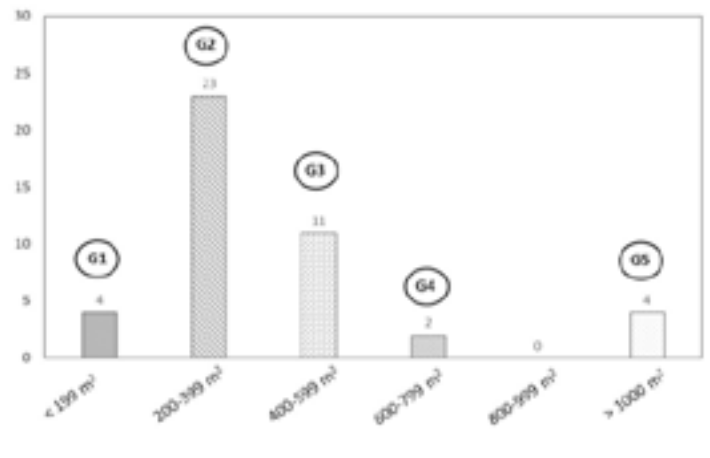


Figure 3: Mosques that are grouped according to floor areas

In the second stage of the process, five sampled mosques from each of the groups were selected for the energy profile and energy intensity case study. The sorting samples had been based on the highest figures of the installed air-conditioning capacity, the annual electricity expenses as well as the energy used with a 415V power supply system. The survey results from Stage 2 had indicated most of the common air-conditioning types found in mosques group G1 to G4 to be those with a ceiling exposed split air conditioning unit, while the centralized air cooled chiller with a combination of air handling unit (AHU) and the ducting system was used in the G5 mosque. The selected G1, G2, G3, G4 and G5 mosques with their respective floor areas and actual capacity of retrofitted air-conditioning systems are shown in Table 1, while the actual annual energy usage from January 2016 to December 2016 of the G1 to G5 groups had been obtained from a local electric utility company (Tenaga National Berhad). All of the data collected were used in the calculation of the energy profile and intensity case study.

Table 1: Selected mosques for the energy profile and energy intensity case study

Mosque name	Group	Cooling floor area (m²)	Retrofitted capacity air conditioning (Horse Power)
Masjid Jame' Bakar Kapor Penaga	G1	160	15
Masjid Jame' Al Ihsaniah S.P.S	G2	315	54
Masjid Sembilang Seberang Jaya	G3	576	89.5
Masjid Pongsu Seribu Kepala Batas	G4	632	67.5
Masjid Negeri Pulau Pinang, Georgetown	G5	2920	378

(1)Building Energy Index (BEI)

A building is defined as an energy-efficient building by benchmarking its efficiency level on a Building Energy Index (BEI), where the BEI is the ratio of a building's total annual energy usage (kWh) to the total building area (m²). Since the Malaysia Standard (MS 1525: 2014) had developed a standard BEI reference for office buildings (135 kWh/ year/ m²) and the 200 kWh/ year/ m² reference for hospitals (Moghimi et al., 2014) with no BEI references for the mosques, the BEI of the mosque was then calculated and compared with the BEI values of the two former buildings. The basic equation of the indices had been based on those suggested by Saidur (2009):

(a) Energy Intensity Index

The Energy Intensity Index (ACEII) in kWh/ year/ m² is estimated by using the following equation:

$$ACEII = \frac{\sum_i^n AEC}{CFA} \quad (1)$$

where AEC is the sum of the annual energy consumption of equipment i to n and CFA is the cooling floor area (m²).

(b) Air conditioning cost index

The air conditioning cost index (ACCI) in RM/year/m² is estimated by using the foll

$$ACCI = \frac{\sum_i^n ACE}{CFA} \quad (2)$$

where ACE is the annual sum of the energy consumed from equipment i to n in Malaysia Ringgit (RM) and CFA is the Cooling floor area (m²).

2.3 Monitoring actual energy profile

In the third stage of the process, only one sample (n=1) from the respective mosque groups (G1-G5) is selected as a field case study due to its religious facility limitation (Figure 1). Hence, the selection criteria of the mosque had

been based on the following:

- Daily operation of a cooling system (daily/Friday prayers)
- Daily operation time of more than 5 hours continuously
- Uses a centralized air-conditioning system
- Highest annual electricity consumption

By fulfilling all of the above criteria, the Penang State Mosque from the G5 group was then selected as a case study model. The mosque is centrally located in the Penang Island with GPS coordinates of 5.406N, 100.3006E, which was built and opened to the public in 1981. The mosque is built like a dome that contains the ground and mezzanine floors. With a total floor area of 2920 m², the main prayer hall on the ground floor is opened every day for praying purposes, while the mezzanine floor area that spans a total of 65.69 m² is only opened for special events and ceremonies such as the IdulFitri prayers and celebrations. Each of the walls had used a single layer shaded glass type with six main entrance doors using the same glass type. The floors are fully furnished with the saf carpets that are placed in parallel to the western part of the wall, while the dome is being used as the roof for the grand tower. The mosque can also fully accommodate up to 5,000 of worshippers at one time and is currently managed by the Penang Religious Affairs Department. A plan view of th

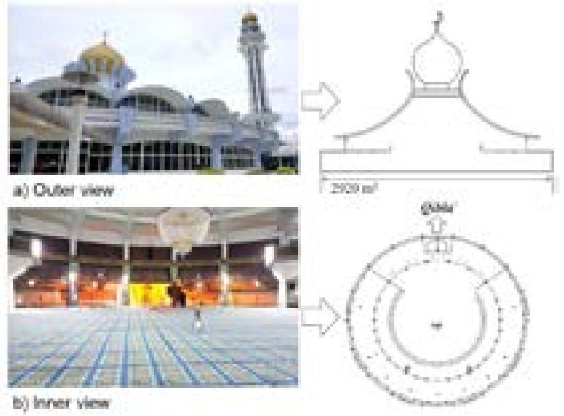


Figure 4: Plan view of Penang State mosque

2.4 Description of the air-conditioning system

The Penang State Mosque was retrofitted with an air-conditioning system in 2003. Each of the three identical air-cooled chillers with a capacity of 100 RT was installed to produce thermal comfort in the main prayer hall. The main air-conditioning system had consisted of a chiller (compressor, condenser, thermal expansion valve and evaporator), air handling unit (AHU), water pump system, air distribution system (ducting and diffusers) and an electrical control panel. A detailed explanation of an air cooled chiller system in the literature had been described by Teke and Timur (2014).

The air cooled chiller component had relied on a reciprocating (semi hermetic) compressor with a maximum power input of 235kW, an air system condenser that uses the surrounding ambient air for cooling down the heat rejection as well as a shell-and-tube evaporator. The cooled water had been designed with an entering water temperature of 54 °C and leaving water temperature of 44 °C from the shell-and-tube evaporator that is circulated to the Air Handling Unit (AHU) by a 3 nos centrifugal end-suction pump (10 horsepower (HP) motor pump each) at the rate of 255 USGPM. The five air handling units are located in the AHU room, which is located beside the mosque, where the continuous supply of air is drawn from a ducting system. The cool air is then distributed to the surrounding space of the main prayer hall by using jet diffusers that had been set at a constant flow rate. The source of the electrical power panel had come from the 3 phase, 415V and 50Hz power supply, where all the controls and power panels for the chiller component, including the ON/OFF button, are located in a special box panel near the chiller unit. The sequence of the start-up components such as chillers, pump and AHU had been synchronized with a proper timer step control by using the single ON/OFF button, where the air conditioning system had been set to operate (ON) at 3.00 PM and shutdown (OFF) at 9.30 PM from Sundays to Thursdays and from 10.00 in the morning until 9.30 at night on Fridays. The air-conditioning system and its physical data are shown in Table 2.

Table 2: Air conditioning system and physical data

Items	Physical data
Air cooled chiller	100RT each x 3 *nos*
Refrigerant	R22
Supply	3Phase/415V/50Hz
Air Handling Unit	AHU-1 = 25,200 CFM
	AHU-2 = 19,200 CFM
	AHU-3 = 24,000 CFM
	AHU 4 = 30,000 CFM
	AHU 5 = 18,000 CFM
Air distribution type	Conventional ducting system with jet diffusers

2.5 Instruments and measurements

The evaluation of the actual energy profile had been based on the measurement that was automatically recorded by the energy data logger, which is connected to the power supply panel of the air-conditioning system. The site measurement at the Penang State Mosque was carried out from 17 May 2017 until 21 May 2017 (n=5 days) with a laptop connected to the power and energy data logger (PEL) Version 102 as a way of measuring the electric power consumption from the air-conditioning system. As shown in Figure 5, the PEL Ver.102 is kept in the electrical room, which is located in front of the air-conditioning electrical power panel.

The MA193 flexible current sensors and black safety leads with black alligator clip voltage sensor were used to measure the instantaneous electric variables from the incoming 415V terminal wire supply without exposing the circuit. The 3 units of black alligator clips together with the voltage sensor had been clipped at the power supply terminal, while another 3 units of the MA193 flexible current sensor were round clamped at the red, yellow and blue power supply wires. The PEL Ver.102 had been enabled to record and measure the electrical power parameters such as the instantaneous electric variables (Root Mean Square (RMS) current, RMS voltage, and phase angle) as well as the power (kW and kVA) used. The accuracy of the current and voltage probes had been set at ± 1% ± 15A and ± 2.5% ± 0.4V, respectively. As shown in Figure 6, all of the instantaneous data were captured automatically at a 5-minute interval and saved directly in the PEL memory card.

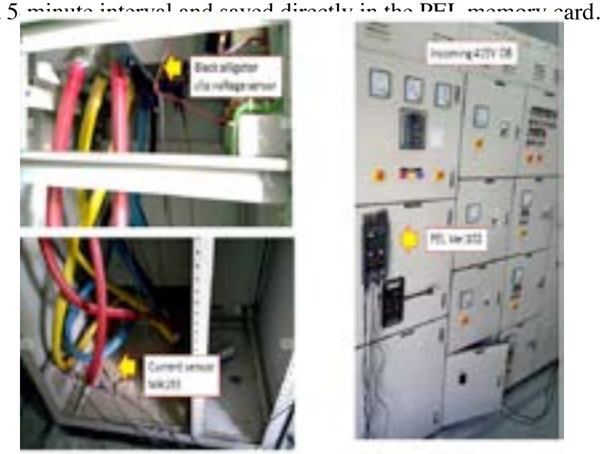


Figure 5: The location of PEL instrument and sensors at the 3 phase electri-

Figure 6: The PEL instrument and sensors used

3. RESULTS AND DISCUSSIONS

3.1 Cost and energy intensity impact

As illustrated in Figures 7 and 8, the actual Tenaga Nasional Berhad (TNB) utility bills (energy and cost) that had incurred from Jan-Dec 2016 had shown the yearly energy consumed from the corresponding air-conditioned mosques group G1, G2, G3, G4 and G5 to be 22 MWh, 39 MWh, 63 MWh, 44 MWh and 942 MWh with a respective electricity cost of RM9, 000, RM24, 000, RM28, 000, RM20, 000 and RM446, 000. As seen from the data, the mosque from the G5 group had exhibited the highest average monthly utility cost usage of RM 37, 177.00, which were followed by those from the G3 (RM2, 320.00), G4 (RM1, 668.00), G2 (RM 1, 987.00) and G1 (RM765.00) groups, respectively. The results had also indicated the total energy consumed by the mosques from each of the group to be equivalent to half of the electricity costs. Furthermore, with the exception of the G4 mosque, a significant difference could be observed between the energy and costs usage with the increasing cooling floor area of each mosque. This may be due to the actual air conditioning capacity (horsepower) of the G4 mosque that had been installed below the estimated values as those indicated in Table 1.

All of the mosque samples had shown a fluctuation of the monthly energy usage, which could be due to the energy wastage (energy loss) associated with less efficient equipment. The actual horsepower of the retrofitted air conditioning system was actually found to have operated below the capacity level. This meant that although the air-conditioning system had seemed to work normally, it had hardly achieved the desired thermal comfort with its high energy consumption as shown by a similar case reported by Al-homoud et al., (2009) in Saudi Arabia. As part of the countermeasure, Al-homoud et al., 2009 had suggested for the height of the supply air outlets to be adjusted as low and as close as possible to the occupied zone as a way of reducing the energy requirement that resulted in air stagnation at the ceilings.

Another reason for the fluctuation in the monthly energy usage had been due to the operation time of the air-conditioning system. According to a majority of the mosque officers who were also assigned with the task of handling the air-conditioning system, the increment of the operation time (ON/OFF system) had been due to the daily preaching session conducted at the main prayer hall. The mosque in the G3 group for example, had shown a 50% increase of energy usage and costs between the months of January and July. The highest usage was found to have occurred in the month of July, where it had coincided with the Ramadhan fasting month, during which intensive activities such as the breaking the fast, special terawikh (pre-midnight) and qiamullail (after midnight) prayers as well as the iktiqaf (spiritual retreat) had been carried out in the mosque. As such, the air-conditioning system had been set to operate fully in meeting the comfort expectations of the devotees during the implementation of such activities, while neglecting the air-conditioning system's energy usage. The fluctuation of the energy usage had also been due to the untrained personnel in handling the system facilities, as corroborated by the study conducted by Terrill & Rasmussen (2016), as well as the different standard operating procedures in the operation of the air-conditioning system

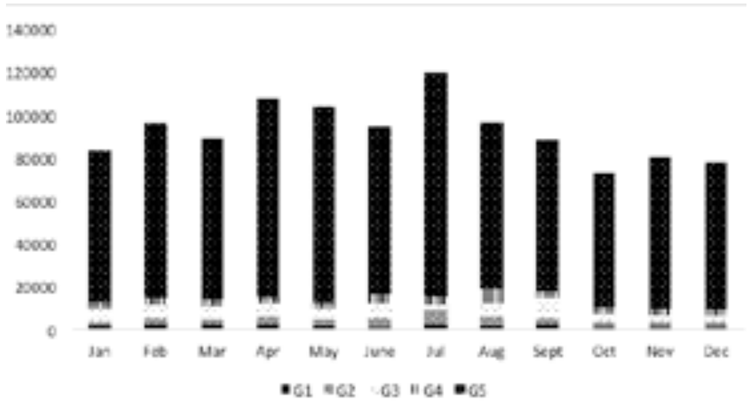


Figure 7: The actual annual energy consumption (kWh) for G1-G5 (Jan-Dec

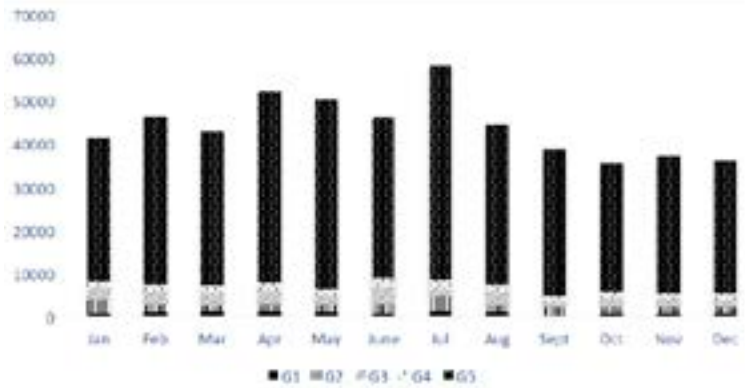


Figure 8: The actual annual TNB cost (RM) for G1-G5 (Jan-Dec 2016)

Table 3 shows the annual Energy Intensity Index (kWh/year/m2) of the five mosque groups. As shown from the data, the lowest indices could be observed in the G4 group (70 kWh/m2/yr. and RM 32/year/ m2), which is followed by the G3 (110 kWh/m2/yr and RM 48/year/ m2), G1 (124 kWh/m2/yr and RM 58/year/ m2) and G2 (124 kWh/m2/yr and RM 76/year/ m2) groups, respectively, while the mosque from the G5 group had produced the highest indices of 323 kWh/m2/yr and RM 153/year/ m2 in order to produce a sufficient cooling ambience of the main prayer hall. The results had also shown the G1 mosque sharing the same energy indices as those with the Malaysia Standard (MS 1525: 2014), while those from the G2-G4 groups had produced energy indices below the MS 1525 and the study conducted by Saidur (2009). Since the mosque in the G5 group was found to have exhibited higher energy indices and almost 16% lower than the study conducted by Moghimi et al. (2014), this implies that the mosques in the G1-G4 groups can be defined as more efficient buildings as compared to those in the G5 group.

Table 3: Study mosques Building Energy Index and Cost Index

Descriptions	RM/yr	kWh/yr	CFA	ACCI	BEI
This Study, mosque G1	9180.28	21457	159	57.59	135
This Study, mosque G2	23845.60	38978	314	75.92	124
This Study, mosque G3	27844.64	63419	577	48.29	110
This Study, mosque G4	20016.17	44100	632	31.67	70
This Study, mosque G5	446134.11	942003	2920	152.79	323
Saidur, 2009		127752000	983000		130
Moghemi et al., 2014		57705036	150196		384
MS 1525 : 2014		Base reference			135

Note:

CFA = Cooling floor area

ACCI = Air conditioning cost Index

BEI = Building Energy Index (BEI)

3.2 Actual energy usage from the Penang State Mosque (G5)

As shown by the measured air-conditioning current (A) and power (kW) consumption as a function of time in Figures 9 and 10, the respective average current and power were found to have varied from 127 A to 239 A and 87 kW to 161 kW. Apart from the halved operation values exhibited on weekdays/ office days (Wednesday and Thursday) and weekends (Saturday and Sunday), the data had also shown a difference in the ON/OFF sequence of the chiller and its components between the working and non-working days. On the contrary, although the Friday measurement results had drawn a respective average current and power at 208A and 142 kW, this was found to be a common phenomenon since the chillers would have started operating at 10.00 a.m. as a way of covering the occupant peak load of Friday prayers between 12.00

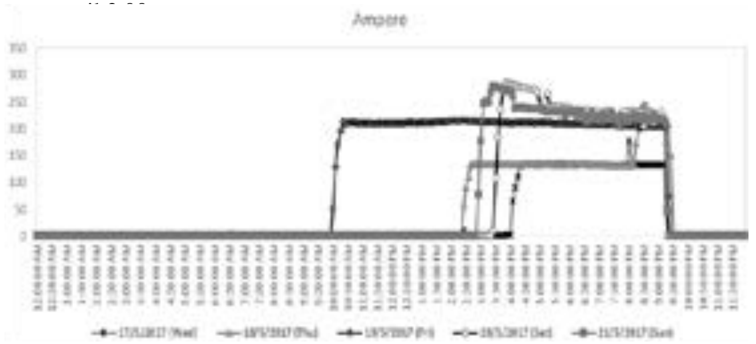


Figure 9: The measured Current, (A) of an air conditioning system for the period of 17th - 21st May 2017

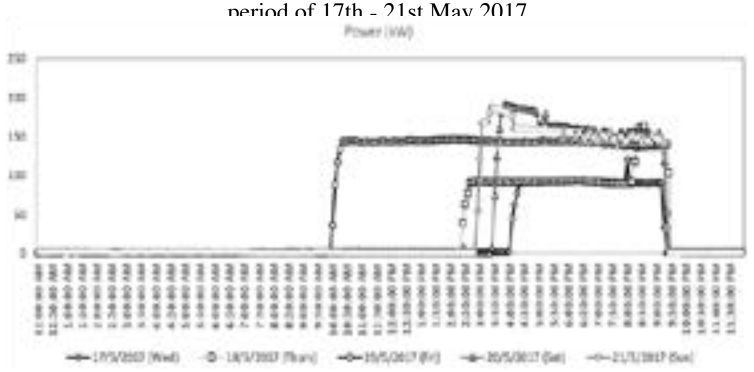


Figure 10: The measured Power, (kW) of an air-conditioning system for the period of 17th - 21st May 2017

Table 4 shows a statistical summary of the power consumption (kW) usage that had been obtained from the case study of the Penang State Mosque. The minimum and maximum power consumption were shown to have varied between 43.48 kW to 162.34 kW, with a respective mean and standard deviation values of 128.63 kW and 17.15. As illustrated from the actual monitoring data of the energy usage in the Penang State Mosque, it is obvious that air-conditioning had been the single largest energy consumed in the provision of thermal comfort for the worshippers, where a total of 63.7% was shown to be associated with the air-cooled chiller operation. The air-cooled chiller is categorized by its capacity and efficiency level, which are influenced by certain factors such as the difference in the physical and operation time as well as the air cooled chiller and the performance of its components such as the condenser. Condenser is considered one of the most important components, where the pressure is cooled down by the various outdoor ambient temperatures that reflect the energy usage. As a result of the climatic condition under a hot and humid weather with a temperature of 34 ºC, it is not only difficult to keep a condenser cooled, but also problematic to increase the energy usage with a polluted coil condenser. For that reason, Alves et al., (2016) had suggested the use of a Seasonal Energy Efficiency Ratio (SEER) in determining the various parameters such as the air conditioning operating time, operating mode (on/off thermostat), the various AC power of compressors and the efficiency degradation of an equipment as a way of checking the equipment's energy efficiency.

Table 4 : Summary power consumption (kW) usage, n=5 days

Descriptions	Mean	Min	Max	S.D
17/5/2017	86.99	33.63	121.01	10.83
18/5/2017	99.56	39.66	163.92	21.47
19/5/2017	141.83	36.01	147.17	13.15
20/5/2017	161.15	74.85	191.83	18.47
21/5/2017	153.61	33.26	187.77	21.79
Total mean (kW)	**128.63**	**43.48**	**162.34**	**17.15**

Note: S.D = Standard Deviation

3.3 Discussions on energy optimization and savings potential

Generally, there is an existing potential for energy-saving opportunities in a building's air-conditioning system. As seen from the above data, factors such as floor area, year of build, fabric and envelope designs, operating hours, costs of energy sources, occupancy load and equipment efficiency had contributed to the different costs and indices for each of the mosque groups, which are similar to those reported by Saidur, 2009 in his research on Malaysia's office buildings. The mosques from the G5 group were found to have produced Energy Intensity and Cost Indices (about 1 to 1.5 times higher) that are not only higher than the Malaysia Standard (MS 1525: 2014), but also the building baseline references of an office (Saidur, 2009) and a hospital (Moghimi et al., 2014). For this reason, the MS 1525 had recommended several low energy usage strategies that can be applied by the buildings (MS 1525: 2014). As indicated by the fluctuating electricity bill recorded from TNB, apart from the manual ON/OFF switch operation of the air conditioning system at different hours, inexperienced mosque officers, as well as the lack of procedures in operating the air conditioning system were also seen to have contributed to the daily inconsistent and varied operation time.

Based on the findings of the Penang State Mosque, the average energy consumed by the air cooled chiller system had been an approximate 128.63 kW, with a temperature of 15ºC set in the thermostat controller. According to the ASHRAE Standard (2013), the temperature level of 22ºC – 26ºC is regarded as a high energy consumption under Malaysia's climatic conditions. Based on the adaptation behaviour, since the worshippers in Malaysia had been shown to be more tolerable to cooler indoor conditions as a result of better body adjustment, the new findings of a favourable thermal comfort in mosques (Hussin et al., 2015) as well as the study conducted on the practices that were based on similar climatic conditions (Yamtraipat et al., 2006; Fasiuddin and Budaiwi, 2011), increasing the pre-set indoor temperature would therefore serve as a good reference for saving energy consumption. The air-conditioning system of the Penang State Mosque was also found to have operated continuously for 6.5 hours on a daily basis during both prayer and non-prayer times, where the emphasis had been on keeping the entire floor area cooled instead of considering the thermal comfort for the worshippers. Since no worshippers were observed during the intermittent prayer times and especially after the Asar prayers, the continuous operation time had therefore led to a high wastage of energy use. As such, apart from being well-informed on the proper operation of the air-conditioning system with regards to the prayer times, the committee members of the mosque can also consider applying for energy audits as a way of reducing energy wastage in the building (Sheikh et al., 2017). The overall findings as well as the suggested short and long term strategies that had considered the availability of budgets and resources of related departments in the Penang State Mosque are listed in Table 5.

Table 5: The findings and optimization strategies for the Penang State Mosque

Findings	Optimization strategy	Implementation
There had been a lack of preventive maintenance conducted in the system. The oil leakage near the adjoining compressor is believed to have originated from the refrigerant.	Frequent maintenance by an expert is required in the prevention of excessive energy wastage from possible faulty equipment or operation failure (Terrill & Rasmussin, 2016).	Short term
Inexperienced mosque officers and the lack of procedures in operating the air-conditioning system had led to the increase of energy usage.	Establishment of Standard Operating Procedures as well as intensive practical trainings to be provided to the mosque officers (Hussin et al., 2015).	Short term
The manual operation of the ON/OFF switch in the air-conditioning system at different hours had resulted in the varied and inconsistent operation time.	A timer can be designed and installed with the controller for the air-conditioning system to operate at a required specific time.	Short term
High energy consumption had occurred in the generation of thermal comfort in the main prayer hall. Although the thermostat setting was found to have been fixed at 15°C, the indoor temperature had recorded a minimum of 22 °C, which is not practical for mosque application.	To test the comfort temperature as suggested in the MS 1525: 2014 (24-26 °C) by using the Predicted Mean Vote (PMV) and Actual Mean Vote (AMV) Indicators with a deviation limit of ± 0.5 (Hussin et al., 2015). To validate the PMV indicators of the indoor climatic performance of a cooled floor area through a computer modelling (CFD) system.	Short term
A high wastage of energy use was observed from the air-cooled chiller, where it was left running at an average of 6.5 hours during prayer and non-prayer times, particularly after the *Asar* prayers.	To test the CFD of the supplied cooled air distribution in the mosque via an appropriate operational zoning system. As suggested by Budaiwi & Abdou, (2013), a large volume of the cooling area can be cooled according to the following proposed segregated zones: Concept 1: Zone 1 –Cooling is only required for the prayer area portion. Concept 2: Zone 2 – Cooling is required for the total floor area during Friday prayer.	Long term
The existing chiller was found to be too old (17 years) and not operating at its optimum level. The blockages that were found in the evaporator pipes had also compromised the cooling efficiency and heat transfer process.	To replace the existing chiller.	Long term

4. CONCLUSIONS

This paper describes the evaluation of the energy profile and the optimization strategies for mosques that had been retrofitted with air-conditioning systems. These air-conditioning systems were found to have performed below the required efficiency level and led to energy wastage as a result of certain factors that had influenced its energy consumption. While providing the best thermal environment for the main prayer hall area, most of these mosques had demonstrated energy indices that were higher than those of the MS 1525 standard and consequently, higher cost expenses. For this reason, this study had proposed several short and long term strategies by considering the available resources and budget such as the upgrading of the system and system knowledge in the optimization of energy usage. Apart from the installation of a timer that automatically operates the ON/OFF switch of the air-conditioning system at a specific time, the setting up of a new thermal comfort or temperature adjustment will also provide advantages in terms of intermittent operation hours and load occupancy. Last but not least, scheduled maintenance of the air-conditioning system as well as the application of zoning operation was also suggested as ways to mitigate the energy wastage of the main prayer hall in the Penang State Mosque.

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THE IMPACT OF AIR GAPS ON THE PERFORMANCE OF REFLECTIVE INSULATIONS

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ABSTRACT

Solar heat gain is the primary issue for cooling energy which accounts for the highest energy consumption in building particularly in hot and humid climate like Malaysia. Approximately 93% of the solar heat gain through a roof is by radiation compared to conduction and convection methods. One of the most effective passive strategies to reduce radiative heat transfer through a roof is by using reflective insulation. Generally, reflective insulations are insulation materials that have low emissivity which ranges from 0.03 to 0.04 with high reflectance values. The assembly of a reflective insulation is characterized by an enclosed air gaps adjacent to low-emittance surfaces like aluminum foil. The performance of reflective insulation is commonly evaluated in accordance to ASTM C518 Standard using Heat Flow Meter. The objective of this paper is to analyze the performance of four different types of reflective insulations with various enclosed air gaps namely the big bubble aluminum foil, small bubble foil, woven foil and metalized foil. Based on the measurement and analysis, it was discovered that the big bubble foil with 50mm top air gap and 75mm bottom air gap has the highest R-value of 2.38.

Keywords: Reflective insulation, solar heat gain, radiation, emissivity, R-value.

1. INTRODUCTION

One of the most effective passive strategies to reduce cooling energy consumption in a building is by using thermal insulation. Generally, high solar radiation in tropical countries is being absorbed by buildings external envelope which causes high amount of solar heat gain emitted inside the building that will increase the energy consumption due to higher cooling load (Escudero et al., 2013). Therefore, for this reason, decreasing the solar heat gain became a big challenge especially in designing green and low energy buildings (Filho and Oliveira Santos 2014).

The insulation materials or products that are used in tropical buildings should have high thermal resistance. Hence, characterization of the insulation properties have to be taken into consideration before deciding its installation assemblies on building components (Hauser et al., 2013). The insulation materials and assemblies are commonly found on roofs, façade, walls and floors components. For tropical countries with high intensity of infra-red solar radiation, it was discovered that the most effective method to reduce the solar heat gain and energy consumption is by installing the insulation on the roof component (Hernández-Pérez et al. 2014). Researchers have also discovered that reflective insulation installation on the roof was able to reduce heat flux by 26% to 50% and cooling load by 6% to 16% (Lee S.W. et al., 2016).

Therefore, most of the studies found that building insulations were conducted on roofs as compared to other building components like walls, façade and floors components. Based on previous research, large size roof of buildings in hot climate especially non-residential buildings such as airports, shopping malls, industrial factories and exhibition halls with proper thermal insulation could able to reduce up to 50% of thermal heat gain inside the buildings (Hernández-Pérez et al. 2014). This high percentage of thermal heat gain is normally due to high solar radiation exposure of the large roof area as compared to the other building components such as external walls and façade. Researchers have also discovered that the internal rate of return (IRR) for installation of reflective insulation on a typical hypermarket is approximately 15.83% (Lee S.W. et al., 2017).

There are mainly two major categories of building insulations namely the mass or bulk insulation and reflective insulations. Studies have found that heat transfer by radiation is the primary mode of heat transfer in buildings envelope in hot climate as compared to other heat transfer methods like conduction and convection (Chang, P.C. et al., 2008). Hence, reflective insulation is considered the most effective method in reducing radiant heat transfer.

The thermal performance of reflective insulation is highly dependent of the thermal properties of its materials and assemblies as building components (Al-Homoud 2005). The key parameters that influence the performance of reflective insulations are air gap, emissivity and surface temperature. There are several characterization methods that can be used to determine the thermal performance of the insulation assemblies for reflective insulations.

The standard thermal characterization methods to evaluate the performance of reflective insulation are the guarded hot-plate apparatus test method under ASTM C177, the heat flow meter apparatus test method under ASTM C518 and the hot-box apparatus test method under ASTM C1363. The heat flow meter test method is commonly accepted as a method to characterize the reflective insulation layer itself whereas the guarded hot-box test method is used to determine the total thermal resistance of a building component or assemblies including radiant barrier (Escudero et al. 2013). In this study, the heat flow meter characterization method is used to determine the R-Value of different thermal insulation assemblies. Researchers have evaluated a double roof prototype insulation assemblies using reflective insulations and it was discovered that the reflective insulations was effective in reducing the radiative heat transfer from the roof to the ceiling (Chang P.C. et al., 2008).

In order to obtain the value of the thermal resistance of different reflective insulations used in building insulation, the heat flow meter apparatus and the guarded hot box method were extensively used by researchers (Escudero et al. 2013). The two different configurations have been tested and compared with simple analytical model according to ISO6946 standards using CFD analysis. It was found that both of the experimental lab methods were suitable for characterization of reflective insulations.

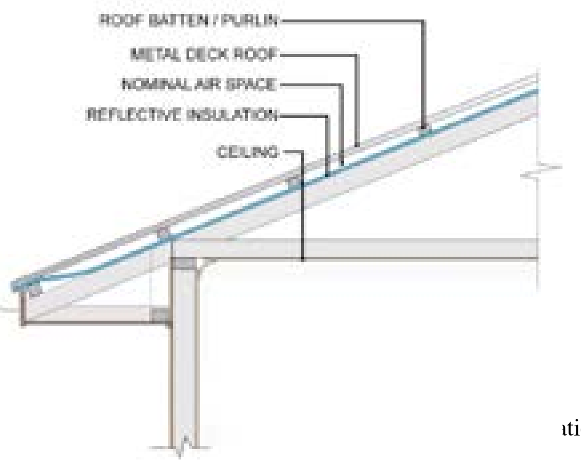
A comparative analytical study of the thermal performance for a large area of metal roof type building was conducted for a building in the tropical climate. Based on heat transfer modelling through the roof of an exhibition hall in Brazil, it was found that the coating of the roof for this type of building could reduce the energy consumption by reducing the solar heat gain into the building (Filho and Oliveira Santos 2014).

Researchers also have studied the effect of energy saving of reflective insulation on exterior building envelopes based on different weather conditions (Guo et al. 2012). The study was carried out under both summer and winter weather conditions. In the experiment, reflective insulation materials was applied to the exterior envelopes as a coating layer. The experimental was carried out on an actual building room conditions to cater for different rooms orientations. The indoor test results revealed that the insulation coating performs better than the non-insulation coating with temperature different of 0.73°C with monthly energy saving of 5.8 kWh/m^2.

In this study, the thermal characteristics performance of reflective insulation materials has been tested experimentally using Heat Flow Meter (HFM) method in accordance to ASTM C518 test method. Different types of reflective insulation materials were used namely: big bubble aluminum foil, small bubble aluminum foil and woven foil with variable air gaps.

2. TYPES OF ROOF REFLECTIVE INSULATION

The reflective insulation product is still a fairly new product that was just introduced in the building market lately as a highly promising new type of thermal insulation material. Due to the commercial market claim of its high performance, it has triggered numerous ongoing debate on this issue particularly in comparison with mass insulation like rockwool (Tenpierik and Hasselaar 2013). Both types of reflective insulation and mass insulation have different functions and applications. The mass insulation such as rockwool primarily reduce heat transfer by trapping air. Hence, it mainly reduces the convective heat transfer and it is not as effective in reducing radiant heat transfer which is often a primary mode of heat transfer in a building envelope. On the other hand, the reflective insulation uses layers of aluminum foil to trap air due to its low emissivity surfaces and it is very effective in reducing radiative heat transfer as much as 97% (Tenpierik and Hasselaar 2013)(RIMA International 2014). Typically the bubble foil construction consists of air bubbles encapsulated in between two sides of aluminum foils with low emissivity values. The material or product itself only has very low thermal resistance. However, if the product is installed with enclosed air gaps facing its reflective surfaces, it has significant thermal resistance values as shown in Figure 1.



Figu[...]ıtion

The main objective of this research to determine the performance or the thermal resistance (R-value) of four different types of reflective insulations namely the big bubble aluminum foil, small bubble foil, woven foil and metalized foil with different configurations of air gaps. Figure 2 shows the types of reflective insulations.

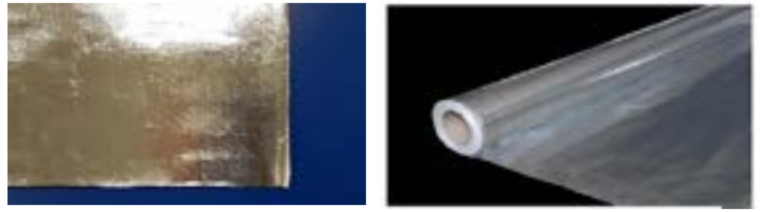
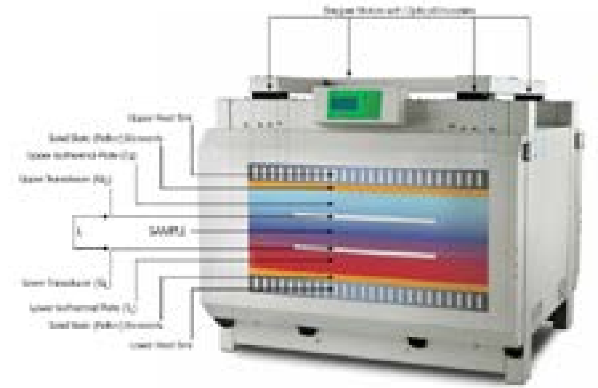


Figure 2: (a) Small bubble foil; (b) Big bubble foil; (c) Woven Foil; (d) Metalized foil

3. METHODOLOGY

The application of heat flow meter for thermal characterization on reflective insulation has been considered as one of the most reliable method in determining the performance of reflective insulation (Saber 2012). In this characterization study, LaserComp Heat Flow Meter model FOX 600 was used to determine the thermal conductivity and subsequently for R-value calculation as shown in Figure 3.



The heat flow meter is a steady state technique for measurement of thermal conductivity and it is also commonly used by researchers and industry professionals to determine the R-VALUE of insulation materials. In order to measure the thermal conductivity of the assemblies of the reflective insulation, the heat flow meter, a sample is positioned in between two temperature controlled plates.

These plates establish the temperature difference (ΔT) across the sample. The sample thickness (L) can be manually keyed into the heat flow meter control panel or allowing the heat flow meter to automatically measure the thickness of the sample. The thickness of the sample is vital because it is used in the calculation of the R-value. The heat flux (Q/A) from the steady –state heat transfer through the sample is measured by two proprietary thin film heat flux transducers covering a large area of upper and lower sample surfaces in order to ensure the exact measurement of the heat flow. The average heat flux is used to calculate the thermal conductivity (λ) and thermal resistance (R), according to Fourier's Law:

$$\lambda = \frac{Q}{A} \times \frac{L}{\Delta T}$$ W/mK (1)

$$R = \frac{1}{\lambda} L$$ m2K/W (2)

In order t[...]he assembly of the reflective insulation with the air gaps, a timber fr[...]sed to create air gaps for top and bottom of the aluminum foil as shown in Figure 4.

Figure 4: [...] for bubble foil for heat flow measurement

Subsequently, the temperature of the top plate of the heat flow meter was set to 35°C and the bottom plate to 20°C respectively. The temperature settings are based on the requirement by MS 2095:2014 Radiant barrier and reflective insulation building materials – Specification (Frist revision). The heat flow direction of the sample assembly was based on downwards flow direction as shown in Figure 5. The sample size was 600mm x 600mm with different configurations of air gaps that ranges from 25mm, 50mm, 75mm, 100mm, 125mm and 150mm.

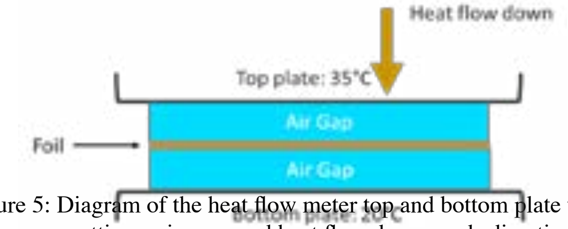


Figure 5: Diagram of the heat flow meter top and bottom plate temperature settings, air gaps and heat flow downwards direction

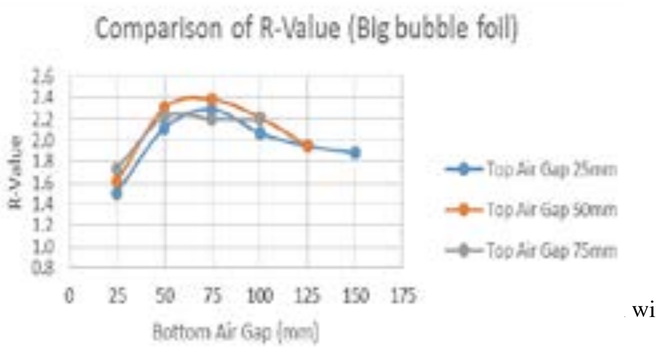
All the heat flow meter measurement settings for small bubble foil, big bubble foil, woven foil and metalized foil with different air gaps configurations are as shown in Table 1. There were total of 14 different types of configurations for this study.

Table 1: Top and Bottom Plate Temperature Settings and different Air Gaps Configurations for Heat Flow Meter Measurement

Top plate temperature (°C)	Bottom plate temperature (°C)	Top air gap (mm)	Bottom air gap (mm)
35	20	25	25
35	20	25	50
35	20	25	75
35	20	25	100
35	20	25	125
35	20	50	25
35	20	50	50
35	20	50	75
35	20	50	100
35	20	50	125
35	20	75	25
35	20	75	50
35	20	75	75
35	20	75	100

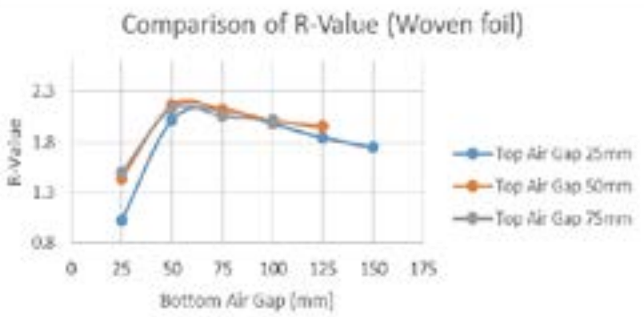
4. R[...]

Based on the results of the heat flow meter measurement and the R-value calculations for big bubble foil, the optimum R-value of 2.38 m2K/W was achieved with top air gap of 50mm and bottom air gap of 75mm as shown in Figure 6. The analysis also revealed that as the air gap exceeded 75mm, the R-value began to decrease. The effect of bigger air gaps influencing the R-value could be due to the occurrence of convective heat transfer or heat lost in the air gaps that caused both top and bottom air gap as ineffective insulation layer. In order for the air gaps to act as an effective insulation layer, it needs to avoid any convective heat transfer to occur.



Figu[...] with

Figure 7 shows the R-value of the Woven foil with different air gaps configurations. Based on the analysis, the highest R-value for Woven foil was 2.16 m2K/W with 50mm for top air gap and 50mm for bottom air gap. The analysis also showed that the R-value for the Woven foil decreases as the air gaps exceeded 75mm.



Fig[...] dif-ferent air gaps configurations

Figure 8 shows the R-value results for Small bubble foil with different air gaps. The study found that the highest R-value for Small bubble foil was 2.32 m2K/W with top air gap of 50mm and bottom air gap of 50mm. The analysis also shows that the R-value decreases when the air gap exceeded 75mm.

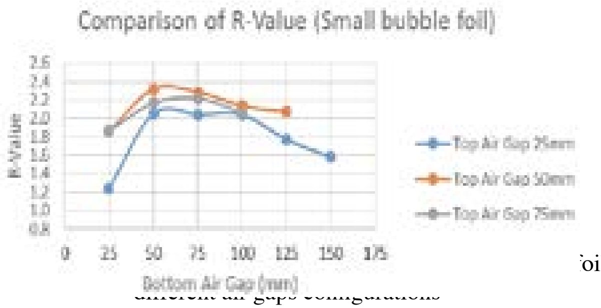


Figure 8[...]foil with different air gaps configurations

Figure. 9 shows the R-value of the metalized foil (MP2) with different air gaps configurations. Based on the measurement re sults, the optimum air gap

configuration for MP2 is 0.63 m2K/W with 75mm for top air gap and 75mm for bottom air gap. The thermal performance of the MP2 was the lowest compared to the big bubble foil, small bubble foil and woven foil.

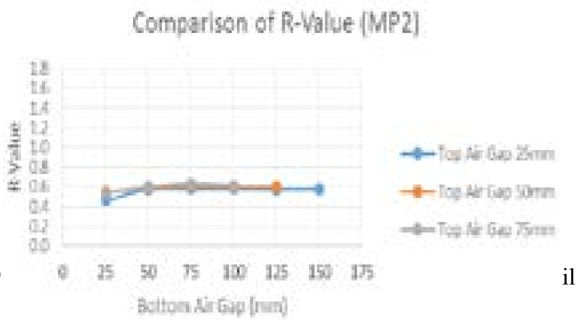


Figure 9[...]il (MP2)

Table 2 shows the summary of the performance of all the 4 types of reflective insulation with optimum air gaps configurations. Based on the analysis, the top air gap of 50mm was the optimum air gap for the three types of reflective insulations and the bottom air gap was 50mm and 75mm. Any lesser or bigger air gap does not assist in increasing the R-value of the reflective insulation.

Table 2: Summary of the performance of all the 3 types of reflective insulation with optimum air gaps.

Types of Reflective insulation	Optimum R-value (m^2K/W)	Optimum air gaps	
		Top air gap (mm)	Bottom air gap (mm)
Big bubble foil	2.38	50	75
Small bubble foil	2.32	50	50
Woven foil	2.16	50	50
Metalized foil	0.63	75	75

5. CONCLUSIONS

Based on this study, it was found that reflective insulation and radiant barrier were effective insulation to reduce the solar radiant heat gain with downwards heat flow from the roof. The test results showed that the R-value for the four types of reflective insulation were namely big bubble foil, small bubble foil, woven foil and metalized foil ranges from 0.63 m2K/W to 2.38 m2K/W. The highest R-value was the big bubble foil with R-value of 2.38 m2K/W. The research also discovered that when the air gaps for top and bottom of the reflective insulation exceeded 75mm, the R-value decreases. This effect was also encountered by other researchers in the studies on reflective insulation using heat flow meter method and it was generally due to the convective heat transfer that occurred when both the top and bottom air gaps of the reflective insulation were larger than 75mm.

ACKNOWLEDGEMENT

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COMPARISON OF MEASURED AND MODELLED MEAN RADIANT TEMPERATURE IN THE TROPICAL URBAN ENVIRONMENT

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ABSTRACT

RayMan is the most popular software package for thermal comfort research and urban planning. RayMan simulates the mean radiant temperature ($T_{mrt)}$ and provides assessment of the human-biometeorology for urban areas. In this study T_{mrt} simulated by RayMan (version 1.2) has been validated with results from the six-directional radiation measurements in tropical urban settings in Malaysia. In addition, a validation of the physiologically equivalent temperature (PET) simulated by RayMan is conducted for the first time in the tropical context. T_{mrt} values from RayMan1.2 show some agreement with the measured values during middle of the validated days; however there was high fluctuation over that time due to rapid changes in radiation by cloud appearing. The results also show that RayMan1.2 considerably underestimated T_{mrt} during morning and evening. The simulated PET values followed the same pattern of the simulated T_{mrt}. However the simulated PET had a closer estimation to the experimentally obtained PET. The study also noted that RayMan1.2 accuracy seems to be site-related. Its simplification to the 3-D radiation environment led to variations in simulation accuracy depending on urban morphology. Therefore improvements of the RayMan software for simple and complex urban settings and tropical climates are required.

Keywords: : mean radiant temperature; six-directional radiation method; RayMan1.2 software; tropical urban environment.

1. INTRODUCTION

Consideration of human-biometeorology and thermal comfort for the assessment of urban areas has increased in recent years in response to different issues (Lee and Mayer, 2016, 2018a, 2018b; Lee, Mayer, and Chen, 2016; Lee, Mayer, and Schindler, 2014). First, the rates of world population living in cities are growing. In addition, urbanization has imposed significant changes to the natural ecosystem and landscape through the creation of largely impervious urban surfaces (Arnfield, 2003). Such changes to urban landscape have caused alteration in the local climate. The most obvious indicator of the alteration in urban climate is the increase in urban air and surface temperatures, a well known effect of Urban Heat Island (UHI) (Arnfield, 2003). Alteration in urban climate and the increase in urban air and surface temperatures are directly affecting outdoor comfort conditions, which can be worsened by climate change events (Changnon, Kunkel, and Reinke, 1996; You et al., 2017). The lack of effective urban planning and design can further exacerbate this situation (Ali-Toudert and Mayer, 2007; Johansson and Emmanuel, 2006; Thani, Mohamad, & Jamaludin, 2013). Hence, human-biometeorological methods for the quantification of urban climatic impacts as well as to assess the effectiveness of adaptation and mitigation measures in improving outdoor conditions have become increasingly important (Ketterer and Matzarakis, 2014; Kuttler, 2011; Lee and Mayer, 2018a, 2018b; Lee et al., 2016; Wamsler, Brink, and Rivera, 2013).

For assessment of urban human-biometeorology and thermal comfort, detailed information of different parameters and processes governing micrometeorological conditions are required. These parameters and processes are often difficult to quantify in complex urban environments. Hence the use of numerical modelling has an advantage in which the involved parameters and processes are supplemented and enhanced with numerical calculations and simulations. A further advantage of numerical modelling is the ability to assess urban human-biometeorological and human thermal comfort conditions in relations to urban design and planning scenarios (Huang, Cedeño-Laurent, and Spengler, 2014; Lee and Mayer, 2018a, 2018b; Lee et al., 2016). However, modelling of microclimate often emerges with simplifications and limitations necessary to deal with the complexity of the urban environment (Ali-Toudert and Mayer, 2006; Thorsson, Lindberg, Eliasson, and Holmer, 2007).

The main feature for the modelling of microclimate is the determination of the 3D radiation fluxes for human beings and the calculation of the mean radiant temperature (T_{mrt}), one of the important parameters for the assessment of outdoor thermal comfort. Tmrt is the parameterization of the combined effect of short-and long-wave radiation fluxes absorbed by the human body. It is the basis of several human thermal indices, e.g., physiologically equivalent temperature (PET) (Höppe, 1999; H. Mayer and Höppe, 1987) and standard effective temperature (SET*) (Gagge, Fobelets, and Berglund, 1986). It is also considered the most spatially variable parameter compared to other parameters influencing thermal comfort. However, the issue of modelling the 3D radiation fluxes and the T_{mrt} is that the calculation procedures are based on simplified methods and formulas (Lee and Mayer, 2016; Naboni, Meloni, Coccolo, Kaempf, & Scartezzini, 2017). Thus, the modelling is not evident particularly in complex urban environments (Ali-Toudert and Mayer, 2006; Thorsson et al., 2007).

2. RAYMAN 1.2

RayMan1.2 is a spot-related software package used for the assessment of human bioclimate and outdoor thermal comfort (Matzarakis, Rutz, and Mayer, 2007, 2010). The inputs of the RayMan1.2 are meteorological data of air temperature, wind speed, water vapour pressure (relative humidity), global radiation and cloud cover, as well as inputs refer to urban morphology and others refer to features representative of a person. Furthermore, factors such as albedo, the Bowen ratio of the ground surface and turbidity of air can be adjusted in the RayMan1.2 software. Outputs of RayMan1.2 consist of the results of thermal indices for human-biometeorological conditions, as well as results of radiation fluxes and T_{mrt}. Also, with inputs of the geographical location and the temporal parameters, the RayMan1.2 software provides possibilities to simulate sun paths in fish-eye view, as well as shadow patterns presented in grid-layout at period of the day.

The simulation tool of RayMan1.2 software is implemented with several features. For example T_{mrt} can be treated as part of the inputs when available. In addition, the RayMan1.2 can handle the simulation based on approximated input, such as input of Sky View Factor (SVF) in a form of fish-eye photo. As the RayMan1.2 takes vegetation and building morphology into account, the ability to evaluate human-biometeorological situation and further the assessment of applying adaptation and mitigation measures, such as urban replanning, street design, or different types of vegetation, is the main advantage of the software (Matzarakis et al., 2007). The RayMan 1.2 software is easy to use and has fast running time and free. These advantages are reflected in the increased popularity of the software in urban microclimate and outdoor thermal comfort research e.g. (Holst and Mayer, 2011; R. L. Hwang, Lin, and Matzarakis, 2011; Krüger, Minella, and Rasia, 2011; Ndetto and Matzarakis, 2017; Niu et al., 2015).

Several researchers validated the performance of RayMan by performing the validation of T_{mrt} based on field measurements (Andrade and Alcoforado, 2008; Chen, Lin, and Matzarakis, 2014; R.-L. Hwang, Lin, and Matzarakis, 2011; Krüger, Minella, & Matzarakis, 2014; Lee & Mayer, 2016; Lin, 2009; Matzarakis et al., 2007, 2010; Thorsson et al., 2007). The validations showed discrepancies in the validation results, where in some studies the RayMan simulation was found consistently underestimates T_{mrt} and in other studies the RayMan simulation tends to overestimate T_{mrt}. In general, RayMan showed a good performance particularly under relatively simple urban settings. Increasing complexity of urban settings and the modelling of conditions where the sun elevation is low would reduce the accuracy of RayMan.

Most of these validation studies however have been conducted in moderate to high latitude locations. This study therefore aims to examine RayMan1.2 in estimating the T_{mrt} in tropical urban settings of Malaysia when compared with the six-directional radiation method. The validation of the comfort index PET simulated by RayMan1.2 is also performed.

3. MEASURING SITES

Measurement were performed at the University campus in the National University of Malaysia, in Bangi, Malaysia (2°.54'N, 101°.47'E). Two different sites were selected for the measurements. The first site is a closed inner courtyard located near seven-story building and a parking lot with SVF value of 0.38 (Figure 1-a). The second site is a semi-open space with horizon limitations and SVF value of 0.79 (Figure 1-b).

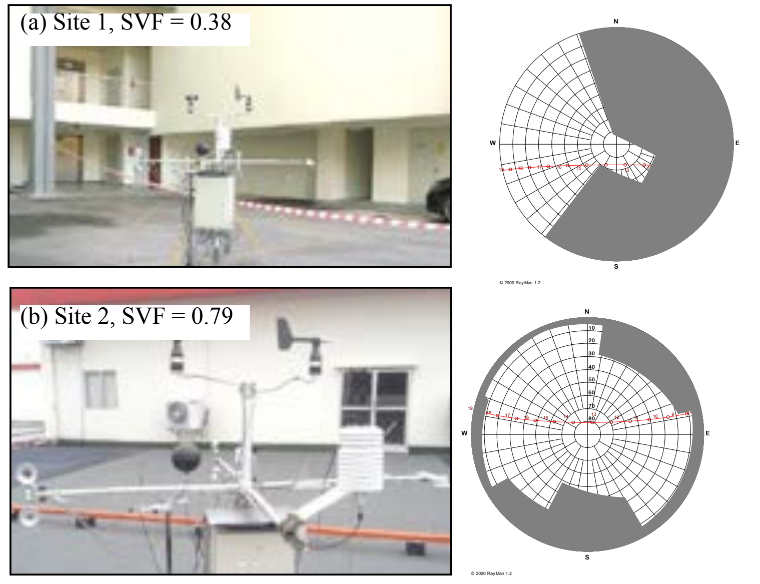


Figure 1 (a, b): Photographs of the measurement sites (left) and fisheye images (right) generated by RayMan1.2.

3.1 Measurements and Methods

Micrometeorological station and Measurements

The micrometeorological station shown in Figure 1(a, b) was equipped with instruments as defined in Table 1. This includes sensors to measure air temperature, relative humidity, and wind speed. Three net-radiometers, each consists of two pyranometers and two pyrgeometers, were set up on the station to measure the six-directional short and long-wave radiation fluxes. All instruments were fixed at a height of 1.1m a.g.l representing the height of the weighting center of a standing person (Thorsson et al., 2007). The recording interval was set to 1-min.

Table 1: Measured parameters and instruments

Quantity	Instrument	Accuracy & range
Air temperature, Ta	Skye inst. rht+ PT100 sensor	0.15°C - 0.35°C (-40 to +80°C)
Relative humidity, RH		Better than +2% RH (0-100 %)
Wind speed, Va	Delta OHM: AP3203 omnidirectional hot-wire	± 0.05 m/s (0.05-1 m/s) ± 0.15 m/s (1-5 m/s)
Short- and long-wave radiation fluxes, K, L	Delta OHM: LP NET 14 2 pyranometers, 2 pyrgeometers temperature sensor (NTC), and thermopiles	Pyranometers: 0-2000 W/m^2 Spectral range: 335 nm ÷ 2200 nm (95%) Pyrgeometers: -300 - +300 W/m^2 Spectral range: 5.5 µm ÷ 45 µm Working temperature: -40 °C - 80 °C

A total of three days of measurements were carried out at the sites: on 14 February 2017 at the site 1 and on 20 August 2017 and 25 February 2018 at the site 2. The measurements were recorded on each day from 8:00 to 21:00. The weather during the days brought hot, humid conditions with intense solar radiation and occasional cloudy skies. The average air temperature at the measured days was between 29.6 and 31.4°C and the average RH was between 55 and 60%. The average wind speed was < 1.8m/s. The average global radiation was between 450 and 550 W/m^2 and the highest recorded global radiation was 1160 W/m^2. These conditions are representative of the local tropical climate in Malaysia where there is no distinct seasons.

The six-directional method to calculate T_{mrt} and PET

An accurate determination of T_{mrt} is very difficult and mostly impossible in complex urban settings because this requires measurements of all short-and long-wave fluxes along with angle factors between a person and the surrounding. An alternative way to T_{mrt} is by limiting the measurements of radiation fluxes to only the six perpendicular directions surrounding a person, i.e., from four lateral directions, upwards and downwards (Holst and Mayer, 2011; Kántor, Kovács, and Lin, 2015; Lee, Holst, and Mayer, 2013; Helmut Mayer, Holst, Dostal, Imbery, & Schindler, 2008; Thorsson et al., 2007). To date this method is the most reliable measuring method to determine T_{mrt} (Kántor et al., 2015; Kántor, Lin, & Matzarakis, 2014; Lee et al., 2016). The six individual measurements of short-wave radiation fluxes Ki and long-wave radiation fluxes Li multiplied by the angle factors Fi between a person and the surrounding (i=1-6) are used to calculate the T_{mrt} following the Stefan–Boltzmann law in equation [1] (Thorsson et al., 2007):

$$T_{mrt} = \sqrt[4]{\frac{a_k \sum_{i=1}^{6} K_i F_i + a_l \sum_{i=1}^{6} L_i F_i}{a_l \sigma}} - 273.15$$

Where σ is the Stefan–Boltzmann constant (5.67×10^{-8} Wm^{-2} K^{-4}), α_k, α_l are the absorption coefficients for short-wave fluxes (standard values is 0.7) and long-wave fluxes (standard values is 0.97). To calculate T_{mrt} for a standing person, Fi is set to 0.22 for radiation fluxes from the lateral directions and 0.06 for upwards and downwards radiation fluxes (Thorsson et al., 2007).

The results of T_{mrt} by the six-directional method (T_{mrt} (rad.)) along with the meteorological data of air temperature, wind speed and water vapour pressure were used to determine the experimentally obtained PET.

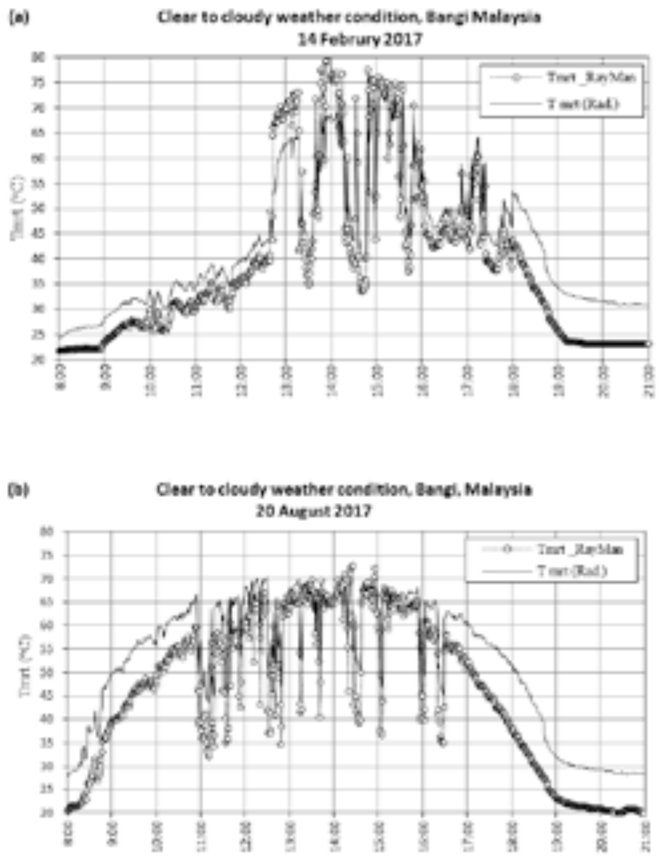
Application of RayMan1.2 to simulate T_{mrt} and PET

The meteorological data of air temperature, wind speed, water vapour pressure (relative humidity), global radiation and cloud cover were used as inputs in RayMan1.2 to simulate T_{mrt} and PET. The default values of the albedo, Bowen ratio and the ratio of diffuse and global radiation have been used. An input of the urban structures of the sites has been considered in RayMan1.2. The simulation results of Tmrt and PET were validated by comparison with the experimentally obtained results.

4. RESULTS AND DISCUSSION

Validation of the simulated T_{mrt} by RayMan1.2

As shown in Figure 2, the variations in T_{mrt} values during the middle of the measuring days can be explained by rapid changes in weather conditions from clear to cloudy conditions. The maximum values of the measured T_{mrt} were between 70-75ºC. The simulated Tmrt followed the same patterns over that time but with more fluctuation with maximum values between 75-80ºC. In morning and afternoon when the sun elevations were low, RayMan 1.2 software considerably underestimated T_{mrt} to about 10ºC in all the three days. By adjusting the default Bowen-ratio, albedo and the ratio of diffuse and global radiation for the local context, the RayMan 1.2 still underestimated T_{mrt} in morning and evening but drastically overestimated it during middle of the measuring days. Thorsson et al. (2007) reported similar results based on measurements and simulations done in the high latitude city of Göteborg, Sweden. Both reflected and diffused short-wave fluxes as well as the emittance of long-wave fluxes from the surrounding surfaces are important for the estimation of T_{mrt}. The formulation used by the RayMan to simulate the 3D radiation fluxes are simplified and does not consider the horizon (Lee and Mayer, 2016). These aspects should be considered for the determination of T_{mrt}.



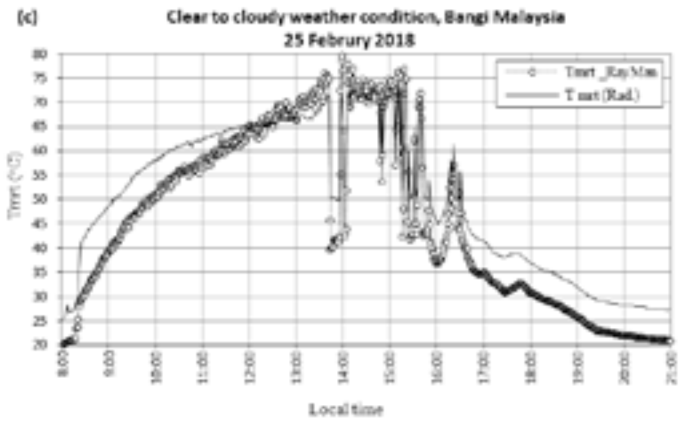
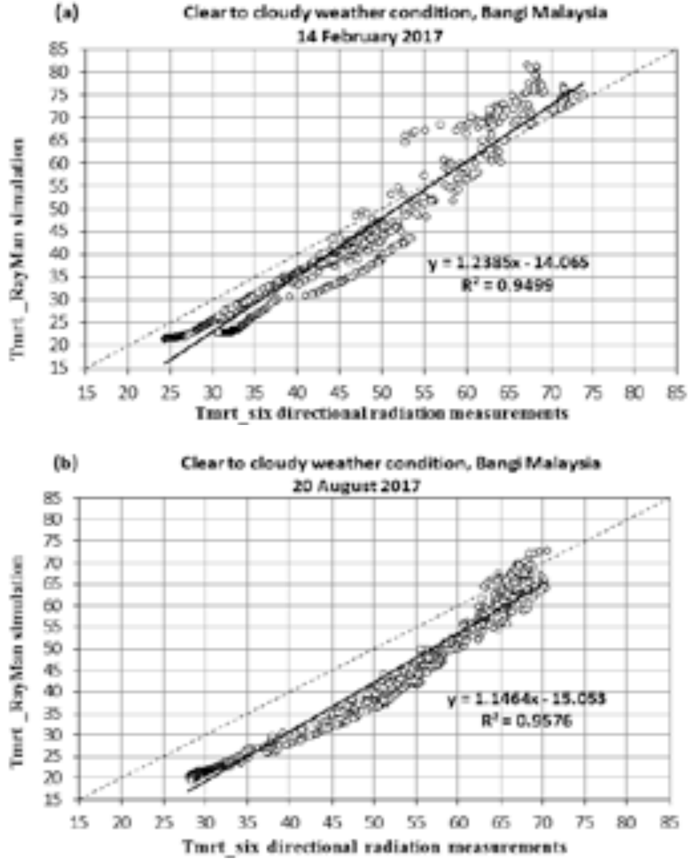


Figure 2 (a-c): Tmrt as calculated by six directional radiation method and the simulated T_{mrt} by RayMan1.2: (a) at the site 1; (b, c) at the site 2.

As shown in Figure 3 a-c the simulated and measured T_{mrt} values were strongly correlated, with R^2 values ranging between 0.95 and 0.97. It is evidence that the RayMan1.2 tends to underestimate T_{mrt} at lower ranges of Tmrt values, and overestimated it at higher ranges of T_{mrt} values. The magnitude of the T_{mrt} underestimation was higher than that of its overestimation particularly in site 2. Also in all three days the RayMan1.2gives a scatter in T_{mrt}. The scatter is increasing at higher ranges of T_{mrt}, i.e., at the middle of the days, which can be interpreted by rapid change in radiation fluxes by cloud appearing.

Furthermore, Figure 3 a-c indicates two differentiated systematic errors in the regressions between simulated and measured T_{mrt}. The simulation results show systematically lower T_{mrt} values at the site 2 compared to the site 1. Probably, the differentiated systematic errors reveal that the accuracy of RayMan1.2 is influenced by urban morphology and SVF. Since the modification of the 3D radiative fluxes (shortwave reflected radiation and longwave radiation) is highly correlated with SVF (Andrade and Alcoforado, 2008), the simplification to these aspects may result in such differences in the accuracy of RayMan1.2. Therefore, RayMan needs to be improved to consider the radiative fluxes for applications in simple and complex urban settings. Furthermore, the quantification of clouds in urban areas and the turbidity estimation need to be enhanced. Improvement of atmospheric turbidity for tropical environments is also important.



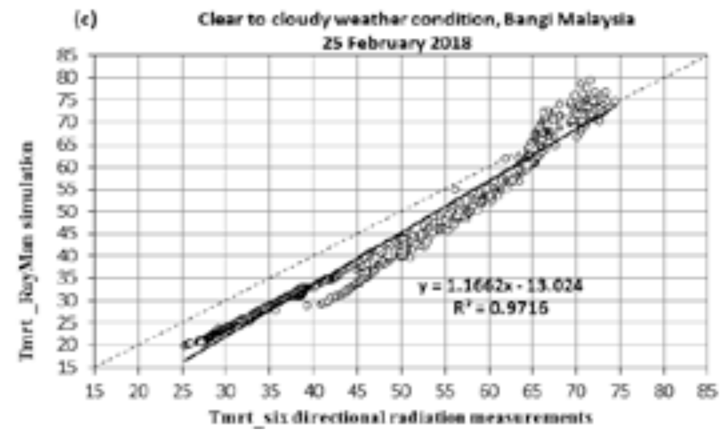


Figure 3 (a-c) : T_{mrt} as calculated by six directional radiation measurements vs. simulated by RayMan1.2: (a) at the site 1; (b, c) at the site 2.

Investigation of the effect of simulated T_{mrt} on thermo-physiological assessment.

The simulated results of PET by RayMan1.2 were validated by comparison with those obtained by experimental procedures. As shown in Figure 4, the scatter and systematic error in the regressions between simulated and measured PET followed the same pattern as the T_{mrt}. This was expected because T_{mrt} is the main factor affecting PET in outdoor environments. Nevertheless the simulated PET by RayMan1.2 is less affected by inaccuracy of the simulated T_{mrt}. The R^2 values ranging between 0.96 and 0.98 indicate stronger correlations between simulated and experimentally obtained PET. Also the simulated PET values have closer approximations to the experimentally obtained PET values particularly when high ranges of T_{mrt} values occurred. The modification in the radiative fluxes has less effect on PET because the thermo-physiological index is also depending on other thermal comfort factors; namely, air temperature, water vapour pressure, air speed, human clothing and activity. Increasing the accuracy of the simulation of PET index requires accurate estimates of all these factors including T_{mrt}.

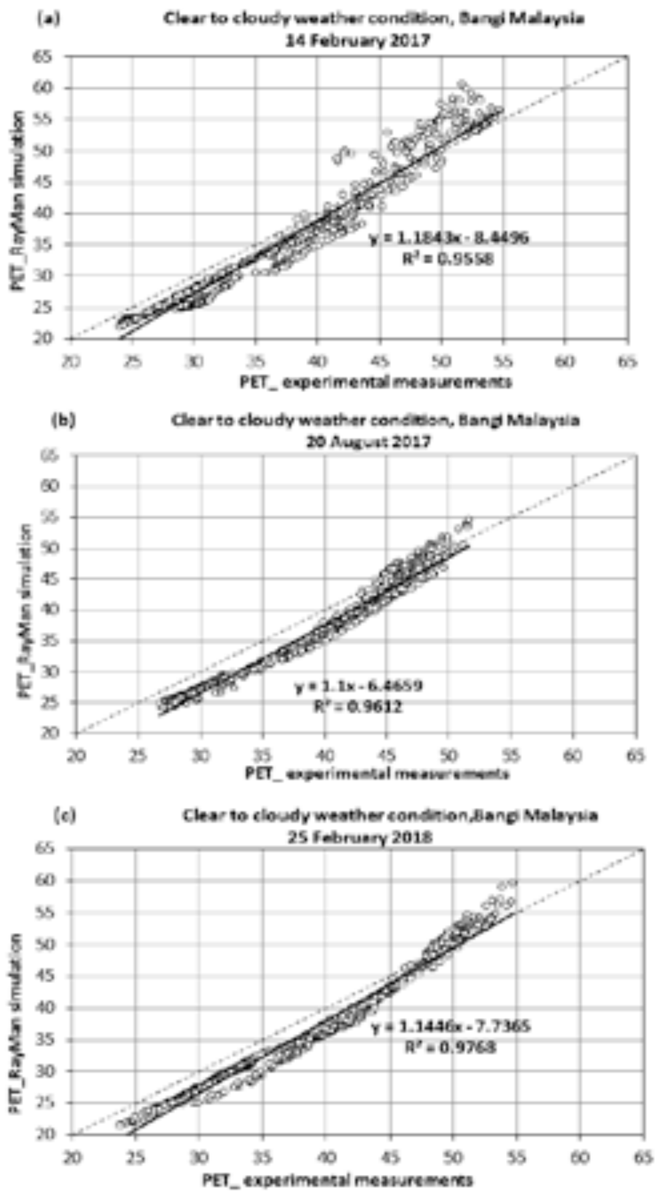


Figure 4 (a-c): PET as calculated by experimental data vs. simulated by RayMan 1.2: (a) at the site 1; (b, c) at the site 2.

5. CONCLUSION

In this study the RayMan1.2 software was validated by comparison with field measurements for the tropical outdoor urban environment. As the T_{mrt} can be determined by field measurements and modelling, the consistency between measured and simulated T_{mrt} was utilized as a criterion for the validation of the RayMan1.2 software. The simulated T_{mrt} results by the RayMan1.2 software were compared with the six-directional radiation method as a reference method. The results are for three day at two different sites in a tropical urban environment.

The study shows that RayMan1.2 software gives reasonable results during the middle of the day. However, in morning and late afternoon the RayMan1.2 drastically underestimates T_{mrt} data. The study also shows that the software simulation of different urban settings leads to different systematic errors depending on the urban morphology and SVF. The reflected and diffused shortwave fluxes as well as the long-wave fluxes from the surrounding surfaces, which are highly correlated with urban morphology, are simplified by RayMan1.2 (Lee and Mayer, 2016 ; Naboni et al., 2017). The results suggest that the accuracy of RayMan1.2 may be dependent on SVF, i.e., the simulation for spaces with different SVFs may achieve different levels of accuracy.

The effect of the simulated T_{mrt} on the thermo-physiological index PET is also analyzed. The index has been chosen for validation because it has been employed in several studies of outdoor thermal comfort. The simulated PET values from RayMan1.2 software followed the same pattern of the simulated T_{mrt}. Nevertheless the simulated PET values have a closer estimation to the experimentally obtained PET. In addition, the RayMan1.2 gives slightly less scatter in PET in comparison to Tmrt.

Therefore, based on the results of the validation, improvements to the RayMan1.2 simulation for the short- and long-wave radiant flux densities from the surrounding 3D environment is required. Moreover, there are some other parameters whose assessments have to be improved; e.g. the quantification of the clouds and atmospheric turbidity.

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PRELIMINARY EVALUATION OF AIR FLOW IN ATRIUM OF BUILDING IN HOT AND HUMID CLIMATE

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ABSTRACT

Atrium is one of the passive design strategies that is known to have certain effects to the indoor environment of a building. These effects can be beneficial or detrimental, depending on the atrium design in response to the climate where it is located. One of the important criteria for designing a building in hot and humid climate is the ventilation aspect. Hence, this study was executed to investigate the air flow in an atrium of a building in hot and humid climate. The investigations were executed using numerical simulation method, which was validated by field measurement. The software used for the numerical simulation was Computational Fluid Dynamic (CFD) which was ANSYS CFX v14.5. The findings indicated that the existence of more air flow paths such as the access corridors that connect the atrium with the outdoor will able to enhance the air velocity inside the atrium. However, further investigations need to be executed in order to improve the air flow inside the atrium. The results and findings from this study will benefit the people in building industry as they provide initial idea on the design strategy of atrium that is appropriate for hot and humid climate.

Keywords: : Atrium; air flow; hot and humid climate

1. INTRODUCTION

Atrium can be defined by three characteristics, which are 1) a small court in a Roman House surrounded by a roofed area or roofless opening in the centre; 2) an open court surrounded by a roofed arcade or colonnaded walk, and 3) a top-lit internal space that is surrounded by several storeys (J. S. Curl, 2006). Therefore, from the definition give, an atrium can be either roofed or roofless. It is slightly different from a courtyard and an air well, where a courtyard is an open area surrounded by walls or buildings (J.S. Curl, 2006), while an air well also has openings, which normally located on top, that allow the air to flow in and out from the building.

Atrium is widely applied all over the world. It is always incorporated in large buildings such as shopping malls, office headquarters and hotels. This is due to many benefits provided by atrium, whether environmental or social benefits. Atrium is normally located at the front part of a building, and it becomes as a welcoming or introductory space that usually portrays the image of the building. Due to its significant role, atrium also becomes an area for socializing, gathering, and conducting activities such as exhibition and performance. Besides social benefits, atrium also contributes to the controlling of indoor environment of a building.

1.1 Previous Studies Related to Atrium

The energy performance of atrium has already been investigated since 1980s. Besides energy performance, among the parameters that are always examined in the previous studies of atrium are shading configuration, roof aperture, type of glazing, ventilation strategies, envelope properties, characteristics of adjacent spaces, geometry and orientation (Wang, Huang, Zhang, Xu, and Yuen, 2017) . All these parameters affect the indoor environmental quality of an atrium such as the lighting, ventilation, air temperature and air quality.

Among the previous studies of atrium are Acred and Hunt (2014), Abdullah and Wang (2012), Chu, Sun, Jing, Sun, and Sun (2017), Ghasemi, Noroozi, Kazemzadeh, and Roshan (2015), Huang, Borong, Yao, and Yingxin (2015) and Acosta, Varela, Molina, Navarro and Sendra (2018). The buoyancy induced ventilation in an atrium of a multi-storey building was investigated by Acred and Hunt (2014). In the study, a glazed atrium was connected to multi-storey spaces, and functioned like a solar chimney as there was opening on top that allowed the air to flow out. The study found that the stack pressure that drove the ventilation was lesser at the upper floor spaces. Meanwhile, Abdullah and Wang (2012) investigated the atrium designs in the tropics which were top-lit and side-lit, as well as with and without clerestory windows. The study indicated that the side-lit atrium with clerestory windows provided better thermal comfort than the fully transparent top-lit atrium. Meanwhile, the air distribution and comfort condition of an atrium that was incorporated with radiant floor heating was examined by Chu et al. (2017).

The daylighting in atrium was studied by Ghasemi et al.(2015), Huang et al.(2015) and Acosta et al. (2018). In the study by Ghasemi et al. (2015), it was found that the increase of clerestory windows' height resulted in the escalation of average daylight factor in the atrium and its adjoining spaces. Huang et al. (2015) investigated the daylighting effects on double atriums, while the study by Acosta et al. (2018) provided recommendation on a rapid and precise method for determining daylight factor of a rectangular courtyard or the central space of an atrium.

Besides the worldwide study and application of atrium, this strategy is also becoming popular in Malaysian buildings due to the benefits mentioned above. However, some of the atriums have been designed to imitate those that are applied in cold and temperate climates. This is because some building projects regard atrium for spatial and aesthetic functions only, and neglect its environmental effects, especially the thermal effect (Abdullah and Wang, 2012).

1.2 Issues Related to Atrium in Hot and Humid Climate

An atrium that is fully glazed has the tendency of increasing the energy load due to greater solar heat gain during summer, and heat loss during winter (Yasa, 2015). Hence, for the hot and humid climate countries like Malaysia, the usage of glass in atrium should be balanced between the daylight amount needed and the solar heat gain. In addition, there are two effects provided by atrium, namely the greenhouse effect and the chimney effect. The greenhouse effect provides positive role during winter, and negative role during summer. Meanwhile, the chimney effect is opposite to the greenhouse effect (Chu et al., 2017). For hot and humid climate countries like Malaysia, the chimney effect is more desirable in allowing the hot air to flow out from the building.

There are three type of ventilation modes usually applied in atrium, namely natural ventilation, mechanical ventilation, and hybrid ventilation which combines mechanical and natural ventilation modes. The examples of mechanical ventilation mode are the utilization of mechanical fan and air conditioning. For an atrium that is fully ventilated by air-conditioning, there is normally no aperture at the roof level, and sometimes the atrium area is made to be air tight. With most of the roof areas finished using glazed materials, such condition provides an atrium with greenhouse effect instead of chimney effect. As the result, the cooling load increases, thus escalating the energy usage of the building.

In an air-conditioned atrium of Malaysian building, the indoor air temperature and relative humidity for thermal comfort are between the range of 20.8 °C to 28.6 °C and 40 % to 80 %, respectively (Abdullah and Wang, 2011). However, for a naturally ventilated atrium, the maximum range can be slightly higher. This depends on the activity level and the presence of air movement, which is generally between 0.5 m/s to 1 m/s (Abdullah and Wang, 2011). This is also in agreement with the study of thermal comfort in naturally ventilated atrium conducted by Yusoff (2017). The study indicated that the presence of air velocity between 0.9 m/s to 1.3 m/s had improved the thermal comfort condition inside the atrium. Although people felt slightly warm during the afternoon hours, they were still satisfied with the indoor thermal condition. Meanwhile, the study by Yusoff (2006) had found that lower air velocity was needed to achieve thermal comfort for sedentary activities in hot and humid climate, which was 0.8 m/s. This is also in accordance with Cândido, de Dear and Lamberts (2011) who stated that the presence of air velocity higher than 0.81 m/s was able to enhance thermal comfort for indoor air temperature between 29 °C to 31 °C.

The implementation of natural ventilation in atrium should be promoted as there are many benefits derived from it. Among them are the reduction of energy consumption, and the improvement of users' health via internal air renewal (Sacht and Lukiantchuki, 2017). In a naturally ventilated atrium, normally alternative such as mechanical fan is provided in case the atrium's indoor environment does not achieve thermal comfort (Yusoff, 2017). However, with the correct strategies of natural ventilation, the atrium's indoor environment may achieve thermal comfort, especially with the presence of sufficient air velocity.

Due to the concern for wrong atrium strategy applied in the hot and humid climate of Malaysia, this study intends to examine the air flow inside the atrium with various numbers of access corridors. The access corridors are selected due to the current scenario where they are normally regarded as the pedestrian walkways that connect the atrium with the outdoor, without considering their importance in functioning as air flow paths. These corridors act as air flow paths that connect the atrium with the outdoor environment. The access corridors are able to create Venturi effect, as they provide constricted areas for the air flow. In Venturi effect, there is a reduction in the fluid pressure and an increase in the fluid velocity when the fluid passes through a constricted area (Fox and McDonald, 1998). In this study, the wind that hits the building facade will be channeled into the access corridors. The air velocity of the wind increases as it has to flow into a smaller area compared to the previous area. Therefore, it is expected that there is velocity increase of the air that flows into the atrium.

In a naturally ventilated atrium, the wind and buoyancy driven ventilations are able to remove the heat that is accumulated at the top of the atrium (Abdullah and Wang, 2012). Nevertheless, the presence of both, the wind and buoyancy driven ventilations will either be beneficial or detrimental to the air flow inside the building, as it depends on many factors such as the positions of inlet and outlet (Yusoff, 2010). However, for this preliminary evaluation, the investigations are focusing on the wind driven ventilation only, where the result analyses, discussion and conclusion are purely based on this wind driven condition. The reason for considering the wind driven ventilation only is because this study is a preliminary investigation conducted with the purpose of deriving an initial idea on how the access corridors affect the air flow inside an atrium. The findings from this study are hoped to provide knowledge that can benefit many people in designing atriums, especially in hot and humid climate. Though this study does not provide a total solution to the right atrium strategy for hot and humid climate, at least it is hoped to give initial idea on the air flow inside the atrium.

2. RESEARCH METHODOLOGY

The research methodology employed in this study was numerical simulation. The CFD software used for the numerical simulation was ANSYS CFX v14.5. This CFD software is able to simulate fluid flow, heat and mass transfer, chemical reactions and other related cases. The results derived from the simulation of this software are relevant in many areas such as conceptual studies of new design, detailed investigation of product development as well as troubleshooting and redesign for betterment. The solvers of this software are based on the disintegrating of a fluid region into a finite set of control volumes. In this set of control volumes, the general conservation equations for mass, energy, momentum and many more are solved.

In ensuring the reliability of the CFD results, the numerical simulation needs to be validated against the experimental data (Ai and Mak, 2018). The validation of the numerical simulation procedures used in this study was already executed and presented by the authors in Muhsin, Yusoff, Mohamed and Sapian (2017). The validation was executed by comparing the numerical simulation results with the field measurement data. The field measurement was conducted at a Malaysian affordable multistorey housing located in Bandar Baru Bangi, Selangor.

The measuring tools utilized were a weather station (P5), two units of air velocity meter (P1 and P4) and two units of thermal comfort meter (P2 and P3). The weather station was placed at the building's rooftop, while the other measuring tools were located in one of the house units and the void area near the selected house unit. The weather station was able to measure the wind direction and wind speed, whilst the other measuring tools were utilized to measure the indoor air velocity. The measurement was executed for 22 days in March 2015 (Muhsin et al., 2017).

Upon deriving data from the field measurement, the similar condition was then developed in the numerical simulation using CFD software ANSYS CFX v14.5. The validation results showed good agreement between the numerical simulation and field measurement as the percentages of deviation were less than 20%, which was an acceptable percentage by the previous studies (Muhsin et al., 2017). The validation results of numerical simulation against field measurement as conducted in Muhsin et al. (2017) are demonstrated in Table 1.

Table 1: The validation results of numerical simulation against field measurement (Muhsin et al.(2017)

Label	Measuring tools	Location	Field measurement results (m/s)	Numerical simulation results (m/s)	Difference	Deviation (%)
P1	Air velocity meter	Sliding door	0.95	0.86	0.09	9.47
P2	Thermal comfort meter	Living	0.16	0.18	0.02	12.5
P3	Thermal comfort meter	Entrance door	0.82	0.68	0.14	17
P4	Air velocity meter	Void	0.56	0.62	0.06	10.7
P5	Weather station	Roof top	1.7	1.48	0.22	12.9

*The data was already presented in Muhsin et al. (2017) in graph format. With the permission, the data is represented in table format for this journal.

For the numerical simulation of this study, the similar procedures in Muhsin et al. (2017) were applied. The differences were just in the building's height, where in Muhsin et al. (2017), the building was seven storeys height, while in this study, the building's height was limited to four storeys only. In addition, the simulation in this study also had limitation where no adjacent building was included. Nevertheless, the building was considered to be in a suburban area by applying the exponent value of the atmospheric boundary layer (ABL) wind profile for a suburban condition. This was also similar to the condition applied in Muhsin et al. (2017). The grid sensitivity test had also been conducted and presented in Muhsin et al. (2017). Hence, in the present numerical simulation, the similar grid characteristic was applied.
For the preliminary evaluation, the study focused on the wind driven ventilation only, without considering the buoyancy effect. The turbulence model used for this investigation was the standard k-epsilon (k-ε), which was widely used in the previous studies also (Muhsin et al., 2017;Montazeri and Montazeri, 2018). Cheung and Liu (2011) conducted a thorough investigation on the reliability of standard k-ε turbulence model for natural ventilation simulation. The findings of the study indicated positive results for cross ventilation performance. Besides Cheung and Liu (2011), other studies that employed k-ε turbulence model in the natural ventilation simulation were Shirzadi, Naghashzadegan, and Mirzaei (2018), Yang and Jian (2017), Yusoff, Sapian, Salleh, Adam, Hamzah and Mamat (2014), Yusoff, Sapian, Salleh, Adam and Hamzah (2014) and Yusoff, Sapian, Salleh, Adam and Johar (2015).

The numerical simulation in this study also employed steady-state airflow, and the ABL wind profile was set to have an exponent value of 0.28 (α = 0.28), which was the value for suburban condition. This value was selected by referring to the location of building in the field measurement that was within the suburban area. The power law equation used for the ABL is as follows:

$$\frac{y}{y_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha} \quad [1]$$

Where y is the wind speed (m/s) measur ed at the height of z (meter). Meanwhile, in this study, the wind speed yref was set to be 1 m/s, at the height, Zref of 10 meter. For this preliminary evaluation, the wind was set up to be from two directions only, which were 0° and 45° wind angles. The windward and the leeward distances were set based on the building height (H), in which the windward distance was five times of the height (5H), while the leeward distance was ten times of the height (10H), as shown in Figure 1(a). These were the minimum leeward and windward distances proposed by Montazeri and Montazeri (2018) and Tominaga et al.(2008) in determining the domain size. The building and ground surfaces were set to be no slip wall condition. The meshing used in this simulation was tetrahedron meshes, as shown in Figure 1(b). The tetrahedron meshes were also utilized by Cheung and Liu (2011) and Farea, Ossen, Alkaff and Kotani (2015) in their natural ventilation investigations. In this study, the maximum number of iteration was set up to be 1000.

(a)

(b)

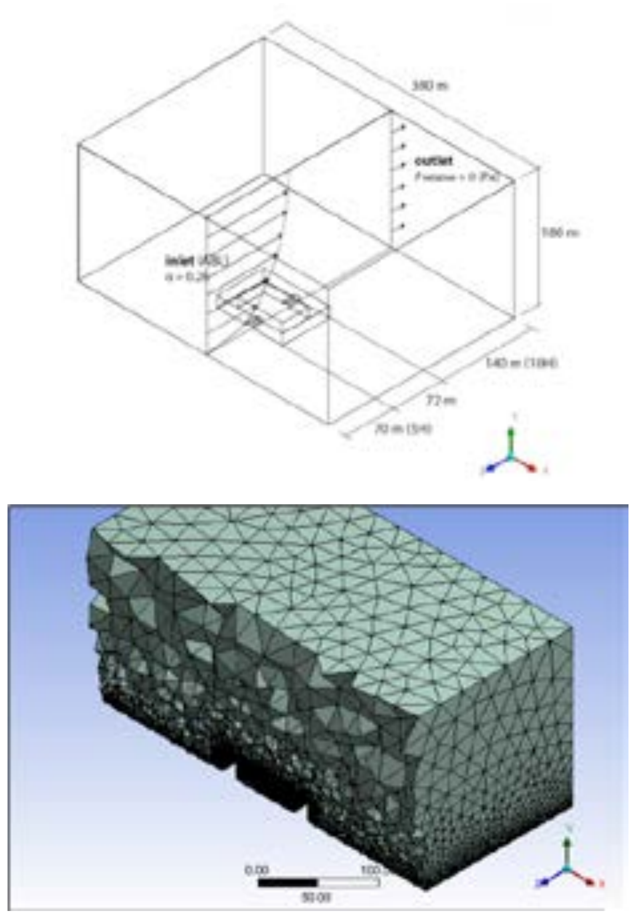
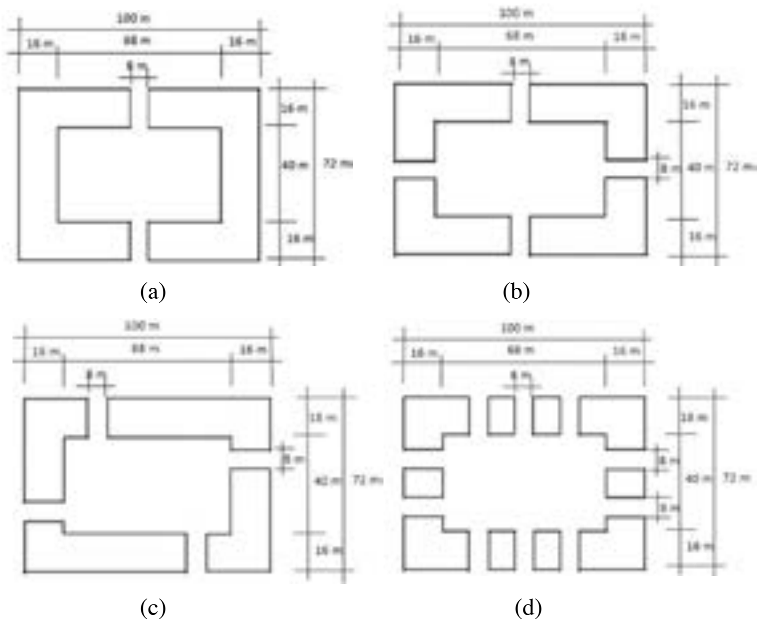


Figure 1: (a) The boundary condition set up for the simulation, and (b) the tetrahedron meshes

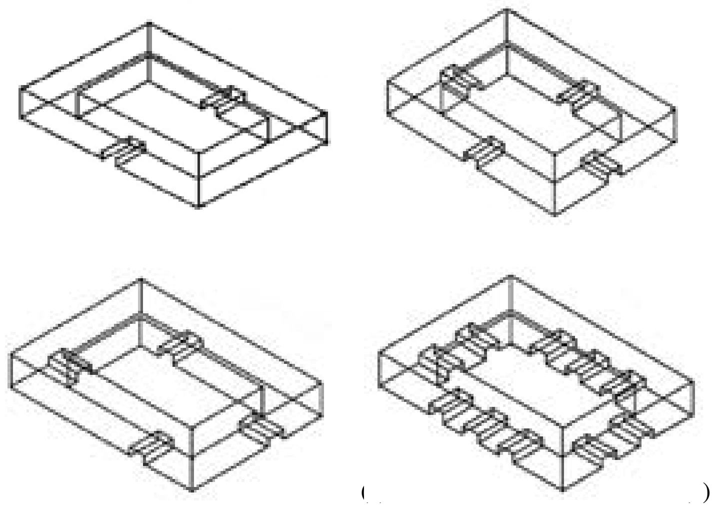
The building model constructed in the simulation consists of an atrium that is located in the middle. It is considered an atrium, and not a courtyard or an air well, as the top of the space is covered by a roof. As mentioned before, the investigation in this study focuses on the wind driven ventilation only, without any consideration of thermal factor. Therefore the top of the atrium is only specified as having a flat roof, with no materials specified for the roof. The investigated atrium was rectangular shape, with the dimensions of 68 m length, 40 m width and 14 m height (Figure 2). The size of the atrium was referred to the previous atrium, located in Bangi Gateway Shopping Mall, that was investigated by the author in Yusoff (2017). The atrium was surrounded by other spaces, and was accessed by corridors that also functioned as air flow paths. The dimensions of the access corridors were 16 m length, 8 m width and 4 m height (Figure 2).



(a) (b) (c) (d)

Figure 2: The plans that indicate the dimensions of the atriums with (a) two access corridors, (b and c) four access corridors, and (d) ten access corridors

The numerical simulation consisted of three stages. The first stage simulation encompassed the investigations executed for two conditions of atrium, which were the atrium with two access corridors, and the atrium with four access corridors. The access corridors were located opposite to each other (Figures 3(a) and (b)). The second stage simulation involved the atrium with four access corridors only. This was due to the findings derived from the first stage simulation, where the higher amount of corridors resulted in greater air velocity. In the second stage simulation, the access corridors were relocated to be not opposite to each other (Figure 3(c)). Meanwhile, in the third stage simulation, the number of access corridors had been increased to ten numbers (Figure 3(d)). The purpose was to obtain larger distribution of high air velocity inside the atrium. Nevertheless, all the corridors had similar dimensions and volumes in all stages of simulations.



( )

Figure 3: The axonometric views of the atriums with (a) two access corridors, (b and c) four access corridors, and (d) ten access corridors

3. RESULTS AND DISCUSSION

The results and discussion were presented for all the three stages of numerical simulations. The results and findings from the first stage simulation influenced the next steps conducted in the second stage simulation. Meanwhile, the third stage simulation was executed due to further enhancement needed to the air velocity resulted from the second stage simulation.

3.1 Numerical Simulation Stage 1

Figures 4 and 5, as well as Tables 1 and 2 indicate the results derived from the first stage simulation. The results of air velocity contours for atrium with two and four access corridors, simulated with 0° wind angle were depicted in Figure 4. Meanwhile, the results of air velocity contours for the similar atrium configurations, simulated with 45° wind angle were demonstrated in Figure 5. The air velocity contours were plotted at the height of 1 meter from the ground level. This height was selected as it is within the height of human scale.

(a) (b)

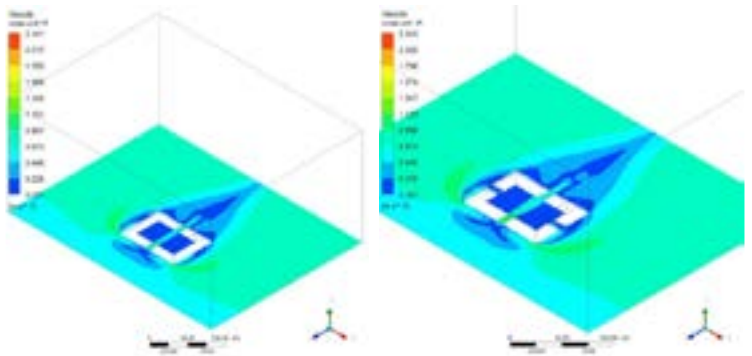
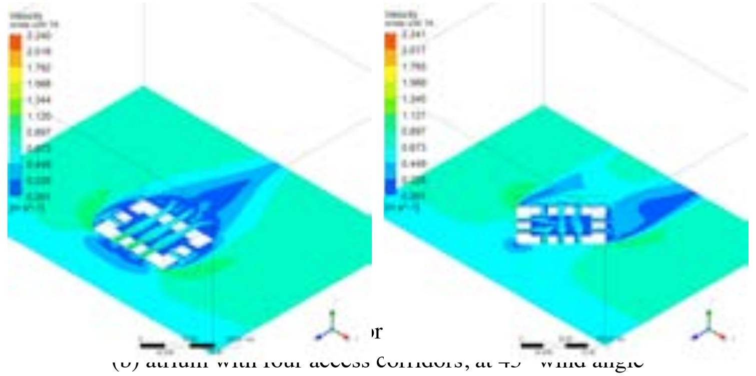


Figure 4: The air velocity contours for (a) atrium with two access corridors, and (b) atrium with four access corridors, at 0° wind angle

From the Figure 4, it can be seen that higher air velocities were concentrated at the centre of the atrium for both; the atrium with two, and four access corridors. This was due to the Venturi effect created inside the corridor. However, the other areas of both atriums suffered low air velocities, which were less than 0.2 m/s. For the atrium with four access corridors (Figure 4b), the side facades experienced negative pressure which resulted in low air velocities that flowed in via the side corridors. However, for 45° wind angle, the atrium with four access corridors had more areas with air velocities of more than 0.4 m/s compared to the atrium with two access corridors (Figure 5).

(a) (b)



(b) atrium with four access corridors, at 45° wind angle

The comparison of average air velocities measured at the height of 1 meter, and at the centre point of the atrium indicated that for 0° wind angle, the atrium with four access corridors experienced higher average air velocity compared to the atrium with two access corridors, as shown in Table 2. However, in contrary, it was found that for the wind angle of 45°, the average air velocity (at 1 meter height, and at the centre of atrium) in the atrium with two access corridors was higher than the atrium with four access corridors (Table 2).

Nevertheless, the average air velocity of the whole area measured at 1 meter height was found to be higher inside the atrium with four corridors compared to the atrium with two corridors, as shown in Table 3. However, it seems that there were not much differences between the average air velocities inside the atrium with two and four access corridors, for both wind angles. Moreover, referring to Figures 4 and 5, it seems that there were many areas that suffered low air velocities which were less than 0.2 m/s for both atriums, and both wind angles. The higher air velocities only occurred along the air flow paths between the inlets and outlets.

Table 2: The average air velocities measured at 1 meter height from the ground level, and at the centre of the atrium

Wind Angle	Air Velocity (m/s)	
	Atrium with two access corridors	*Atrium with four access corridors*
0° wind angle	0.683 m/s	0.844 m/s
45° wind angle	0.635 m/s	0.487 m/s

Table 3: The average air velocities of the whole atrium area measured at 1 meter height from the ground level

Wind Angle	Air Velocity (m/s)	
	Atrium with two access corridors	*Atrium with four access corridors*
0° wind angle	0.673 m/s	0.675 m/s
45° wind angle	0.685 m/s	0.695 m/s

The results from the first stage simulation (Tables 2 and 3) show that in average, the air velocities were higher inside the atrium with four access corridors. However, the differences of air velocities between both atriums were insignificant, as in average, the differences were approximately 0.2 m/s and lower. In addition, the average air velocities inside the atrium with four access corridors were also lower than 0.8 m/s, except at the centre of the atrium for 0° wind angle. Therefore, further numerical simulation was executed in the second stage simulation with the purpose of searching ways to enhance the air velocity and air distribution inside the atrium.

3.2 Numerical Simulation Stage 2

In the second stage simulation, only the atrium with four access corridors was selected. The access corridors were arranged to be not opposite to each other as depicted in Figure 3(c). Nevertheless, the sizes and dimensions of the access corridors and atrium were still similar to the first stage simulation (Fig 2(c)). The results of second stage simulation were shown in Figure 6 and Table 4.

Figure 6 demonstrated the air velocity contours distribution inside the atrium for 0° and 45° wind angles. For 0° wind angle (Figure 6(a)), it can be seen that high air velocities still concentrated within the corridors and the air flow path outside the corridor that faced the wind direction. Outside the mentioned area, the air velocities were very low. The average air velocity measured at the centre of the atrium and 1 m height from the ground level was 0.101 m/s (Table 4). In addition, the air velocities at most of the atrium areas were below 0.2 m/s, which were represented by the dark blue colour. Meanwhile, the average air velocity for the whole atrium area measured at 1 m height from the ground level was 0.543 m/s (Table 4).

For the 45° wind angle (Figure 6(b)), the air velocity contours seemed to be distributed wider inside the atrium, though the average air velocity values were only 0.082 m/s (measured at the centre of atrium and 1 m height from the ground level), and 0.579 m/s (for the who le atrium area measured at 1 m height from the ground level).

(a) (b)

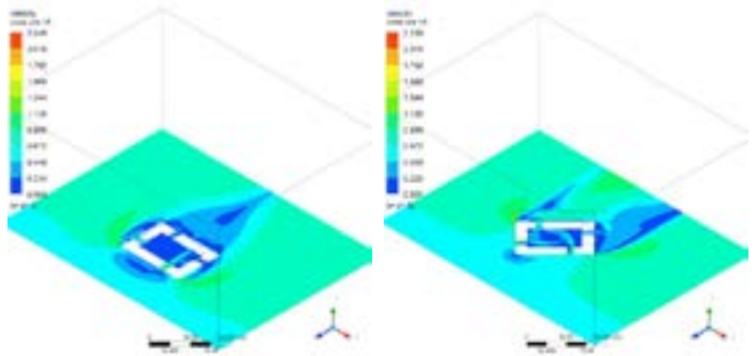


Figure 6: The air velocity contours in atrium with four access corridors that were located not opposite to each other for (a) 0° wind angle, (b) 45° wind angle

Table 4: The average air velocities inside the atrium with four access corridors that were located not opposite to each other

Wind Angle	Air Velocity (m/s)	
	Centre of atrium measured at 1m height from ground level	*Whole atrium area measured at 1 m height from ground level*
0° wind angle	0.101 m/s	0.543 m/s
45° wind angle	0.082 m/s	0.579 m/s

From the second stage simulation, the findings show that such arrangement of access corridors were able to distribute wider air velocities of higher than 0.2 m/s for 45° wind angle. However, the amount of average air velocity for the whole atrium area measured at 1 m height from the ground level was still lower compared to the first stage simulation. Therefore, further simulation was executed, which was the third stage simulation, in searching the strategy to enhance air velocities inside the atrium with access corridors.

3.3 Numerical Simulation Stage 3

In the third stage simulation, the amount of access corridors had been increased, as shown in Figure 3(d). Nevertheless, the sizes and dimensions of the access corridors and atrium were still similar to the first and second stage simulations (Figure2(d)). The results derived for the third stage simulation were shown in Figure 7 and Table 5. Figure 7 indicates the air velocity contours inside the atrium with ten access corridors, for both, 0° and 45° wind angles. It was found that there was greater distribution of air velocities more than 0.45 m/s inside the atriums for both wind angles. The results also indicated that for 0° wind angle, the average air velocity was found to be more than 0.8 m/s at the centre of the atrium. Meanwhile, the average air velocities for the whole atrium area measured at 1 m height from the ground level were found to be more than 0.5 m/s for both wind angles (Table 5). Though the velocities of air inside the atrium with ten access corridors were found to have not much differences with the other atriums, the advantage of this configuration was in term of the air velocity distribution. The findings show that greater amount of access corridors resulted in wider distribution of higher air velocities inside the atrium.

(a) (b)

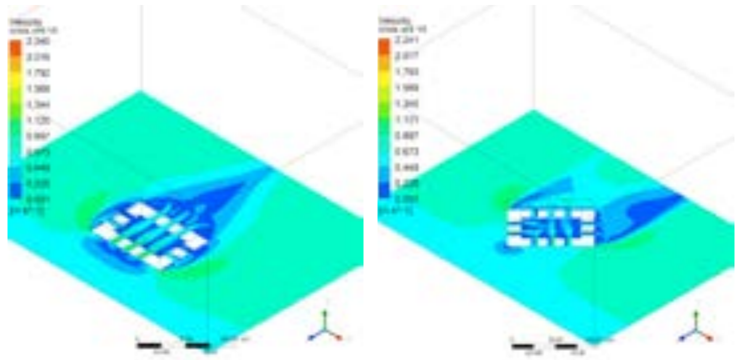


Figure 7: The air velocity contours in atrium with ten access corridors, for (a) 0° wind angle, and (b) 45° wind angle

Table 5: The average air velocities inside the atrium with ten access corridors

Wind Angle	Air Velocity (m/s)	
	Centre of atrium measured at 1m height from ground level	*Whole atrium area measured at 1 m height from ground level*
0° wind angle	0.101 m/s	0.543 m/s
45° wind angle	0.082 m/s	0.579 m/s

From the findings of all simulation stages, it can be summarized that the access corridors create Venturi effect which enhances the velocities of air that flow into the atrium. Based on the power law equation used for the ABL in this simulation, the outdoor wind speed at the height of 1 meter from the ground level was found to be approximately 0.5 m/s.

For 0° wind angle, it was found that the average air velocities for the whole atrium area, measured at 1 m height from the ground level, were more than 0.5 m/s. In addition, the average air velocities at the centre of atriums with four and ten access corridors had achieved more than 0.8 m/s, which was the recommended air velocity to obtain thermal comfort for sedentary activities in hot and humid climate (Yusoff, 2006;Cândido et al., 2011). For 45° wind angle, the average air velocities for the whole atrium areas, measured at 1 m height from the ground level, were also found to be more than 0.5 m/s. Therefore, it is believed that the velocity of air inside the atrium may increase with the increasing of outdoor wind speed.

4. CONCLUSION

The findings from the investigations of air flow inside atriums with two and four access corridors indicate that the increase number of access corridors that connect the inside and outside, and function as air flow path, will result in higher air velocities inside the atrium. However, the findings also demonstrate that higher air velocities are just concentrated at the area where the corridors are located, and along the air flow paths between the inlets and outlets. This is due to the Venturi effect created inside the corridors. Meanwhile, the areas inside the atrium that are far from the corridors and air flow paths between the inlets and outlets suffer low air velocity. Therefore, in ensuring wider distribution of higher air velocities inside the atrium, it is suggested to allocate as many amount of access corridors as possible. The appropriate locations of the access corridors can be decided based on the area or space functions, as well as activities inside the atrium.

The findings from this study is expected to create awareness among the people in built environment such as designers, building owners, developers and many others, to highly consider the importance of appropriate amount and location of air flow paths in the atrium design. This is due to the current situation where the access corridors in atrium are just being regarded as the pedestrian walkways, without considering their importance in determining the air flow inside the atrium.

The study in this paper focuses on wind driven ventilation only, without considering buoyancy effect. Therefore, it is recommended in future to extend the investigations by examining the effects of both; the wind and buoyancy driven ventilations, to the air flow inside the atrium. The atrium with openings at the top level creates chimney effect, which is desirable for hot and humid climate.

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SKEWED WIND FLOWS ENERGY EXPLOITATION IN BUILT ENVIRONMENT

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ABSTRACT

Currently the available wind energy devices, either the horizontal or vertical axis wind turbines, are designed to operate in orthogonal wind flows to generate power. However, in an urban environment, the vertical axis wind turbine is thought to be better suited for building integrated applications due to its durability and better performance in skewed and turbulent flows compared to the more common horizontal axis wind turbine. Application of wind turbines in skewed flow is a subject of increasing interest due to the improved power output of turbines in this wind condition. Skewed flow in the built environment can be referred to as the deflected wind vector at the roofs or edges of buildings that is not horizontal. Therefore, there exists a potential for better diffusion of renewable energy in the urban built environment, especially in the implementation of vertical axis wind turbines on buildings. This paper provides a critical review of the skewed wind flow phenomena, the physical characteristics of the interaction between the skewed flow with the vertical rotor, and the state-of-the-art studies of wind energy devices in skewed flow, especially in the built environment.

Keywords: : Building integrated wind turbine, On-site power generation, Skewed wind flow, Urban energy, Wind energy

1. INTRODUCTION

Developments on small wind turbines for urban areas have gained much attention due to the rising concern in global energy issues. Wind energy is recognized as a potential source of free, clean and inexhaustible energy, especially for use in urban cities where it is urged to place wind turbines closer to populated areas due to the decreasing number of economic sites (Fazlizan, Chong, Yip, Hew, and Poh, 2015; Wagner, Bareiß, and Guidati, 1996). A wind turbine is a device that converts energy from the wind into electrical power that can be used for various applications. Wind farms use large horizontal axis wind turbines (HAWTs) with long blades. These larger wind turbines generate noise and vibration that are not suitable for urban use. In recent years, small vertical axis wind turbines (VAWTs) have been employed in urban areas for local off-grid applications.

It is widely known that the lower efficiency of the VAWT compared to the HAWT is due to the highly unsteady operating conditions of the VAWT at all wind speeds caused by the periodic variation of the rotor and the direction of the apparent wind velocity perceived by the blades (Brahimi, Allet, and Paraschivoiu, 1995). Moreover, as the VAWT rotates, the interactions between wakes shed by the blades rotating in the upwind and downwind regions of the rotor causes dynamic and reliability issues in which the blades have to go through a dynamic stall in every revolution (Amet, Maître, Pellone, and Achard, 2009; Simão Ferreira, van Zuijlen, Bijl, van Bussel, and van Kuik, 2010). Intrinsically, the understanding of the aerodynamic phenomena manifested in VAWTs presents challenging tasks for researchers to thoroughly understand the complex fluid mechanics of such devices to estimate their performances (Almohammadi, Ingham, Ma, and Pourkashan, 2013; Daróczy, Janiga, Petrasch, Webner, and Thévenin, 2015; Howell, Qin, Edwards, and Durrani, 2010; Salvadore, Bernardini, and Botti, 2013). Furthermore, new concepts of vertical axis wind energy devices are being introduced to overcome the disadvantages of the conventional design of VAWTs. Some of these wind turbine concepts are being adopted in the design of the building (Meinhold, 2010; Sharpe and Proven, 2010) or mounted on top of a building for maximum exploitation of wind energy (Wong et al., 2014).

The complex nature of urban winds requires wind turbines that are designed to receive the wind from various directions. Moreover, urban winds are erratic, insubstantial and inconsistent due to the many obstacles (e.g. buildings and other obstructions), creating blockages that can reduce wind turbine performances (Abohela, Hamza, and Dudek, 2013). Hence, necessitating wind turbines with excellent self-starting characteristics (Drew, Barlow, and Cockerill, 2013). For a wind energy generation system to be installed in urban areas, several factors need to be considered, i.e. blade failures, noise levels, visual impacts, structural issues, and electromagnetic interference (Knight, 2004; Möllerström, Ottermo, Hylander, and Bernhoff, 2015; Oppenheim, Owen, and White, 2004). Recent investigations on Darrieus vertical axis wind turbines, however, showed that in some cases the behavior of the rotors performed better than a horizontal axis wind turbine in misaligned flow conditions (airflow parallel to the vertical axis of the rotor), though this varies on the design and geometry of the turbine rotor (Mertens, van Kuik, and van Bussel, 2003b, 2003a; Simão Ferreira, van Bussel, and van Kuik, 2006; Simão Ferreira, Van Bussel, and Van Kuik, 2006).

2. SKEWED WIND FLOW IN BUILT ENVIRONMENT

Diffusion of wind energy technology, in particular, small vertical axis wind turbines can effectively be exploited for on-site power generation in the built environment. Theoretically, small wind turbines can be placed on top of buildings to harness a larger potential of wind energy due to the higher zone of wind profile, which is usually exploited by a large horizontal axis wind turbine (Figure 1). The atmospheric boundary layer is the lowest part of the atmosphere that contains most atmospheric gases and humidity (Pandolfi et al., 2013). From a climatological viewpoint, the urban atmosphere has been considered as a boundary layer over a fully rough wall which consists of several layers, including a roughness sublayer and an inertial sublayer (Rotach et al., 2005). Within the inertial sublayer, vertical profiles of environmental variables such as velocity have been known to satisfy the similarity theory characterised by several aerodynamic parameters including the roughness length and displacement height, which depend on urban geometry (Rahmat, Hagishima, and Ikegaya, 2016). The accurate estimation of aerodynamic parameters of rough urban surfaces, roughness length and displacement height is important for prediction of airflow, dispersion of pollutants, and other atmospheric phenomena (Zaki, Hagishima, Tanimoto, Mohammad, and Razak, 2014). These parameters directly affect the wind flow patterns in the respective area, which alter the surrounding wind environment. The wind profile in the internal boundary layer of urban locations is, in fact, different from the classical profile as shown in Figure 1 (Balduzzi, Bianchini, and Ferrari, 2012). This figure shows how buildings as the solid bodies slow the wind near to the ground and increase the turbulence in the wind.

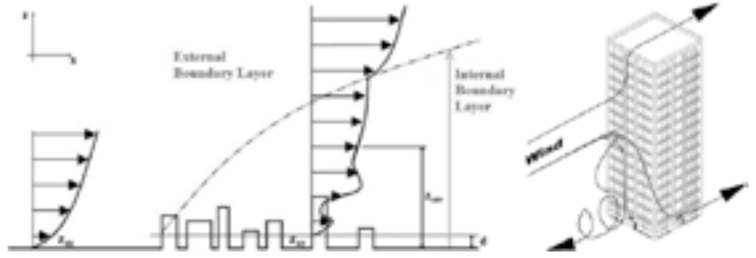


Figure 1: (a) Wind profile visualisation in the internal boundary layer of a built environment (Balduzzi, Bianchini, and Ferrari, 2012). (b) Simplified sketch of wind flow around a tall building (Ayhan and Sağlam, 2012).

The boundary layer separates at the windward edge of the building, and the flow forms a separation bubble on the outer surface below the streamlines above the surface (Mertens et al., 2003b). Approaching a solid obstacle, the separation bubble makes an angle to the velocity vector with the building's surface as shown in Figure 1 (b). This angle is subsequently referred to as the skew angle. The wind is either rising flow up vertical surfaces or toward the prevailing wind direction on building corners or ridges. Several studies have shown that the Darrieus type VAWT's power output increases while operating in skewed flow condition (Mertens et al., 2003a; Simão Ferreira et al., 2006). This is mainly due to the possibility of increased projected swept area based on the cosine angle of the skewed flow. However, further investigations must be carried out to determine the exact parameters and variables related to the performance of a VAWT in skewed wind flow, i.e. airfoil profile, geometric ratios, turbine design structure, etc.

2.1 Aerodynamics of Wind Energy Devices in Skewed Flow

The basic expression for power generation by the wind energy devices, which is derived from the kinetic energy equation, is as below:

$$P = \frac{1}{2}\rho AV^3 \times C_p \quad (1)$$

where P represents the power generation, ϱ is the air density, A is the turbine swept area and V is the free stream wind velocity. Cp is the power coefficient that represents the ratio of electricity produced by the wind device to the power available in the wind. However, there are many parameters that affecting a wind turbine aerodynamic characteristics along with the power coefficient.

The lift and drag coefficient of an airfoil blade are the major parameters that determine its aerodynamic performance. These coefficients vary with every angle of attack (AOA) of the airfoil blade. The AOA is a term used in wind turbine design to describe the angle between the chord line of an airfoil and the oncoming wind flow. Lift coefficient, CL is the factor that contributes to the elevation of the blade (lift is always perpendicular to the wind flow). Drag coefficient, CD is used to quantify the drag, i.e. the resistance of an object in the air. These dimensionless units are expressed in the following equations:

$$C_L = F_L/(0.5\rho AV^2) \quad (2)$$

$$C_D = F_D/(0.5\rho AV^2) \quad (3)$$

where FL and FD is the lift and drag force respectively. Figure 2 shows the pressure distribution on an airfoil. The AOA of an airfoil controls the distribution of pressure above and below it. An airfoil at positive AOA develops negative pressure on its upper surface and positive pressure below it. The result of this pressure difference creates lift. Whereas, an airfoil at negative AOA develops negative pressure on the upper and lower surfaces of the airfoil, and positive pressure at its leading edge. This leads to the separation of flow at its trailing edge resulting in higher resistance or drag. Aerodynamic performance is fundamental for efficient rotor design. The lift-to-drag ratio is the amount of lift generated by the airfoil over the aerodynamic drag that it creates while moving through the air. A higher value of CL/CD ratio is more favourable as the higher lift with lower drag leads to a better performance of wind turbine. Traditionally, the airfoil is tested experimentally with tables correlating lift and drag at given AOA and Reynolds numbers. Wind turbine airfoil designs have been adapted from aircraft technologies with similar Reynolds numbers and section thicknesses that are suitable for conditions at the blade tip. However, due to the differences in operating conditions and mechanical loads, special considerations should be made for the design of wind turbine specific profiles and in low Reynolds number regime.

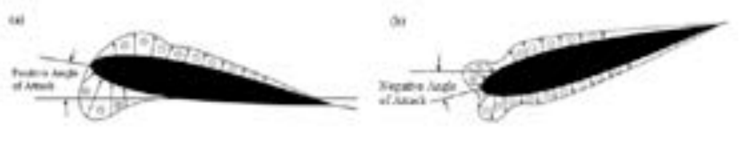


Figure 2: (a) An airfoil at positive angle of attack, (b) at negative angle of attack.

Figure 3 illustrates the diagram of a wind turbine configuration in the wind stream and the force components acting on the airfoil blades. During the rotating motion of the turbine, there exists varying forces along the airfoil blades as the blades change from one azimuth angle to another. The passing airfoils will encounter the wake of the previous passing airfoils as they move to the downwind region of the wind turbine rotor (azimuth angle between 180° to 360°). In an aligned flow, the whole length of each airfoil is exposed to the wake of the turbine in the downwind region of the rotor; see Figure 4(a). In misaligned flow, the convection of the wake follows the skew angles of the oncoming flow as shown in Figure 4(b), therefore allowing the undisturbed portion of the skewed flow to interact with some parts of the downwind airfoil blades. The resultant effect, and in comparison, between these two flows, are in the tangential force produced by each of the airfoil blades.

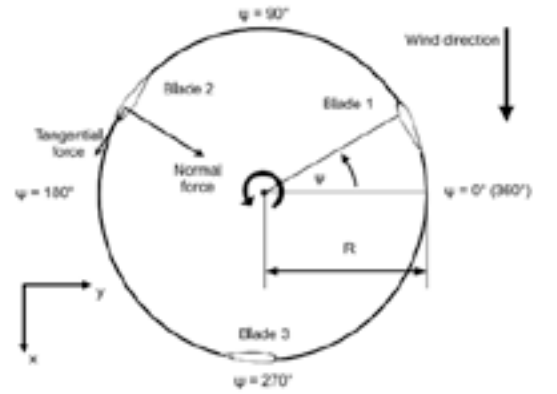
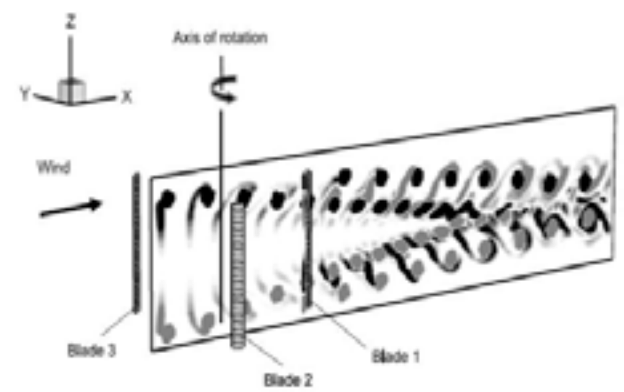


Figure 3: Diagram showing the wind direction, the definition of rotor azimuth angle, ψ and direction of positive normal and tangential forces, as well as the relative positions of the rotor blades (Scheurich and Brown, 2011).
(a)



(b)

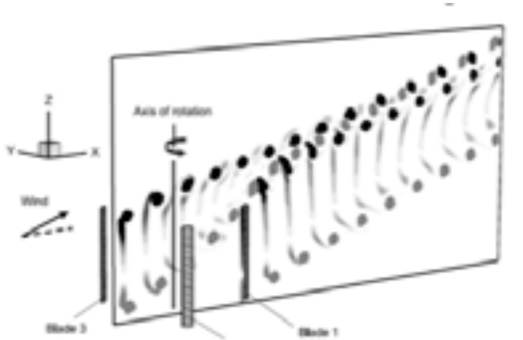


Figure 4: (a ... (b) Wake characteristics during skewed flow (Scheurich and Brown, 2011).

In normal flow, the interaction between the wake and the blades in the downwind region suppresses the potential torque due to the turbulent and low Reynolds number condition of the downwind wake. Therefore, the airfoil blades in the upwind region of the rotor produce much of the torque output. In skewed flow, however, the undisturbed portion of the downwind wake that interacts with each of the airfoil blades contributes to the overall increase of rotor power output. Hence, the skewed flow condition presents a significant impact on the overall performance of the turbine.

Regarding the configuration, a lower height-to-radius (H/R) ratio turbine in a normal flow has a slightly lower aerodynamic efficiency due to the lower aspect ratio (AR) of the blades. This is the fundamental reason for the lower performance of turbines with small AR. From the swept-wing theory (Jones, 2014), the vertical component of the oncoming wind that is parallel to the VAWT axis has no aerodynamic effects on the turbine. Therefore, the performance of the turbine in skewed flow is strictly influenced by the cosine angle of the oncoming velocity, with an increased effective tip speed ratio. Findings from the literature showed that the performance of the VAWT in skewed flow conditions could be further improved. However, this depends on the design and geometry of the rotor, and limited range of skew angles. In a skewed airflow, it was shown that the VAWT with the smallest H/R ratio could generate a higher power output than the other turbines with larger H/R ratios, especially at higher tip speed ratios (Scheurich & Brown, 2011) (see Figure 4).

The effect of skewed wind flows, and the resultant wakes is more significant in the higher tip speed ratio of the turbine. After the vortex filaments are shed by the blades, a coalescence of vorticity in the immediate surroundings of the blades in the downwind cycle was observed (Scheurich, Fletcher, & Brown, 2011). This coalescence enhanced the influence of the wake to improve the load produced by the blades during their passage downwind of the rotational axis of the turbine. At higher tip speed ratios, the convection of the wake relative to the motion of the blades is slower than at low tip speed ratios and the coalescence of the vorticity is more noticeable. At lower tip speed ratios, the effect of the coalescence did not take place due to the wake being swept away from the rotational trajectory of the blades, therefore reducing the influence of the wake on the loads produced by the blades. Therefore, the improved performance of the VAWT in skewed airflow is due to the wake convection that covers a larger area in the downstream and upstream regions of the rotor.

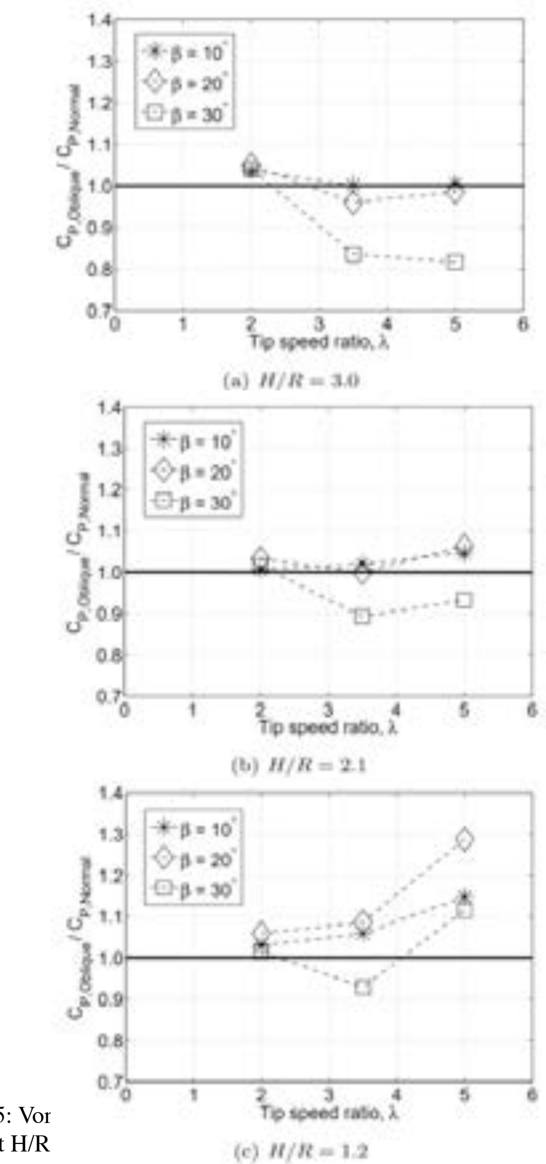


Figure 5: Vor ... ance with different H/R ... n, 2011).

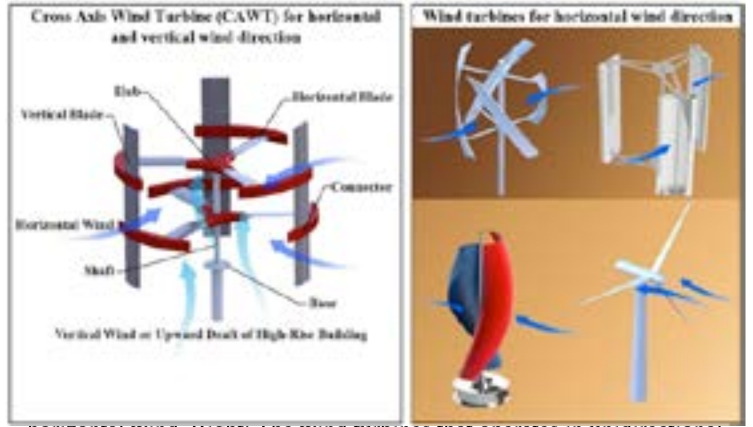
2.2 Wind Ener... on Rooftops

Recent studies have shown that the progress of vertical axis wind turbine (VAWT) should be focused on optimization of the struts' shape and configuration, as the supporting structures can influence the performance of wind turbine rotors, particularly in small wind turbines (Bianchini, Ferrara, and Ferrari, 2015). Airfoil-shaped struts can reduce the parasitic drag commonly found in normal struts and produce additional torque from the lift force of the airfoil struts. Some suggest that the airfoil struts in skewed flow conditions can further increase the performance of the wind turbine (Islam, Fartaj, and Carriveau, 2008). However, many of the current research work only deal with the conventional wind turbine in skewed wind flow conditions.

Ferreira (Simão Ferreira et al., 2006) showed that with normal flow, the characteristics of the flow in and around the rotor, and in the wake, are mostly influenced by the upwind passage of the blades. Therefore, the downwind region of the VAWT operates in the wake of the upwind half of the rotor, which results in reduced energy potential. The stronger vorticity in the upwind area of the VAWT (due to higher lateral wind loading) generates wake and alters the downwind stream which saw the loss of energy potential in the downstream position (Worasinchai, Ingram, and Dominy, 2015). Similar observations were made by Balduzzi et al. (Balduzzi, Bianchini, Carnevale, Ferrari, and Magnani, 2012) who carried out computational fluid dynamics (CFD) studies on different roof shapes with different geometrical proportions. The results showed that the power output from the VAWT increased by up to 12% for skew angles between 15° to 30°. In another study, Orlandi et al. (Orlandi, Collu, Zanforlin, and Shires, 2015) developed an unsteady RANS 3D approach to predict the performance of an H-rotor VAWT in skewed flow conditions. Comparable observations were made, in which the improvement of power potential produced by the VAWT in skewed flows are due to the reduced disturbance in the wake generated during the upwind phase.

In the urban context, wind turbines operate close to the wakes induced by buildings that may cause skewed flow conditions. In investigating the performance of an H-Darrieus performance on a roof, Mertens et al. (Mertens et al., 2003b) had shown that the rotor power output increased by 30% when the rotor was exposed to 10°-40° skewed angle wind flow. Mertens et al. suggested that in skewed flow conditions, the lift and drag forces generated by the airfoils depend only on the orthogonal component of the oncoming wind velocity, whereas the parallel component contributes to the zero effect on the surface of the airfoils. This is known as the cross-flow principle, which describes the wind speed interacting with the blades of the vertical rotor in skewed flow to become a function of both the induction factor of a stream tube and the skew angle. Lee et al. (Lee, Tsao, Tzeng, and Lin, 2017) investigated the influence of the vertical wind and wind direction on the performance of a small VAWT on the rooftop of a building. Their study showed that the vertical wind coming off from the sides of the building greatly influence the power output of the VAWT, in which 90% of the power was generated when the vertical angle is less than or equal to 45°, and when the horizontal wind speed is between 5 m/s and 8 m/s.

Up to now, not many researchers propose a design that specifically for skewed flow application. Van Bussel et al. (G.J.W. van Bussel, S. Mertens, H. Polinder, 2004) introduced a VAWT called Turby® that focused on the design of the skewed vertical blades, with fixed diameter from top to bottom. The authors claimed that the performance of the Turby® wind turbine is better than conventional VAWT in the built environment where it demonstrated a performance increase of 35% at the skew angles of 25 to 30 degrees. A wind turbine called the Cross Axis Wind Turbine (CAWT) was introduced by Chong et al. to suit the unpredictable nature of complex wind flows in an urban environment (W.T. Chong et al., 2017, 2019; W. T. Chong et al., 2016). Unlike the conventional VAWT, CAWT incorporates airfoil-shaped struts to utilize the undisturbed portion of the skewed flow, both in the downwind and upwind regions of the turbine. Figure 5 depicts a comparison between the CAWT and conventional wind turbines. According to the experiments, CAWT at 45 degrees deflected flow produced a power coefficient 2.8 times higher than a VAWT.



horizontal wind. Right: The wind turbines that operates in unidirectional wind.

Table 1 summarizes the wind turbine performance in the skewed wind flow condition compared horizontal wind flow. It can be concluded that the conventional VAWT is operational with an improved performance at a certain range of skewed flow. Further improve of performance is demonstrated by the wind turbines that specifically designed for the skewed flow.

Table 1: Performance of wind turbines in the skewed flow stream

Reference	Turbine feature	Finding
(Balduzzi et al. 2012)	H-Darrieus VAWT	Power output from the VAWT increased by up to 12% for skew angles between 15° to 30°
(Orlandi et al. 2015)	H- Darrieus VAWT	Power coefficient increased by up to 1.2 times at skew angle of 20° compared to the 0°
(Mertens, van Kuik, and van Bussel 2003)	H- Darrieus VAWT	Rotor power output increased by 30% when the rotor was exposed to 10°-40° skewed angle wind flow
(G.J.W. van Bussel, S. Mertens, H. Polinder 2004)	New design of VAWT called Turby®: skewed vertical blades, with fixed diameter from top to bottom	Turby® produced a performance increase of 35% at the skew angles of 25 to 30 degrees compared to the conventional VAWT.
(Chong et al. 2019)	New design of wind turbine called the Cross Axis Wind Tuebine (CAWT): a combination of VAWT and HAWT principle	CAWT at 45 degrees deflected flow produced a power coefficient 2.8 times higher than a VAWT

3. CONCLUSION

There is increasing attention to the performance of wind turbines in skewed wind flow. Normally, the expected flow conditions are parallel to the rotor axis of the HAWTs or perpendicular to the VAWTs. Experimental and numerical investigations on VAWTs showed that the power output was increased in skewed flows, depending on the geometrical ratios of the rotor. In the varying interaction between the blades and the oncoming flow volume, the blades of the vertical rotor describe a cylindrical volume, different from the planar surface generated by the horizontal rotor. Therefore, the total swept area of the vertical rotor is increased, mostly due to the contribution of the skewed flow in the downwind region that balances the decrease of the projected upwind area. Hence, the misaligned flow interacts with an increased available surface area of the rotor. Also, the increased swept area may be due to the expanded airflow in the downwind region of the rotor. If the aspect ratio of the vertical rotor is sufficiently small, the skewed convection of the wake could cover a larger surface area in the downwind and upwind regions of the rotor. Therefore, the interaction between the skewed airflow and the blades of the vertical rotor could potentially generate more lift, hence producing higher torque and better power output. The study has shown that the Darrieus vertical axis

wind turbine has the potential for the built environment due to the effect of the skewed wind flows. Evidently, the remarkable outcome of many of the studies has illustrated that the VAWT can generate a higher power output in skewed flow, compared to VAWT in normal flow. To optimize the siting of VAWT on top of rooftops, it is recommended that wind profile studies must be carried out to determine the best placement of VAWT in skewed airflows. This is to ensure that the performance of the VAWT can be maximized, and therefore the diffusion of wind energy technology in the urban environment can be more efficient.

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BUILDING INFORMATION MODELLING (BIM) FOR SUSTAINABLE INDUSTRY: THE MALAYSIAN ARCHITECT'S PERSPECTIVE

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ABSTRACT

The Malaysian construction industry is steadily gearing its way towards the adoption of Building Information Modelling (BIM). Subsequently, architects hold a significant role being one of the key players in the industry. Despite rapid development, BIM adoption within the industry is extremely low and only a few organisations are putting it into practice. Previous research has enumerated a broader aspect of BIM in the context of the construction industry holistically, but merely a small number concentrate specifically on local architects thus forming a knowledge gap. Therefore, this paper focused primarily on addressing the minimal BIM adoption amongst architects by exploring its current utilisation, benefits and driving factors as well as awareness. The study was quantitative, whereby a survey was created to study the trends and elicit the opinions of architects. The findings consequently showed that the current BIM usage was still low, with majority of the architects displaying moderate level of awareness. Several driving factors were identified relating to people, process, policy and technology which should be addressed in the future. This study would provide the industry with invaluable insight regarding BIM adoption and serve as a critical reference in assessing the changes and effects of its progress in Malaysia.

Keywords: : Building Information Modelling, BIM Adoption, Malaysian Architecture Industry

1. INTRODUCTION

The Malaysian construction industry is projected to grow by at least 10.3% for the year 2018. In order to achieve the projected growth rate, the annual demand for construction sector is projected at RM180 billion (CIDB, 2014). Subsequently, the local architectural service sector serving as one of the key players is attributed to contribute their momentous role in the country's economic development. Building Information Modelling (BIM) is regarded as the future of the construction industry in which its potential use will result in greater benefits such as reduced construction delay, cost reduction, smoother project coordination, increased productivity and a better control of design projects (Gardezi, Shafiq, Nuruddin, Farhan & Umar, 2014). The uptake of BIM would transform the local industry into a highly productive and sustainable landscape in line with the strategic Vision 2020. To date, BIM has been associated with a rapid expansion process through numerous initiatives and programmes planned by public and private bodies alike. As stated in the Construction Industry Transformation Plan (CITP), the industry is aiming to transform the domestic construction industry and achieve level 2 of BIM maturity by the year 2020. This will be reflected in a minimum of 40% of implementation rate for public projects valued at RM100 million and above (CIDB, 2017). Some of the key objectives is increasing the number of highly trained BIM manpower, underlining the adoption of BIM protocols by the Local Authorities (PBT), enhancing BIM resources, enforcement of numerous pilot projects and facilitating BIM adoption programmes for the industry (CIDB, 2017). However, BIM adoption in the Malaysian construction industry is still lagging behind other developing countries despite the multitude of benefits identified (CIDB, 2017; Zahrizan, Ali, Haron, Marshall-Pointing & Hamid, 2014; Gardezi et al., 2014). According to the latest national BIM report by CIDB, despite extensive awareness and willingness of construction players to adopt BIM, the percentage of its adopters are extremely low at 17%. A majority of them are still reporting a low exposure to BIM usage, including the architects, whereby the implementation remains dependable on 2D drafting and the single disciplinary use of 3D modelling (CIDB, 2017). Currently, there is no tangible case study or report highlighting the benefits of BIM, superimposed with the industry's difficulties in understanding the benefits of putting it into practice (CIDB, 2017; Ghaffarianhoseini, Tookey, Ghaffarianhoseini, Naismith, Azhar, Efinova & Raahemifar, 2017). Although BIM is predominantly enforced by the government, only a few organisations have actually implemented it in their project deliverables. Meanwhile, some organisations opt to outsource their BIM works rather than implementing the technology into their organization itself (Mohd-Nor & Grant, 2014). Numerous research have highlighted the potential benefits of BIM as a supplementary tool to support the industrial evolution, but most of the industry players are not ready to move forward, architects included. Hence, it is essential for further emphasis to be placed in specific areas in ensuring that the industry continuously strives to adopt sustainable and innovative construction methods throughout the value chain. This paper aims to address the issues of BIM adoption by investigating current BIM awareness as well as the state of its adoption from the perspective of an architect.

2. LITERATURE REVIEW

2.1 Overview of Building Information Modelling

BIM is a process involving the coordination of non-digital and digital information about a building project throughout its entire lifecycle (Eastman, Teicholz, Sacks, & Liston, 2011). It collectively involves the elements of efficient workflow, coordination, process, documentation, people, graphical/non-graphical assets and technology (Eastman et al., 2011; NBS, 2017). The depth of information contained within BIM enables a richer analysis to be obtained in comparison with the conventional processes; it potentially allows the integration of a large quantity of data across several disciplines throughout the building's project lifecycle (Talebi, 2014). BIM brings forward significant influence towards every level of design projects, thus encouraging the construction players to put it into practice. The transition towards BIM is not solely dependent on software and hardware change, the socio-cultural environment is an important factor that provides a significant context for its implementation (Smith & Tardif, 2009; Kensek & Noble, 2014). A successful BIM implementation will firstly require organisations to allocate adequate support to facilitate the expected changes towards organisational work process, policies, people and technological assets within their internal and external environment (NBS, 2017). As the current industry's perception varies across different disciplines, while the levels of expectation increased alongside time, an effective BIM adoption and maximizing its impact render, it is essential to establish the BIM ecosystem within people and organisations (Kensek & Noble, 2014).

2.2 BIM Adoption Issues in the Malaysian Architecture Industry

The local architecture industry has to face numerous issues in attaining successful BIM adoption and emerge progressive, aligning with the construction industry's initiatives and requirements. Several studies have highlighted the low rate of BIM adoption and architect awareness (CIDB, 2017; Mohd-Nor & Grant, 2014). Such considerably low uptake underscores the significance of BIM dissemination within the architectural landscape in understanding its challenges. Currently, BIM adoption is hindered by several factors that is comprised of four core components namely people, process, policy and technology. These factors have been identified as the potential causes of low adoption rate amongst architects (CIDB, 2017; NBS, 2017; Eastman et al., 2012; Smith & Tardif, 2009). In the context of people, the salient factors encountered is the shortage of skilled and knowledgeable BIM workforce in construction organisations (Zahrizan et al., 2014). This is attributable to the difficulties of the learning curve, especially for those completely unfamiliar with BIM, while resistance to its organizational implementation is due to its complexity and high monetary investments required. Inexperienced users may inadvertently change the content of the data, thus imposing risks to a project. In addition, many managers and organisational leaders lack the knowledge on adopting BIM in their respective organisations (Zahrizan et al., 2014). Moreover, the fragmented nature of construction projects contributes towards BIM resistance among the project collaborators (Nanajkar & Gao, 2014). BIM demand changes in an organisation's working 'process' whereby an integrated BIM model development requires efficient communication and greater collaborative efforts across multiple disciplines. Therefore, consented mutual protocols and standard processes are required to initiate responsibility assignment and execute design reviews and validation (Kensek & Noble, 2014). According to Eastman et al., (2011), the standard and guideline are still not well defined in the current practice, organisations remain working in a proprietary format for model exchange. Subsequently, CIDB has raised concerns regarding the need to develop national BIM standards and guideline to manage BIM workflow and adoption (CIDB, 2017), however, many have overlooked the element of construction firm's adoption apart from the sets intended for government projects (Latiffi, Mohd, & Rakiman, 2015). Furthermore, several technology related issues have been distinguished, such as limited inter-operability between relevant BIM software and the complexities of the software, which lead to ineffective collaboration and workflow (Kensek & Noble, 2014; Memon, Rahman, Memon, & Azman, 2014). BIM technology is often alleged to be costly for implementation and deployment (Eastman et al., 2011; Smith & Tardif, 2009; Memon et al., 2014). Its initiation alone requires a large initial investment of cost to obtain the technology, as well as due to the additional costs of training and development. Meanwhile, Howell and Batcheler (2005) have stated that the difficulties of collaboration are caused by the expectation for the team to inter-operate and adopt single BIM system. This is difficult and limited due to the involvement of a large number of collaborators in a project team. In the context of policy, Eastman et al. (2011) have highlighted legal and contractual problems as one of the challenges for BIM implementation, as the current laws and contracts are ambiguous on BIM matters, including the obligations for the entire BIM project duration. Then, Chien, Wu, & Huang (2014) reports that the legal liabilities and procedures relevant to BIM are unclear in various areas, such as policies, standards contract, ownership of data, insurance, risks and allocation of roles and responsibilities. As the allocation of rights and roles to the project is ambiguous, it is hard to ensure and achieve smooth project progression, thus imposing greater risks to the project.

2.3 Benefits of BIM within the Building Project Lifecycle

BIM application in the construction industry contributes great benefits towards project delivery as it improves the communication between different construction parties, as well as facilitating a faster design decision-making (Cho, Lee, Lee, Lee, Cho, Kim, & Nam, 2011). Figure 1 shows that BIM is capable of project managements at different stages namely Schematic Design, Design Development and Construction Stage (Arayici, Coates, Koskela, Kagioglou, Usher, & O'Reilly, 2011; Azhar, Khalfan & Maqsood, 2015). In order to fully leverage the benefits of BIM, it needs to be implement in all construction stages (Newman, 2013; Weygant, 2011).

F 4)

Numerous benefits can be gained by implementing BIM during the pre-design stage, such as early visualisation, preliminary cost estimation, integration with Geographic Information System (GIS) to generate the existing site condition modelling, environmental and building analysis and spatial planning design (Eastman et al., 2011; Arayici et al., 2011; Azhar, Khalfan, & Maqsood, 2015; Abdullah, Sulaiman, Ahmad Latiffi, & David, 2014). BIM is also beneficial in mitigating risks through reviewing the clashes that occurred, highlighting potential errors, conducting a code and compliance review and supporting building component fabrication. (Eastman et al., 2011; Azhar, Khalfan, & Maqsood, 2015). An enriched BIM database will significantly support work processes throughout the whole project lifecycle, which ensures better decision-making, reduction of costs, disputes and time delay; this affirms the quality control, minimized risks of reproduction and reworking of work tasks (Kensek & Noble, 2014). In the recent years, efforts have been made to leverage the potential benefits of BIM in supporting the industry's development. Hence, Table 1 summarize the potential application of BIM in a typical architecture project life cycle ranging from Schematic Design Phase to the Post-Construction Phase.

Table 1: Benefits and Capabilities of BIM

Stages	BIM Capabilities	Sources
Schematic Design Phase (Initiation Stage)	• GIS to analyse, embed and reconstruct the precise existing conditions of a site. • Plan the spatial need and design as defined by the project owner/clients. • Support design communication and ensure better decision-making.	• Dore et al. (2013) • Eastman et al. (2011) • Lahdou & Zetterman (2011)
Design Development Phase (Planning Stage)	• Constructability analysis via clash detection activities during the pre-construction stage. • Extract accurate quantity take-off and estimation. • Environmental analysis such as energy analysis, wind analysis, thermal conditions, solar and lighting study. • Review for compliance with the national building code and regulations.	• Zhang et al. (2016) • Barkokebas, Hamdan, Al-Hussein, & Manrique, (2015) • Eastman et al. (2011) • Lahdou & Zetterman (2011)
Construction Phase (Execution Stage)	• Compute automated construction scheduling, work tasks distribution and duration of activity. • Early identification of design faults via clash detections coordination to reduce risks and ambiguity prior to construction. • Support fabrication and delivery of building components/materials/Industrialised Building System (IBS) • Reduce wastage during construction	• Kim et al. (2013) • Eastman et al. (2011) • Li & Yang (2017) • Lahdou & Zetterman (2011) • Katranuschkov et al. (2013)
Post – Construction (Project Closure)	• The completed BIM model will be occupied by relevant building component information, such as product data and details, operation manual, manufacturer information, contacts and more for scheduled maintenance and effective facility management.	• Katranuschkov et al. (2013) • Eastman et al. (2011)

2.3.1 Quantity Take-off and Cost Estimation

One of the salient use of BIM for construction purposes is regarding its ability to extract accurate material quantity take-off and estimation in order to reduce material wastage, as well as minimise the risks of reproduction. Barkokebas, Hamdan, Al-Hussein, & Manrique, (2015) have demonstrated the application of parametric estimation for a building project, with findings obtained showing a significant reduction of estimated time, change orders and controlled uncertainties, as well as reduction of overall risks associated with the project.

2.3.2 Constructability Detection and Building Analysis

BIM can also be linked with its ability to produce constructability analysis via clash detection activities during the pre-construction stage. Zhang, Long, Lv, & Xiang (2016) observation made using a case study regarding a construction company in China indicates that BIM had solved numerous constructability and reproduction issues happening on-site during the fabrication process. This has been achieved by pre-reviewing the 3D BIM building components in a virtual construction environment. Through clash detection, the manufacturer has also obtained a comprehensive support on the design integration, fabrication, construction, and up to the operation and maintenance processes.

2.3.3 Construction Phasing and Simulation

Kim, Anderson, Lee, & Hildreth. (2013) have stated that one of the important feature of BIM is its ability to compute automated construction scheduling, work tasks distribution, duration of activity based on the production rates and the sequencing rules. These activities can be shared and extracted from an open-data environment using various data exchange formats. The comprehensive 4D BIM data benefits the holistic manufacturing process, which includes material ordering, in-factory logistics, packaging, stocking, and transportation to the construction site. With a streamlined data, a close coordination within the construction value chain is possible and may eventually impact greatly in terms of time and cost (Li & Yang, 2017).

2.3.4 Point Cloud and GIS Integration

The use of Point Cloud Laser Scanning technology and GIS allows, designers to analyse, embed, and reconstruct the precise existing conditions of a site. Utilising both technologies greatly benefits the designers in obtaining accurate data during the initiation of the preliminary design. Point cloud utilisation alone enables precise documentation of buildings for refurbishment and conservation works. In a study by Dore & Murphy (2012), a Heritage-BIM documentation approach has been demonstrated involving a 3D modelling stage. The 3D model integration into a 3D GIS has allowed further building documentation management and analysis.

2.3.5 Code and Compliance Review

BIM is an important digital assets in communicating design, and it is a key instrument in reviewing and obtaining the approval from statutory bodies. BIM model may be authorised for conducting plan review and ensuring conformance for the building code (Eastman et al., 2011), as the approaches to develop an automated code-review have been studied in past research (Eastman et al., 2011; Greenwood, Lockley, Malsane, & Matthews (2010). Several countries like Singapore and Australia have proceeded to implement online-based E-Submission platform compliance to code and building plan approval, namely Construction and Real Estate Network (CORENET) and DesignCheck, respectively.

3. RESEARCH METHODOLOGY

3.1 Research Approach

Quantitative research is defined as a proper, methodical, and objective-based process of obtaining data by applying numerical data retrieved from a sample of population such as by using surveys. The advantage of applying the approach to this study was that it enabled the study of trends, attitudes, or opinions of a population which in this case referred to the architecture industry (Creswell & Creswell, 2013). Survey questionnaire was chosen as the method of collecting data as the approach was deemed effective in collecting objective-based and measurable data required for this research (Kumar, 2014). The questionnaire's format consisted of four (4) sections containing mostly close-ended questions. The first section (1) aimed to identify the respondent's profile and details of their participation in BIM. Then, Section Two (2) elicited the benefits of BIM implementation and, Section Three (3), the barriers and drivers of BIM. Lastly for Section Four (4) incorporated an open-ended question to extract the respondents' personal opinions and comments on the context of research. Prior to the actual data collection process, a preliminary survey was conducted with the participation of experienced academicians, professional architects and BIM professionals so as to obtain preliminary content validity for the questionnaires.

3.2 Sampling Method

Random sampling method was used to determine the sample size for this study as it was appropriate to be applied for a preliminary study in which a complete list of the population was available (Kumar, 2014). A total of 322 survey questionnaires were sent out in a period of one (1) month to respondents who are working as an architect either on the behalf of architecture firms, clients, or BIM consultants within all states of Malaysia. The population sample size was drawn from the current registrants of Malaysia Board of Architects (LAM), whereby, there are currently 2,250 Professional Architects (Ar.) and 2428 Graduate Architects (GA) registered. Thus based on the study by Krejcie and Morgan (1970), a sample size of 354 respondents was suitable for this research in which the potential respondents were preferably architects with experience in BIM projects. Out of the 354 questionnaires distributed, 108 questionnaires were completed and returned, with a representation of 31%. The response rate was similar with previous construction studies conducted by Newton & Chileshe (2012) and Jin, Li, Zhou, Wanatowski, & Piroozfar (2017), which obtained 39% and 13%, respectively.

3.3 Statistical Approach

The study used the descriptive statistic approach to analyse the data collected using specific analysis techniques, such as frequency distributions and ranking analysis (Ary, Jacobs, Sorensen & Razavieh, 2010). The use of frequency analysis was critically required to support other statistical methods, as detailed by Kumar, (2014). The data collected from the survey were inserted and analysed using IBM SPSS software. Furthermore, ensuring the responses obtained from the questionnaires were transformed into accurate and meaningful data resulted in the analysis being undertaken using various data analysis tools. They included the mean rating (MR) and standard deviations (SD); they are regarded as the most significant method to calculate the central tendencies in representing the average group of data for a variable (Ary et al., 2010). The MR, in particular, indicated the relative magnitude of variables in areas concerning the research objectives, namely the level of importance, awareness and agreement.

3.4 Demographic Profile

Table 2 shows a total of 108 respondents who participated in the survey, whereby a majority of them were categorised into managerial and operational groups, namely Graduate Architects (41.7%), Senior Architects (30.6%), Principal (9.3%) and Associates/Directors (7.4%). Most of the respondents' possessed more than 5 years of working experience (70%), thus indicating a high level of confidence in responses based on their involvement in design projects. Furthermore, 49 respondents (45.4%) representing different companies did not use BIM within their practice, while 12 respondents (11.1%) showed fresh involvement in BIM implementation with less than a year of experience. Then 40 respondents (37%) had moderate experience between 1 to 5 years with BIM while only 7 respondents (6.5%) possessed more than 5 years of BIM experience. The high percentage of non-BIM usage indicated that the level of BIM adoption within the industry is still at an infancy stage, thus underlining the need to further analyse the impact factors of its BIM adoption. The study also compared the senior and junior role groups (i.e. Senior Group consisting of Senior Architects, Associates, and Principal; and Junior Group consisting of Assistant Architects and Graduate Architects) from the survey to assess the presence of any non-response bias in the data (Churchill & Iacobucci, 2009). Hence, an independent t-test was executed and the results did not show any statistically significant difference of opinions between both groups.

Table 2 : Respondent's Demographic Profile

		Frequency (N)	Percentage (%)
Role of Respondents	Principal	10	9.30%
	Associate/ Director	7	6.50%
	Senior Architect	32	29.60%
	Graduate Architect	45	41.70%
	BIM Executive	2	1.90%
	Assistant Architect	12	11.10%
	Total	108	100.00%
Work Experience	Less than 5 years	41	38.0%
	5 to 10 years	48	44.0%
	More than 10 years	19	18.0%
	Total	108	100.00%
BIM Working Experience	Less than 2 years	40	37.0%
	2 to 5 years	12	11.1%
	More than 5 years	7	6.5%
	None	49	45.4%
	Total	108	100.00%
Age Group	Above 40 years old	9	8.3%
	30 – 40 years old	60	55.6%
	Below 30 years old	39	36.1%
	Total	108	100.00%

4. RESULTS

4.1 BIM Adoption within the Architecture Industry

Table 3 shows that a majority of the respondents at 45.4% had no BIM working experience, while the second highest group of 37% had less than 2 years. This was followed by 2 to 5 years (11.1%) of experience, while the remaining 6.5% of the lowest group had more than 5 years of BIM experience. Although the majority group lacked BIM experience, they remained to relatively aware of BIM. Only one (1) person declared to be unfamiliar with BIM. Overall, this indicated that the level of BIM usage was still at a low level, and the trend of BIM was comparatively fresh in the industry.

Table 3 : Cross-tabulation between respondent's BIM experience and awareness of BIM

BIM Working Experience		Are you aware of BIM: Yes	Moderate	No	Total
Below 2 years	Count	34	6	0	40
	% of Total	38.20%	33.30%	0.00%	37.00%
2 - 5 years	Count	12	0	0	12
	% of Total	13.50%	0.00%	0.00%	11.10%
Above 5 years	Count	7	0	0	7
	% of Total	7.90%	0.00%	0.00%	6.50%
None	Count	36	12	1	49
	% of Total	40.40%	66.70%	100%	45.40%
Total	Count	89	18	1	108
	% of Total	82.40%	16.70%	0.90%	100.00%

Tab … e of the firms. The responses to this question showed that the percentage of BIM users among the larger firms was higher (53%) than the medium firms (31%) and smaller firms (16%), accordingly this results was consistent with BIM reports conducted in the United Kingdom (UK) and Australia, whereby such trend strengthened the claim that larger firms were more capable and willing to invest in BIM technology (NBS, 2017; Rodgers, 2015). Meanwhile, most of the small to medium firms did not use BIM in their practice (54.6%). As highlighted in Construction (2014), large firms had an added advantage to adopt BIM due to the high level of resources and expertise they possessed. In contrast, projects delivered by Small and Medium-Sized Enterprise (SME) firms might take better advantage of BIM than large-sized projects (Arayici, 2014).

4.2 BIM Benefits and Capabilities from the Architect's Perspectives

The research further studied the level of BIM awareness from the perspective of an architect, whereby the Cronbach's alpha obtained for the set of inventory scale was highly reliable (α=0.91). Furthermore, the variables obtained from the secondary data were grouped into three (3) main stages of design project namely the Schematic Design (SD), Design Development (DD), and Construction Stage (CS). The respondents were required to rate the scale of importance from '5' as the most important to '1' as the least important. The results are shown in Table 5 below.

Table 4: Company Size and BIM Usage

Company Size	BIM Usage in Firm: Yes	No	Outsourced
Below 10 person	8	21	1
10 - 30 person	13	22	4
30 - 50 person	2	1	0
Above 50 person	26	8	2
Total	49	52	7

Overall, the design development stage (DD) displayed the highest degree of importance compared to other stages. Ranked as first, the majority of respondents highly agreed that the most important BIM benefits was its ability to produce integrated 2D and 3D drawings (M: 4.46, SD: 0.79). Secondly, the respondents were highly aware that apart from the production tools, it also provided an information platform for better communication within the project team (M: 4.43, SD: 0.776). They also highly agreed that BIM required a high level of involvement between the stakeholders in a project team (M: 4.43, SD: 0.751). Meanwhile, in the context of the schematic stage, the respondents were highly aware that BIM model could be utilised to detect any design clashes between relevant disciplines (M: 4.35, SD: 0.91), as well as to conduct complex building structural analysis (M: 4.28, SD: 0.818). The areas with the least degree of importance were identified as 1) the use of BIM for code and compliance review (M: 3.29, SD: 1.231), 2) the use of point cloud and laser scanning to produce accurate existing site condition modelling (M: 3.18, SD: 1.303) and 3) the integration of BIM and GIS to produce accurate physical and non-physical representations of the site conditions (M: 3.06, SD: 1.334). The architect's awareness placed more emphasis on the benefits within the schematic and design development. Additionally, the construction stage (CS) displayed the most consistency of somewhat to moderate awareness, whereas all of its variables were within the intermediate ranking of 12 to 18 and most were below M: 4.00.

Stages	BIM Benefits and Capabilities	Mean (M)	Std. Deviation (SD)	Rank
SD	High level of collaboration in a project team.	4.43	0.751	3
SD	BIM is able to provide early and accurate visualisation.	4.12	0.862	6
SD	Improved delivery throughout all project lifecycles.	4.08	0.887	7
SD	BIM is able to plan spatial needs as defined by owners.	3.86	0.961	10
SD	BIM is able to generate conceptual massing.	3.83	1.18	11
SD	Point cloud technology for existing condition modelling.	3.18	1.303	20
SD	Integration of GIS with BIM.	3.06	1.334	21
DD	2D to 3D drawing production.	4.46	0.79	1
DD	Information platform for better communicaton.	4.43	0.776	2
DD	Detect clashes between various diciplines.	4.35	0.91	4
DD	Conduct complex structural analysis.	4.28	0.818	5
DD	High degree of realism.	3.99	0.891	8
DD	Conduct simulation / immersive virtual lab.	3.94	1.061	9
DD	Digital record storing (Common Data Environment).	3.83	1.00	11
DD	Producing cost estimates and quantity takeoff.	3.65	1.122	14
DD	Environmetal simulation and analysis.	3.56	1.154	16
DD	Code and compliance review.	3.29	1.231	19
CS	Early identification of design constraints.	3.80	1.066	12
CS	Reduce construction wastage.	3.74	1.08	13
CS	Reduced 'Request for Information' (RFI) and variation order in construction.	3.64	1.18	15
CS	Comprehensive data on provider and product detail.	3.56	1.178	16
CS	Support fabrication of building components.	3.54	1.089	17
CS	4D BIM - construction phasing and simulation.	3.40	1.215	18

Table 5: Benefits of BIM Implementation

4.3 BIM Readiness and Driving Factors

BIM organisational readiness can be expressed as the level of preparation, participation and capability to innovate (Succar & Kassem, 2015). The study further investigates the tendency of an organisation to adopt BIM. Figure 2 shows that the majority of organisations were generally positive towards adopting BIM as 59.8% of them were currently investing in BIM training and development within their organization. Meanwhile, 66.2% had shown their readiness to adopt BIM by investing in BIM software and hardware. All respondents also revealed significant confidence for BIM to further impact the future of construction project management, with 96.3% representation.

Figure 2 : Company Readiness to Implement BIM

The survey further identified the most impactful BIM improvements. As shown in Table 6, the scope was narrowed to the most salient driving factors for pushing BIM adoption as perceived by Malaysian architects. Based on the findings obtained from the secondary data, a total of 20 variables were categorised under four BIM components (ie. people, process, technology, and policy) and consequently 14 salient driving factors were identified for the research. The people factors revealed the most consistency of agreements, whereby the majority agreed that increasing the pace for BIM required gaining the support from professional bodies like Malaysia Board of Architects (LAM) and Malaysian Institute of Architects (PAM), (M: 4.51, SD: 0.74). Another important driver was enhancing BIM education and awareness within the architecture profession, with an overall mean of 4.48 (SD: 0.767). The third driver called for further involvement and cooperation from the governmental bodies in providing support, as well as in enforcing BIM utilisation in design projects (M: 4.43, SD: 0.726). The findings were in line with several past studies that highlighted the enforcement of BIM by the government that would help and enhance BIM practices in construction projects (Latiffi et al., 2015). Furthermore, all respondents agreed for the need of public and private bodies to conduct in-depth BIM research and development (M: 4.43, SD: 0.700). Moreover, BIM enforcement by clients was another important aspect in spearheading its implementation (M: 4.40, SD: 0.785). In addition, all respondents agreed that the investment and support from the organisational leader were important to drive the process of BIM adoption by companies (M: 4.38, SD: 0.817). Apart from that, a BIM standard and guideline (M: 4.30; SD: 0.788) should be developed to further support the change of processes in an organization for adopting BIM. In the context of policy, the respondents' agreed regarding the need to establish relevant policies and incentives to promote BIM (M: 4.34, SD: 0.738), as well as developing a standard legal or contractual agreement relating to BIM (M: 4.25, SD: 0.822). Several technology factors were also identified especially to address the technical complexity of BIM such as to standardize the open BIM standard for efficient inter-operability (M: 4.31; SD: 0.719) and to establish a BIM technical group to resolve any BIM complexities (M: 4.29, SD: 0.786).

Table 6 : Driving Factors of BIM Adoption

Factors	Driving Factors of BIM	Mean (M)	Standard Deviation (SD)	Rank
Technology	Technical progress in computing and IT technologies.	4.26	0.836	11
People	Enhancing BIM education and certifications.	4.48	0.767	2
Policy	Establish policies and incentives to promote BIM.	4.34	0.738	7
People	Support from architecture professional bodies (LAM, PAM).	4.51	0.704	1
People	R&D collaboration with universities to enhance BIM education.	4.43	0.700	4
Policy	Development of BIM standard legal or contractual agreement.	4.25	0.822	12
People	Demand of BIM from clients.	4.40	0.785	5
People	BIM enforcement by government / local authorities.	4.43	0.726	3
Process	Specialisation of design services towards BIM.	4.23	0.860	13
Technology	Grant subsidies and provide affordable BIM.	4.25	0.822	12
Process	Support for BIM from top management of organisation.	4.38	0.817	6
Process	Develop complete BIM standard and guideline for organisations to adopt.	4.30	0.788	9
Technology	Establish BIM technical group to solve technical / complexity issues.	4.29	0.786	10
Technology	Standardise open BIM file format for inter-operability.	4.31	0.719	8

5. DISCUSSIONS

5.1 BIM Usage and Awareness from the Architect's Perspectives

Overall, the results show positive signs of BIM awareness by architects, as more than 80% of the respondents were generally aware of BIM and its capabilities. However, the level of BIM usage was still low as only 17.6% of the architects had more than 2 years of experience working with BIM. The rate was significantly increased from the previous study conducted, whereby less than 50% of the construction players were aware of BIM (CIDB, 2017). The results also show that 45.4% of the firms had the tendency to adopt BIM into practice, but the amount of BIM projects executed by these firms was still low at the capacity of below 20%. This clearly indicates that the BIM trend by organisation was still at the embracement stage, which was similarly faced by the overall construction industry (CIDB, 2017; Mohd-Nor & Grant, 2014). Furthermore, the findings identified the larger firms to be relatively more prone towards using BIM as compared to SME firms. Therefore, it is important to further study the impact of BIM to these SME firms, as the projects delivered by SME firms might take advantage of BIM as compared to large scale projects (CREAM, 2014; Arayici et al., 2011). Besides, a majority of the respondents were collectively aware regarding the concept and the technical aspects of BIM. In the schematic design stage, key findings show that most respondents scored the lowest mean values on the technical aspects, such as the use of point cloud and 3D laser scanning technology, supporting existing condition modelling, and the integration of BIM and GIS technology. In many instances, the benefits of GIS especially in design and planning organisations were perceived by an individual as a threat and an opportunity to others (Hussain, 2011). Thus there is a need to provide exposure to the architects in leveraging the potential benefits of GIS integration in design (Azhar et al., 2015). In the design development stage, the least known factors were the use of BIM to conduct environmental simulation and analysis and for code and compliance review. In comparison to the traditional approach, the code and compliance process with BIM could motivate users to adopt BIM at an earlier stage (Martins & Abrantes 2010). Lastly, in the construction stage, the architects possessed the least awareness of BIM in the approach to support the fabrication of building components and 4D BIM construction phasing and simulation. BIM has the ability to produce construction simulation in order to mitigate risks, reduce wastage, and enhance the health and safety for construction (Eadie, Odeyinka, Browne, McKeown, & Yohanis, 2013), highlighting the benefits of its implementation in the context of architecture. In specific, the variables that revealed the least awareness overall were the use of BIM for building code and compliance review, point cloud and laser scanning that enabled the generation of 3D BIM existing condition, and the potential integration of BIM with GIS. Therefore, there is a need for further study to establish its potential usage and application.

5.2 BIM Readiness and Driving Factors from the Architect's Perspectives

The study further observed organisation readiness to adopt BIM, whereby it is interestingly to note that over 60% of the architecture firms started to initiate their financial investment in preparing their internal assets and manpower towards BIM. This is a significant improvement from the previous national

BIM report that reported over 60% of companies within the industry were unwilling to allocate any financial incentives or support to use BIM, as well as invest in BIM trainings and assets (CIDB, 2017). As the implementation of BIM requires change to the organisational values and culture, the findings clearly show positive signs of future BIM adoption within the industry. The study further identified the salient driving factors to be imposed for propelling BIM forward in the architectural landscape. The people factor had the highest consistencies of agreement, whereby among the key highlights is the increased demand for the government, education sector, and support of architectural professional bodies to play a leading role and support the development of BIM adoption within the industry. This has been highlighted by Kushwaha (2016) and Eadie et al. (2013), claiming the lack of initiative from the government, professional organisations, and educational institutes as the major factor attributable for the limited awareness and implementation of BIM. Therefore, governmental and professional bodies (e.g. PAM and LAM) may organise a series of awareness and motivation programmes, such as seminars and workshops for architecture professionals and students. In addition, CIDB has been proactively taking the lead in BIM development with the establishment of MyBIM centre to facilitate trainings and seminars on BIM adoption (CIDB, 2017). Apart from that, enforcement is a key step to drive the use of BIM. Singapore, as an example, has enforced the practice of code checking and building plan e-submission for its local authorities through CORENET (Construction and Real Estate NETwork). With regard to the education aspect, numerous research have highlighted the importance of having a structured BIM courses at the level of tertiary education (Rogers, Chong, & Preece, 2015; Haron, Soh, Ana, & Harun, 2017). Institutions of higher learning throughout Malaysia are encouraged to incorporate BIM courses in their syllabus to allow their graduates to understand BIM technology as a preparation to meet the challenging demands of the industry. In addition, the trend of low BIM usage by architects can be changed through the role and influence of clients. Several studies have revealed that the adoption rate by clients or developers is at the lowest amongst the construction players. The lack of demand is due to the reluctance to change, fear of increased cost, and lack of knowledge and awareness on BIM (CIDB, 2017; Memon et al., 2014). Such lack of demand would ultimately hinder BIM adoption as it is vital for clients to increase their involvement in order to realise a sustainable construction industry (Memon et al., 2014). Meanwhile, BIM requires significant procedural and technological changes in an organisation (Araiyici et al., 2011). Hence, adapting such processes rendered the respondents' collective agreement for the organisational leaders to play an important role towards the transition. Currently, no effective standard and guideline has been developed specifically for BIM adoption by organisations (Zahrizan et al., 2013). Further risks may emerge should organisations develop their own BIM standards and protocol, causing unclear collaborative procedures between the project teams. In the technology context, findings from the secondary data revealed that several BIM limitations experienced by construction organisations included issues like interoperability, complexity of software, requirement of enhanced collaboration and requirement of coordinated drawing (Memon et al., 2014; Kensek & Noble, 2014; Howell & Batcheler, 2005). In addressing these technological obstacles, the respondents collectively agreed regarding the need to develop an open-BIM standard for interoperability. This can be addressed by establishing a dedicated technical group to resolve any technical complexities or issues that arise from BIM usage. Moreover, its implementation is costly as it demands copious amount of investment to transform the work process and flow of an organisation. Thus, the provision of grants and subsidies to attain BIM was highlighted by the respondents to promote the use of BIM technology.

6. CONCLUSION

Despite the rapid development to harness the benefits of BIM as a means of sustainable project delivery in the construction industry, the current adoption rate by Malaysian architects were still low with the majority of firms remained in a preliminary state. Most of the architects are aware of BIM and its capabilities, with the majority demonstrating a somewhat moderate level of awareness. Furthermore, the research identified the current level of awareness according to the stages of building project, whereby the findings showed that the construction stage had the most consistency of low awareness level as compared to other project stages. In specific, the benefit that displayed the lowest level of awareness was the potential of adoption between BIM with GIS, as well as for building code compliance and review. In contradictory with previous studies in the construction industry, most of the architects believed that BIM would impact the future of design project management and subsequently initiate their commitment towards adopting BIM. Several driving factors were also determined by the respondents to improve the use of BIM in the industry. The low BIM uptake revealed, underscores the significance of BIM diffusion within architectural organisations to further understand the barriers and drivers of BIM adoption. Consequently, this study provided further insight and findings regarding the adoption of BIM, which serves as a critical reference point for local architects to assess the changes and effects that are crucial in determining the progress of BIM in Malaysia. Finally, several limitations need to be acknowledged, specifically, time constraint and relatively small sample sizes, which may lead to concerns on generalisation of the research findings.

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ENERGY EFFICIENCY ACTION PLAN FOR A PUBLIC HOSPITAL IN MALAYSIA

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ABSTRACT

Sustainable buildings are becoming a focus nowadays because they are cost effective and affect our society and environment. Hospitals, which are categorized as commercial buildings, also aim to become sustainable. Sustainable hospitals hope to provide health facilities to humankind while reducing their greenhouse gas emissions to the environment. In terms of energy consumption, hospitals consume much electricity because of their non-stop operation 24 hours a day. This high electricity consumption leads to high electricity costs and adversely affects the environment. This study examines the electricity usage of a public hospital near Kuala Lumpur, Malaysia, through a preliminary energy audit. Energy conservation measures (ECMs) are recommended to the hospital to reduce its electricity consumption. The recommended ECMs, namely, unplugging or awareness campaign, replacement of existing personal computers with laptops and regular maintenance and replacement of refrigerators, are expected to achieve a total electricity saving, cost saving and CO_2 emission reduction of 429,743.39 kWh/year, RM 152,127.57/year and 296,522.94 kg/year, respectively.

Keywords: : Energy Efficiency, Hospital, Sustainable Building

1. INTRODUCTION

In 2015, the overall electricity consumption of Malaysia was 132,199 GWh, from which industrial, commercial, residential, transport and agricultural sectors accounted for 45.9%, 32.2%, 21.4%, 0.2% and 0.4%, respectively [Suruhanjaya Tenaga (Malaysian Energy Comission), 2015]. The electricity in Malaysia is mainly supplied by power stations, and reports have shown that non-renewable energy sources, such as coal (47.2%), natural gas (40.4%), hydropower (10.8%), diesel oil (0.8%) and fuel oil (0.3%), and renewable sources (0.3%) provided a total of 33,134 ktoe of energy input to power stations in 2015 [Suruhanjaya Tenaga (Malaysian Energy Comission), 2015]. The commercial sector, especially buildings, consumed 32.2% of the total electricity consumption [Suruhanjaya Tenaga (Malaysian Energy Comission), 2015]. Therefore, commercial buildings are contributors to the country's greenhouse gas emission, which is projected to decrease by 23% and 30% in 2020 and 2030, respectively, relative to 2005 levels (Sion et al., 2013). Malaysia is concerned about the energy efficiency of buildings because it is an important factor in achieving Malaysia's target of reducing 40% of its carbon emission by 2020 whilst saving energy and costs; this importance has been proven by the construction of the Low Energy Office (LEO), Green Tech Malaysia Building and Diamond Building (Hameed et al., 2016; Sion et al., 2013).

1.1 Support from Governmental and Non-Governmental Organizations

Malaysia has been supporting energy-saving efforts through the Ministry of Energy, Green Technology and Water as the ministry aims to achieve considerable development in the building sector by adopting green technology in the construction, management, conservation and abolishment of buildings ('Sektor Utama Dasar Teknologi Hijau Negara', 2018). Additionally, other government agencies, such as Malaysia Green Tech Corporation ('Who We Are - GreenTech Malaysia', 2016), Yayasan Hijau MY (YaHijau) ('Yayasan Hijau Malaysia (YaHijau)', 2018), Energy Commission (National Energy Efficiency Action Plan, 2014, 'Roles and Functions', 2015) and Sustainable Energy Development Authority (SEDA) ('Overview of SEDA', 2018), strive to promote energy efficiency through their roles and projects. Meanwhile, non-governmental organizations (NGOs), such as Malaysia Green Building Confederation (MGBC), are promoting sustainable buildings (Hameed et al., 2016).

1.2 Studies on the Energy Efficiency of Hospital Buildings

Commercial buildings, such as hospitals, have elicited the attention of researchers worldwide. Various energy efficiency strategies must be implemented in hospital buildings because they operate 24 hours a day, leading to high energy consumption (Table 1). These strategies may be in the form of engineering approaches (Krarti, 2011), such as improvement of heating, ventilation and air-conditioning (HVAC) systems, the building envelope, electrical usage, central heating, cooling equipment, energy management control, compressed air, thermal energy storage (TES), charging/discharging of TES, cogeneration, heat recovery and water management. Other strategies may involve financial schemes or policies/regulations (Yong and Hor, 2017). In 2016, 11 hospitals in Malaysia were recognized as green hospitals under the Green Building Index (GBI) Hospital Tool (Tan, 2016).

Table 1: Energy efficiency strategies for hospitals

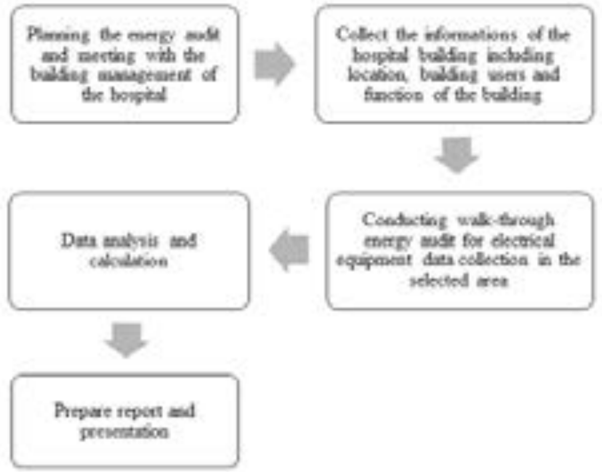
Year	Location	ECMs	Reference
2010	Malaysia	▪ Use high- efficiency motors ▪ Use variable speed drive	(Saidur et al., 2010)
2011	United States	▪ Turn off all computers after office hour	(Prasanna et al., 2011)
2013	Malaysia	▪ Balance the electricity usage in each peak and off-peak time separately ▪ Shifting the electricity usage from peak time to off-peak time therefore reduce the maximum demand and peak time energy usage	(Moghimi et al., 2013)
2013	Italy	▪ Building envelope refurbishment	(Ascione, Bianco, De Masi, & Vanoli, 2013)
2014	Naples, Italy	▪ Adopt radiators thermostatic valves and AHU regulations ▪ Install roofs thermal insulations	(Buonomano, Calise, Ferruzzi, & Palombo, 2014)
2014	Ireland	▪ In radiology department; suggest to upgrade the equipment to support hibernate and sleep mode. ▪ Create a workgroup policy to implement the plan of hibernating machines at a certain times each day ▪ Introduce a programme to recycle the packaging which is associated with catheters and other devices in the radiology suite. ▪ Install motion sensor to switch off lighting automatically as it detects the room is empty	(McCarthy et al., 2014)
2014	Ireland	▪ Change behaviour of staff by switch off all lightings and computers after work-hour	(Burke & Stowe, 2014)
2016	Egypt	▪ Apply Demand Control Ventilation (DCV) system to improve indoor air quality ▪ To apply building construction regulations are a must for all governmental buildings and private sector	(Radwan, Hanafy, Elhelw, & El-Sayed, 2016)
2016	Italy	▪ Innovative financial strategies by providing capital to retrofit the hospital via Energy Performance Contracting; 77% and 35-40% energy can be saved up for high cost investments and low cost investments respectively.	(Principi, Roberto, Carbonari, & Lemma, 2016)
2016	Ireland	▪ Implement systematic environmental initiatives which are taking into account of these aspects: environmental concern, supports bodies and voluntary environmental initiatives, informing and involving groups, environmental education and green-charter and continuity	(Ryan-fogarty, Regan, & Moles, 2016)
2017	Egypt	▪ Apply simple retrofit strategies such as solar shading, window glazing, air tightness and insulation	(El-Darwish & Gomaa, 2017)
2017	Spain	▪ Increase the time spent for preventive maintenance therefore reduce the demand for corrective maintenance and energy consumption	(García-Sanz-Calcedo & Gómez-Chaparro, 2017)
2017	China	▪ Implementation of web-based online control system in a chiller plant	(Zhao, 2017)
2018	Italy	▪ (Simulation Study) - Retrofit the building by installing smart rotating windows with sealing hydraulic gasket and LED system give the shortest payback period.	(Silenzi, Priarone, & Fossa, 2018)

2. METHODOLOGY

In this study, a public hospital near Kuala Lumpur, Malaysia, was selected as the study case. The criteria of the selected hospital as the study case is based on the electricity consumption which is more than 3,000,000 kWh per month for six consequences month based on the Efficient Management of Electrical Energy Regulation 2008 (EMEER 2008) enforced by the Energy Commission [Suruhanjaya Tenaga (Malaysia Energy Commission), 2008] . The hospital operates 24 hours a day (24/7) and consumes large amounts of electricity. The hospital's bills showed that the hospital consumed 4,000,000 kWh per month of electricity and spent about RM 1.5 million per month (from 2015 to 2017) on electricity. The electricity usage of the hospital was assessed through a preliminary energy audit in this study. This study highlighted the electricity saving potential that can be obtained from the use of electrical equipment in various departments of the hospital. The research framework design, which includes the research objectives, data collection methodology, data analysis and research outcomes, is shown in Figure 1. Moreover, this section also describes the flow of data collection through a walk-through energy audit, which is the process of energy audit and formulation used to calculate electricity consumption.

2.1 Data Collection: Walk-through Energy Audit

Based on the 'Electrical Energy Audit Guideline for Buildings' by the Energy Commission of Malaysia (Energy Commission, 2016), an energy audit was conducted to collect information on the equipment used in the hospital. Figure 2 shows the flowchart of the audit.



2.2 Electricity Consumption Formulation

To analyse the collected data, the formulation for electricity consumption was calculated. Suitable energy conservation measures were developed from the results.

The measurement of total electricity consumption was performed by using build load data collected through desktop and field collection methods. It is the summation of the electricity consumption of all equipment, which are assumed to operate in full capacity. Equation [1] shows the calculation of electricity consumption for each type of equipment (Saidur, Hasanuzzaman, Yogeswaran, Mohammed, and Hossain, 2010). In the equation, E is electricity consumption (kWh), P is the power rating of the equipment, M is operation hour and Neq is number of equipment. Moreover, the reading only covered weekdays, and we assumed that the total daily electricity consumption was similar throughout a year with only 260 days (52 weeks × 5 days).

$$E = P \times M \times N_{eq} \quad [1]$$

3. RESULTS AND DISCUSSION

3.1 Electricity Consumption

The equipment that were audited in the walk-through audit were categorised into five groups: office equipment, medical equipment, electrical appliances, refrigerator/chillers and kitchen utensils. Overall, the total number of active and operating appliances (assets and non-assets) in the hospital was 3422 units.

Medical equipment had the highest electricity consumption throughout the year; it accounted for 71.85% (Figure 3) of the hospital's total electricity consumption, which was 11,255,203.45 kWh/year.

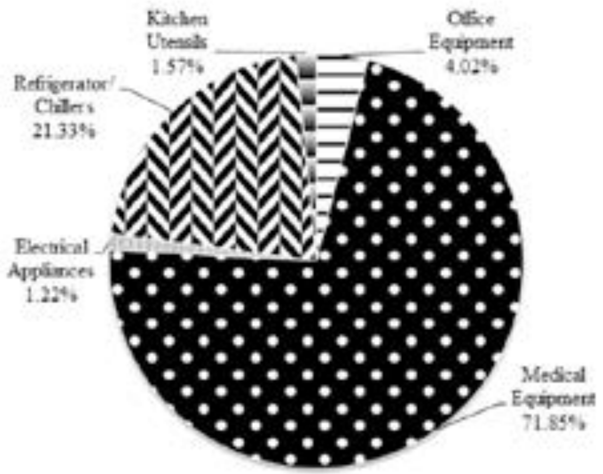


Figure 3 : Percentage of electricity consumption by categories

Most of the audited floors showed similar result patterns. Medical equipment on the basement, ground and second floors contributed 75.72%, 49.08% and 90.6% to the electricity consumption, respectively. The first floor had the highest electricity consumption primarily because of the office (34.12%) and medical (30.02%) equipment on it.

A study conducted in another public hospital in Malaysia showed that lighting consumes the highest electricity usage among electrical appliances, followed by biomedical and office equipment (Saidur et al., 2010). Other studies that aimed to reduce the electricity consumption of electrical equipment in radiology departments (Burke and Stowe, 2014; McCarthy et al., 2014; Prasanna, Siegel, and Kunce, 2011) found that these departments consume large amounts of electricity. They discovered that energy use in these departments can be reduced by turning off computers and other office appliances when not in use. Similarly, the present study discovered that the radiology department consumed the largest amount of electricity on the ground floor of the hospital. Meanwhile, the radiotherapy and oncology department, psychiatry and labour area and operation theatre complex consumed the largest amount of electricity on the basement floor, first floor and second floor, respectively.

3.2 Electricity Cost

The electricity usage was calculated based on the utility bills by Tenaga National Berhad (TNB) Tariff C2–medium voltage peak/off-peak commercial tariff (Commercial tariffs, 2018). All kWh during peak and off-peak periods were calculated regardless the fact that each kW of maximum demand per month during the peak period should be considered. The cost of electricity was calculated by multiplying the total electricity consumption with the rate of electricity. The total electricity cost for all electrical equipment in the hospital was determined to be RM 3,900,467.64/year. The electricity cost depended heavily on the electricity usage of the building.

4. ENERGY CONSERVATION MEASURES

The audit team came up with a few solutions that can be implemented to reduce the energy consumption of the audited area. These solutions are called energy conservation measures (ECMs) and can be categorised as active and passive actions. Active actions entail costs, whereas passive actions do not need costs or are low cost.

4.1 ECM #1: Unplugging/Awareness Campaign

A low-cost ECM that can be implemented for energy saving is to conduct basic energy awareness activities within the centres and clinics in the building. The programme focuses on the cost savings and environmental issues associated with energy use. Information can be disseminated through websites or newsletters. This measure focuses on lighting and computer systems because these are often switched on during operation hours.

For this clinical building, a passive ECM can be implemented by conducting an awareness campaign to educate and discipline the staff on how to change their bad habits, such as leaving computers on during idle hours and leaving other appliances (microwave, electric kettle and water heater) on standby

mode most of the time. Phantom power is constantly being drawn when appliances are turned off but still plugged to power outlets (Beth Brindle, 2011). Therefore, it is strongly recommended to connect office equipment, such as computers, printers and copiers, to a single power strip so that they can be switched off all together.

According to the Standby Power Summary Table (2018), a computer in off mode draws about 2.84 Wh of energy on the average. If an unplugging campaign is implemented, 2.84 Wh of energy can be saved by a single computer for an hour. For example, the first floor of the studied hospital had the most computers (about 318) among all floors. Therefore, unplugging for an hour can save about 903.12 Wh of energy per day and 234.81 kWh of energy per year. In terms of cost, RM 85.70/year can be saved based on the TNB tariff of 0.365 RM/kWh. If an unplugging campaign is applied to many appliances, then a high percentage of saved energy will be achieved. A study performed on a radiology department also found that turning off computers after working hours can save electricity usage by up to 25,040 kWh/year (McCarthy et al., 2014).

4.2 ECM #2: Replacement of Existing Personal Computers with Laptops

We recommend an active ECM, i.e., replacing computers with laptops, under the assumption that the lifespan and investment/cost of renting computers and laptops are similar. A laptop can function even if it only uses its battery compared with personal computers that need continuous electrical supply. Given that laptops are battery operated, only the battery itself needs to be charged. For example, our calculation indicated that replacement with 318 laptops on first floor will consume about 14,892.32 kWh/year compared with the energy usage of existing personal computers, which is 138,860.8 kWh/year. This figure shows that 89% of electricity (123,968 kWh/year) can be saved from the replacement of existing personal computers by laptops. In terms of cost, RM 45,248.32 (1.16%) can be reduced annually from the total electricity cost of the hospital.

4.3 ECM #3: Regular Maintenance

The working conditions of equipment play a major role in their efficiency and energy consumption. Periodic maintenance of electrical equipment is important for these equipment to operate at the optimum level. Malfunctioning appliances pose hazards to building occupants and reduce system efficiency. Repair and maintenance of sub-par electrical equipment should be conducted immediately to minimise unnecessary losses. Energy savings can reach approximately 7% if preventive and corrective maintenance are conducted for appliances relative to not conducting such maintenance (Koo and Hoy, 2003). However, an additional maintenance cost will be incurred if this maintenance is conducted because this maintenance is an active ECM. We assume that 5% of the maintenance cost is from electrical consumption; hence, we can still achieve 2% cost saving each year. As a result, 22,104.069 kWh/year of electricity can be saved, which is equal to RM 82,162.99/year.

4.4 ECM #4: Refrigerator Replacement

During the walk-through energy audit, we found very old models of refrigerators without any energy-efficient star rating in various departments and clinics either for medical storage or general use (as in pantry) purposes. Sixty refrigerators were found on the ground floor, and they operate 24 hours a day for 365 days a year to ensure that items are kept fresh. These old models should be upgraded to five-star-rated energy-efficient refrigerators as an active ECM, and doing so could save up to 20% of energy (5-Star Energy Appliances: How Much Can You Roughly Save Annually?, 2016). Refrigerators that are still in good condition need not be replaced immediately. Replacing refrigerators once they malfunction is virtually a cost-free strategy. As a result, the electricity and cost savings would be 80,436.61 kWh/year and RM 24,630.55/year, respectively, with ~2 years of simple payback period.

5. ELECTRICITY SAVING, COST SAVING AND EMISSION REDUCTION

By applying these recommended ECMs, electricity saving, cost saving and reduction in carbon dioxide (CO_2) emission (emission factor: 0.69 kg/kWh; Mohamed et al., 2016) were calculated. Table 2 shows that 3.82% of electricity usage can be saved annually by implementing all of the ECMs. This percentage is equal to RM 152,127.57/year of cost saving and 296,522.94 kg/year of CO_2 reduction.

Table 2 : Electricity saving, cost saving and emission reduction by applying

the recommended ECMs

ECMs	Electricity saving (kWh/year)	Cost saving (RM/year)	CO_2 emission reduction (kg/year)
ECM #1	234.81	85.71	162.02
ECM #2	123,968.00	45,248.32	85,537.92
ECM #3	225,104.07	82,162.99	155,321.81
ECM #4	80,436.51	24,630.55	55,501.19
Total	429,743.39	152,127.57	296,522.94

Another point to be made is that the main barrier in adopting energy-efficient aspects in this hospital is finance. Large funding is required to improve the efficiency of equipment with high power ratings or to replace them with improved ones. Therefore, we suggest implementing ECM #1 and ECM #2 first because they do not require an additional cost. Despite their small percentage of electricity saving, the cost saving from their implementation could be used to implement ECM #3 and ECM #4 later on.

6. CONCLUSION

Four ECMs were recommended based on the recognised energy-saving potential of a public hospital near Kuala Lumpur, Malaysia. The total electricity consumption of the hospital is 11,255,203.45 kWh/year. This value is expected to decrease by 3.82% per year (equal to RM 152,127.57/year of cost saving and 296,522.94 kg/year of CO^2 reduction) when all of the recommended ECMs are implemented. Thus, the hospital must implement the recommended ECMs to reduce its electricity consumption, electricity cost and CO_2 emission.

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ASSESSMENT OF INDOOR THERMAL CONDITION OF A LOW-COST SINGLE STORY DETACHED HOUSE: A CASE STUDY IN MALAYSIA

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ABSTRACT

Thermal comfort is an important factor to ensure good thermal condition of a house. To understand the current indoor thermal situation of a typical low-cost single story detached house in Malaysia, several parameters of thermal comfort need to be measured. The main objective of this study is to analyse the indoor thermal condition of a low-cost single story detached house through measurement of the indoor air temperature. The methodology applied in this study was field measurement to validate the IESVE simulation model of a low-cost single story detached house of a rural area, located in Kuala Pilah. Field measurement was done under two different conditions: (i) windows and door closed and (ii) windows and door opened. Air temperature, air velocity, and relative humidity data were collected using thermal comfort meters and a weather station. The data were used to validate the model generated by IES<VE> simulation software. Therefore, the objectives of this paper are to find out the statistical significance between the variables and to initiate passive design strategies using IES<VE> software to make indoor thermal condition more comfortable. Statistical analysis revealed that indoor air temperature (Ta) is statistically significant with time but not with the conditions. In opposition, air velocity (Va) is correlated with the conditions but not with indoor air temperature and time. Afterward, the window sizes were enlarged, and roof insulation was added to the simulation-based models to observe the temperature changes. Results show that in both cases, the temperature reduced to some extent but was not satisfactory nor in the recommended indoor air temperature range. Therefore, more careful deliberation is needed to design the layouts for the low-cost detached houses. Using roof insulation material is also important to improve the indoor thermal condition of the low-cost single story detached houses in Malaysia.

Keywords: Indoor air temperature, low-cost single story detached house, thermal condition, IES<VE> simulation.

1. INTRODUCTION

Low-cost housing had been a minor category of housing for both government and private sectors of housing in the early period of Malaysia. However, during the 7th Malaysian plan (Economic Planning Unit, 1996), 8th Malaysian plan (E. M. Plan, 2001; Unit, 2001) and 9th Malaysia plan (Bakhtyar et al., 2013; N. M. Plan, 2008; Zaid and Graham, 2010), the government paid attention towards low-cost and low-medium-cost houses under the affordable housing category (Cagamas Holdings Berhad, 2013). In recent days, housing rules are being executed for masses of people and their development. The Malaysian government is trying to create an easy pathway to provide affordable housing for its people.

Besides, the climatic condition of Malaysia has a direct impact on the indoor thermal condition of a house. According to the Malaysian Meteorological Department, the daytime minimum and maximum temperature ranges are 23 °C to 27 °C and 30 °C to 34 °C respectively. The windows, walls and roof surfaces of a house gain direct heat from solar radiation (Al-tamimi, Fairuz, and Fadzil, 2011; Al-Tamimi and Syed Fadzil, 2011; Datta, 2001). The relative humidity also remains very high which is nearly 75% with heavy rainfall (Tinker, Ibrahim, and Ghisi, 2004).

Thermal comfort issues have always been one of the most discussed topics for architects and academicians of tropical countries. As stated in MS 1525:2007, 23 °C to 26 °C is the recommended indoor air temperature range for the Malaysian climate (Department of Standards Malaysia, 2007; Jamaludin and Izma, 2015). Additionally, many researchers indicated the range of 25 °C to 28 °C as the recommended indoor air temperature for Malaysia (Hanafi, 2014; Heating, Refrigerating, Engineers, and Institute, 2004; Ibrahim, 2004; Madros, 1998; Zain-Ahmed, Sayigh, and Othman, 1997).

Henceforth, different experiments and studies were done for different categories of housing to determine the recommended indoor air temperature. An experiment by Jamaludin and Izma (2015) revealed that under Kuala Lumpur climatic condition, the highest indoor temperature of master bedroom was 32.6 °C. But in Kuching and Bayan Lepas, 31.10 °C and 31.60 °C were recorded respectively (Jamaludin & Izma, 2015). For terrace houses, many researchers found that 23 °C to 28 °C could be the comfort range under the Malaysian climate (Jamaludin & Izma, 2015; Zain, Taib, & Baki, 2007).

1.1 The recent scenario of low-cost houses in Malaysia

In Malaysia, the quality of low-cost housing has not been upgraded as compared to other categories of housing. One of the reasons for introducing affordable housing in Malaysia was dissatisfaction of the residents with the quality of low-cost housing (Musa et al., 2015). Despite the government's endeavour, the quality of low-cost housing is still not satisfactory. The causes include the building standards, planning layouts, materials' quality and thermal comfort (Hanafi 2014; Isnin et al. 2012). However, in most cases, thermal comfort issues have always been neglected in low-cost housing design. As a result, the thermal condition of these houses lead to higher indoor air temperature during the daytime (Tinker et al., 2004). Liang (2010) also enlightened that the indoor environmental quality of a low-cost house is always an overlooked issue (Isnin et al., 2012; Liang, 2010). There was always a matter of costing in choosing the materials for constructing the low-cost houses.

Furthermore, the indoor air temperature of low-cost houses is much higher than the recommended indoor air temperature for tropical climate (Hanafi, 2014). Incompetent thermal designs have affected the thermal comfort of low-cost houses as well as the residents of the houses (Hanafi 2014; Madros 1998; Ibrahim and Baharun 2014).

A comparative study was conducted by Ibrahim et al. (Hanafi 2014; Madros 1998; Ibrahim and Baharun 2014) on two different houses in Betong and Saratok. The indoor air temperature readings under different conditions were 34.2 °C and 34.5 °C for Betong and Saratok houses respectively, which were far from the recommended indoor air temperature in Malaysia. However, after opening the windows and doors, the air movement had increased but the indoor environmental condition was not comfortable at all.

The Malaysian government still puts the effort to improve the environmental quality of the low-cost houses (Musa et al. 2015). Typical layouts of single-story detached houses are shown in Figure 1 and 2. A standard guideline is available for low-cost housing, which is noted as the Construction Industry Standard (CIS 1: 1998). The guideline is for one- to two-story buildings, compiled by the Construction Industry Development Board Standard (Ismail, 2003; Suzaini Zaid and Peter Graham, 2010). The guide by the Construction Industry Standard (CIS 1: 1998) (Mohit, Ibrahim, & Rashid, 2010; Roadmap & Roadmap, 2003) is as follows:

- A minimum floor area of 63 square meter
- Three (3) bedrooms
- A kitchen
- A living and dining area
- A storeroom
- A bathroom, and
- A toilet

2. METHODS

The field measurement was chosen as a method for this study. A typical low-cost single-story detached house was selected to measure the thermal condition of the house which is built by the Rubber Industry Smallholders Development Authority (RISDA). As air temperature is one of the most important variables to determine human comfort (Kordjamshidi & Energy, 2011), this paper specifically focuses on the indoor air temperature measurement to find out the indoor thermal condition of the house.

Figure 1: Typical low-cost single-story detached house

Figure 2 : Typical layout of a low-cost house

2.1 Equipment calibration

All the equipment was calibrated within a controlled environment before taking the on-site measurements to find out the error values. The list of the equipment used in the calibration is shown in Table 1 and Figure 3.

Table 1 : Equipment calibration

No.	Instruments	Units
1	Delta Ohm HD32.3 WBGT-PMV	02
2	Weather station	01

Figure 3: Calibration of all instruments in the indoor controlled environment

2.2 Field measurement

The field measurement was conducted on a low-cost single-story detached house located at ‘Kampung Parit Seberang’, ‘Kuala Pilah’, Negeri Sembilan (Latitude: 2°45’9.72” Longitude: 102°13’47.27”). The house had three bedrooms, one bathroom, one toilet, kitchen, dining and living room area of 57.88 square meter (623 square feet), as shown in Figure 4 and Figure 5. The measurement was conducted for three days from morning to evening for each condition (08:15 am to 19:15 pm). The first three days were under the setup where the door and windows were closed. The last three days, the door and windows were opened. During field measurement, a weather station was set outside the house to measure the outside meteorological conditions and two thermal comfort meters were set in different rooms of the house (labelled F2 and J1 in Figure 5).

Figure 4: Surroundings of the low-cost location single story detached house used for field measurement.

F rs

Figure 5 shows the location of both thermal comfort meters. The thermal comfort meters labelled as F2 was located in between the living and dining rooms and J1 was set to 1.1 meter above the floor level based on a similar study of Nguyen (Anh Tuan Nguyen 2012).

Figure 6: The position of J1 and F2 thermal comfort meters

2.3 Data collection

After completing the field measurement, the measured data were transferred and analysed. Thermal condition assessment were carried out under two different conditions (Ibrahim and Baharun 2014; Tinker et al. 2004):
Condition 1: Windows and door closed
Condition 2: Windows and door opened

The air temperature, wind speed, relative humidity and PMV data were collected for both conditions. However, in this paper only discusses the air temperature data. All data were statistically analysed using Microsoft Excel and SPSS.

2.4 Integrated environmental solutions <virtual environment> simulation

Integrated environmental solutions <virtual environment> (IES<VE>) is one of the efficient simulation software that can perform a detailed analysis of thermal performance (Doyle 2008; Nikpour et al. 2013). Three different models were developed to run three different simulations to attain a sound thermal condition of the house. Afterwards, changes were made to the base model to see the results. The window sizes were enlarged and different insulation materials like bubble foil and glass wool were used in the roof for the simulation model.

3. RESULTS AND DISCUSSIONS

The main emphasis was on the changes in the indoor air temperature under different conditions of the selected low-cost single-story detached house. At first, the obtained data from the field measurement were validated. Afterward, the validated data were analysed to see the relations between the variables. The indoor air temperature from both conditions was compared with the recommended temperature for Malaysia. Then, the base models of the IES<VE> simulation for two different conditions were improved to give further passive design suggestions.

3.1 Validation of IES<VE> model

Validation is very important for any kind of thermal simulation program. After comparing different simulation models, Hensen disclosed that IES<VE> validation is one of the best (Hensen 2004). Other than that, IES Apache simulation is also a trustable simulation tool for getting high accuracy (Ahmad et al. 2012; Attia 2010; Nikpour et al. 2013; Saleem et al.). However, the data from the field measurement and IES<VE> model simulation were compared for validation purpose (Saleem et al.).

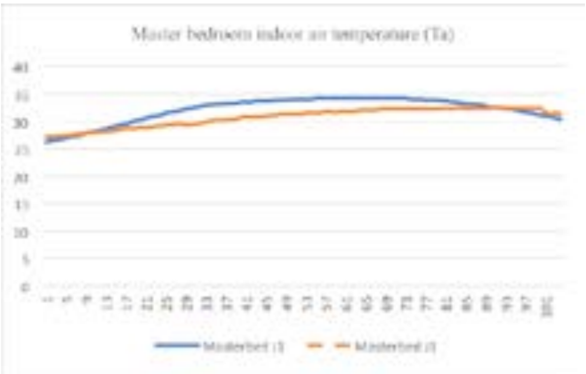

Figure 7: Indoor air temperature (°C) at the simulated and field measured data (Condition 1)

At first, the simulated data of two different conditions were validated with the field-measured data. Table 2 represents the difference in the indoor air temperature and the deviation percentage for two thermal comfort meters set in the master bedroom and living room area in condition 1.

Table 2 : Uncertainty estimation of the indoor air temperature (°C) sensors as calibrated:

Condition 1	Master bedroom (F2)	Living room (J1)
Diff of temp (°C)	0.5	1.5
Deviation (%)	1.9	2.3

Figure 8: Indoor air temperature (°C) at the simulated and field measured data (Condition 1)

For condition 1, the maximum uncertainty in calibrated data found in the living room area was ± 1.5 (°C) with the standard deviation at ± 2.3% (Table 2 and Figure 9). Under the setup of condition 2, the maximum uncertainty in calibrated data found in the living room area was ± 0.9 (°C) with ± 3.2% standard deviation (Table 3 and Figure 10). The weather station was excluded from uncertainty estimation (Muhsin, Fatimah, Yusoff, and Farid, 2017).

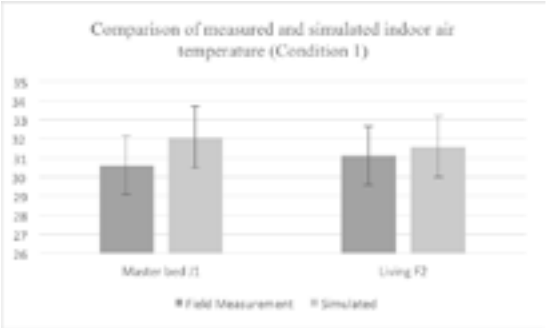

Figure 9: The comparison of air temperature (°C) between IESVE model and field measurement data (Condition 1)

Table 3 : Uncertainty estimation of the indoor air temperature (°C) sensors as calibrated:

Condition 2	Master bedroom (F2)	Living room (J1)
Diff of temp (°C)	0.7	0.9
Deviation (%)	2.6	3.2

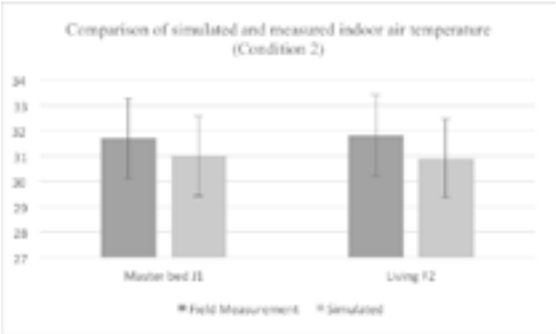

Figure 10: The comparison of air temperature (°C) between IESVE model and field measurement data (Condition 2)

The results revealed that for both conditions, the deviation (%) between IES<VE> model and field measurement was less than 5% for indoor air temperature data which indicates that IES has the validity to calculate the thermal analysis (Ahmad et al., 2012; Nikpour et al., 2013).

3.2 Pearson's correlation test

The Pearson's correlation test was conducted to see the impact of time and condition on indoor air temperature. The test results in Table 4 show that the indoor air temperature increased throughout the day and highly correlated with time.

Table 4 : Pearson Correlation test for different variables with time and conditions

		Time	Conditions	Indoor air temp.	Air velocity
Indoor air temperature	Pearson Correlation	.705**	-.118	1	-.068
	Sig. (2-tailed)	.000	.324		.571
	N	72	72	72	72

**. Correlation is significant at the 0.01 level (2-tailed)

3.3 Comparison between indoor air temperature and recommended temperature

According to the guidelines of Department of Standard Malaysia, the recommended temperature range for Malaysian climate is between 23 °C and 26 °C that indicates an average temperature of 24.5 °C. The measured indoor air temperature of the house was listed to compare with the recommended temperature under condition 1 and 2, for three different times of day (Table 5 and Table 6).

Table 5 : Condition 1: Indoor air temperature and recommended air temperature (°C):

Condition 1: (Windows/door closed)	Temperature	
	Indoor air temperature (°C)	Indoor recommended temperature (°C)
Morning 0900	29.2	24.5
Noon 1200	31.2	24.5
Evening 1700	33.0	24.5

Table 6 : Condition 2: Indoor temperature and recommended air temperature (°C):

Condition:2 Windows/door opened	Temperature	
	Indoor air temperature (°C)	Indoor recommended temperature (°C)
Morning 0900	29.7	24.5
Noon 1200	33.1	24.5
Evening 1700	31.4	24.5

In the morning (9.00 am), for Condition 1 and 2, 29.2 °C and 29.7 °C are the lowest indoor air temperature. Even being the lowest temperature recorded, both values were still higher than the recommended indoor air temperature.

3.4 Comparison between indoor air temperature and outdoor air temperature

The average indoor air temperature was compared with the monitored average outdoor temperature at 9.00 am under the windows and door closed condition. The results show that the average indoor air temperature is higher than the average outdoor air temperature (Table 7).

Table 7 : Condition 1: Indoor temperature and outdoor temperature (°C):

Condition 1: (Windows/door closed)	Temperature	
	Indoor air temperature (°C)	Outdoor air temperature (°C)
Morning 0900	28	25.2

3.5 IES<VE> simulation with different design strategies

IES<VE> simulation was used to initiate further passive design strategies for this study. After doing different statistical analyses, the indoor air temperature was observed by developing different simulation models by making changes on the base models for both conditions. The selected typical low-cost single-story house was modelled in the IES<VE> simulation to provide further recommendations for the betterment of the indoor thermal comfort of the house using selective passive design strategies. The base model obtained from the IES<VE> software was improved to run different simulations with different passive strategies for the betterment of the indoor environmental condition of the selected house (Figures 11 and 12).

1 are illustrated in Table 8.

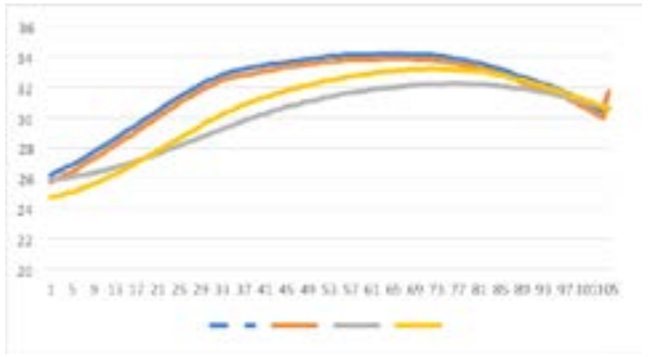

Figure 11: Changes in indoor air temperature of master bedroom in different simulations (Condition 1)

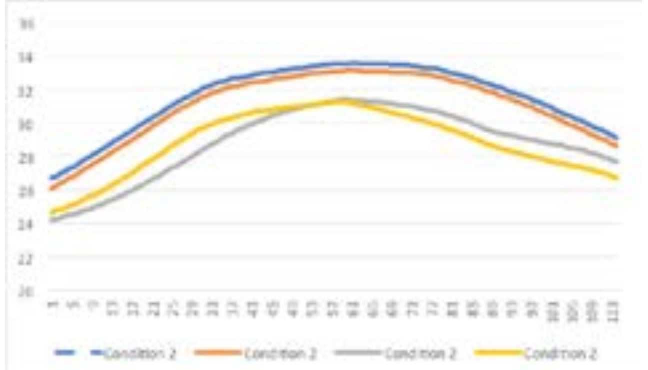

Figure 12:. Changes in indoor air temperature of master bed in different simulations (Condition 2)

In the first model, the openings sizes were increased to 4.5% from the original size. In the second and third models, roof insulation materials were replaced with bubble foil and glass wool insulation. The indoor air temperature of master bedroom dropped to 26.4 °C in the morning (9.00 am) when the window sizes were enlarged. The temperature dropped to 28.3 °C and 26.7 °C when using the glass wool and bubble foil insulation material respectively. It means the maximum indoor air temperature was decreased by 2.3 °C when the windows were larger.

The indoor air temperature was compared for three different times of day: Morning (0900), noon (1200) and afternoon (1700). The results of condition 1 are illustrated in Table 8.

Table 8 : Master bedroom and living room indoor air temperature analysis with three different IES<VE> simulation models: Condition 1

Condition 1					
Master bedroom	Time	Base model	Glass wool	Bubble insulation	Larger window
	9:00	28.7	28.3	26.7	26.4
	12:00	33.6	33.2	30.5	31.6
	17:00	32.1	31.7	31.6	32.0
Living and dining area	9:00	28.7	28.3	26.7	26.4
	12:00	33.6	33.2	30.5	31.6
	17:00	32.1	31.7	31.6	32.0

On the other side, for condition 2, while bubble foil insulation used in the simulation, the maximum temperature dropped to 25.5 °C indicating 2.4 °C reduction in the indoor air temperature. Using glass wool insulation did not result in much lower temperature, with 0.3 °C drop in the minimum temperature, as shown in Table 9.

Table 9 : Master bedroom and living room indoor air temperature analysis with three different IES<VE> simulation models: Condition 2

Condition 2					
Master bedroom	Time	Base model	Glass wool	Bubble foil insulation	Larger window
	9:00	27.9	27.6	25.5	26.6
	12:00	31.8	31.7	31.0	31.3
	17:00	32.2	32.1	32.4	32.1
Living and dining area	9:00	27.6	27.4	27.1	27.0
	12:00	31.5	31.4	31.2	31.2
	17:00	32.3	32.2	32.1	32.3

3.5.1 Analysing different passive design strategies

For all cases, simulation results were not highly satisfactory. But the measured indoor air temperature values were higher than the simulated model obtained values of the study house. With larger windows, the temperature decreased the most at 2.4 °C and 1.3 °C for both tested conditions. Windows can be enlarged easily to reduce the indoor air temperature. However, the installation of the roof insulation materials went well for condition 1 as all the windows were closed and the heat could not enter directly through the windows. But interestingly for condition 2, the temperature increased in the evening. For both conditions, the roof indoor temperature reduction is much higher in the model using bubble foil insulation than in the model using glass wool insulation. The roof insulation materials can be assessed under conventional metal deck roof by adding some extra cost. Applying different strategies can reduce the temperature to some extent but these strategies need to be improved or combined with other strategies to achieve a comfortable thermal environment

inside the house.

4. CONCLUSION

The results from statistical analysis and IES<VE> simulation model analysis showed that the indoor air temperature was not in the range of the recommended air temperature. For improvement of the indoor thermal condition of a low-cost house, indoor air temperature should be reduced for more conductive thermal environment for the occupants. Although the indoor air temperature was dropped after the windows and door being opened, the results were neither satisfying nor falling in the suggested indoor air temperature range. Hence, there is a need for an alteration in the windows and roof materials and an implementation of the low-cost design strategies to make the indoor thermal environment of these houses more liveable. The results showed that the passive design strategies have made positive impacts on the indoor thermal condition of the houses. The objectives have been fulfilled by initiating different low-cost passive design strategies from the methodology in reducing the indoor air temperature. Using bubble foil roof insulation materials could be one of the suitable strategies by spending a bit more to reduce the indoor air temperature of the low-cost single-story detached houses significantly. The findings of this study offer potential guidelines for the developers and builders to make the decision in building new low-cost houses more efficiently. This study only focused on the indoor air temperature issue of single-story detached low-cost houses in Malaysia. Therefore, further studies involving different types of low-cost houses should be carried out in the near future to improve the indoor thermal quality of the low-cost houses in Malaysia.

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INSTRUCTIONS TO AUTHORS

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Regular articles are full-length original empirical investigations, consisting of introduction, materials and methods, results and discussion, conclusions. Original work must provide references and an explanation on research findings that contain new and significant findings.

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2. REVIEW ARTICLE

These report critical evaluation of materials about current research that has already been published by organizing, integrating, and evaluating previously published materials. It summarizes the status of knowledge and outline future directions of research within the journal scope. Review articles should aim to provide systemic overviews, evaluations and interpretations of research in a given field. Re-analyses as meta-analysis and systemic reviews are encouraged. The manuscript title must start with "Review Article:"

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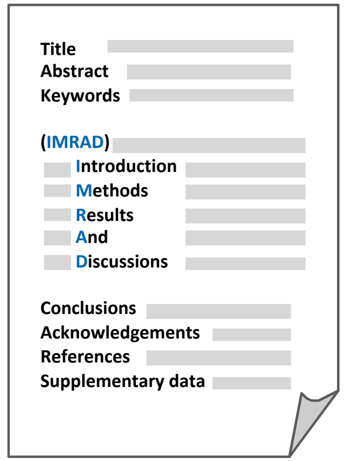

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