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IMPACTS OF DIFFERENT ROOF DESIGNS AND AIR-CONDITIONING OPERATIONS ON ENERGY CONSUMPTION AND COSTS IN AIR-CONDITIONED MOSQUES IN THE KLANG VALLEY , MALAYSIA

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By

NUR AMALINA SYAIRAH MOHAMED

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Energy efficiency in mosques, particularly in Malaysia, receives little attention even though this building typology has a significant total floor area comparable to commercial buildings. Although roofs are the major contributors to buildings' energy consumption and mosques generally have a unique occupancy and energy use pattern, there are scant records on the effect of roof designs on energy consumption for air-conditioned mosques in Malaysia. Furthermore, using air-conditioning (AC) in conjunction with high-volume low-speed (HVLS) fan has become a trend in retrofitted mosque buildings in Malaysia to improve thermal comfort conditions. However, the energy impact of operating AC and HVLS fan simultaneously is unknown. Therefore, this study aims to investigate the impacts of different roof designs and adjustments of AC temperature setpoints and operational profiles on the energy consumption and costs of air-conditioned mosques in the Klang Valley with the following objective: 1) To identify and classify the specific roof forms designed for air-conditioned mosques built in the Klang Valley between 1998 and 2018., 2) To analyse and compare the BEIs and electricity costs of air-conditioned mosques with different roof forms and between those with and without HVLS fan, and 3) To assess air-conditioned mosques' energy and cost savings potential through different air-conditioning temperature setpoints and operational profiles adjustments. A total of 467 mosques were identified in the Klang Valley, and 54 were found to comply with the selection criteria. Based on these 54 mosques, the study identified three roof classifications, namely "dome on flat roof", "dome on pitch roof", and "no dome", with "dome on pitch roof" being the most popular roof type. Five mosques were selected to represent these three roof classifications, and their BEIs were calculated and compared using 2-5years' electricity bill data. The BEI of mosques with and without HVLS fans were also compared. Then, two mosques with the highest BEI were further investigated through computer simulations to determine the optimum AC operational profile and temperature setpoints to reduce the mosques' energy consumption. The mosque with "dome on flat roof" had the highest BEI, i.e. 204 kWh/m^2/yr and 230 kWh/m^2/yr based on 5-year and 2-year electricity bills, respectively. From the simulations, both studied mosques could produce around 1-4.9% energy reduction when the AC temperature setpoint was increased by 1˚C and could result in the highest cost-saving of about 4.9% when the temperature was set at 27˚C. A 30-minute AC operation during each daily prayer, except Subuh, could save between 14.8-16.7% annual energy consumption and about 15.2-16.6% annual energy cost. The study concludes that the selection of 24-27˚C temperature setpoints with a 30-minute AC operational profile during prayers time, considering Friday prayers and Ramadan activities, produced 18.4-20.6% savings in energy cost. This study provides the BEI results for energy benchmarking of a typical air-conditioned mosque in the Klang Valley. It calls for the AC temperature setpoints configuration standards and operational profiles of existing mosques to be reevaluated to reduce their energy consumption. Ultimately, it will contribute to developing future energy standards for mosque designs and operations in Malaysia.

Keywords: Roof design, temperature setpoints, operational profile, Building Energy Intensity (BEI), high-volume low-speed (HVLS) fan, mosques, Klang Valley, Malaysia.

Abstrak tesis dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

IMPAK REKA BENTUK BUMBUNG DAN OPERASI PENGHAWA DINGIN TERHADAP PENGGUNAAN TENAGA DAN KOS BAGI MASJID BERHAWA DINGIN DI LEMBAH KLANG, MALAYSIA

Oleh

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Kecekapan tenaga di masjid, khususnya di Malaysia, kurang mendapat perhatian sekalipun tipologi bangunan jenis ini mempunyai jumlah keluasan lantai yang ketara setanding dengan bangunan komersial. Walaupun bumbung merupakan penyumbang utama dalam penggunaan tenaga bangunan dan masjid secara amnya mempunyai penghunian dan pola penggunaan tenaga yang unik, rekod berkenaan kesan reka bentuk bumbung terhadap penggunaan tenaga bagi masjid berhawa dingin di Malaysia masih terhad. Tambahan pula, penggunaan penghawa dingin (AC) beserta kipas berkelajuan rendah volum tinggi (HVLS) kini menjadi tren (*trend*) di dalam bangunan masjid yang dinaik taraf di Malaysia untuk menambah baik keadaan keselesaan haba. Walau bagaimanapun, impak kipas AC dan HVLS yang beroperasi secara serentak dari segi tenaga belum diketahui. Oleh itu, kajian ini bertujuan untuk menyiasat impak perbezaan jenis reka bentuk bumbung dan pelarasan titik tetapan suhu AC dan profil operasi terhadap penggunaan tenaga dan kos bagi masjid berhawa dingin di Lembah Klang, Malaysia dengan objektif seperti berikut: 1) Mengenal pasti dan membuat pengkelasan jenis bumbung tertentu yang direka bentuk bagi masjid berhawa dingin yang dibangunkan di Lembah Klang, Malaysia dari tahun 1998 sehingga 2018., 2) Menganalisis dan membandingkan BEI dan kos elektrik bagi masjid berhawa dingin mengikut bentuk bumbung serta perbandingan antara masjid berhawa dingin yang dilengkapi kipas HVLS dengan yang tiada kipas HVLS, dan 3) Menilai potensi penjimatan tenaga dan kos bagi masjid berhawa dingin mengikut titik tetapan suhu penghawa dingin dan pelarasan profil operasi. Sebanyak 467 masjid dikenal pasti di Lembah Klang, dan 54 didapati mematuhi kriteria pemilihan. Berdasarkan 54 masjid ini, tiga jenis bumbung dikenalpasti, iaitu “kubah di atas bumbung rata”, “kubah di atas bumbung curam”, dan “tiada kubah”, jenis yang popular ialah “kubah di atas bumbung curam”. Lima buah masjid dipilih bagi mewakili tiga jenis klasifikasi bumbung , dan BEI dikira serta dibandingkan menggunakan data bil elektrik bagi 2-5 tahun. BEI antara masjid yang dilengkapi kipas HVLS dengan yang tiada kipas HVLS juga dibandingkan.

Seterusnya dua kajian kes yang mencapai BEI tertinggi di kaji lebih lanjut melalui simulasi komputer *IES-VE*. Simulasi ini bertujuan untuk menentukan profil operasi AC dan titik tetapan suhu yang dapat mengurangkan penggunaan tenaga dalam masjid. Masjid yang memiliki "kubah di atas bumbung rata" mencapai BEI yang tertinggi,sebanyak 204 kWj/m^2/thn dan 230 kWj/m^2/thn dengan menggunakan bil elektrik bagi tempoh 5 tahun dan 2 tahun. Berdasarkan simulasi kedua-dua kriteria masjid yang dikaji, sebanyak 1–4.9% pengurangan tenaga boleh dicapai apabila titik tetapan suhu AC dinaikkan sebanyak 1 °C dan penjimatan kos paling optimum sebanyak 4.9% dicapai apabila suhu ditetapkan pada 27 °C. AC yang beroperasi selama 30 minit bagi setiap waktu solat kecuali Subuh, boleh menjimatkan sebanyak 14.8–16.7% penggunaan tenaga tahunan dan kira-kira 15.2-16.6% daripada kos tenaga tahunan. Oleh itu, kajian ini menemukan pemilihan titik tetapan suhu pada 24–27 °C dengan tempoh operasi AC selama 30 minit semasa waktu solat, termasuklah solat Jumaat dan aktiviti di masjid sepanjang Ramadan boleh menjimatkan kos tenaga sebanyak 18.4–20.6%. Penemuan sebegini membentuk asas dari segi pengkelasan reka bentuk bumbung dan penandaarasan tenaga berdasarkan BEI bagi kebanyakan masjid berhawa dingin di Lembah Klang. Penyelidikan ini selanjutnya menggesa penilaian semula standard konfigurasi titik tetapan suhu AC dan ciri-ciri operasi di dalam bangunan masjid demi mengurangkan penggunaan tenaga. Akhirnya kajian ini menyumbang pada pembangunan piawaian tenaga pada masa depan bagi reka bentuk dan pengendalian masjid di Malaysia.

Kata kunci: Reka bentuk bumbung, titik tetapan suhu, profil operasi, kipas berkelajuan rendah volum tinggi (HVLS), masjid, Lembah Klang, Malaysia.

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I certify that a Thesis Examination Committee has met on (23 June 2022) to conduct the final examination of Nur Amalina Syairah Binti Mohamed on her thesis entitled "Impacts Of Different Roof Designs And Air-Conditioning Operations On Energy Consumption And Costs In Air-Conditioned Mosques In The Klang Valley , Malaysia" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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I hereby confirm that:

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This is to confirm that:

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Signature: ______________________________
Name of Chairman of Supervisory Committee: Zalina binti Shari

Signature: ______________________________
Name of Member of Supervisory Committee: Nur Dalilah binti Dahlan

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AC	Air-Conditioning
UPM	Universiti Putra Malaysia
BEI	Building Energy Intensity
EPU	Economic Planning Unit
kWh	Killowatt Hour
HVLS	High Volume Low Speed
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MS	Malaysia Standard
SPSS	Stastical Package for Social Science
IES-VE	Integrated Environmental Solution <Virtual Environment>
TNB	Tenaga Nasional Berhad
USD	United States Dollar

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Energy is a key pillar in global economic development (Kiran et al., 2014; Liobikienė and Butkus, 2018). Currently, 80% of energy demands are provided using natural sources such as coal, oil and gas. The widely used natural resources have caused significant harm in greenhouse gas emissions and pollution; hence, they contribute to climate change and global warming issues (T. Hui et al., 2018; Subramanyam et al., 2015). These issues have started to be widely discussed, and strategies to tackle these issues have been formulated since the World Commission on Environment and Development (WCED) released the Brundtland Report in 1987 and the United Nations Conference on Environment and Development (UNCED or Earth Summit) in 1992.

Energy use in the building sector accounts for approximately 40% of global energy usage and results in over a third of global energy-related carbon dioxide emissions (Abergel et al., 2017). The causes of the growth in energy usage in buildings are twofold: 1) the use of heating, ventilation, and air-conditioning (HVAC) in response to the growing demand for better thermal comfort and the rising trend of people spending more time indoors (Lin et al., 2017; Afroz et al., 2018) and 2) the improper estimation of cooling loads and inefficient use of air-conditioning (Homoud et al., 2005; Sadineni et al., 2011; Sharizatul et al., 2016).

The current trend of using air-conditioning (AC) systems to provide better indoor thermal comfort will increase the operating costs of the buildings and negatively impact the environment. Therefore, a good understanding of factors contributing to energy-efficient building design is necessary to reduce building cooling loads. These factors are related to climates, architectural design, and occupants. In relation to architectural design factors, how the building envelope is designed significantly impacts building energy consumption in most cases. A "building envelope," defined as the barrier between the indoor and outdoor environments of a building, has an important function in the building energy consumption (Cao et al., 2016; Sadineni et al., 2011).

Previous studies on building envelopes suggest that advances in building envelope designs can potentially reduce building energy consumption (Bano and Kamal, 2016; Budaiwi et al., 2013; De Silva and Sandanayake, 2012; El-darwish & Gomaa, 2017; Lagimich et al., 2018; Mirrahimi et al., 2016; Mohamed et al., 2018; Salleh and Kandar,2012; Volf et al.,2018). A building envelope comprises various elements such as walls, roofs, thermal insulation, fenestration, and exterior shading systems. Of all these components, the roofs have the most significant effect on a building's energy consumption and thermal comfort because they are highly vulnerable to solar radiation and other environmental effects (Wang and Shen, 2012; Dahlan and Ghaffarianhoseini, 2016; Peng et al., 2017; Lapisa et al., 2018; Seifhashemi et al., 2018). The heat gained through building surfaces is essential to determining the building's cooling loads.

The more solar radiation received in a building's roofing surface area, the more heat gains will be produced (Faghih and Bahadori, 2009; Mohammadzadeh et al., 2015; Rudianto et al., 2017; Baniassadi et al., 2018). Especially in buildings with large roof areas, such as educational facilities, sports centres, exhibition halls, and religious buildings, roofs account for a significant amount of heat loss or gain. A single-storey building had the most heat penetration from the roof compared with multi-storey buildings, where most of the penetrations are from the windows and walls (Bano and Kamal, 2016; De Silva and Sandanayake, 2012).

Many studies have shown that roof designs could help improve building energy performance (Elwell et al., 2017; Gagliano et al., 2015; Piselli et al., 2018; Sadeghifam et al., 2015; S. Wang et al., 2012). Besides energy-efficient designs for new buildings, energy-efficient operations for existing buildings are equally important. Energy retrofit is one of the tools used to enhance the energy efficiency of existing buildings (Rogeau et al., 2020). There are two types of energy retrofits: technical configurations and behavioural interventions (i.e. human-based retrofits).

Technical configurations involve rearranging, replacing, adding and deleting some existing components of the buildings (Brown et al., 2014; Mancini and Nastasi, 2019; Sánka and Petráš, 2019). The discussion of this approach revolved around better bioclimatic designs and more energy-efficient insulation, windows and HVAC systems (Ariosto et al., 2019; Fang and Cho, 2019; Jankovic, 2019). Technical configurations type of energy retrofits has been widely studied for schools (H. Ali and Hashlamun, 2019; Tahsildoost and Zomorodian, 2015), commercial (Li, Li et al., 2020), offices (Mohamad et al., 2018; Somasundaram et al., 2020) and residential buildings (Friedman et al., 2014; Wu et al., 2017).

Despite their advantages, such retrofit measures are complex as they involve large-scale modifications, high upfront capital cost, and long implementation time (Cajot et al., 2017; Mirakyan and De Guio, 2013). Behavioural intervention or human-based retrofits, on the other hand, refers to modifications of human (occupants or building managers) behaviour or actions that they can take to improve the existing building operation towards achieving energy efficiency (Ascione et al., 2020; Barthelmes et al., 2017; Pan et al., 2017). Examples of such actions include adjusting the HVAC thermostat setpoints, opening windows for natural ventilation, and reducing the use of artificial lighting, equipment and appliances, to name a few (Dall'O' et al., 2012).

Many studies have been conducted on behavioural intervention type of retrofits (Dall'O' et al., 2012). Human-based retrofits are generally more cost-effective (i.e. they come with little or no implementation costs) and practical than technical retrofits (Xia et al., 2019). However, the success depends on the occupants-building interaction and the occupants' and management staff's level of commitment (Jami et al., 2020; Xu et al., 2013). Among the behavioural interventions to reduce energy consumption are fine-tuning the AC temperature setpoints and revisiting the AC operational profiles.

An adjustment to the AC temperature setpoints is made according to the desired indoor thermal comfort (Aghniaey and Lawrence, 2018; Yan et al., 2019b), but research has shown that an increase of 1°C in AC temperature setpoint will reduce at least 7% of energy consumption (Ho et al., 2009). A reevaluation of the AC operational profile, on the other hand, involves strategising the AC operation schedule based on a deep understanding of the building usage, occupancy load, climate factors, and occupancy duration of the building (Knight, 2016; Xia et al., 2019; Z. Yang and Becerik-gerber, 2014). In summary, it is essential to understand the following two aspects: (1) how different roof designs affect the building energy consumption; and (2) how behavioural interventions or human-based retrofits could be used to lower the building energy consumption, which are the subjects of this study.

1.2 Statement of the Problem

Mosques are considered an essential facility for the Muslim community in Malaysia, comprising 61.5% of the total population. As of 2020, the total number of mosques in Malaysia is 6446, and 467 are in the Klang Valley (Department of Standards Malaysia, 2020). Mosques are public buildings in which the operating costs, including the utility bills, are paid by public funds (Rashdi and Embi, 2016). Hence, the energy efficiency of mosques is deemed to be of importance and must be addressed.

Mosques are a building typology with intermittent occupancy, and they have a significant total floor area and consume a considerable amount of energy comparable to commercial buildings (Terrill et al., 2015). Understanding the functions and operations of mosques reflects the importance of thermal design for occupants' comfortable praying experience. Intermittent occupancy means mosques may not perform thermally the same as typical commercial buildings. Installations of air-conditioning (AC) systems in mosque buildings to achieve the required thermal comfort have become common in the hot and humid climate region, particularly in Malaysian urban areas (Department of Standards Malaysia, 2014; Hussin et al., 2014). AC systems are responsible for a significant percentage of energy consumption in buildings.

Recently, the trend of adding High-Volume, Low-Speed (HVLS) fans in air-conditioned mosques has emerged in Malaysia (Nor et al., 2019). However, the extent to which the concurrent operation of both AC and HVLS fan affects the mosques' energy performance still remains unclear. Do these mosques achieve the required thermal comfort while consuming the least energy? This thesis argues that when the operations of both AC system and HVLS fans are improperly designed, it could result in additional, unnecessary energy.

Little information on mosque buildings' energy performance or Building Energy Intensity (BEI) is available. An early study by Al-Homoud et al. (2005a) showed that the average BEI value of 5 mosques in Saudi Arabia was 167 kWh/yr/m2. After the subsequent data collection and analyses, the figure increased to 181.9 kWh/yr/m2 (Al-Homoud et al., 2005b). In Malaysia, a recent study by Hussin et al. (2019) on five retrofitted air-conditioned mosques in Penang reported an average BEI of 130 kWh/year/m^2, with the highest and lowest BEI of 325 kWh/year/m^2 and 70 kWh/year/m^2, respectively.

They found that the BEI values of mosques are generally high; some are even higher than the BEI of office and hospital buildings. As Hussin et al. (2019) is the only study on mosque BEI in Malaysia so far, it was considered appropriate for their BEI values to be used as the baseline. The high BEI results from Al-Homoud et al. (2005b) and Hussin et al. (2019) highlight the need for more energy retrofit measures in mosque buildings. Although these studies focused on air-conditioned mosques, they ignored the usage of HVLS fan. Mosques are typically built as single-storey or low-rise buildings with large roof areas.

Although mosques in Malaysia are primarily similar in spatial organisation and direction (R. Othman et al., 2007), they differ considerably in roof designs (Ismail and M.Rasdi, 2010). The differences in roof designs are based on the revolution of architecture in Malaysia (Ismail and M.Rasdi, 2010; M.Rasdi, 2007; Mohd Taib et al., 2016). Many studies have shown that efficient and integrated design, particularly roof design, could save considerable amounts of energy (Dabaieh et al., 2015; Elwell et al., 2017; Lubis and Koerniawan, 2017; Piselli et al., 2018; Sadeghifam et al., 2015; S. Wang et al., 2012).

Furthermore, it has been well accepted that a heating, ventilation and air-conditioning (HVAC) system is required to ensure proper building pressurisation, excellent indoor air quality, and a suitable thermal climate for building occupants. However, it is essential to note that the size and costs of an HVAC system can be reduced through an integrated and efficient building envelope design (Building Science, 2018). In Malaysia, Maarof (2014) found that the temperature of a pitched-roof mosque warmed and cooled faster than a domed-roof mosque.

Roofs, he discovered, supplied more thermal energy to the interior area than other building envelope components. Early design consideration is vital for designers and construction players to optimise energy and recommend the best roof configuration for minimum cooling loads. Many building operators know that an improvement in the operation of AC systems can significantly produce energy and financial savings.

However, according to Homoud et al. (2005), an AC system's improper operation and temperature setpoints, which result in under- or over-cooling, is frequently practised in many mosques. The AC operational profile for a mosque may differ from other building types as mosques generally have intermittent occupancy. The AC operation strategies for mosques are expected to significantly impact mosque thermal and energy performance (Al-Homoud et al., 2005b; Al-shaalan and Alohaly, 2017; Budaiwi and Abdou, 2013; Omar et al., 2020). The function and operational strategies depend on the end-users, over whom the designers have no or less control (Atmaca and Gedik, 2019; Hussin et al., 2019).

Therefore, it is also crucial to involve the end-users in implementing energy conservation measures without compromising the indoor environmental conditions of building users. It could be argued that behavioural interventions or human-based retrofits are more suitable for buildings with intermittent occupancies, such as mosques, than technical retrofits. The evidence gathered here suggests two crucial points. First, more studies are needed to configure the best roof design to reduce energy consumption in mosques to minimise environmental impact and gas emission.

Second, optimising a building's AC temperature setpoints and operational profile can achieve cooling energy reduction and thermal comfort improvement. There is also a need to clearly understand the energy impacts of operating AC and HVLS fans in mosques and how behavioural interventions could minimise energy consumption without compromising their indoor thermal comfort levels. This study aims to address these two issues.

1.3 Research Gaps

Significant literature exists on the impact of roof designs (e.g. in terms of forms, materials, and component configurations) on cooling loads and indoor thermal comfort as part of passive cooling strategies. These studies have shown that roof design could help in the energy performance of a building. However, instead of mosque buildings, many of these studies were conducted on residential buildings (Wang and Shen, 2012a; Mohamed et al., 2015; Mirrahimi et al., 2016; Elnokaly et al., 2019), industrial buildings (Trabelsi et al., 2011; Lapisa et al., 2018; Seifhashemi et al., 2018), commercial buildings (Hosseini and Akbari, 2016; Piselli et al., 2019), and others (Androutsopoulus et al., 2017).

Studies on mosques and energy efficiency have been conducted (L. Abdallah and El-Shannawy, 2017; Al-shaalan et al., 2014; AM Al-shaalan and Alohaly, 2017; Lagimich et al., 2018; Nordin and Misni, 2018). However, the influence of mosque roof design on energy consumption, specifically in hot and humid climate regions for air-conditioned buildings, is poorly understood and yet is essential to understand the factors affecting the building energy consumption. The published work on the impact of non-roof design and operation of mosques is accessible.

These include the handling of mosques' air-conditioning system (Hussin et al., 2019), the spatial arrangement and zoning (Ali and Sanusi, 2013; Nusi, 2017) and façade design (Abdullah et al., 2016). However, there are scant records on the energy performance of air-conditioned mosques in Malaysia due to specific roof designs. This aspect is often overlooked even though much research has shown the link between roof design and energy performance (Lubis and Koerniawan, 2017). To the authors' best knowledge, only one published study shows the relationship between thermal comfort and roof designs (pitched roof and dome) in mosque buildings in Malaysia (Maarof, 2014).

This study has found no direct correlation between roof design and thermal comfort, but there is a significant relationship between thermal comfort and air temperature. Furthermore, the study highlighted that pitched roof mosques warm and cooled down faster than mosques with domed roof. However, this study was conducted only in naturally ventilated mosques. Therefore, this study aims to address this gap. Previous studies have shown that cooling and heating setpoints in different climatic zones will result in different energy-saving levels (Ho et al., 2009; Guo et al., 2019). The highest energy saving was found in buildings in the coldest region (Guo et al., 2019). In cold climates, cooling hours are less than in hotter climates; hence, the potential for accumulated cooling savings in cold climates is small (Papadopoulos et al., 2019). Indeed, a building's energy consumption is greatly affected by the outdoor environment (Li, et al., 2020).

Therefore, it could be argued that an optimal AC setpoint strategy in cold climates could not apply to hotter climates, particularly Malaysia's hot and humid climate. Many studies in hot-humid climatic regions show that adjustments to the AC temperature setpoints significantly impact building energy consumption. These studies were conducted in Singapore (Tom, 2008; Tushar et al., 2016), Malaysia (Mustapa et al., 2017), Thailand (Yamtraipat et al., 2005), Indonesia (Hamzah et al., 2018; Sunardi et al., 2020) and South Africa (Wang et al., 2013).

These studies have recommended different ranges of temperature setpoints for thermal comfort. Although there is no specific point when the effect of temperature is dissatisfactory in terms of thermal comfort to the users, controlling the AC temperature setpoints has been reported to be one of the means of managing building energy consumption (Aghniaey and Lawrence, 2018). Therefore, it is necessary to determine a suitable range of AC temperature setpoints for building energy efficiency in hot-humid climatic regions.

Previous literature has also suggested that AC operating profiles highly affect energy consumption (Budiawi and Abdou, 2013; Al-Tamimi et al., 2020; Birkha et al., 2021). Furthermore, the effectiveness of the operational profile depends on understanding the AC response time and the amount of time needed for the AC system to cool down space to the temperature setpoint (Hui et al., 2017). Hence, the cooling duration must be examined and integrated into AC operating profiles. Besides the AC system, HVLS fans' usage has become popular in industrial and commercial buildings for thermal comfort improvement and energy reduction (Khare et al., 2020; Present et al., 2019).

Furthermore, a few inventions have been developed to encourage more widespread usage of the fans (Darrin et al., 2019; Toy, 2014). Recently, the trend of using HVLS fans in air-conditioned buildings has raised questions regarding its energy implications. However, no studies have been conducted so far to demonstrate the energy impacts of concurrent operation of AC system and HVLS fan or how best to operate both systems to achieve the required thermal comfort while consuming the least energy. Therefore this research attempts to address these gaps.

1.4 Research Aim and Objectives

This study aims to investigate the impacts of different roof designs and adjustments of AC temperature setpoints and operational profiles on the energy consumption and costs of air-conditioned mosques in the Klang Valley, Malaysia. To achieve this aim, the following objectives have been derived:

1. To identify and classify the specific roof forms designed for air-conditioned mosques built in the Klang Valley, Malaysia, between 1998 and 2018.

2. To analyse and compare the BEIs and electricity costs of air-conditioned mosques with different roof forms and between those with and without HVLS fan.

3. To assess air-conditioned mosques' energy and cost savings potential through different air-conditioning temperature setpoints and operational profiles adjustments.

1.5 Research Questions

Below are the research questions:

1. What are the roof form classifications of air-conditioned mosques built in Klang Valley, Malaysia, between 1998 and 2018?

2. What are the effects of different roof designs and the usage of HVLS fans on the mosques' average BEIs and electricity costs?
3. How much can energy and cost savings be made with different air-conditioning temperature setpoints and operational profiles adjustments?

1.6 Research Focus

This research focuses on air-conditioned mosques in the Klang Valley, Malaysia, regarding the implication of their roof designs on energy consumption. Air-conditioning usage has become the current trend for mosques, especially in urban areas such as the Klang Valley, to achieve thermal comfort during prayers time. The roof component of a building envelope was chosen not only because it protects the building occupant from the environmental impacts but also because it is an important architectural identity for mosques. Previous studies have depicted that mosques have almost similar layouts, but their uniqueness or identity lies in their roof typology that has revolved since the 1800s.

1.7 Research Methodology

In order to fulfil the **first research objective**, this study involved three steps: 1) identify the air-conditioned mosques built in the Klang Valley between 1998 and 2018 from various government departments' and agencies' websites; 2) select the mosques that meet specific criteria; and 3) classify them according to their roof form category. In order to fulfil the **second research objective**, i.e. to compare the Building Energy Intensity (BEI) of mosques with different roof forms, a sample of mosques from each roof form group was selected based on the best judgement that the mosque could represent the group.

Achieving the second research objective also requires the BEIs to be compared between mosques with and without HVLS fan. Hence, the sampling from each roof form group was ensured to comprise mosques with and without HVLS fan. 5-year electricity bill data were obtained to compare the BEI of mosques with different roof forms, and 2-year electricity bill data to compare mosques with and without HVLS fan. Then walk-through audits were performed on all the sampled mosques to examine the buildings' design conditions and record their energy end uses using a building inventory survey form. Subsequently, all mosques' BEIs and electricity costs were calculated and compared using SPSS statistical software.

In order to achieve the **third research objective,** the mosque with the highest BEI from each group (i.e. one mosque with HVLS fan and one without HVLS fan) was simulated using the IES-VE Software. The purpose of the simulation was to determine the best temperature setpoints and operational profile that resulted in the most significant reduction in energy consumption. One-year electricity bill data were used to validate the simulation models, establishing reasonable confidence in the simulation results.

1.8 Significance of the Research

The research demonstrates the impact of roof designs and air-conditioning operations on mosque building energy consumption and costs. This study is essential to understand the main classifications of mosque roof designs available in the Klang Valley and their respective energy performance. So far in Malaysia, there are no concise guidelines for developing a sustainable mosque, except for general planning (Department of Standards Malaysia, 2014). Therefore, the findings can potentially serve as the basis for the government in Malaysia to develop new design and retrofit guidelines for both future and existing mosques in the country. In addition, the findings motivate the need to revisit AC setpoint configuration and operational profile standards in mosque buildings, either as a segment of individual building retrofit preparation or as a segment of energy standards for mosque designs and operations in Malaysia. It is envisaged that the cost savings realised by the proposed strategies could be used to fund communal activities instead. The research also contributes to the development of future energy-related design codes for mosques. Although the research focuses on mosques in Malaysia, the outcomes and recommendations described in this research could be adopted for other building types with a significant total roof area and energy consumption, such as warehouses, commercial buildings, and other religious buildings located in hot-humid climatic regions.

1.9 Thesis Structure

The remaining part of this thesis is presented in four chapters, as explained below:

Chapter 2 – Literature Review: This chapter reviews the related literature on Malaysia's background, i.e., climate, religion, population, and energy source. It also discusses the building energy consumption in tropical countries, including the factors affecting energy use in buildings, previous studies on roofs and building energy consumption, and evaluation methods suitable for building energy consumption. In relation to mosques in Malaysia, this chapter reviews the evolution of mosque designs, the typical characteristics of mosque roof designs, air conditioning usage, and previous mosque and energy consumption studies. This chapter ends with the research hypotheses and theoretical framework of the research.

Chapter 3 – Methodology: This chapter details the research methodology used to achieve the research objectives, emphasising quantitative methods. The research design and the three phases of this study are explained in detail: Phase 1 taxonomy study, Phase 2 statistical analysis, and Phase 3 computer simulation using IES-VE software.

Chapter 4 – Result and Discussion: This chapter presents the data analysis and results from the taxonomy study, selected building inventory survey, statistical analysis, and computer-based simulation.

Chapter 5 – Conclusion: This final chapter offers the researcher's conclusion of the study, research limitations, and recommendations for future studies. The research flowchart is illustrated in Figure 1.1.

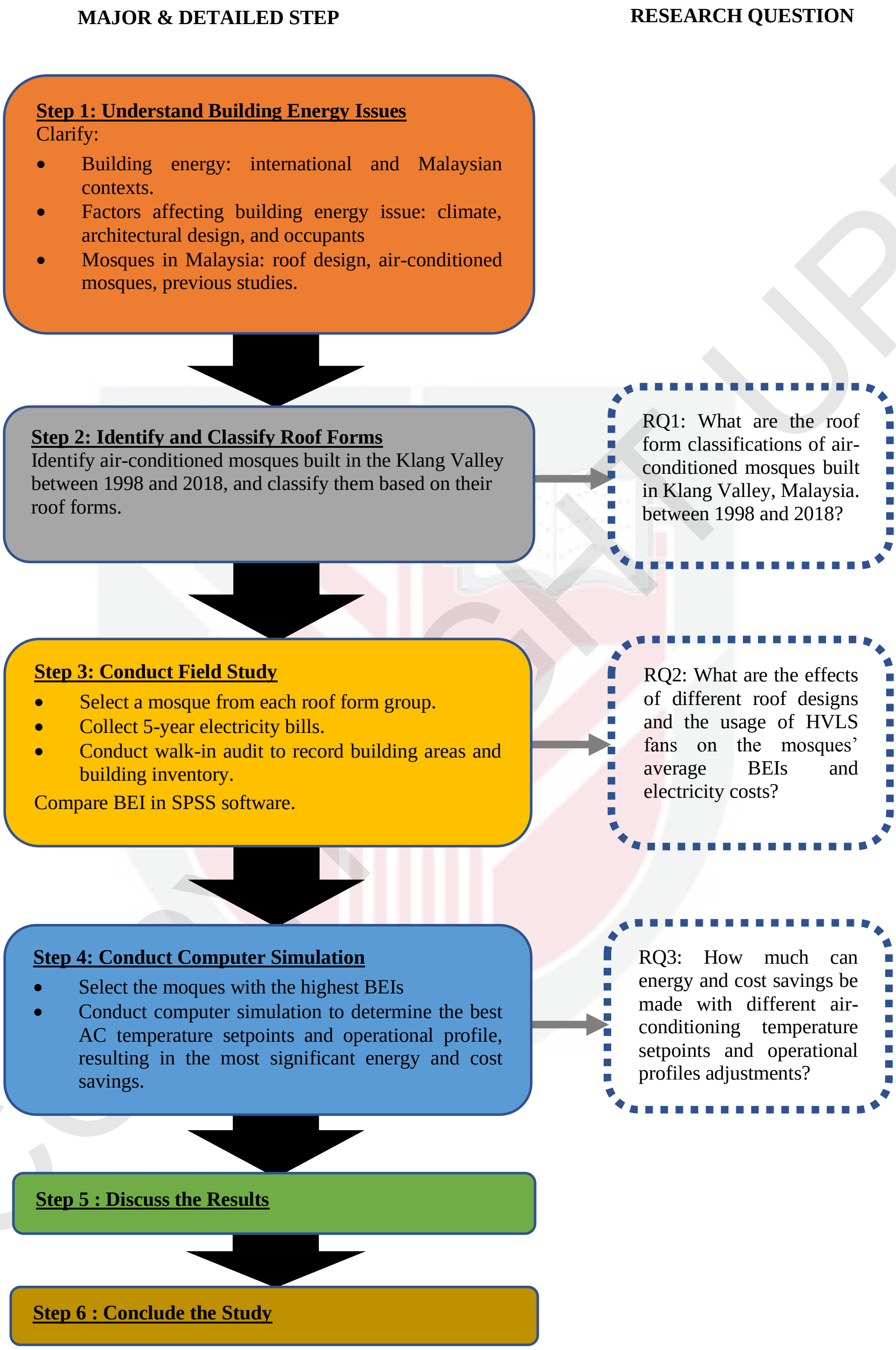

Figure 1.1: Research Flowchart

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