INNOVATIVE ROOFING SYSTEM FOR SOLAR HEAT REDUCTION UNDER MALAYSIAN SKY CONDITIONS

By

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LIST OF ABBREVIATIONS

ASHRAE	- American Society of Heating, Refrigerating and Air Conditioning Engineers
BSEEP	- Building Sector Energy Efficiency Projects
CIBSE	- Chartered Institution of Building Services Engineers
CIE	- International Commission on Illumination
COG	- Centre of Glass
CRRC	- Cool Roof Rating Council
DBT	- Dry Bulb Temperature
EE	- Energy Efficiency
GBI	- Green Building Index
HTV	- Hybrid Turbine Ventilator
IEA	- International Energy Agency
IEC	- Indoor Environmental Condition
IES	- Integrated Environmental Solutions
IR	- Infrared Radiation
IRS	- Innovative Roofing System
LSG	- Light-to-Solar Gain Ratio
MRT	- Mean Radiant Temperature
OEC	- Outdoor Environmental Condition
OII	- Outdoor Environment, IRS and Indoor Environment
PVC	- Poly vinyl chloride
RE	- Renewable Energy
REHDA	- The Real Estate and Housing Developers' Association of Malaysia
SC	- Shading Coefficient
SHGC	- Solar Heat Gain Coefficient
SIG	- Sealed Insulating Glass
VLT	- Visible Light Transmission

LIST OF SYMBOLS

Ø	- Diameter
CO_2	- Carbon Dioxide
R^2	- Coefficient of Determination
CFM	- Cubic Meter of Air per Minute
ΔT	- Indoor – Outdoor Temperature Difference (°C)
ΔRH	- Indoor – Outdoor Relative Humidity Difference (%)

LIST OF PUBLICATIONS

The following are papers published by the candidate in conjunction with supervisors as a direct result of this research. They are:

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2. **Al-Obaidi, K.M.**, Ismail, M., & Abdul Rahman, A.M. (2014). A review of the potential of attic ventilation by passive and active turbine ventilators in tropical Malaysia. *Sustainable Cities and Society*, *10*, p.232-240.

3. **Al-Obaidi, K.M.**, Ismail, M., & Abdul Rahman, A.M. (2014). A comparative study between unvented and vented attics powered by the hybrid turbine ventilator in Malaysian houses. *International Journal of Sustainable Energy*. DOI:10.1080/14786451.2013.873801

4. **Al-Obaidi, K.M.**, Ismail, M., & Rahman, A. M. A. (2014). Passive cooling techniques through reflective and radiative roofs in tropical houses in Southeast Asia: A literature review. *Frontiers of Architectural Research*, *3*(3), p.283-297.

5. **Al-Obaidi, K.M.**, Ismail, M., & Abdul Rahman, A.M. (2014). A study of the impact of environmental loads that penetrate a passive skylight roofing system in Malaysian buildings. *Frontiers of Architectural Research*, *3*(2), p.178–191.

6. **Al-Obaidi, K.M.**, Ismail, M., & Abdul Rahman, A.M. (2014). A Review of Skylight Glazing Materials in Architectural Designs for a Better Indoor Environment. *Modern Applied Science*, *8*(1), p.68-82.

7. **Al-Obaidi, K.M.**, Ismail, M., & Rahman, A. M. A. (2014). Investigation of Passive Design Techniques for Pitched Roof Systems in the Tropical Region. *Modern Applied Science*, *8*(3), p.182-191.

8. **Al-Obaidi, K.M.**, Ismail, M., Rahman, A., & Malek, A. (2014). Energy Efficient Skylight Design in Tropical Houses. *Key Engineering Materials*, 632, p.45-56.

9. Rahman, A.M.A., Rahim, A., **Al-Obaidi, K.**, Ismail, M., & Mui, L. Y. (2013). Rethinking the Malaysian Affordable Housing Design Typology in View of Global Warming Considerations. *Journal of Sustainable Development*, *6*(7), p.134-146.

10. **Al-Obaidi, K.M.**, Ismail M., & Abdul Rahman A.M. (2013). An innovative roofing system for tropical building interiors: Separating heat from useful visible light. *International Journal of Energy and Environment*, *4*(1), p.103-116.

International Conferences

11. **Al-Obaidi, K.M.**, & Abdul Rahman A.M. (2015). Innovative roofing system for reducing solar heat gain from natural light under Malaysian sky condition. 20-21 January, Kuala Lumpur, Malaysia: Malaysia University-Industry Green Building Collaboration (2015 MU-IGBC) Symposium.

12. **Al-Obaidi, K.M.**, Ismail M. & Abdul Rahman A.M. (2012). Day-lighting tropical building interiors from skylight: the case for separating heat from useful visible light. 20–22 Nov 2012, Kuantan, Malaysia: The International Conference on Science, Technology and Social Sciences (ICSTSS 2012) “Synthesizing Ideas & Innovation into a Better Future”.

13. **Al-Obaidi, K.M.**, Ismail M. & Abdul Rahman A.M. (2012). Daylighting potential from innovative roof construction system for a healthy indoor environment in the Malaysian tropical climate. 6-7 June, Penang, Malaysia: The International Environment and Health Conference.

14. **Al-Obaidi, K.M.**, Ismail M. & Abdul Rahman A.M. (2012). Tropical roof-lighting building interiors: Design factors that make it possible. 29-30 May, Kuala Lumpur – Malaysia: The International Conference on ‘Green’ in the Built Environment.

SISTEM BUMBUNG INOVATIF BAGI PENGURANGAN HABA SOLAR DI BAWAH KONDISI LANGIT MALAYSIA

ABSTRAK

Sistem lurang cahaya-langit di tropika Malaysia menyebabkan ketidakselesaan haba justeru meningkatkan penggunaan sistem penyaman udara bagi tujuan penyejukan, khususnya di bangunan setingkat. Literatur menunjukkan rekabentuk pasif ialah salah satu strategi yang paling efektif dari segi kos bagi sistem bumbung di rantau yang tinggi radiasi solar dan beriklim panas-lembab. Tujuan utama kajian ini ialah merekabentuk satu sistem yang dapat mengurangkan kesan haba solar daripada cahaya langit di bangunan satu tingkat (3m tinggi). Tesis ini membentangkan keputusan daripada kajian simulasi dan empirikal berkenaan penambambaikan persekitaran dalaman yang dicapai melalui pengaplikasian beberapa modifikasi terpilih sistem bumbung bersepadu yang dintegrasi dengan lurang cahaya-langit. Simulasi dan suatu siri kajian pengukuran tapak berskala penuh yang dilakukan dalam cuaca sebenar menunjukkan bahawa penambahbaikan ketara pada persekitaran dalaman telah dicapai dengan menggunakan penapis terma, teknik pewarnaan dan pengudaraan di loteng. Simulasi menggunakan perisian Penyelesaian Alam Sekitar Bersepadu daripada 'Virtual Environment' telah dilaksanakan di 'sel ujian' yang dibina di Universiti Sains Malaysia bagi mengkaji kesan daripada beberapa pengubahsuaian terhadap konfigurasi bumbung. Kajian empirikal kemudiannya dilakukan bagi mengenalpasti hasil daripada tiga strategi bumbung yang berbeza, iaitu, (1) bumbung tanpa loteng, (2) bumbung berserta loteng dan (3) sistem bumbung inovatif (IRS), di bawah situasi gelap dan cahaya-siang. Keputusan kajian menunjukkan penggabungan strategi polikarbonat dua-lapis, pantulan dan serakan bumbung serta siling lutsinar yang menggunakan pengudaraan turbin hibrid di zon loteng telah meningkatkan perbezaan suhu udara (T_i–T_o) di bawah IRS sebanyak 121% di bawah keadaan cahaya-siang pada strategi pertama berbanding sebanyak 23% pada strategi kedua. Perbezaan maksima pada situasi dalaman antara cahaya-siang dengan keadaan gelap mengunakan IRS mencapai 0.31 ^{o}C bagi suhu dalaman, 2.22 ^{o}C bagi suhu radiasi min (MRT) dan 0.38 ^{o}C bagi suhu di dalam loteng. Tambahan pula, IRS mengawal kemasukan cahaya-siang ke dalam sel ujian antara 55% hingga 75% di bawah 700 lux. IRS telah dibuktikan sebagai ubahsuai terbaik dalam mengurangkan kesan haba solar.

INNOVATIVE ROOFING SYSTEM FOR SOLAR HEAT REDUCTION UNDER MALAYSIAN SKY CONDITIONS

ABSTRACT

Skylight systems in tropical Malaysia inherently produce an unacceptable level of comfort and thus result in greater use of air-conditioning systems for cooling, particularly in single-storey buildings. Literature indicates that the passive design method is one of the most cost-effective strategies for roofing systems in high-solar-radiation and hot–humid tropical regions. The main aim of this research is to design a system that reduces solar heat gain from natural light for tropical single-storey buildings (3 m height). This thesis presents the results of a simulation and empirical studies on the extent of indoor climatic improvement achieved by applying selected modifications to a roofing system integrated with a skylight. The simulation and series of full-scale field measurement studies conducted under actual weather conditions reveal that a significant improvement in indoor climate can be achieved by applying thermal glazing, pigment techniques and attic ventilation. Simulations with 'Integrated Environmental Solutions' Virtual Environment software were performed on a 'test cell' constructed in Universiti Sains Malaysia to investigate the effects of different modifications to the roofing configurations. Empirical studies were then conducted to explore the performance of three different roofing strategies, namely, (1) roof without an attic, (2) roof with an attic and (3) innovative roofing system (IRS), under blacked out and daylight conditions. Results show that combining strategies, such as double polycarbonate, reflective and radiative roof and transparent ceiling with a hybrid turbine ventilator for the attic zone, improves the maximum difference in air temperature (T_i–T_o) in IRS by 121% under daylight condition compared with the first strategy and by 23% compared with the second strategy. The maximum difference in indoor condition between daylight and blacked out with the IRS reached 0.31 °C for indoor air temperature, 2.22 °C for Mean Radiant Temperature (MRT) and 0.38 °C for attic air temperature. Furthermore, IRS controlled more daylight inside the test cell with approximately 55% to 75% below 700 lux. IRS was found to be the best modification to reduce the impact of solar heat.

CHAPTER 1

INTRODUCTION

1.1 Background

Energy issues, particularly energy consumption and CO_2 emission in building sectors, are a common topic of discussions and debates around the world. The Energy Commission (2010) reported that the maximum demand for electricity in Peninsular Malaysia increased from 14,245 MW in 2009 to 15,476 MW in 2011. According to the International Energy Agency (IEA; 2009), CO_2 emissions in Malaysia have been increasing critically since 1970. CO_2 is a greenhouse gas with the highest emission in Southeast Asia.

With regard to this issue on a small scale, Malaysia had approximately 7.3 million residential dwellings in 2010; this figure is expected to increase by approximately 150,000 each year (Department of Statistics Malaysia, 2010; REHDA, 2010). Furthermore, the electricity generated in 2010 (9,791 ktoe) almost doubled compared with that in 2000, which was 5,955 ktoe (Economic Planning Unit, 2012). The amount reached 11,565 ktoe in 2012 (Malaysian Energy Info Hub, 2012). Presently, almost more than 20% of the energy consumption in the nation is consumed by the residential sector (IEA, 2009). The urban population in Malaysia increased rapidly from 25% in 1960 to 72% in 2010. The estimation is that by 2030, more than three-quarters of the overall population in Malaysia will settle in urban areas (World Bank, 2011).

The abovementioned indicators generally represent one of the main factors that aggravate the increasing demand for cooling energy in Malaysian houses. The widespread use of air-conditioning systems is rather unsatisfactory. According to Chan (2004), the number of residential air-conditioning units owned by Malaysians in 1999 was 493,082. This number increased by 6.7% in 2000 with 528,792 units and is anticipated to increase by approximately 42% in 2009 with 907,670 units (Saidur et al., 2007). According to a study conducted by Al Yacouby et al. (2011), approximately 75% of Malaysians rely on air conditioning to maintain a comfortable indoor environment. Zain-Ahmed (2008) showed that the average consumption of energy in a building reaches 233 kWh/m^2/year, of which about 60% is dedicated to air conditioning and around 25.3% to electric lighting. In reality, the problem is aggravated further in modern residential buildings constructed with a highly airtight design, lightweight materials and poor natural ventilation that consequently leads to the adoption of a mechanical cooling system (Abdul Rahman et al., 2013).

The roofing system represents the main source of heat build-up in low-rise residential structures and accounts for approximately 70% of the total heat gain (Vijaykumar, 2007). Roofing systems are affected directly by direct solar radiation of up to 1 kW/m^2; the absorption level in their fabric is between 20% and 90% (Suehrcke, 2008). Unlike countries with temperate and cold climates, Malaysia is a tropical country exposed to a very large amount of solar insolation. The country is considered an uncomfortable climatic zone given that this region experiences summer and gains excessive heat almost all the time during a typical year.

Therefore, single-storey buildings in the tropics rarely have roof lights simply because such lights result in thermal discomfort at human height level because of heat gain. According to Robertson and Mortgage (2002), Energy Simulation Research conducted a study on buildings with and without daylighting features. Their results showed that the annual lighting saving is large for day-lit buildings. However, the thermal loads increase because of the penetration of solar radiation to the indoor space with natural light. Jinghua et al. (2008) conducted a study in China and found that heat gain through glazing openings accounts for 25% to 28% of the overall heat gain; when infiltration is considered, it can reach 40% in hot weather. In the tropics, a skylight heats up the interior quickly, and air-conditioning systems have to work harder to cool the air mass. In the past, such was the means to overcome thermal discomfort (heat build-up). However, with the gradual increase in energy cost, it is no more considered as a tropical design element. Although buildings are normally incorporated with courtyards and air wells to light the indoor environment and overcome heat-build up, land is gradually becoming expensive. Hence, having courtyards or air wells in urban areas in Malaysia has become a luxury and may not be practical or economical.

Isa et al. (2010) indicated that more than 1.6 million terrace houses in Malaysia are inhabited by more than 7 million people, and most of the roofs of these buildings are installed with cement or clay tiles. In addition, most of these buildings are not insulated and involve only some modifications, such as a thin layer under the roof tiles. According to a survey conducted by Allen et al. (2008), the type of roofing materials in Malaysia is divided into 85% concrete tiles, 10% clay tiles and 5% metal deck. A study conducted by Al Yacouby et al. (2011) in Malaysia indicated that most roof tiles are dark in colour; red accounts for 38%, brown for 25.9%, white for 9.5%, beige and blue for 7.8%, black for 4.9% and grey for 2.9%.

As a result, Malaysian houses suffer from large solar radiation gain, particularly from roofs that provide an uncomfortable indoor environment to their occupants. Poor ventilation and air circulation make the situation worse because openings in Malaysian houses are only located in the front and back facades; consequently, the heat gain inside the building is trapped by rooms, doors and partitions and leads to an increase in the temperature of internal spaces especially at night (Isa et al., 2010; Kubota et al., 2009). Therefore, existing buildings in tropical Malaysia would have a major problem when the electricity cost increases gradually over the years.

To overcome this issue, building professionals are advised to re-examine the environmental factors involved in designing buildings for tropical regions. However, the climate characteristics of the Equator have always been a problem to human comfort both inside and outside buildings (Szokolay, 1998). The integration of building construction with sufficient knowledge and technology to achieve sustainability and energy efficiency can contribute to low-energy usage for future building operation and maintenance. Therefore, the design considerations in building construction must be in balance with the environment, natural resources and relevant technologies to meet our current needs.

Energy sources from the sun in the tropics can only be utilised in buildings by understanding the methods and strategies of passive solar design to improve daylighting and the indoor thermal environment to alleviate the need for mechanical cooling devices. A passive solar design is generally a design concept that involves the use of the sun's energy in response to local climatic conditions (Zaki et al., 2007); buildings that adopt such design concept are also known as 'energy efficient buildings' (Zhu and Lin, 2004). The theory behind this design combines several trends, such as climatology, thermodynamics and optics, whilst primarily focusing on controlling sunlight and avoiding solar heat to achieve cooling methods independent of or infrequently requiring active systems.

These trends, especially their application to an actual building in a hot–humid region, have not been well studied as a design in roofing systems. In addition, the building codes of Malaysia, namely, Uniform Building By-Laws (1984), MS1525-2007, Green Building Index (2011a and 2011b) and Building Sector Energy Efficiency Project (2013), provide no specific standard to encourage the use of this approach. No specific policy measure related to the application of this type of technique to roofing systems exists. The effectiveness of the technique when applied to an actual building requires further investigation to obtain quantitative data on the performance of such a system in a tropical climate.

1.2 Problem Statement and Hypothesis

The skylight or rooflight system represents one of the suitable passive design solutions to overcome the issue of high-energy consumption in upper latitudes. Temperate and cold climates allow for more flexibility in heating and daylighting design because of the mild temperature and variety of seasons. In domestic buildings, sunlight is still welcomed during summertime. Providing natural air circulation through openings as a cross ventilation is all that is necessary to overcome the heat gain issue. However, this system cannot be simply applied in a tropical region, particularly in single-storey buildings, because of the high intensity and concentration of tropical sunlight with unpredictable and weak wind movement in the urban areas of this region.

Unlike countries with temperate and cold climates, Malaysia is a tropical country located at approximately 3° N. Malaysia is exposed to a very large amount of solar insolation that ranges between 1400 and 1900 kWh/m^2 (Ahmed el al., 2011), with an annual average of approximately 1643 kWh/m^2 (Haris, 2008), and more than 10 sun hours per day (Amin et al., 2009). The problem of high energy consumption arises when radiant energy in the form of heat originates primary from the sun and secondarily from the sky, which affects the roofing system. According to technical data from Air Vent Inc. (2013), the typical temperature for a house with a closed and dark attic with outside air on a hot day is 32 °C; the temperature on the roof surface could be as high as 77 °C, and the temperature on the attic's floor could be 60 °C. Hence, an uncomfortable environment is created in spaces directly under the attic. Occupants have to switch on their fans and air-conditioning units. As the hot days continue, these electrical devices are operated for longer periods. Thus, more money is spent for energy.

Single-storey buildings rarely have a skylight simply because a skylight increases heat gain and brings in glare at human height level. In addition, daylighting in tropical countries is a completely different issue that requires several critical considerations on the positioning of openings in the building fabric to permit light entrance and avoid extreme heat gain and brightness (glare) caused by direct sunlight (Zain-Ahmed et al., 2002a; Fadzil and Sia, 2003). Zain-Ahmed (2002b) indicated that the Malaysian sky delivers illumination between 60,000 and 80,000 lux at noon during the months when solar radiation is the highest. This amount is more than the required amount of sunlight necessary for effective day-to-day living. Stifling heat and glare are a major problem. Thus, the raw exposure provided by this amount must be tampered for productive use of sunlight.

The Building Sector Energy Efficiency Project (2013) in the daylight field (solar heat gain minimisation) and Yunus et al. (2011a and 2011b), who focused only on overcast sky conditions to design a rooflight system for non-residential buildings, believed that direct sunlight is a disadvantage. This study involves designing a system that can solve the problem of delivering a high level of sunlight with reduced heat gain.

For this reason, the hypothesis of the current study is that a new design named as innovative roofing system (IRS) would help reduce solar heat gain from natural light. The proposed IRS involves the use of two rooflights (polycarbonate) on the roof and attic floor incorporated with pigment techniques (reflective and radiative) on the roof surfaces (lightweight) and integrated with attic ventilation (hybrid turbine ventilator).

As a result, the proposed IRS is expected to deliver an abundant and uniform amount of natural light from the roof with minimal impact on heat gain, as experienced in buildings in upper latitudes.

1.3 Research Questions

Owing to the fact that the Malaysian sun is intense, most buildings in this region experience a high level of heat build-up. A skylight system is a challenge for architects and building designers because its effectiveness depends entirely on local climatic conditions. Therefore, the practical applicability of IRS in a hot–humid region requires further exploration. The following particular research questions are formulated.

Q1: What is the performance efficiency of IRS under Malaysian sky conditions?

Q2: What is the optimum IRS model and is the proposed IRS design effective when compared with different roofing designs?

Q3: Can IRS significantly reduce the load of solar heat from natural light most of the time?

1.4 Research Objectives

The main objective of this study is to investigate the application possibility and limitations of a sustainable roofing design under Malaysian climatic conditions. This study focuses on improving indoor climatic conditions by reducing solar heat obtained from natural light in the attic space in a specific test cell. The particular objectives of this study are provided below.

i) To investigate the performance efficiency of IRS under Malaysian sky conditions.

ii) To obtain quantitative results from IRS in terms of improving indoor climatic conditions in comparison with several roofing designs under Malaysian sky conditions.

iii) To identify the capability of IRS to reduce solar heat gain from natural light and control the indoor environmental condition at a specific attic and room volume.

1.5 Research Approach and Methods

To achieve the objectives specified in Section 1.4 and answer the research questions stated in Section 1.3, this study involves several phases of research tasks, as presented in Figure 1.1.

Firstly, a literature review on the actual scenarios of design concepts and environmental issues in the Malaysian region were discussed extensively to identify the potential and limitations of IRS. Secondly, different passive strategies for the roof were applied to discover the most appropriate approaches to reduce solar heat from natural light in the roof–attic of buildings in the tropics. A survey of related studies led to the inference that the combination of several passive and active solar strategies, such as glazing technology (polycarbonate) integrated with pigment properties in lightweight roof materials incorporated with attic ventilation provided by a hybrid turbine ventilator with a polycrystalline solar panel, would help enhance the effectiveness of the skylight system in single-storey buildings. This combination in one roofing system could maximise the daylight level whilst overcoming heat build-up issues in tropical buildings.

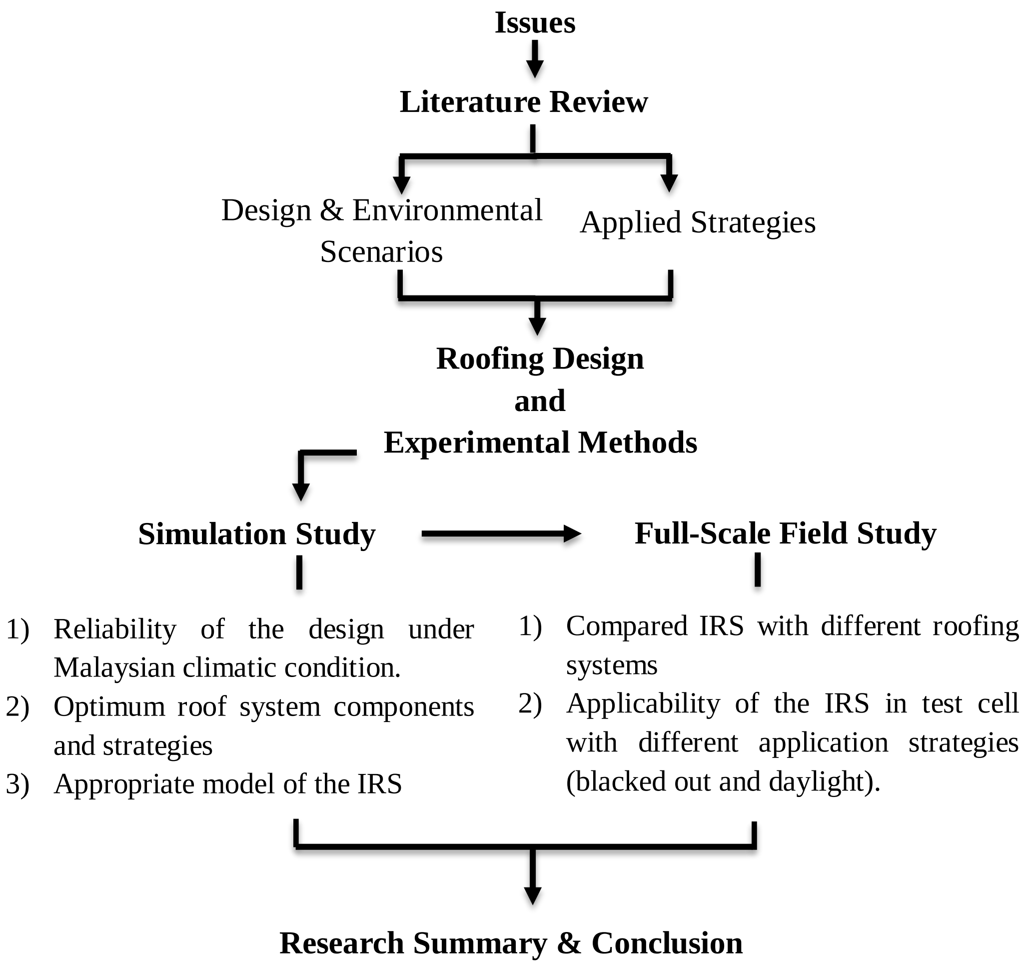


Figure 1.1: Summary of the methodology employed in examining the possibilities of using IRS to improve indoor environment conditions

Actual exploration was conducted to identify the suitable roofing system configuration and its efficiency in enhancing the indoor climatic condition in the actual Malaysian environment as well as actual building size. Such exploration was conducted through experimental methods that comprised both simulation and field studies.

In the simulation, which employs mathematical equations, the reliability of the outcomes depends on software validity and outdoor environment records. The targeted factors were investigated (roof materials, roof solar reflectance, roof angles, glazing types, glazing sizes and roof orientations) with several design parameters, such as roof with an attic, black body concept and ventilation strategy, as shown in Figure 1.2. The effectiveness of a specific turbine ventilator type and size was based on previous studies conducted in the same environment, location and climatic conditions.

Meanwhile, the capability of the system to deliver a suitable natural light level for tenants in single-storey buildings was investigated through a series of field studies conducted in a test cell. For this purpose, the visual and thermal environments of a specific model size were studied for the different strategies. A number of parameters, such as ambient climatic conditions, effect of attic space on indoor behaviour and influence of blacked out and daylight conditions on enhancing indoor climate performance, were investigated. The thermal conditions and natural light levels of each case were assessed and compared by measurements of air temperature, mean radiant temperature, illuminance level, relative humidity and surface temperature (transparent ceiling) in the occupied space and by measuring air temperature, relative humidity and air velocity in the attic space. All these measurements were synchronised with an outdoor weather station that measures ambient temperature, outdoor illuminance level, solar intensity, wind velocity and ambient relative humidity.

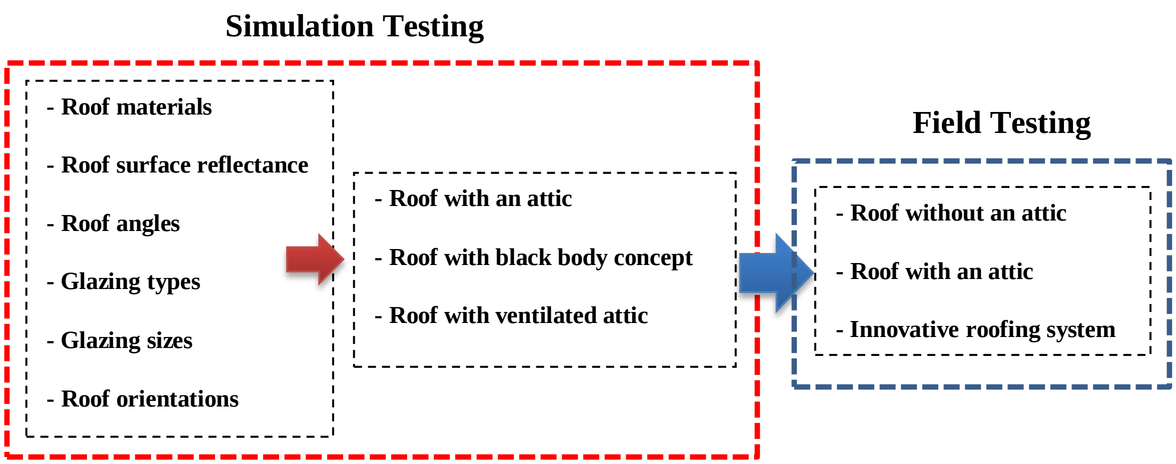


Figure 1.2: Targeted factors employed in examining the possibilities of using IRS

1.6 Scope and Limitations

This paper presents a study on the effectiveness of IRS in improving indoor climatic conditions through the reduction of solar heat from natural light to utilise natural light energy in spaces with a roof height of 3 m from the ground in the tropics. Although several possible combinations of different renewable energy sources can be combined to form IRS, only the combination of passive and active solar designs, which depends on the interaction with solar energy in the attic zone, is considered in this study. Such combination involves the application of glazing technology and pigments methods in lightweight roof materials and attic ventilation through a regular opening for the inlet and a hybrid turbine ventilator integrated with polycrystalline photovoltaic panels and natural wind energy for the outlet.

In this respect, the studied concept design of IRS should be differentiated from complex and expensive solar design techniques, which are frequently composed of several energy systems, power conditioning equipment and controllers. With respect to the simplicity of the passive solar design and environmental concern, none of the technologies reviewed in this study employs a chemical and extremely complex refrigerant system to work; in fact, each technology was applied based entirely on physical form. However, a new design combination of state-of-the-art cooling natural light in a tropical region limits the scope of this research. As a result, only reasonably priced and easily acquired materials in the Malaysian market were utilised and investigated in this study. As stated earlier, the thesis focused only on the performance of combined strategies in a single system (IRS) to deliver minimal heat load from natural light in a hot–humid region.

The thesis focused on the effectiveness of the proposed IRS in enhancing indoor climatic conditions. However, several specific limitations exist. Firstly, a clear glazing feature was adopted based on the recommendations of Heschong and Resources (1998) and the Building

Sector Energy Efficiency Project (2013) because of the predominant behaviour of Malaysian skies (from overcast to mean intermediate) in a year and the lack of evidence on clear sky conditions in this region (Zain-Ahmed et al., 2002b). Secondly, the investigations were performed in a closed space condition (no windows and no door opening) in the occupant zone, which eliminated the presence of any air circulation and extra heat gain. Thirdly, the testing days followed Malaysian metrological data through 21 years and the Penang sun path diagram that specifies the hottest and driest days with a high impact of solar radiation and high level of ambient air temperature as well as the dates wherein the solar elevation angle between 80° to 90°. These specifications represent the worst case condition, and any variation should be below this case. Furthermore, this study does not cover OTTV or RTTV because no air-conditioning system is used. Likewise, in the calculation of natural light level, the daylight factor was not considered because the daylight factor calculates the horizontal illumination of an unobstructed outdoor point for overcast and moderate sky conditions.

Therefore, the probable effects of the system on other significant aspects of indoor environmental quality, such as visual comfort and lighting quality, thermal comfort, indoor air quality and acoustic comfort, indicated in MS1525:2007 (DSM, 2007) and Green Building Index (GBI, 2011) for residential and non-residential buildings were not covered in this research.

1.7 Research Significance

This research on the design of IRS for hot–humid tropical buildings is important for the following reasons.

i) The research encourages the application of a sustainable building design to increase the use of renewable energy (RE) and energy efficiency (EE) in the built environment to meet the requirements of MS1525:2007 (DSM, 2007), Green Building Index (2011a and 2011b) and Building Energy Efficiency Technical Guideline for Passive Design (Building Sector Energy Efficiency Project, 2013).

ii) The study is designed to save energy and resources and is in harmony with the local climate to sustain and enhance the quality of human life for operational energy savings and increased workplace productivity.

iii) This thesis produces an original system that maximises the benefits of solar energy in the tropics in terms of environmental concerns and technical function. The functionality of the system also improves single-storey buildings by increasing their value for the purpose of commercialisation.

iv) This study is the first research designed for spaces with a roof height of 3 m from the ground. The Building Sector Energy Efficiency Project (2013) and Yunus et al. (2011a and 2011b) only studied only the performance of the skylight system for non-residential buildings.

v) This research delivers a new message to architects and buildings designers: understand substantial issues in hybrid science for future building design. It provides abundant information on sustainable roofing design and detailed explanations on IRS that are valuable not only for architects and building designers but also for increasing public awareness on environmental cooling approaches.

1.8 Organisation of the Thesis

This thesis consists of seven chapters, which are shown in Figure 1.3. The chapters are described below.

Chapter 1 presents a brief description of why and how IRS as a new approach improves the quality of indoor climatic conditions. It begins by introducing a brief background of the study and its problem statements, hypothesis, research questions, research objectives, approach and methods, scope, limitations and significance. The outline of the research is summarised and explained in the last part of this chapter.

Chapter 2 presents a review of literature on the topics associated with sustainable roofing design in consideration of the environmental concerns in Malaysian conditions. It covers issues on the main concept of sustainability in architectural design and presents sustainable roofing methods. In addition, a general review on Malaysian environmental scenarios in outdoor and indoor built environments is presented to provide a clear picture. Thus, sky conditions, natural light types, climate and weather parameters in the outdoor environment as well as lighting and thermal loads in the indoor environment are explained broadly. This chapter also summarises the overall situation to determine the actual issues that could help in the design of an optimum system for hot–humid regions.

Chapter 3 presents a review of literature on several applicable approaches that support the scenarios in presented in Chapter 2 and are associated with passive and active solar strategies in roofing design. Two trends, namely, reduce and reject, are identified as classifications of roofing systems. This chapter reviews a number of studies on analytical and experimental investigations that evaluated the effectiveness of several methods and configurations in different climatic conditions. The results from these studies are discussed based on their possible application in the Malaysian climatic condition.

Chapter 4 presents the methods and approaches adopted in this study, including a simulation study and a series of empirical investigations. The rationale of selecting these methods is clearly explained. These methods are obtained from existing literature and specially selected to achieve the objectives of this research. The results of the simulation and empirical studies on IRS are presented and analysed in Chapters 5 and 6.

Chapter 5 presents the roofing system outcomes from the simulation study based on several components (roof materials, roof surface reflectance, roof angles, glazing types, glazing sizes and building orientations) and design parameters (roof with attic, black body concept and ventilation strategy) to identify the reliability and effectiveness of the roofing system in terms of enhancing the performance of IRS. Several observations led to the determination of the most appropriate design for the system.

Chapter 6 elaborates the outcomes of the empirical studies to explore the possibility of reducing solar heat via IRS whilst maintaining an abundant level of natural light in the attic zone under the actual climate condition of Malaysia. Firstly, it discusses different roofing strategies and the IRS design. Further in-depth analysis regarding the comparative study of different roofing systems is also presented. Experiments are conducted in two conditions (blacked out and daylight) to determine the significance of the differences.

Chapter 7 presents the overall research findings. The chapter also summarises the potential and limitations of IRS in an actual test cell in a hot–humid region. Several recommendations for future studies on roofing system development, particularly on areas beyond the scope of this thesis, are likewise provided.

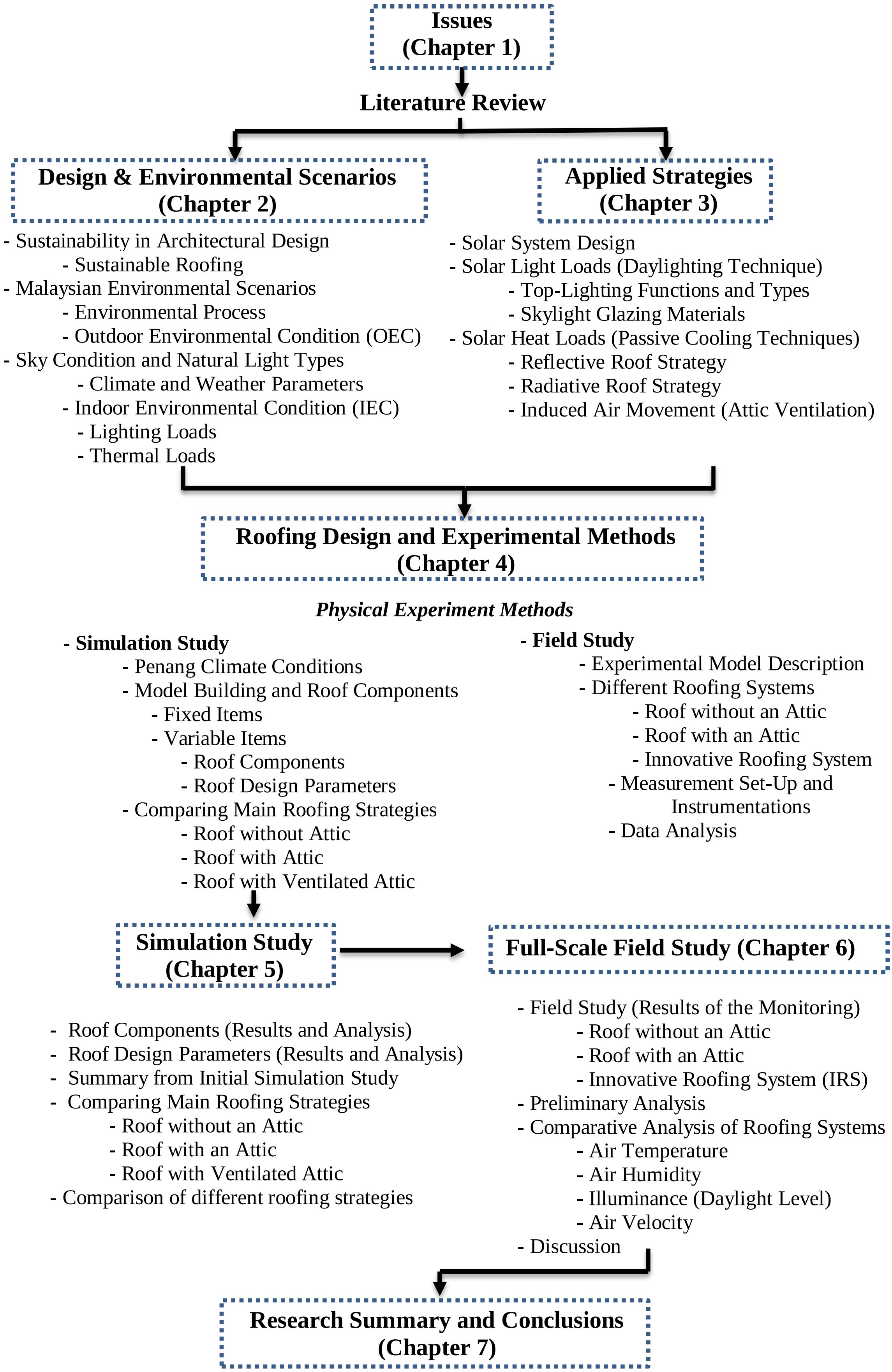


Figure 1.3: Research framework diagram explaining the overall theory, structure and approaches involved in the thesis

CHAPTER 2

PRINCIPLES OF SUSTAINABILITY IN ROOFING DESIGN AND MALAYSIAN ENVIRONMENTAL SCENARIOS

2.1 Introduction

This chapter presents a review of literature on the topics associated with the sustainability of roofing design in consideration of the environmental issues in the Malaysian condition. It begins with an introduction of the main concept of sustainability in architectural design and then explains the principles and basic trends to identify sustainable roofing methods. This explanation is followed by a review of Malaysian environmental scenarios in outdoor and indoor built environments covering sky conditions, natural light types, climate and weather parameters (for the outdoor environment) as well as lighting and thermal loads (for the indoor environment). Towards the end of this chapter, the overall situation is summarised to identify the actual issues that could assist in designing an optimum daylight system for the Malaysian environment.

2.2 Main Concept of Sustainability in Architectural Design

Sustainability in architecture is a way of thinking or philosophy of designing physical objects to build a proper environment. It is a comprehensive topic that provides efficiency and moderation in the design and use of energy, materials and cost (Jong-Jin and Rigdon, 1998). It aims to avoid environmental degradation caused by facilities during their life cycle and create built environments that are comfortable, liveable, productive and safe (McLennan, 2004; WBDG Sustainable Committee, 2013).

Sustainability in architecture is a challenge in designing buildings with minimal pollution and low energy use to provide improved indoor environmental quality (IEQ), including thermal, visual, air and acoustic quality (American Society of Heating, Refrigerating and Air-Conditioning Engineers or ASHRAE Guideline 10-2011). According to Jong-Jin and Rigdon (1998), the principles of sustainable architecture have developed through a framework that is divided into three levels; principles, strategies and methods correspond to the objectives of the architectural environment. They proposed three principles of sustainability in architecture: (i) economy of resources (energy, water and material conservation), (ii) life cycle design (pre-building, building and post-building phases) and (iii) human design (preservation of natural conditions and design for human comfort). These principles help architects and building designers develop their designs with understanding and broad awareness of the environmental impact both locally and globally.

2.2.1 Sustainable Roofing

Owing to the increasing public concern on climate change and global warming, international conferences are challenging construction industries, particularly roofing industries, to translate the demands of reducing energy consumption through practical guidelines and systems (Hutchinson, 2004a). Various conceptual definitions have been proposed to understand the meaning of sustainable roof, but the most effective one is the definition from the proceedings of the Sustainable Low-Slope Roofing Workshop, Oak Ridge National Laboratory, USA, in October 1996. According to the proceedings of the said workshop, a sustainable roof is *‘a roofing system that is designed, constructed, maintained, rehabilitated and demolished with an emphasis throughout its life cycle on using natural resources efficiently and preserving the global environment’.*

According to Hutchinson (2004b), the definition is difficult to comprehend, and implementing its values is extremely complex because of their far-reaching scope. To meet the requirements of sustainable development, an international committee (CIB W83/RILEM 166 RMS) summarised a document entitled 'Tenets of Sustainable Roofing' in 2002. This document has helped architects and designers make headway in three important sectors of sustainability: (i) minimising the burden on the environment, (ii) conserving energy and (iii) extending the life span of roof systems (Hutchinson, 2004a). These tenets of sustainable roofing are summarised in Table 2.1.

Table 2.1: Summary of the most important trends in sustainable roofing (Hutchinson, 2004a)

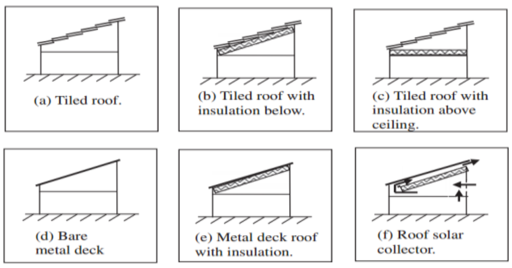
Tenets of Sustainable Roofing
(a) Minimise the Environmental Burden 1- Use products made from raw materials whose extraction do not cause harm to the environment. 2- Adopt systems and working practices that reduce wastage. 3- Avoid products that result in hazardous waste. 4- Understand regional climatic and geographical factors. 5- Where logical, use products that could be reused or recycled. 6- Consider roof designs that simplify the classification and salvaging of materials at the end of the roof system's life.
(b) Conserve Energy 7- Enhance the actual thermal performance of roofing systems; understand that thermal insulation can significantly minimise heating or cooling costs throughout the building's life cycle. 8- Use local labour, materials and services when practical to reduce the effect of transportation. 9- Know that embodied energy values are effective measures for comparing alternative systems of construction. 10- Consider roof system performance by evaluating the roof surface colour and texture with regard to climate.
(c) Extend Roof Lifespan 11- Employ adequately trained designers, contractors, suppliers, trades people and facility managers with proper skills. 12- Adopt a responsible design approach and recognise the value of a robust and durable roof system. 13- Know the importance of a properly supported structure. 14- Reduce the number of penetrations through a roof system. 15- Ensure that high-maintenance elements are easily accessible for repair or replacement.

According to Liu (2005), building owners demand more roofing systems that are environmentally friendly and have low impact to support the idea of sustainable development. At this stage, designers and manufacturers have responded by

- Using materials that are compatible with the environment,
- Producing durable products and
- Developing methods and system designs that enhance life-cycle costs.

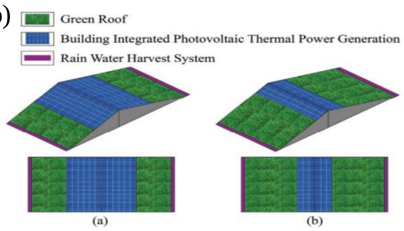
Ong (2011), Ismail et al. (2011), Al Yacouby et al. (2011), Sheng (2011), Ismail et al. (2012) and Yew et al. (2013) introduced a number of approaches to develop the roofing system in Malaysia, as shown in Figure 2.1. However, none of these studies combined daylighting and passive cooling techniques in one roofing design. The proposed design is novel because it combines these techniques.

(a)



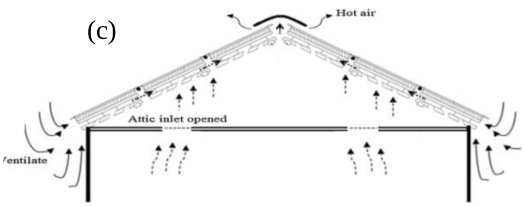
Temperature reduction in attic and ceiling via insulation of several passive roof designs- Source: Ong (2011)

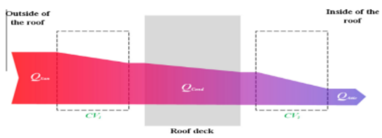
(b)



Integrated sustainable roof design Source: Sheng et al. (2011)

(c)





Integration of thermal insulation coating and moving-air-cavity in a cool roof system for attic temperature reduction, Source: Yew et al. (2013)

(d)

The investigation of green roof and white roof cooling potential on single storey residential building in the Malaysian climate Source: Ismail et al. (2011)

Figure 2.1: Approaches to develop the roofing system in Malaysia

Several examples of sustainable roofs have also been developed.

- **Green Roof Systems (Garden Roof System):** Roche and Berardi (2014) studied comfort and energy savings with active green roofs. Jim (2014) investigated air-conditioning energy consumption by using green roofs with different building thermal insulation. Wong and Jim (2014) quantitatively studied the hydrologic performance of an extensive green roof in a humid–tropical rainfall regime. Zhao et al. (2014) investigated the effects of plant and substrate selection on the thermal performance of green roofs during summer.

- **Reflective Roofs (Cool Roof):** Roels and Deurinck (2011) studied the effect of a reflective underlay on the global thermal behaviour of pitched roofs. Jo et al. (2011) investigated an integrated empirical and modeling methodology to analyse solar reflective roof technologies in commercial buildings. Santamouris et al. (2011) studied the use of advanced cooling materials in an urban-built environment to mitigate heat islands and improve thermal comfort conditions. Akbari et al. (2009) investigated global cooling by increasing worldwide urban albedos to offset CO_2.

- **Roof Photovoltaic:** Mainzer et al. (2014) studied the high-resolution determination of the technical potential of residential-roof-mounted photovoltaic systems in Germany. Ban-Weiss et al. (2013) investigated the electricity production of and cooling energy savings from installing a building-integrated photovoltaic roof on an office building. Lamnatou and Chemisana (2014) studied photovoltaic–green roofs. Chemisana and Lamnatou (2014) investigated photovoltaic–green roofs by conducting an experimental evaluation of system performance.

The current research presents a novel model of sustainable roofing design for the tropics. As a result, exploring a new approach such as IRS is worthwhile given that such a new approach will become an original and new application locally and globally.

Based on the criteria mentioned above, IRS could contribute to design sustainability through the following trends.

1- Understand regional climatic and geographical factors.
2- Use products that could be reused or recycled.
3- Adopt systems and working practices that reduce wastage.
4- Use materials that are compatible with the environment.
5- Avoid products that result in hazardous waste.
6- Consider roof system performance by evaluating the roof surface colour and texture with regard to climate.
7- Know that embodied energy values are effective measures for comparing alternative systems of construction.
8- Develop methods and system designs that enhance life-cycle costs.

2.3 Malaysian Environmental Scenarios

Designing a sustainable roofing system that permits natural light in single-storey buildings in Malaysia initially requires an understanding of Malaysian conditions (outdoor and indoor) before implementing any strategy because this system could allow for the transfer of high levels of solar light and solar heat. Therefore, the aim from this section is to identify key factors in the design of a specific sustainable roofing system.

Literature reviews have found that most studies in the tropics, particularly in Malaysia, have resulted in an unclear vision in the review of solar radiation (light and heat) behaviours in outdoor and indoor built environments. Studies on different climatic regions have not clearly addressed any descriptive connection to evaluate the environmental loads that interact with the skylight roofing system from outside and inside buildings. Studies have consistently focused on one side or one point of view rather than consider different viewpoints in one process.

Most reviews (The European Commission Directorate-General for Energy, 1994; Heschong and Resources, 1998; Muneer and Kinghorn, 2000; Ruck et al., 2000; Edmonds and Greenup, 2002; Boyce et al., 2003; Mardaljevic, 2007; MS1525:2007; Boubekri, 2008; Szokolay, 2008; National Association of Rooflight Manufacturers, 2009; Kittler et al., 2012) generally discussed only the strategies and types of skylights; no clarification was provided as one holistic approach towards a single design in tropical architecture.

2.3.1 Environmental Process

Solar radiation as a main source of natural light is the primary issue in designing any sustainable roofing system. Solar radiation exhibits diverse behaviours and interactions that contribute to various environmental loads. These loads either increase or decrease after entering the built environment. Therefore, this section provides a review of only the behaviours of solar radiation (light and heat) in the Malaysian outdoor environment and its impact on indoor environmental standards.

Figure 2.2 shows that the basic theoretical concept of the load process is influenced by the outdoor environment, modified by the mediator (roofing system), transferred from the system to the indoor environment and eventually affect the outcomes of system design. To comprehend the concept, one must understand that direct load from the sun is different from indirect load that is modified by the roofing system and reaches indoor spaces. These loads represent actions and reactions that interact in buildings and are controlled by a medium. Therefore, targeting the characteristics of each parameter would identify the key points for an optimum design.

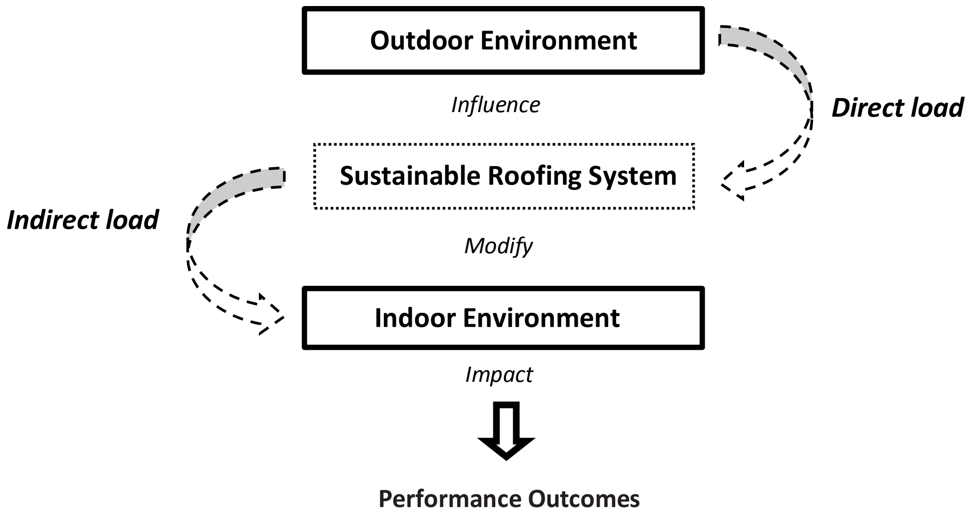


Figure 2.2: Theoretical concept of the environmental load process

Mardaljevic (2007) and Szokolay (2008) posited that climate is a main parameter that controls the outdoor environment. Heschong and Resources (1998) and Kittler et al. (2012) specifically identified building components as the most important aspect in daylighting and thermal design. The European Commission Directorate-General for Energy (1994) and Boubekri (2008) identified human comfort as the basis for evaluating indoor conditions. These independent aspects share one common dependent variable, that is, solar radiation that embodies light and heat. Solar radiation is an electromagnetic spectrum given off by the sun mainly in three wavelengths: visible light radiation (light), infrared and ultraviolet radiation in the form of heat. Therefore, light and heat that originate from solar rays are discussed as the most targeted variables in this chapter. Figure 2.3 shows the environmental load process that relates to any roofing system.