PERFORMANCE OF HORIZONTAL LIGHT PIPE FOR DAYLIGHTING IN HIGH-RISE OFFICE BUILDING IN TROPICAL REGION

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Specially dedicated to my Lord and Saviour Jesus Christ,

Mom, Dad and Rachel.

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ABSTRACT

Deep open-plan design is common in high-rise office building due to economic profits. Daylight, which has benefits for energy conservation and both human physiology and psychology; however, is unable to reach the deep area of the office through side windows causing the dependency on electrical lighting. Therefore, this study discourses the usage of light distribution systems, particularly light pipe (LP), to provide illumination in a deep open-plan office in tropical climate. It also focuses on south-facing facade which is the most potential orientation for LP due to the sun position of Johor Bahru that is above the Equator line (latitude of 1^{o} 3' N and longitude of 103^{o} 37' E). Most of the previous research was done in temperate climate where the sun position is different from tropical region and focuses on the collector and extractor of LP. The emphasis of this research is on the daylighting performance of the various shapes of transporter and numbers of opening. Nine (9) LP transporters with different numbers of side and a base case were assessed using computer simulation software, *Integrated Environment Solution: Virtual Environment (IESVE)* that was validated with physical scaled model experiment. Simulations were carried out under overcast sky and intermediate sky with sun condition. The results showed that all the LP cases improve the daylighting performance of an empty open-plan office room. Semi-circle transporter with two openings, which has 14% lesser surface area than a typical rectangular transporter, shows the best performance both quantitatively and qualitatively. This helps to save cost in terms of material usage and creates additional spaces for wiring and ducting in the plenum. This study also concluded that the shape of LP transporter affects the efficiency of LP while the influence of the number of polygon sides and height of the sides without altering the overall height of the transporter are not significant. Thus, the findings of this study promote the usage of LP in deep open-plan high-rise office buildings by proposing design recommendations and guides for building designers.

ABSTRAK

Rekabentuk pelan terbuka yang dalam adalah lazim dalam bangunan pejabat tinggi untuk keuntungan ekonomi. Cahaya siang yang mempunyai manfaat bagi penjimatan tenaga dan kedua-dua fisiologi dan psikologi manusia tidak dapat mencapai kawasan pejabat yang dalam melalui tingkap sisi dan menyebabkan pergantungan kepada pencahayaan elektrik. Oleh itu, kajian ini mengkaji penggunaan sistem pengedaran cahaya, khususnya paip cahaya (LP), untuk memberikan pencahayaan ke dalam pejabat yang mempunyai pelan terbuka yang dalam di iklim tropika. Kajian ini memberi tumpuan kepada fasad bangunan yang menghadap ke arah selatan iaitu orientasi yang paling berpotensi untuk LP disebabkan oleh kedudukan Johor Bahru terletak di utara garisan Khatulistiwa (latitud 1^{o} 3’ N dan longitud 103^{o} 37’ E). Kebanyakan kajian sebelum ini dijalankan dalam iklim sederhana di mana kedudukan matahari adalah berbeza daripada rantau tropika dan hanya memberi tumpuan terhadap pemungut dan pengekstrak LP. Fokus utama kajian ini adalah terhadap prestasi cahaya siang bagi pelbagai bentuk pengangkut dan bilangan bukaan. Sembilan (9) pengangkut LP dengan bilangan sisi yang berlainan dan satu model asas dinilai menggunakan perisian simulasi komputer, *Integrated Environment Solution: Virtual Environment (IESVE)* yang telah divalidasikan dengan eksperimen model fizikal berskala. Simulasi telah dijalankan di bawah langit mendung dan langit perantaraan dengan matahari. Hasil kajian menunjukkan bahawa kesemua kes LP meningkatkan prestasi cahaya siang di dalam bilik pejabat pelan terbuka yang kosong. Pengangkut LP berbentuk semi bulatan dengan dua bukaan yang mempunyai 14% luas permukaan yang lebih kecil daripada pengangkut segi empat tepat yang tipikal, menunjukkan prestasi kuantitatif dan kualitatif yang terbaik. Ini dapat membantu untuk menjimatkan kos dari segi penggunaan bahan dan mencipta ruang tambahan untuk pendawaian dan penyaluran dalam plenum. Kajian ini juga menyimpulkan bahawa bentuk pengangkut LP mempengaruhi kecekapan LP manakala pengaruh bilangan sisi poligon dan ketinggian sisi tanpa mengubah ketinggian keseluruhan pengangkut LP adalah tidak ketara. Oleh itu, hasil kajian ini menggalakkan penggunaan LP dalam pejabat bangunan tinggi yang mempunyai pelan terbuka yang dalam dengan mencadangkan saranan reka bentuk dan panduan untuk pereka bangunan.

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LIST OF ABBREVIATIONS

CIBSE	-	Chartered Institution of Building Services Engineers
CIE	-	International Commission on Illumination
CPC	-	Compound Parabolic Concentrator
CRI	-	Colour Rendering Index
DF	-	Daylight Factor
DGI	-	Daylight Glare Index
DPP	-	Du Mortier-Perraudeau-Page
DR	-	Daylight Ratio
EII	-	Estimated Indoor Illuminance
GBI	-	Green Building Index
HLP	-	Horizontal Light Pipe
HOE	-	Holographic Optical Elements
HPP	-	Hollow Prismatic Pipes
IES	-	Illuminating Engineering Society
IESVE	-	Integrated Environmental Solutions: Virtual Environment
LCP	-	Laser Cut Panels
LDS	-	Light Distribution System
LGS	-	Light Guide System
LP	-	Light Pipe
LTS	-	Light Transport System
MBE	-	Mean Bias Error
MLP	-	Mirror Light Pipe
MS	-	Malaysia Standard
NI	-	Nebulosity Index
NIA	-	Net Internal Area

RGB	-	Red, Green and Blue
RMSE	-	Root Mean Square Error
SEA	-	Southeast Asia
SR	-	Saturation Ratio
UDI	-	Useful Daylight Illuminance
UTM	-	Universiti Teknologi Malaysia
WPI	-	Work Plane Illuminance
WPIR	-	Work Plane Illuminance Ratio
WWR	-	Window-to-wall Ratio
VDT	-	Visual Display Terminal
VLP	-	Vertical Light Pipe
ZERO	-	Zero Energy Office

LIST OF SYMBOLS

$\sum$	-	Sum
$E_{average}$	-	Average Illuminance
E_G	-	Global Illuminance
E_{indoor}	-	Indoor Illuminance
E_{max}	-	Maximum Illuminance
E_{min}	-	Minimum Illuminance
$E_{outdoor}$	-	Outdoor Illuminance
L_s	-	Source of Luminance
L_b	-	Average Background of Luminance
$N(\theta)$	-	Average Number of Reflection at Angle θ
ω	-	Angular Size of the Source as Seen by Eye
Ω	-	Solid Angle Subtended by the Source

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.0. Introduction

Daylight has proven to bring a lot of benefits to human kind. Throughout the centuries, daylight plays an important role in one of the three most fundamental elements for human being to survive: shelter, food and clothes (Kraybill and Olivet, 2006; Al Faruque, 2014). Settlements of the old had made use of daylight in architecture elements such as Pantheon and Roman patio buildings. Besides that, according to Rosemann *et al.* (2008), this renewable resource helps in creating a sustainable building design that conserve the non-renewable resource and energy. Other than that, researchers have proven that daylight has the capability to bring benefits to office workers, both physiologically and psychologically (Paevere, 2009; Mayhoub and Carter, 2011). Besides increasing the productivity of the workers, it also creates a heathier environment, thus, lessening the absentees. Moreover, daylight can also bring a significant impact on the indoor environment quality such as thermal comfort (Paevere, 2009; Baird and Thompson, 2012).

In tropical climate such as Malaysia, the outdoor illuminance can reach as high as 120, 000 lux whereas temperate climate can only reach to about 20, 000 lux. However, the unpredictable cloud formation that affects the availability of a constant global illuminance level complicates the daylight utilisation in a building (Mohd Hamdan, 1996; Ossen, 2005; Lim, 2011). Furthermore, high energy consumption from air-conditioning system was noticed during working hours and thus, showed that the high illuminance from the natural lighting was not utilised in high-rise building (Lim, 2011).

High-rise buildings with large floor are or having deep open-plans are sprouting everywhere in the current world to maximise the floor efficiency. Deep open-plans are spaces which have a long depth spanning from one end to another with no obstruction in between such as partition or work cubicles. These buildings which includes office buildings tend to utilize large amount of electricity for lighting and air-conditioning due to the disability to harvest natural daylight (Gissen, 2002). Furthermore, Saidur *et al.* (2009) and Sadrzadehrafiei et. al (2012) stated that air conditioning and electric lighting is accounted for 57-58% and 19-20% of total energy use in a typical office building in Malaysia. While in US and Europe, lighting is responsible for 25% and 14% respectively (DOE, 2009; EC, 2007). The deep open-plan also caused the occurrence of glare due to the contrasting illuminance level between the opening and the back of the room. This will affect the visual comfort of the occupants. Hence, the emergence of deep open-plan building increases the use of electrical lighting as well as creating problems for daylight utilisation.

The use of light transport system such as light pipe (LP) helps in bringing daylight into the interior of the deep open-plan building. However, in a high-rise office, the use of vertical light pipe (VLP) is not feasible as the system works best with the shortest distance from the source as stated by Hansen (2006). Hence, horizontal light pipe (HLP) provides the better solution in transporting daylight in a high-rise building where the installation of HLP will require some space above the ceiling level. Previous studies on HLP focused mainly on the improvement on the collector and extractor, rather than the transporter.

This research assesses horizontal passive daylighting solutions to bring in daylight into deep open-plan high-rise office building. It focuses on experimenting with different transporter shapes and numbers of openings for HLP. This study also aims to provide adequate daylighting and uniform daylight distribution in office building through the proposed HLP where it can accommodate various subsystem of a building at the plenum space.

1.1. Problem Statement

I. Increasing numbers of deep open-plan high-rise office buildings.

The economic view of maximising cost return causes buildings to have larger and deeper open-plan to increase the usable area in a building. The high land cost and unavailability of empty spaces in the urban area resulted in the blooming of more multi-storey or high-rise buildings (Singh and Jain, 2013). Tenants in high-rise offices prefer their workspace to be on the same floor with open-plan layout for the purposes of communication and collaboration (Section 2.3.2). The typical depth of an office building in Malaysia ranges from 4.5m to 12m with an optimum 2000m^2 to 2500^2 m (Harrison, 1998; Lim, 2011) which is explained further in Section 2.3.1. The limitation of the daylight availability inside the office space and the lack of awareness in making use of natural daylight that is in abundance in tropical country leads to increasing energy consumption in the form of electrical lighting and cooling in high-rise buildings.

II. Non-uniform daylight distribution across the deep open-plan office layout.

Baker and Steemers (2014) asserted that the depth of zone which can be day lit is limited to twice of the ceiling height. Hence, the front portion of a room where the window is located gets illuminated while the rear of the room does not receive adequate daylight level. This condition caused visual discomfort to the occupants as there is a huge contrast in the uniformity level across the room from the opening to the rear portion of the room.

III. Limited plenum space for light pipe integration.

HLP is a more suitable light distribution system in a high-rise building compared to other strategies such as atrium, VLP and light shelves. Atrium and VLP's installation require large floor area while light shelves have limited daylight penetration depth. HLP is a light distribution system that functions to transport natural daylight from the perimeter to the interior through internal reflection. Many previous studies used a rectangular-shaped transporter which is placed at the plenum area above the ceiling. The transporter occupies a certain portion of the ceiling which causes obstruction for electrical wiring and air conditioning ductings. Furthermore, Edmonds (2010) pointed that for a vertical LP with the shape of circle, hexagon, square, 45^{o} and 60^{o} triangle, there were differences in their efficiency of transporting daylight. However, there are no research for the HLP on these shapes.

1.2. Research Questions

This thesis will address these few questions with regards to daylighting in deep open-plan high-rise building in tropical climate.

1. What is the current lighting condition of deep open-plan high-rise office building in tropical climate?
2. How is the daylighting performance of a typical LP?
3. What is the optimal transporter shape of a light pipe in a deep open-plan, high-rise office building in terms of daylight quantity and distribution?
4. What is the optimal number of openings in a LP's transporter to provide a good daylight distribution?

1.3. Research Aim and Objectives

The aim of this thesis is to propose an efficient horizontal daylighting in a south facing deep open-plan high-rise office in a tropical region, specifically in Malaysia with the use of LP. It is achieved through the following objectives:

1. To investigate and evaluate the current daylighting issues and daylighting distribution system in deep open-plan high-rise office.
2. To assess and compare the efficiency of various LP transporter shapes with a typical LP design.
3. To evaluate the impact of numbers of openings in a LP's transporter on daylight uniformity and quantitative performance.
4. To propose LP design recommendations for daylighting in high-rise office building in the tropics.

1.4. Research Hypothesis

A LP performance can be optimised by using the most efficient transporter shape as well as numbers of openings along the transporter. The optimised LP should be able to illuminate the deepest portion of the deep open-plan office room while maintaining the uniformity of the daylight distribution as shown in Figure 1.1. This creates more usable space in the office and reduce the need of artificial lighting.

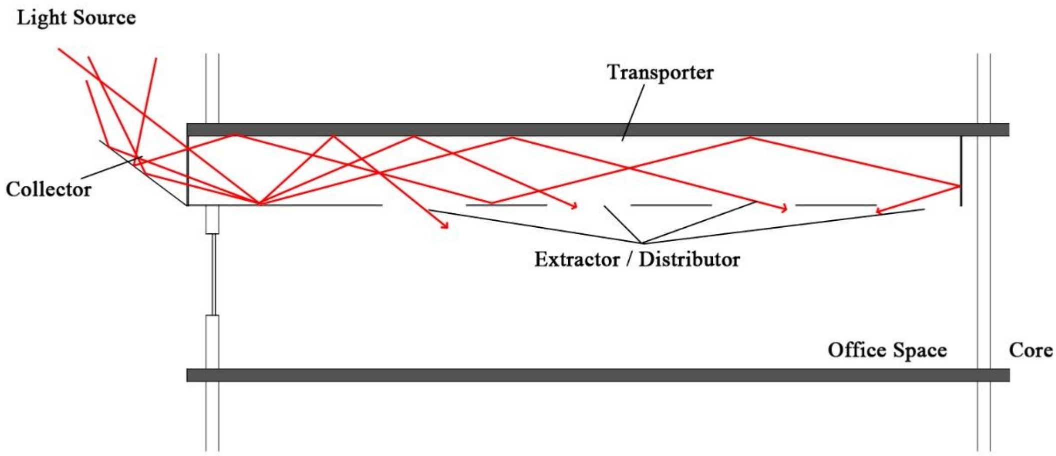

Figure 1.1: Illustration on the function of distribution of light pipe

1.5. Research Gap

Previous studies on daylight and its distribution in buildings had largely focussed on shallow plan building and based on non-tropical climate. Studies on daylight distribution by Gupta *et al.* (2001), Canziani *et al.* (2004), Koshel *et al.* (2005), Baroncini *et al.* (2010), Hansen *et al.* (2009), Edmonds (2010) and Boccia *et al.* (2012) were done in a temperate and Mediterranean climate. Tropical climate has different characteristics comparing to a temperate climate. Further explanation is given in Section 2.2. The same scenario applies through the use of computer simulation.

Although it provides an effective way to gauge the lighting performance, the sky model used in this software usually do not account to a tropical climate's data but deployed most temperate climatic data. Besides that, the building depth used in most of the LP research only reached up to 6m (Chirarattananon *et al.*, 2000; Paroncini *et al.*, 2007; Baroncini *et al.*, 2010; Boccia *et al.*, 2012; Malet-Damour *et al.*, 2014; Toledo *et al.*, 2016). Although there was few research that reached more than 6m (Canziani *et al.*, 2004; Li *et al.*, 2010), they were conducted in a temperate climatic location.

LP is one of the light transport system to distribute daylight into interior spaces in a building. HLP offers a more feasible option to be used in a high-rise building than a VLP as explained in Section 2.5.2.2. Studies have been done on the collector and the extractor (Hansen *et al.*, 2003, Hansen *et al.*, 2009, Linhart *et al.*, 2010) with the use of various technology such as laser cut panels. Other research is based on creating a new type of LP such as double LP (Canziani *et al.*, 2004, Baroncini *et al.*, 2010, Boccia *et al.*, 2012). Other than that, although some research has been done on the shape of the transporter, they are limited to a vertical system and mathematical prediction (Gupta *et al.*, 2001, Koshel *et al.*, 2005, Edmonds, 2010). Previous study on the comparison of LP's transporter has only involves a VLP where shapes such as circle, hexagon, square, 45º and 60º triangle were tested on their efficiency. There are no studies on the HLP with regards to this variable. The usage of different shapes on the LP's transporter can provide the opportunity to reduce the material needed to construct the LP while having the same efficiency. Table 1.1 shows a summary of previous studies in tropical region that are related to LP while Table 1.2 and 1.3 show the past studies on LP in the last 10 years.

Table 1.1: Previous research on LP studies in tropical climate

Author(s)	Climate		Light Pipe (Component)			Light Pipe		Area of Research				Method		
	Tropics	Temperate	Collector	Transporter	Extractor	Horizontal	Vertical	Daylight Effeciency	Costing	Energy	Thermal	Experiment	Calculation	Simulation
Hansen et. al., 2001	●		●		●	●		●				●		
Hansen et. al., 2003	●	●	●		●	●	●	●				●	●	
Chirarattananon et. al., 2000	●			●		●		●			●	●	●	
Taengchum et. al., 2013	●		●	●			●	●			●	●	●	
Linhart et. al., 2010	●		●	●	●	●		●		●		●		●
Wu et. al., 2012	●						●	●				●		
Taengchum et. al., 2014	●		●				●	●				●	●	●
Present Research	✓			✓		✓		✓				✓		✓

Table 1.2: Previous research on LP studies in the last 10 years in temperate climate

Author(s)	Climate		Light Pipe (Component)			Light Pipe		Area of Research				Method		
	Tropics	Temperate	Collector	Transporter	Extractor	Horizontal	Vertical	Daylight Effeciency	Costing	Energy	Thermal	Experiment	Calculation	Simulation
Luz et. al., 2014		●					●	●				●		●
Vasilakopoulou et. al., 2014		●					●	●		●			●	●
Hansen et. al., 2015		●	●				●	●				●		
Kennedy, et. al., 2015		●		●			●	●				●		
Toledo et. al., 2016		●			●		●	●				●		
Shin et. al., 2012		●					●	●		●			●	
Sikula et. al., 2014		●		●			●				●			●
Singh et. al., 2013		●	●	●	●	●	●	●		●		●		
Gil-Martín, et. al., 2014		●		●		●		●				●	●	
Mayhoub et. al., 2011		●	●			●	●		●				●	
Present Research	✓			✓		✓		✓				✓		✓

Table 1.3: Previous research on LP studies in the last 10 years in temperate climate

Author(s)	Climate		Light Pipe (Component)			Light Pipe		Area of Research				Method		
	Tropics	Temperate	Collector	Transporter	Extractor	Horizontal	Vertical	Daylight Effeciency	Costing	Energy	Thermal	Experiment	Calculation	Simulation
Boccia et. al., 2011		●		●			●	●			●			●
Hansen et. al., 2009		●	●				●	●				●	●	
Baroncini et. al., 2009		●		●			●	●				●		
Li et. al., 2010		●					●	●		●		●	●	
Edmonds, 2010		●		●			●	●					●	
Paroncini et. al., 2007		●	●		●		●	●				●		
Rosemann et. al., 2008		●		●		●			●			●		
Swift, 2009		●		●			●	●					●	
Swift et. al., 2008		●		●			●	●				●	●	
Toledo et. al., 2014		●	●		●		●	●		●		●	●	
Malet-Damour et. al., 2013		●					●	●				●		●
Present Research	✓			✓		✓		✓				✓		✓

Edmonds *et al.* (1997) and Hansen *et al.* (2001) demonstrated that addition of another 3 openings at the LP's transporter helped to increase the uniformity of daylight distribution in the room. They showed that the added extraction points can 'divide' the captured daylight in the LP and then disseminated along the transporter. However, there were limited research on the effect of numbers of openings on the daylight distribution performance of a LP. Therefore, there is a need to understand the relationship between the number of openings and the efficiency in providing a uniform daylight distribution.

This study focuses on the daylighting performance in a south facing deep open-plan high-rise office building using different LP transporter shapes and also the number of openings.

1.6. Research Scope and Limitations

The scope of this study covers only for a typical high-rise office building with open-plan. Other spaces with different functions such as cubicle or partitioned office space, pantry and washrooms are not included in this study. Furthermore, the open-plan spaces used in this research does not include the presence of furniture and occupants due to the numerous possibility of space arrangements. Hence, the outcome represents a reference for a simple open-plan without the consideration of the reflectance and light obstruction of these elements.

This study only focuses on the daylight performance of the office room. Although there are a number of criteria that constitute the working environment, they are not included in this study due to the limitation of time. These criteria comprise of energy consumption or savings (lighting and cooling), cost of daylighting system and installation and users' responses (psychological and physiological benefits).

The whole design of this study is based on a tropical climate specifically in Malaysia, where it has a hot and humid weather throughout the year. The sky type used is an intermediate sky with sun and is being applied throughout the research. The dates used for this study are also limited to 21 March, 22 June and 22 December which represents the most critical angle of the sun path. During the two latter dates, the sun is positioned at the furthest point from the equator during solstices. Besides that, due to identical sun position on 21 March and 23 September, where the sun is closest to the equator, only the former date is used.

The experiments and simulations used south orientation as a research scope throughout the study. It was chosen due to the position of the chosen location, Johor Bahru, Malaysia, which is located above the Equator line and thus, receiving more daylight due to the sun angle. This corresponded to a statement by Edmonds *et al.* (1997) where, for a southern hemisphere location, the author suggested a North facing placement of daylight collimation device's opening instead of south. Furthermore, as this study involved horizontal, one-sided daylight transport system, placing the collection point towards south allows a daylong direct illumination from the Sun. The West and East orientation only will respectively illuminate the test room for either in the afternoon or morning.

The focus of this study is on the shape of the LP's transporter and the number of openings along the transporter. Therefore, other variables of the LP such as the collector and surface reflectivity were kept constant throughout the study. The extraction point of this LP study only used a simple opening as a mean to distribute the daylight more evenly across the office room. Although there were methods done by other researchers where system such as placing a 45^{o} acrylic plastic right above the extraction point, these measures required additional device with complex calculation and additional costing (Edmonds *et al.*, 1997; Hansen *et al.*, 2001). Besides that, the shapes selection for the LP's transporter was based on geometry with increasing numbers of sides which have symmetrical and congruent identity, i.e. the cross section of the shape has a similar reflection on any side into an image of itself. These shapes presented cross-sections which were suitable for different installation conditions and needs. They also served as a comparison to other researchers' result on similar symmetrical, congruent geometry.

This study utilised computer simulation results as the main data collection for the whole research. Physical measurable quantities like illuminance and daylight factor were used for further analysis and discussions. Real office workers are not employed to determine the human response on the research subject and thus, should be appreciated as a major limitation.

1.7. Significance of Research

This study helps in creating an efficient daylighting distribution in a deep open-plan office in a high-rise building in tropical climate by exploring the shape of transporter as well as the number of openings. The integration of LP increases the uniformity across the deep open-plan office and thus, creates a better visual comfort for the users. The variation of numbers of openings on the LP's transporter also helps to produce better daylight distribution performance across the room.

The study also creates options through the use of alternative LP shapes. This eases the integration into existing buildings through retrofitting and also new buildings where it curbs the problem of space limitation in the plenum. It also saves space by enabling integration of LP's transporter with the existing electrical wiring and air-conditioning ducting at the plenum space. The alternative shapes of variety enable the saving of material used for constructing the LP while giving the same efficiency when comparing to the conventional rectangular-shaped LP.

The outcome from this research helps to give design recommendations and guides for building designers as well as architects on LP integration in deep open-plan high-rise office buildings.

1.8. Thesis Organisation

This thesis is divided into five chapters as shown in Figure 1.2. **Chapter One** highlights the main issue of this study. It also discusses on the research aim and objectives, research questions, research gaps together with the scope and limitation of this study. The significance and the organisation of this research are shown here too.

Chapter Two summarises previous studies on daylighting in architecture and energy conservation in building while reviewing the impact of daylight towards human. The daylight characteristics in tropical climate, especially in Malaysia are also reviewed in this chapter alongside with the characteristics of high-rise office building. Besides that, a review on daylight distribution system which consists of light guide system and light transport system are discussed in this chapter.

Chapter Three confers the methodology used in previous as well as this study. It also explains the credibility and feasibility of the method used. All the settings in the simulation software, physical scaled model, criteria of analysis and performance indicators are stated in this chapter.

Chapter Four presents the results, analysis and findings of the research. It is divided into two sections: LP transporter shapes and numbers of openings. The quantitative and qualitative performance are analysed where the former is based on daylight factor and daylight ratio which is then converted to an estimated illuminance and while the latter is based on work plane illuminance ratio.

Chapter Five summarises the overall research objectives and findings. Several recommendations and suggestions for further research are also presented.

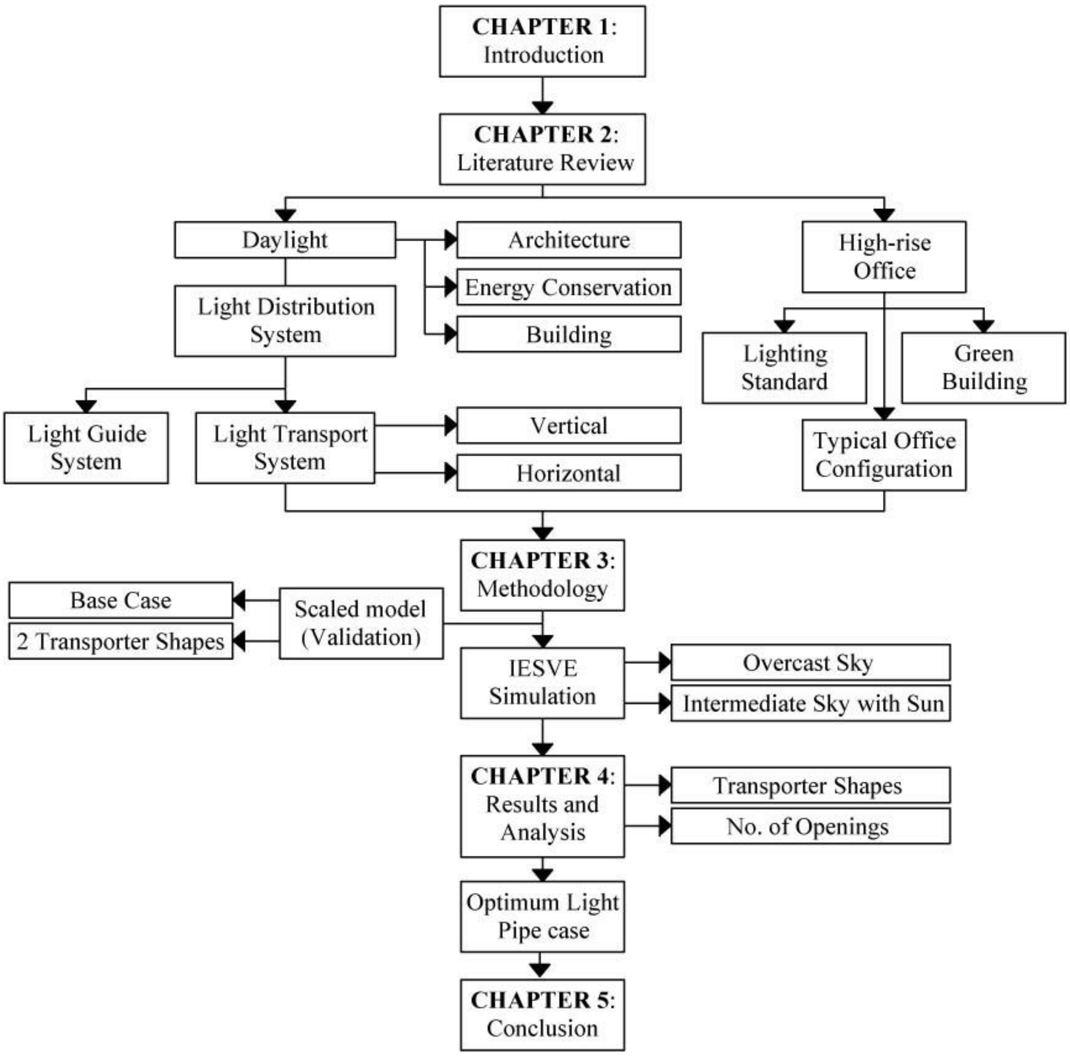

Figure 1.2: Research flow and thesis organisation

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