THE EFFECT OF WINDOW DESIGN ON DAYLIGHTING AND THERMAL PERFORMANCE OF CLASSROOMS IN PENANG, MALAYSIA

NAJIB TAHER AHMED AL-ASHWAL

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by

NAJIB TAHER AHMED AL-ASHWAL

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABC	Awareness & Building Capacity
ASE	Annual Sun Exposure
ASEAN	Association of South-East Asian Nations
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
BREEAM	Building Research Establishment Environmental Assessment Method
CDD	Cooling Degree-Days
CETDEM	Center for Environment, Technology, and Development, Malaysia
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institution of Building Services Engineers
CIE	Standard Overcast Sky
COHSR	Canada Occupational Health and Safety Regulations
DA	Daylight Autonomy
DDC	Demonstration & Documentation Centre
DF	Daylight Factor
DOE	Department of Energy
ERC	Externally Reflected Components
GDDM	Graphic Daylighting Design Method
HDD	Heating Degree-Days
HVAC	Heating, Ventilation, And Air Conditioning
IESNA	Illuminating Engineering Society of North America
IGDB	The International Glazing Database
IR	Infrared
IWEC	International Weather for Energy Calculations

IES-VE	Integrated Environmental Solution
JKR	Jabatan Kerja Raya
LBNL	Lawrence Berkeley National Laboratory
lx	Lux
MEIH	Malaysia Energy Information Hub
MS	Malaysia Standard
NI	Nebulosity Index
PWD	Public Works Department
RI	Room Index
SAD	Seasonal Affective Disorder
SC	Shading Coefficient
SHGC	Solar Heat Gain Coefficient
SMK	Sekolah Menengah Kebangsaan
SSEEAP	Secondary School Energy Efficiency Action Project
TMY	Typical Meteorological Year
T_{vis}/VT	The Visible Light Transmittance
UDI	Useful Daylight Illuminance
USM	Universiti Sains Malaysia
UV	Ultraviolet
WCPJ	Working with the Community in Petaling Jaya
WFR	Window to Floor Area Ratio
WPI	work Plane Illuminance
WWR	Window-To-Wall Ratio

KESAN REKA BENTUK TINGKAP TERHADAP PRESTASI PENCAHAYAAN SIANG DAN BEBAN TERMA DI DALAM BILIK DARJAH DI PULAU PINANG, MALAYSIA

ABSTRAK

Kualiti persekitaran tertutup melibatkan keadaan pencahayaan adalah penting dalam ruang bilik darjah kerana ia memberi kesan langsung kepada prestasi dan produktiviti pelajar. Pencahayaan semulajadi merupakan sumber cahaya terbaik dari perspektif visual dan estetik dan pandangan kecekapan tenaga. Keberkesanan cahaya pada waktu siang hari di Malaysia sangat baik dan ia dapat memenuhi keperluan pencahayaan pada waktu siang di dalam bilik darjah. Walau bagaimanapun, lampu sentiasa dihidrpkan sepanjang hari dan hanya dimatikan semasa waktu rehat dan apabila tamat sesi persekolahan. Kajian ini menyiasat kesan elemen reka bentuk tingkap terhadap prestasi pencahayaan pada waktu siang dan beban terma di bilik darjah di sekolah menengah kebangsaan di Pulau Pinang, Malaysia. Kajian ini terbahagi kepada dua fasa. Fasa pertama ialah fasa lapangan, yang bertujuan menilai prestasi pencahayaan di bilik darjah sekolah menengah di Pulau Pinang melalui kaedah pengukuran tahap pencahayaan di dalam bilik darjah yang diperiksa. Hasilnya kajian mendapati lebih banyak cahaya siang diterima di kebanyakan bilik darjah kerana reka bentuk tingkap pada bilik darjah yang agak besar dengan bahan binaan kaca yang jelas. Purata pencahayaan hasil dari pengukuran adalah antara 400 lux lebih daripada 1000 lux dan lebih tinggi daripada nilai yang disyorkan piawai. Faktor purata penggunaan lampu pada waktu siang yang direkodkan dalam bilik darjah adalah antara 6.4 dan 9.2% pada kebanyakan masa. Nilai-nilai ini agak tinggi dan boleh menyebabkan masalah silau. Fasa kedua melibatkan pemodelan dan

simulasi menggunakan *Design-Builder* ke atas kesemua jenis bilik darjah di sekolah menengah di Pulau Pinang. Penilaian ini termasuk elemen reka bentuk tingkap yang dipilih, seperti saiz tingkap, jenis kaca, dan ketinggian tingkap. Hasil penemuan mendapati bahawa setiap elemen reka bentuk tingkap mempunyai tahap pengaruh yang berbeza terhadap prestasi pencahayaan siang dan beban terma. Walau bagaimanapun, perbezaan gabungan elemen tingkap yang diperiksa telah dinilai. Oleh itu, cadangan telah dikemukakan bagi menjadi panduan dan rujukan kepada arkitek dan pereka untuk memilih reka bentuk tingkap yang sesuai untuk mencapai prestasi pencahayaan yang cekap, mengurangkan beban terma, dan mengurangkan penggunaan tenaga lampu. Ia diilustrasikan dalam tiga alternatif yang dapat membantu pereka untuk menilai elemen reka bentuk tetingkap semasa peringkat awal reka bentuk bangunan. Ia dibentangkan dalam betuk satu set data jadual, carta grafik serta perisian di laman web.

THE EFFECT OF WINDOW DESIGN ON DAYLIGHTING AND THERMAL PERFORMANCE OF CLASSROOMS IN PENANG, MALAYSIA

ABSTRACT

The quality of the indoor environment including the lighting conditions is crucial in classrooms as it directly affects students' performance and productivity. Natural light is the best source of light from visual and aesthetic perspectives and energy efficiency views. The luminous efficacy of daylight in Malaysia is excellent and could meet most of the required luminance during the day. However, in Malaysian schools, it was found that all the lights are switched on throughout the day and only be off during break time and at the end of the day. Besides, most of the classrooms in Malaysia, in schools or higher institutions, daylighting is not efficiently utilised. This study investigates the impact of window design elements on the daylighting performance and thermal load in classrooms in national high schools in Penang, Malaysia. The study is divided into two phases. First, the fieldwork phase, which aims at evaluating daylighting performance in high schools' classrooms in Penang through measuring incident illumination levels inside the examined classrooms. The results revealed that more than enough daylight is provided in most classrooms because of the relatively large classrooms' windows with clear glass. The average illuminance found from these measurements is between 400 lux more than 1000 lux which is higher than by the standards recommended value. The average daylight factor recorded in the classrooms is between 6.4 and 9.2% in most of the times. These values are relatively high and may result in glare problems. The second phase includes the modelling and simulation using Design-Builder for a typical classroom in the high schools in Penang. This evaluation includes selected window design elements, i.e., window size, glazing type, and window-sill height. The Findings show that each window design element has a different level of influence on the daylighting performance and thermal load. However, a different combination of the examined window elements was evaluated. Accordingly, recommendations were proposed to guide architects and designers to properly select specific elements of designing windows to achieve efficient daylighting performance, to decrease the thermal load, and to reduce the lighting energy consumption. They are illustrated in three alternatives to assist designers to evaluate the proposed window design elements during the early stage of building design. They are presented in a set of data in a table, graphical charts, as well as the researcher, developed software on a website (https://objective-shockley-d19b75.netlify.com/).

CHAPTER 1

INTRODUCTION

1.1 Background

Light gives life to the form, to the pattern, to the void and solid. Architecture forms the spaces' shapes for daily activities in the shape of the void and solid, as well as the pattern, and form. For many years throughout human history, natural lighting has always been an efficient light source, and thus it was difficult to perform visual tasks during night-time or cloudy days. This indicates that the basic lighting condition is required to do various visual tasks. Human beings, therefore, searched for alternatives to light sources other than natural lighting to provide the required lighting conditions. Nowadays, daylight is not the only source of light. The electric lighting fixtures were significantly developed and working hours have become longer.

It was essential to making proper daylighting designs before the existence of artificial lighting. Because of the shortage of daylight in northern Europe, especially in winter, large windows, as well as high ceilings have been used so that adequate natural lighting is provided into interior spaces. Various designs of windows were implemented in southern countries to reduce the heat gain in summer and to provide enough natural lighting. According to previous studies, it was found that when a courtyard is incorporated into a building, this will provide appropriate solutions to solve the problem of internal spaces' daylight (Phillips, 2004).

In the 20th century, architectural styles have been developed and at the same time maintaining the traditional design for daylight. However, the environmental aspects and energy conservation were not considered during the design process. Daylighting design was noticeably disregarded due to the wide use of low-cost fluorescent lamps. Many buildings were found to be poorly designed for daylighting, particularly between 1945 and 1975, when compared with historical buildings (Baker et al., 2013).

Around the turn of the 20th century, awareness towards daylight designs has been increased with the great influence of remarkable architects such as Frank Lloyd Wright, le Corbusier, Louis Kahn, and Louis Sullivan. These architects tried to integrate daylighting designs with the buildings' aesthetic values and functional requirements (Mazharuddin, 2000). Currently, many books, articles, and methods have been produced concerning the efficient utilization of natural light from the visual and aesthetic aspects, as well as energy efficiency views (Phillips, 2004).

It has become obvious from observations based on human behaviours that working and living space arrangement and research studies indicated that natural lighting is desirable by building occupants. Windows are important in buildings not only to provide adequate natural lighting but also to maintain a connection with the outside view. The quality, variability and spectral composition are additional important factors to illuminate spaces with daylight. Building occupants' reactions to indoor environments were reviewed and recorded. Occupants pointed out that natural lighting is preferred to fulfil two basic human visual needs. The first is the ability to perform a visual task and see the space well, whereas the second is to gain some environmental stimulation. People admitted that health is highly affected by long-term working under artificial lighting. They believed that less stress and discomfort are major advantages of working in a space illuminated mainly with natural lighting (Hwang & Kim, 2011).

Daylighting can be defined as the method at which admission of natural light—direct sunlight and diffuse skylight—into a building space to replace or supplement artificial lighting is controlled. Daylighting creates an environment that is visually stimulating, as well as productive for the occupants and at the same time reduces the energy consumption of the building.

A daylighting system can be more efficient when daylight openings like skylights, as well as windows, are equipped with a lighting control system that is daylight-responsive. The lighting control system is capable to reduce artificial lighting power when there is sufficient natural lighting in the ambient environment. This can be done either by switching off the whole electric lightings or part of them. An efficient integration between the system of artificial lighting, as well as daylight, takes place if the artificial system is switched on or switched off as a function of daylighting levels' function that reaches the spaces' working surface.

In addition, window design elements have to be designed and considered at the early stage of the design process to allow adequate and sufficient natural lighting and also to avoid the admittance of excessive heat gain and direct glare. Larger windows permit more daylight in spaces and, thus, using artificial lighting is reduced. However, larger glazed areas allow extreme heat gain or loss in the building. This increases the heating load and energy consumption as a result. Small windows would result in lower heat gain or loss. However, artificial lighting might be used throughout working days to provide the desired luminance level on working surfaces. Accordingly, designing windows to strike a balance between the lighting design, as well as the consumed energy through artificial lighting that is associated with heat gain represents the best scenario.

Based on previous studies, it was found that daylight proper utilization has enhanced students' performance, as well as their mood. Also, it has increased the teachers', and the students' attendance. It has reduced the energy consumption level and inflicted a positive environmental effect. It was reported that the students', as well as the teachers' attendance, were enhanced and the achievement rates were increased. It was also reported that fatigue factors were reduced, students' health was enhanced in addition to general development. Noise, as well as flickering that is caused by electric light, are reduced via natural lighting. Quality light can be provided by using natural light in classrooms and gymnasiums, as well as corridors at schools. Students tend to behave in a more hostile way in classrooms, which do not have windows. They are hesitant, disturbed, less interested in their classwork, and they always complain (Edwards & Torcellini, 2002).

With this list of benefits, it was found that enhancing daylight in classrooms is design preference and no responsibility and, therefore, it is important to focus on daylighting when the school project starts. This includes proper designs and window design elements, i.e., window area, glazing type, window configuration, and shading devices. It is easy to locate a school with daylight performance, as well as levels of energy efficiency that are below and/or above the specified requirements. This can be attributed to inadequate architectural standards and unsuitable designs. In Malaysian schools, It was found that all the lights are switched on throughout the day and only be off during break time and at the end of the day according to daily basis activity.

There exist various reasons justifying that daylight is very useful. It is a light source in many kinds of buildings and the learning environment, in particular. The strong reason for choosing natural light is because of the quality of light is far better than any electrical lighting to be used as a task lighting for reading and writing purposes. The luminous efficacy of daylight in Malaysia is excellent and could meet most of the required luminance during the day (Zain-Ahmed, Sopian, Othman, et al., 2002).

The energy consumption of five secondary schools in Kuala Lumpur in 2009 is illustrated in Figure 1.1. The study conducted by the Secondary School Energy Efficiency Action Project (SSEEAP). SSEEAP is a 12 months project managed by Center for Environment, Technology, and Development, Malaysia (CETDEM). CETDEM is the only Malaysian NGO that has done such studies, through the Demonstration & Documentation Centre for Sustainable Energy Solutions for Urban Households (DDC), Increasing Awareness & Building Capacity of Urban Malaysians on Sustainable Energy Options (ABC) and Working with the Community on Energy Efficiency at Household Level in Petaling Jaya (WCPJ) Projects (SSEEAP, 2009). The project generally aimed to encourage the students of the secondary school, as well as the teachers to decrease energy consumption levels to cut greenhouse gas emission through saving energy and implementing energy-efficient measures in the schools. It was found that the air condition system consumed the highest amount of energy (35%), followed by artificial lighting (30%).

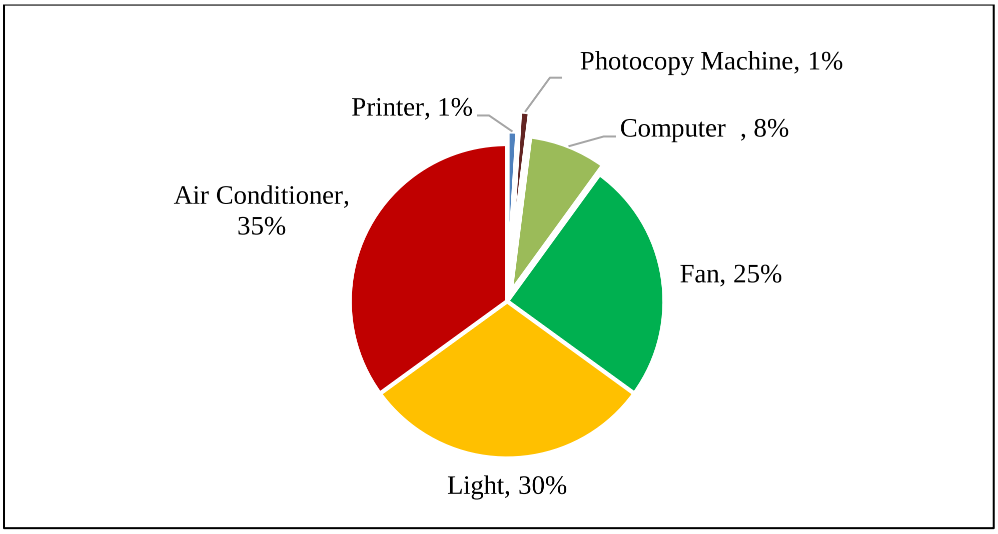

Figure 1.1 Energy consumption breakdown in Malaysian schools

Source: (SSEEAP, 2009)

1.2 Problem Statement

It is reported that the effective use of daylight can enhance students' performance, as well as their mood. Additionally, it increases the attendance of teachers and students. Quality light can be provided by using natural light in classrooms and gymnasiums, as well as corridors at schools. (Edwards & Torcellini, 2002).

According to Zain-Ahmed, Sopian, Zainol Abidin, et al. (2002), the luminous efficacy of daylight in Malaysia is excellent and could meet most of the required luminance during the day, However, in Malaysian schools, It was found that all the lights are switched on throughout the day and only be off during break time and at the end of the day according to daily basis activity (Mathalamuthu & Ibrahim, 2014). This might be due to the use of curtains in classrooms to reduce heat gain and avoid glare resulted from the large windows. Additionally, most of the classrooms in Malaysia, in schools or higher institutions, daylighting is not efficiently utilised and more natural light is admitted. Illuminance results higher than the recommended values were found and ununiform daylight distribution was recorded.

It is reported that about 20-30% of total electricity consumption in educational buildings in Malaysia is related to lighting (SSEEAP, 2009; Tang & Chin, 2013). The efficient use of daylight can result in about 10%-14% reduction in energy consumption (Ossen et al., 2005; Zain-Ahmed, Sopian, Othman, et al., 2002). There has been a growing concern towards sustainable and green building design during the last decades. As a result, several measures and strategies have been developed for passive energy conservation in buildings. Daylight integration is one of these strategies. If effectively used, it provides natural lighting and reduces lighting energy consumption.

Larger windows allow more daylight in spaces and, thus, using artificial lighting is reduced. However, larger glazed areas result in more heat gain or loss. Small windows would result in lower heat gain. However, artificial lighting might be used throughout working days to provide the desired luminance level on working surfaces. Accordingly, the best scenario is to specify windows where there is a balance between the lighting requirements and heat gain through windows.

However, architects and building engineers experience various problems when designing windows such as lack of evaluation tools, insufficient analysis of building performance, misuse of windows. Another major problem is related to simulation tools. These tools are complex and difficult to use. Hence, the main objective of this research is to provide architects and engineers with guidelines and recommendations to assist in window design in the classroom for daylighting and energy efficiency.

1.3 Research Objectives

The main objective of this research is to assess the daylighting performance and thermal performance of window design elements in a classroom in schools due to the integration of daylight supplied with artificial lighting based on a tropical climate, using building energy simulation program Design-Builder to achieve the main objectives of the study which are listed below:

1) To investigate the daylighting performance in classrooms with the existing window design elements.
2) To investigate the effect of different window design elements on daylighting performance and thermal load.
3) To develop guidelines to assist architects/designers to select window design elements to optimize daylighting performance and reduce thermal load.

1.4 Research Questions

The research questions of this study are as follows:

A) Objective 1:

1) How is the daylighting performance in terms of illumination level and daylight factor in classrooms with the existing windows?

B) Objective 2:

1) How do basic window elements, (window size, window’s sill height and glazing type), affect indoor lighting conditions; and how each element affects in average daylight factor and illumination level?

2) How do window size, window’s sill height and glazing type affect space thermal performance; Particularly, how each element affects to reduce direct heat gain, cooling load and lighting energy consumption?
3) What are important elements of a window which have a significant contribution to indoor lighting conditions?

C) Objective 3:

1) What recommendations and guidelines can be made for window design elements selection and their daylighting performance as well as reduce direct solar heat gain and thermal load?

1.5 Significance of the Study

Energy-saving, which results from daylight does not lower the expenditure of electric lighting and reduces the peak electrical demand only but also it lowers the cooling energy levels of consumption. It can be the potential for small plants of air conditioning (Li & Lam, 2001). The primary significance of this research is the development of guidelines which can help in determining window properties and design factors for better thermal and daylight performance in the classroom.

In summary, this research expects to be significant concerning daylight and thermal performance in the classroom in schools in the following ways:

1. It will provide information about the current daylighting performance in the classroom in Penang, Malaysia and consequently provide an objective assessment to improve the lighting conditions for the students and teachers.

2. It will provide useful information about the initial prediction of daylighting performance and expected energy savings due to the integration of daylight with artificial lighting.
3. Developed design recommendations can be useful for architects/designers in their decision making during the schematic design process.
4. It contributes to the existing research about the analysis of daylight, as well as building energy applications using building energy simulation program Design-Builder. It also formulates specific recommendations on the daylighting techniques' efficiency.
5. Since the lighting and daylighting strategies are one of the major aspects in Green Building Index (GBI), this study is significant towards the application of green buildings in Malaysia which is currently an important issue and highly considered from all level in Malaysian society.

1.6 Scope and Limitations

The scope of this study is limited to the school classrooms in Malaysia that experience to the tropical climate, low-latitude locations where there is mostly no heating period all year, particularly in the city of Penang. This study is limited to studying daylight as the integration impact of daylight, as well as the impact of the artificial lighting on the daylighting performance in addition to the heat gain and lighting's energy consumption, are investigated. This study addresses the design of a window in the recessed exterior wall of the classroom. Moreover, window design elements including window size, glazing properties, and window-sill will be the main factors that will be evaluated in this research. This study is conducted during the dry season and not in rainy or mansion season where the sky outdoor illuminance level, solar radiation and outdoor temperature are significantly different. Therefore, the different cases of study during fieldwork which need to be measured in different days corresponding to slightly different weather conditions. Besides, the fieldwork is conducted during 19-23 March 2018 because it is a school holiday so that preparation and record measurements can be done without any interruption from students. This study focuses on typical classroom based on JKR school drawings. The rectangular shape of the window with different sizes is addressed in this study. This research will not attempt to evaluate window performance in aspects other than thermal and daylighting performance.

1.7 Research Framework

To accomplish the study objectives, a research framework is placed including the following phases and illustrated in Figure 1.2:

Phase One: A comprehensive literature review will be conducted to cover different aspect related to daylighting performance. This includes daylighting background, availability of daylight, the importance of daylight, and its impact on schools' occupants. In addition, this part of the study addresses daylighting and energy efficiency in buildings, window design parameters and their influence on lighting conditions and energy performance. An overview of simulation programs is provided and the selection procedure of the software that will be used for the simulation process.

Phase Two: Field measurements are conducted in selected classrooms in high schools in Penang to investigate the current daylighting performance inside the classrooms. The illumination level is recorded in different points on the working plane inside the classroom.

Phase Three: a computer simulation is conducted to investigate the impact of various window design elements on daylighting performance and thermal loads. This includes the size of the window, glazing type, and window-sill height. Daylighting performance variables includes illuminance, average daylight factor, and annual daylighting performance. Recommendations are placed to provide better indoor lighting conditions inside the classroom through the selection of proper window design elements.

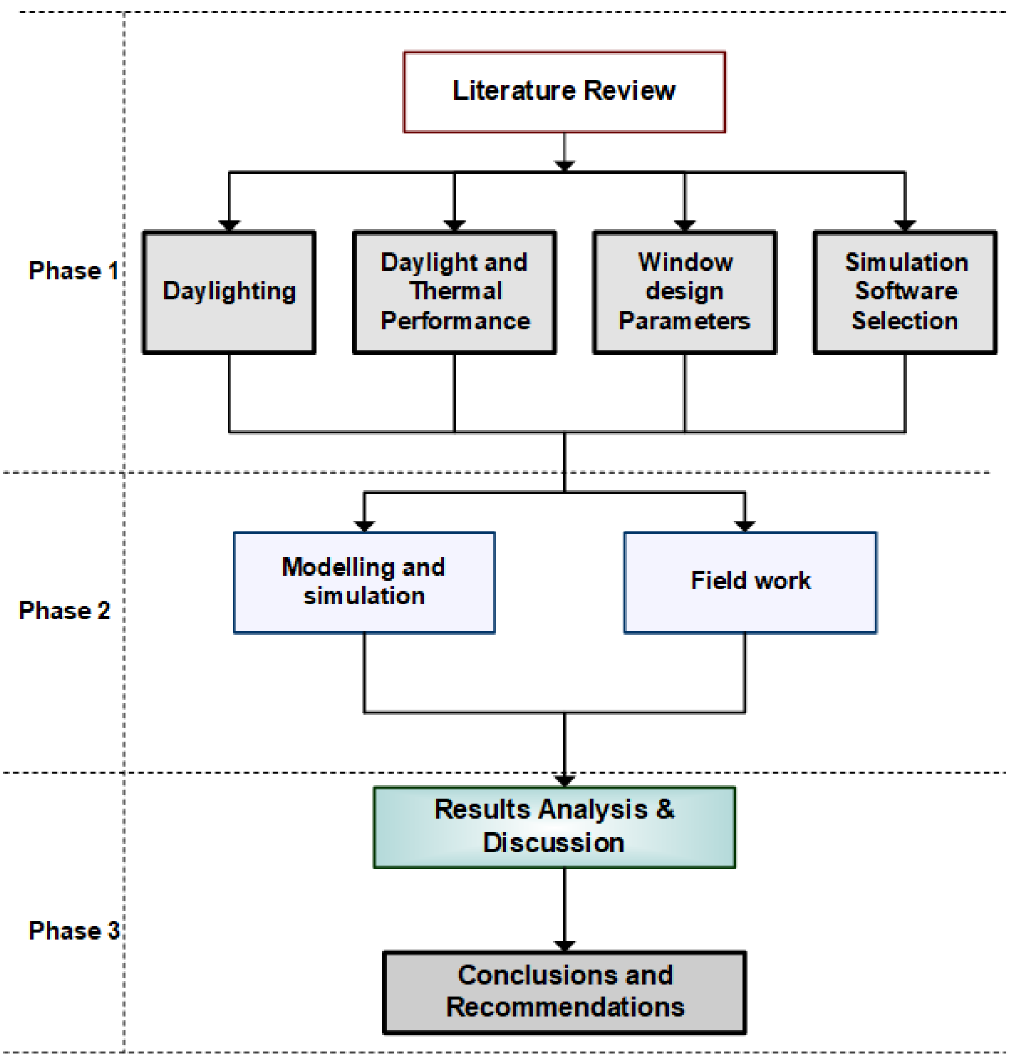

Figure 1.2 Research Framework

1.8 Organization of the Study

The study falls into five chapters. **Chapter 1** introduces the topic of the current study. It includes the background of the study, the statement of the problem, the objectives, as well as the research questions of the study. The chapter includes the scope and limitations of the study, the research framework, and the organization of the study.

Chapter 2 reviews previous studies that were conducted in the area, which formulated the key basis for developing this study. The chapter also discusses the building daylighting performance basic principles and an assessment of the impact of the window components on daylighting performance and thermal performance. Daylighting strategies and lighting control systems are also addressed in this chapter.

Chapter 3 presents and discusses the methodology, which is used in the study. It presents the fieldwork process and the selection of the simulation software for modelling. The chapter outlines the study simulation scheme for the analysis.

Chapter 4 presents and analyze the results of the fieldwork in term of daylighting performance. It explains the simulation results for different window design parameters. This includes daylighting performance results as well as lighting energy consumption and solar heat gain.

Chapter 5 answer the research objectives regarding the research results and presents general design recommendations for window design to improve daylighting performance and at the same time reduce solar heat gain, thermal load and lighting energy consumption.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The design of buildings to provide acceptable indoor lighting conditions must begin with an understanding of the main concept of daylighting, light and lighting design strategies. Furthermore, the factors which influence daylighting performance and thermal loads need to be carefully considered at the early stage of the design of buildings, especially educational buildings. This is related to the importance of lighting conditions in this kind of buildings to perform the visual task of writing and reading mostly during daytime. This literature review includes an overview of basic daylight principles, the historical background of daylight, the importance of daylight and the effect of daylight on occupants' health, productivity, and performance. This chapter covers also the impact of the integration of daylighting with artificial lighting on energy and thermal performance as well as the effect of window design elements on energy performance. Based on previous studies that investigated different properties of daylighting design components and related research, which investigated different options aiming at enhancing indoor lighting conditions in various buildings in the hot humid climate of South Asian countries is summarized in this part of the study.

2.2 Definition of Key Terms

Many scientific terms are used in this study. The definitions of the main terms are illustrated in this section.

2.2.1 Daylighting Performance

Daylighting can be defined as the practice of placing windows, skylights, other openings, and reflective surfaces to provide effective internal lighting from direct and indirect sunlight (Reinhart & Weissman, 2012). The daylighting performance of a building is always assessed in terms of the daylight factor (DF), which by definition is the ratio of the internal illumination to the illumination simultaneously available on a horizontal plane from the whole of an unobstructed overcast sky, expressed as a percentage (Hopkinson et al., 1966). In addition to the illumination level and Daylight Factor, daylighting performance is assessed through daylight uniformity, annual sun exposure (ASE), daylight autonomy (DA), and useful daylight illuminance (UDI). These factors are briefly described in the following paragraphs.

2.2.1.1 Illuminance or Illumination Level

Illuminance is the total luminous flux incident on a surface, per unit area measured in lux (lx). It measures how much incident light is illuminating the surface and the wavelength that is weighted by the luminosity function to relate to the human perception of brightness (Rea, 2000).

2.2.1.2 Daylight Factor (DF)

The daylight factor approach is considered the most common method of daylight analysis is, where the diffuse internal horizontal illuminance is directly proportional to the diffuse external horizontal illuminance (Fadzil et al., 2015; Hopkinson et al., 1966). Daylight factor is the Illumination level ratio in a specific space to the level of the illumination outside the building and found as follows:

$$DF = (Ei / Eo) \times 100\%$$

, where Ei = illuminance based on the daylight at a certain point on a working plane, Eo = simultaneous outdoor illuminance on the horizontal plane (Hopkinson et al., 1966).

To find Ei, the amount of light received from the outside to the inside of a building needs to be calculated. There are three ways by which light can penetrate to a point in a room:

- The sky component (SC) which the direct light from sky visible at the point considered.
- The external reflected component (ERC) which is the light reflected from an exterior surface and then reaching the point inside the space.
- The internal reflected component (IRC) which is the light reflected from internal surfaces such as walls, floor and ceiling.

The Illumination level (Ei) at the point inside the room is the sum of these three components (Hopkinson et al., 1966).

2.2.1.3 Daylight Uniformity

The distribution and difference daylighting levels throughout the space are called daylight uniformity. When the incident illumination level significantly diverges in space, it may cause an eye strain. CIBSE code offers some guidance on the measurement of the daylight uniformity, as well as distribution. The daylight illuminance uniformity is the minimum illuminance ratio to an average illuminance over a task area, which must not below 0.3.

2.2.1.4 Annual Sun Exposure (ASE)

It describes how much of the space receives considerable direct sunlight which can be a cause of discomfort glare and result in an excessive cooling load. It is measured by several hours where daylight illuminance exceeds the upper limit.

2.2.1.5 Daylight Autonomy (DA)

Daylight Autonomy (DA) was the first of a string of annual daylight metrics. It is commonly called ‘dynamic daylight metrics’ nowadays. It is characterized as an annual daytime hours’ percentage that a specific point in the space is above the lower level of illumination (Reinhart et al., 2007).

2.2.1.6 Useful Daylight Illuminance (UDI)

The percentage of time that space receives adequate daylight is called Useful Daylight Illuminances (UDI). It quantifies if light levels are very high and very low. The UDI draws upon three standard norms as follows (Nabil & Mardaljevic, 2006):

- Below 100lux, the daylight is insufficient.
- Within 100 lux and 2000 lux, the daylight is useful.
- Above 2000 lux, the daylight is too much and, therefore, it results in visual, as well as thermal discomfort.

2.2.2 Window Design Elements

A window is an opening in a wall, door, roof or vehicle that allows the passage of light, sound, and sometimes air. When designing windows, many elements should be considered. This includes mainly the size of the window or area of the window, the glazing type used, the height of window sill from the floor as well as the use of interior and exterior shading devices. This study focuses on the window size in terms of width and height, the glazing type and addresses the effect of the window sill height on admitted daylight and thermal loads inside the classroom. This is because they are the basic window elements that can be easily modified and adjusted and have a direct impact on daylight transmitted into space and direct heat gain through windows. If windows incorrectly designed, shadowed or oriented, unnecessary energy consumption in a building can be attained. If windows are over-dimensioned, they can contribute to the increase of the heating loads or cooling loads due to over-exposure to solar radiation. When under-dimensioned, the same space may benefit from reduced heat gain or loss through the glazing surface but does not benefit from available daylight. Therefore, it is important to find the optimum design that minimizes both the heating or cooling load and utilize available natural lighting.

Amaral et al. (2015) reviewed the literature and it is reported that researchers mainly focused on advances of window technologies. However, different results can be achieved by proposing an approach which focuses on several aspects, such as glazing type, window size, and orientation, taking into consideration that geographical location and building systems provide specific conditions (Amaral et al., 2015).

2.3 Daylight

The ancient human being did not use to have light measuring tools like our equipment today as he used to rely on his eyesight. At nighttime or on cloudy days, he could not perform his visual tasks as he used to perform his daily visual tasks on sunny days only. This indicates that he needed the basic requirements for lighting.

The man's raising awareness of the necessary lighting requirements to carry out his visual tasks has made him look for various light sources to replace sunlight. Therefore, he successfully started with fire to provide him with heat in winter, to cook food, and to provide him with light. Daylight was now not the only source of light anymore; a form of artificial light was available. Later developments like whale oil and candles were supposed to provide more photometric comfort and the possibility to work at night. In later years, the electric lamp was developed and with it, days in the built environment became longer.

2.3.1 Historical Background

Organized awareness about good daylighting practice for buildings has a very long history in Europe, and the Romans were pioneers. For example, good daylighting practice is discussed in the classical writings of Vitruvius. Above all, he stressed the importance of properly considering window orientation. However, we now have at our disposal a far wider variety of glazing materials with which to deal with daylighting tasks, what was written in Roman times still has significant relevance for today. The challenge of providing good daylighting without unnecessary heat gains in the overheated season remains while the actual techniques used for summer cooling have changed. It can be perceived that the nature of historic daylight solutions in existing Roman structures is still in use, such as the Pantheon in Rome, and the excavated residential buildings at Pompeii (Baker et al., 2013).

It is highlighted that the traditional Islamic architecture had an efficient method for merging the solids of buildings with voids of streets to create a comfortable city using daylight in the urban context (Mazharuddin, 2000).

Before the artificial lighting has become available, it was vital to get the right daylighting design. In northern Europe, shortage of daylight, especially in winter, making it necessary to provide relatively large windows and to secure good daylighting penetration by use of high ceilings and open plan forms. In the southern countries, the dominating needs to control summer overheating in conjunction with more adequate winter lighting led to very different window designs and the use of variable plan forms. The courtyard plan was found to provide very agreeable solutions. The sunlight was reflected in buildings from properly placed external surfaces, instead of being allowed to penetrate directly (Phillips, 2004).

The development of the architectural style in the 20th century was not environmental and energetically conscious. It used to connect to the daylight design's earlier traditions. The cheap fluorescent electrical lighting, which has become available, resulted in neglecting daylighting designs. Many buildings from 1945 until 1975 failed in conditions of daylighting designs in comparison with the historic solutions (Baker et al., 2013).

Around the turn of the 20th century, daylight design consciousness has arisen with the hands of the great architects le Corbusier, Louis Sullivan, Louis Kahn and notably Frank Lloyd Wright to be neither ignored nor taken on as an afterthought, but as an integral element of the functional requirement and aesthetic character of the building (Mazharuddin, 2000).

However, the international style changed with the glass boxes of the 50s, 60s, and early 70s, which were almost insensitive to the environment. These buildings created their own thermal and luminous environments fueled by the availability of substantial cheap, petroleum-based energy and seldom responded to site-specific or climatic information. The glass box began to fall apart when the energy prices increased in the early 70s. Architects and engineers tried to implement any lighting solution that would conserve energy regardless of the impact on visual performance, quality or aesthetics. By the mid-80s and to the 90s, quiet reflection based on solid research and experience took place the previous reaction. Nowadays, there is an exciting production of books, data, methods, and articles concerned with using natural light to its fullest advantages not only from an economic view but also visual and aesthetic views (Phillips, 2004).

2.3.2 Defining Daylight and Daylighting Systems

According to Baker et al. (2013), daylight is a combination of diffused skylight and sunlight. Daylight has been, for centuries, the only available efficient light source. From a historical perspective, the building openings were built to allow enough penetration of daylight into the interior space. With scientific advancements, the artificial lighting system was invented. Accordingly, designers have ignored daylighting and overlooked its significance. The rising awareness today on reducing non-renewable natural resources has directed the designers' attention towards using natural light (daylight) in building designs.

Ander (2003) indicated that the relation between people and daylight, as well as the architectural form, is an intimate relationship. Daylighting plays a key role in buildings' designs. Studies investigated the potential psychological advantages as a result of using daylight in the design of the building. Based on Baker and Steemers (2014), the system of daylighting is defined as "a device located near or in the openings of building envelope, whose primary function is to redirect a significant part of the incoming natural light flux to improve interior lighting conditions".

Nowadays, the innovative delighting systems provide daylight and user-friendly environments in addition to energy-efficient buildings.

2.4 Daylight Sources and Availability

A pattern that is predictable of the amount, as well as the direction of the available daylight, has been produced by the sun daily movement in addition to its seasonal movement regarding a specific geographic location on our planet ‘the earth’. Additionally, there exists a variation, which is resulted from weather changes, temperature changes, as well as air pollution. Moreover, 40% of the solar energy, which is received on the earth’s surface, is considered as visible radiation and 60% of the solar energy is ultraviolet (UV), as well as infrared (IR) wavelengths. All the solar radiant energy is virtually transformed to heat if it is absorbed. The amount of the usable visible energy in the solar spectrum differs according to the depth, as well as the atmosphere condition that light passes through (Rea, 2000).

2.4.1 Daylight Sources

The quantity and quality of light available for illumination in a building are determined by the regional climatic conditions. Available daylight patterns are modified by factors, such as adjacent landforms, vegetation, and structures. The varying light conditions create dramatically different perceptual environments and architectural responses. Three main resources can give daylight:

- Diffuse light via clouds or a partly cloudy sky.
- Direct sunlight via clear or a partly cloudy sky.
- Reflected light via natural, as well as surfaces that are man-made.

2.4.1.1 The Sky as a Light Source

When sunlight passes the atmosphere, part of this light is scattered by the dust and the water vapour, as well as the suspended particles. This scattering, which acts with the clouds, will produce sky luminance. Moreover, the sky falls into three types: the clear sky, the partly cloudy sky, as well as the overcast sky. When it is not totally overcast, its luminance distribution might rapidly change as the sun is alternately or partly obscured, or it can be fully revealed (Rea, 2000). In its overcast condition, the sky is, in general, the brightest element in the outdoor scene as the light, which is reflected off surfaces, has much lower levels of luminance. The illuminance in the fully overcast condition may exceed 2500 fc. The partly cloudy sky is more common. It continuously changes between direct sunlight, as well as hazy daylight. It and fluctuates in intensity and distribution, as well as colour temperature (Egan & Olgyay, 2002).

Besides, Zain-Ahmed (2000) mentioned that several sky types have been established. They are defined as follows:

- **The Uniform Sky,** this type of sky is covered with thick, milky-white clouds and an atmosphere full of dust where the sun is not visible.
- **The CIE Standard Overcast Sky**, the luminance of this sky is not uniform but varies with geometrical parameters. It is a sky with a light cloud in a clear atmosphere where the sun is not visible. The luminance of the Overcast Sky is three times more at the zenith than at the horizon. Most parts of Europe have a Standard Overcast sky. An overcast sky normally produces illumination on the ground in the range of 5000 - 20,000 lux.

- **The Clear Blue Sky,** this sky has a variable luminance according to geometrical factors and positions of the sun, but the direct sunlight is not considered. The Clear Blue Sky is generally associated with mountainous regions with clean atmospheres and can generate illuminance values of between 50,000 - 100,000 lux.
- **Cloudy Sky,** the cloudy sky is associated with skies that are partly or fully covered with clouds. They normally produce illuminance of between 20,000 - 100,000 lux.
- **Intermediate Sky, Real Sky or All-Sky;** The real sky does not come under any category, but it is very difficult to model.

2.4.1.2 Direct Sunlight

The sun is the ultimate source of natural light. Sunlight is considered as a concentrated source of light and radiant heat. Bright sunshine illumination can be as high as 100,000 lux and brings thermal radiation of about 1 kW/m^2. The sunlight arriving on earth passes through the atmosphere, being partly diffused, absorbed and scattered by the prevailing clouds and atmospheric content. Only the unobstructed portion of the sunlight will reach the interior as a direct sunlight component. Diffused light from the reflection and reflection of the sunlight will result in various forms of sky conditions (Hassan et al., 2015).

The solar radiation is the energy that is obtained by the sun. Daylight is regarded as one part of electromagnetic radiation’s energy spectrum. It is released by the sun within a visible waveband, which is received on the earth’s surface after it is absorbed and scattered in the atmosphere of the earth. Sunlight is defined as a direct light component. The solar radiation, as well as the daylight, have the same physical properties in addition to the modelling of one involving the other. The availability of the modelling solar, as well as the daylight, needs slope irradiation in addition to illuminance monthly and daily, as well as hourly according to the analysis (Baker et al., 2013). Solar radiation in Watts per square meter (W/m^2) and luminance in candelas per square meters (cd/m^2) measure the energy intensity emanating from the sun. Luminance is the energy contained within the visible solar spectrum of wavelengths between 0.39-0.78 Jlm. Irradiation in Watt-hour per square meter (Wh/m^2) or Joules per square meter (J/m^2) is the cumulative energy incident on a surface in a given time. Irradiance (W/m^2) and illuminance (lumens/m^2 or lux) is the instantaneous incident energy (Zain-Ahmed, 2000).

2.4.1.3 Reflected Light

The surfaces are illuminated by the sun. This creates secondary light sources. The light-coloured surfaces, which reflect sunlight, are naturally the second-brightest light source in our environment. On sunny days, these surfaces are the most dominant source of light. The light, which is reflected from a ground, might be significant in the daylighting designs. This light is reflected from a ceiling or the walls on interior surfaces. On a daylighted elevation, light, which is reflected from a ground represents 10-15% of total daylight that reaches windows. It often surpasses this with the light-coloured ground surfaces like sand, snow, etc. On the shaded exposure, it might account for more total light that reaches windows; this depends on the conditions of the sky and the building design (Rea, 2000).