INVESTIGATION OF ADJUSTABLE LIGHTSHELF FOR DAYLIGHTING CLASSROOMS CONSIDERING DIFFERENT SKY CONDITIONS OF DHAKA

By

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Dedicated to my ‘Father’

Md. Ahsan Ullah

who inspired me to go ahead and never give up….

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Abstract

In a classroom the students near the windows may get enough daylight for their learning activities but individuals far from the windows often do not get sufficient daylight. Most of the schools experience the same problem in dense Dhaka city. Increasing the size of windows to penetrate daylight into the deep of the classrooms can create glare problem near the windows. Windows are usually shut down to avoid glare near the windows and depend on the artificial light for visual works, which increase the load of electrical energy. The situation also varies time to time for the different sky conditions and seasons. Light shelf can be an effective solution in this condition as light shelf is supposed to reflect daylight to the inner part of a room.

Studies show, in a tropical location, such as Bangladesh, the introduction of light shelf at any height produces an overall reduction of illumination on the work plane throughout the interior space. However, light shelf can be an effective element to enhance the quality of daylight in tropical buildings, if designed and located properly. The objective of this research is to study the impact of the width of light shelf on indoor day lighting quality considering different seasons and sky conditions in context of Dhaka, at the same time consider the performance of adjustable light shelf for better results.

Three case classrooms of different depths were selected after field survey. One is prototype Govt. primary school classroom designed by Local Government Engineering Department (LGED). Another is a high school classroom and third one is a university classroom. 3D Modeling was done by ECOTECT software and daylight simulation was performed by a dynamic annual Climate-Based Daylight Modeling (CBDM) method considering all weather sky luminance model (i.e. DAYSIM). As in Dhaka the sky condition differs in seasons it has been tried to get the effective width of light shelf through computer simulation study in four different dates of a year: 20 March, 21 June, 22 September and 21 December; which are the equinox and solstice dates for Dhaka.

Primary analysis shows 300mm wide light shelf is effective to increase illuminance level at deeper parts of the classroom throughout the year in context of Dhaka. Due to different conditions of sky and seasons of a tropical city, a fixed width does not perform effectively throughout the year. Detail study shows that it need different width in different times. For February, March and April 450 mm wide external light shelf works skillfully. For May, June and July 300 mm wide external light shelf works best. For August, September and October 600 mm wide external light shelf can work effectively. For November, December and January 750 mm is effective. An adjustable light shelf is feasible as it not only fulfill the need all over the year but also can serve in a day if necessary as illuminace varies in a day in different times. It is expected that the outcome of this research will help architects and designers to generate some guidelines for light shelf configurations to improve the luminous environment of school buildings in Dhaka as well as in the other cities of Bangladesh.

Keywords

Sky condition; Adjustable light shelf; Daylighting; Classroom; CBDM simulation.

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List of Abbreviation

AGS	Architectural Graphic Standards
BANBEIS	Bangladesh Bureau of Educational Information and Statistics
BMD	Bangladesh Meteorological Department
BNBC	Bangladesh National Building Code
BOCA	Building Official Code Administrators
BUET	Bangladesh University of Engineering & Technology
CBDM	Climate-Based Daylight Modelling
CBECS	Commercial Buildings Energy Consumption Survey
CIE	International Commission on illumination
DA	Daylight Autonomy
DDS	Dynamic Daylight Simulation
DF	Daylight Factor
DGP	Daylight Glare Probability
DGI	Daylight Glare Index
DoA	Department of Architecture
EIA	Environmental Impact Assessment
ERC	External Reflected Component
IESNA	Illuminating Engineering Society of North America
IES	Illuminating Engineering Society
IESNA	Illuminating Engineering Society of North America
IRC	Internally Reflected Component
ISO	International Organization for Standardization
LEED	Leadership in Energy and Environmental Design
LGED	Local Government Engineering Department
NI	Nebulosity Index
PEDP	Primary Education Development Project
PGSV	Predicted Glare Sensation Vote

RAJUK	Rajdhani Unnayan Kartripakhya
TLC	Tridonic Lighting Components
UDI	Useful Daylight Illuminance
UDLE	Useful Daylight Enhancement
USA	United States of America
USDE	United States Department of Education
VALRA	Variable Area Light Reflecting Assembly
VDT	Video Display Terminal
WC	Window Configuration
WWR	Window-to-Wall Ratio

1. CHAPTER ONE: INTRODUCTION

Preamble

Problem statement

Aim and objectives

Overview of research methodology

Scope and limitation of the research

Structure of the thesis

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CHAPTER 1 INTRODUCTION

1.1 Preamble

A large number of students are enrolling in the primary education level and it is the highest group of population in Bangladesh. According to Bangladesh Education Statistics Report 2015 by Bangladesh Bureau of Educational Information and Statistics (BANBEIS, 2015) the total number of primary school is 80,397 and the enrolling student number is 16,225,658; which is a large number and environment of the classroom demands attention.

Students spend long hours of a day in classrooms. The environment of classroom has a great impact on students. Luminous environment is an important factor of classroom design. Research has confirmed that the well-being and performance of students depend significantly on the quality of the luminous environment, which can be achieved through daylight utilization (Axarli and Tsikaloudaki, 2007). Daylight has its negative impact, if it has not evenly distributed. Daylight in classrooms is a critical factor in school design, in terms of its impact on students' health, learning and visual performance. Providing adequate amount of evenly distributed daylight and glare prevention are important challenges in classroom design.

Before electric lighting, daylight was the primary illumination source for different building types. Designers, later tend to rely on electric lighting (Robertson, 2003). Artificial lighting for illuminating buildings needs large quantities of electricity, which affects negatively on total energy consumption (Sharmin, 2011). Now-a-days, daylight is encouraged in the buildings, as it is not only a promising green building design strategy for energy savings, but also its physiological and psychological benefits (Sharaf, 2014).

There are several shading elements available that can enhance the quality of daylighting in indoor spaces, such as sunshade, overhang and light shelf. Light shelf was developed to create uniform indoor illuminance. Light shelf is a daylight-redirecting system intended to bounce daylight to the deepest side of a room. This function suites well to most of the climates (IEA-ECBCS, 2010) and the performances have been studied under various climates and sky conditions. Clear sky is the favorable condition to provide high average indoor illuminance level with even illumination distribution. A Lightscape simulation based study, which was validated by field measurements (Wong and Istiadji, 2004), proved that light shelves could improve the indoor illuminance under a partly cloudy sky in Singapore. Another study on light shelf in warm tropics has been conducted under clear sky and overcast sky conditions in Yogyakarta, Indonesia based on Radiance simulations. This study shows in case of side windows with overhang, substitution of overhang with light shelf could improve the classroom's visual uniformity (Binarti, 2005).

This research focuses on classrooms of primary school buildings located at different areas in Dhaka to study the potential of different light shelf widths in providing adequate daylight penetration over the year for different sky conditions. This research has tried to find out an effective light shelf width for primary school classrooms which will be suitable in different seasons to specific climatic regions, i.e. in tropical cities, such as Dhaka.

1.2 Problem statement

In Bangladesh few studies have been done on the impact of daylight and student performance. As a result the consideration of natural lighting quality in classroom is in less concern during designing educational buildings. Studies on primary school classrooms in Dhaka show that, individual student in a classroom often does not get similar types of daylight on their desk. The students near to the windows get much light than the ones sit far from the windows. On the other hand, those who sit just beside the window sometime get excess daylight, which creates glare problem. As a result they often shut down the window and use artificial light. Eventually the electricity bill raises unnecessarily, which gives a negative impact on the national energy consumption. Over and above the situation changes with the changing of the seasons as the sky condition differs and the lighting quality is different for individual seasons. The situation is more or less same in most of the schools in Bangladesh.

School systems or learning environments in general are one of the most critical environments with some correlative actions (Higgins et al., 2005). Special attention is a prior need for providing such conditions to improve the situation, as learning has a special place and role in human life. Now with the developed technology the facilities for upgrading educational places are improved as well. Among all environmental elements lighting has a very powerful impact in people's life and health (One workplace, 1999).

Students' performance is negatively affected if there is no well controlled windows and lighting in a classroom (Johnson, 2011). Designing a learning place is one of the most critical and important situations but most of the time this importance are ignored. Good environmental designing in schools is a kind of stimuli for students and even teachers to have better performance. To upgrade the lighting condition in buildings in tropical area light shelf acts effectively if designed properly (Joarder at el., 2009).

To address this problem, architecture design strategies should be developed by proposing appropriate light shelf width to incorporate useful daylight in luminous environment of classrooms of primary schools with maximum possible utilization of daylight without glare for different sky conditions and climatic context of Dhaka.

1.3 Aim and objectives

The aim of this research is to identify the effectiveness of adjustable light shelf for classroom windows to ensure effective daylighting for learning activities throughout the year, considering regional and climatic context of Dhaka.

To achieve this aim, following three objectives have been developed.

- Objective 1: To rationalize the necessities of light shelf for efficient daylighting in classroom.
- Objective 2: To find out an effective light shelf width to increase illuminance level at deeper parts of the classroom throughout the year in context of Dhaka.
- Objective 3: To identify different light shelf widths to increase illuminance level at deeper parts of the classroom for different sky conditions on distinct parts of the year in context of Dhaka.

1.4 Overview of the research methodology

This section provides a brief overview of the research methodology for the thesis. A detailed description of the research methodology, used for this research, has been discussed in Chapter 3. Figure 1.1 shows a flow diagram of the overall research process, which integrates the main research methods: literature review, field survey and simulation analysis.

The research started with a literature survey to gather knowledge and information on the national and international illumination standards; climatic context of Dhaka and existing illumination level in classrooms of primary schools in Dhaka to understand the nature of expected luminous environment in classrooms.

Six school buildings were selected from the LGED designed buildings for pilot survey to understand the lighting conditions and problems. Then three of them was selected for physical survey based on specific criteria (Section 3.2.3). Measurement of illuminance at classrooms, window details, materials, window bottom and top levels, shading devices, work plane heights, aisle widths, exterior interior photographs, detail observations and related information were collected for these three schools. From these three schools, three classrooms were shortlisted and among them, the most suitable one was selected as ‘case classroom’ based on convenience sampling method, for simulation analysis.

With the selected classroom model five different width of light shelf was simulated for four particular dates (20 March, 21 June, 22 September and 21 December) under the climatic context of Dhaka keeping the indoor and outdoor conditions constant. Simulation study was pursued by ECOTECT-RADIANCE-DAYSIM software.

Finally, the understanding of literature review, findings of the field survey and experiences of the simulation study were compiled to rationalize the necessities of light shelf and identify the widths of light shelves to ensure glare free environment and uniform illuminance in the classroom throughout the year and during different seasons of the year in context of Dhaka.

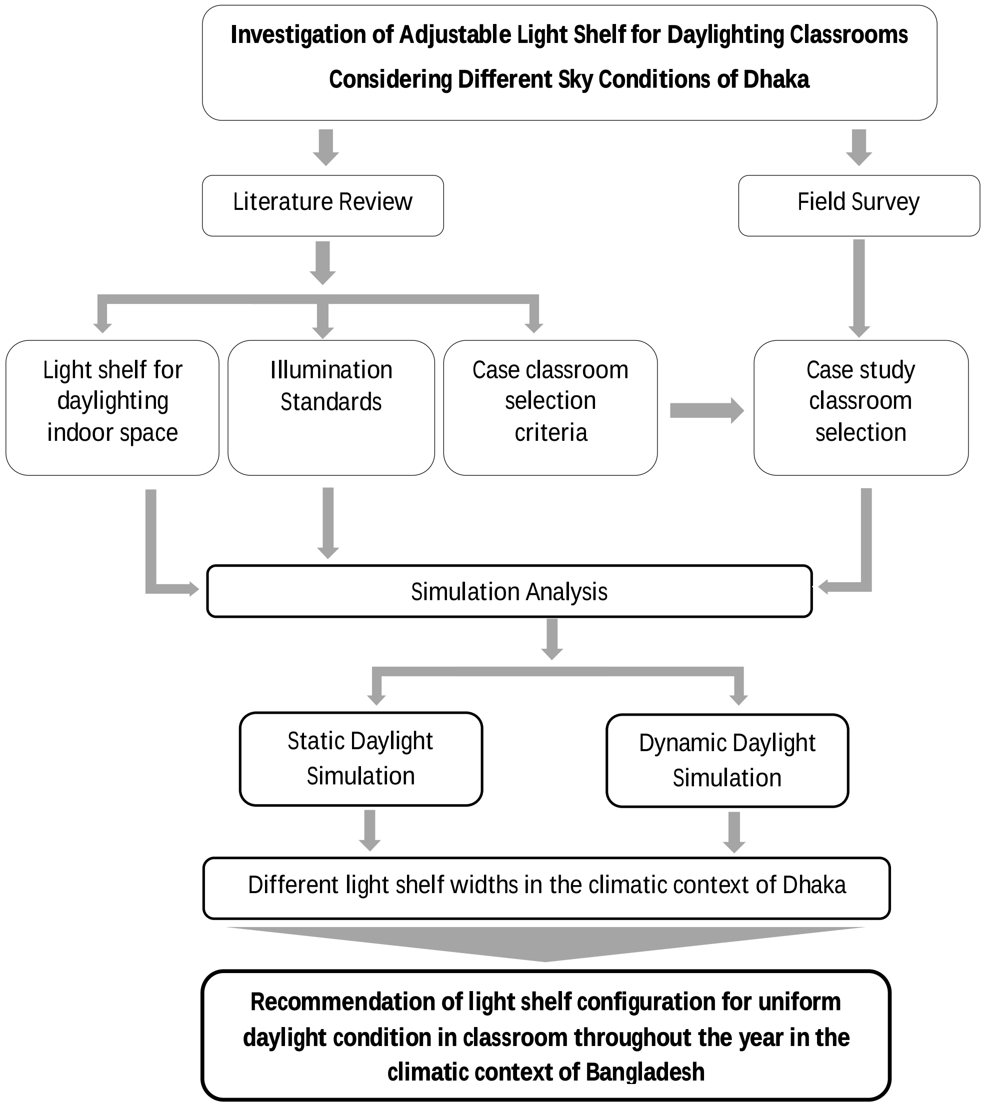


Figure 1.1 Flow diagram of the research process

1.5 Scope and limitation of the research

The recommendations and design guidelines in this research are made considering north south oriented building and for the south façade windows. The outdoor context is differ for every single building. This study concentrates on strategies for daylight inclusion and a comfortable illuminated environment in classrooms under the climatic context of Dhaka region to save energy for lighting and comfort purpose. Classroom environment depends on many other factors for example, aesthetics, sound transmission, economics, glare control, ventilation, safety, security and subjective concerns of privacy and view of a space. Considering time and resource constraint for the research, the said concerns were kept beyond the scope of this thesis, which may be addressed by further studies.

1.6 Structure of the thesis

This Section provides an overview of each of the following five chapters, which is shown graphically in Figure 1.2.

Chapter 1 is an introduction to the thesis; describes subjects that might be necessary for understanding this research, problem statement with the aim, objectives, brief methodology, scope of the research and limitations.

Chapter 2 focuses on the outcome of the literature review, based on established research and published sources, to provide a knowledge base for this research, which helped to focus on the issues on which the simulation is conducted later.

Chapter 3 describes the detail steps of the methodology for simulation study for this research. This chapter also provides a general climatic overview of Bangladesh based on published data from different published thesis books, papers and collected data from Dhaka Meteorological Department, mainly focused on the case area of this research- Dhaka city. The purpose is to formulate an environmental database for field study, to select the whole year for dynamic daylight simulation. Field investigation, explained in this chapter focuses on the criteria of the selection of the case study classroom for simulation study.

Chapter 4 provides the detail description and output of the simulation exercise. This chapter consists of three major parts. In the first portion, Static daylight simulation with one sky model are conducted to find out the best light shelf width for natural lighting in classrooms in the climatic context of Dhaka and then the second portion describes the Dynamic climate based daylight modelling (CBDM) simulation in particular date and time to propose the best light shelf for comfortable illuminated environment. Finally, the most feasible light shelf is proposed by combined result from the static and dynamic simulation results. This chapter also validates the measured existing indoor lighting condition with computer simulated data to understand the deviation from real world.

Chapter 5 discusses the architecture design strategies of light shelf for incorporation of useful daylight illumination in primary school classroom. This chapter also provides some general recommendations along with some directions and guidelines for future research, in the field of daylighting within the defined context.

Figure 1.2 shows the structure of the thesis with organization of the chapters.

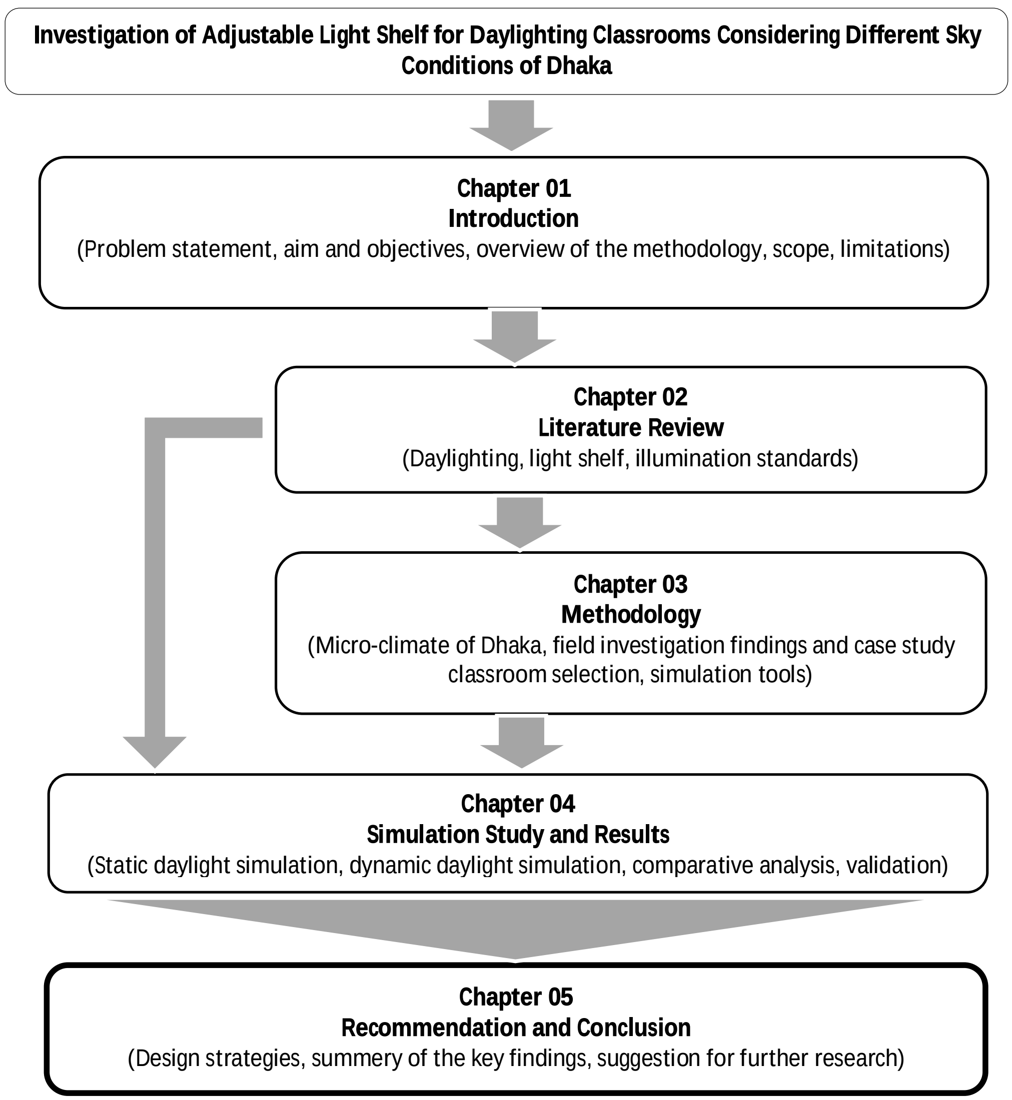


Figure 1.2 Organization of the chapters and structure of the thesis

1.7 Summery

The research started to overcome some constraints mentioned at Section 1.2. With the gradual development of the research from the literature review and incorporation of research findings at different stages made objectives, methodology and limitations of the research more defined, refined and detailed. Appendix A presents a summary of the key findings of the research in relation to the objectives, methodologies and concerned chapters.

2. CHAPTER TWO: LITERATURE REVIEW

CHAPTER 2 LITERATURE REVIEW

2.1 Preamble

The first chapter introduces the research. This chapter discusses the outcomes of the literature review to describe the basic information required to study the impact of light shelf for daylighting in classroom in the context of Dhaka. This chapter mainly consists of four major parts. The first part describes daylight as a potential source of lighting for learning space, and different aspects of window and glare. The second part focuses on national and international illumination standards for classroom. The third part describes how light shelves are using for indoor lighting; potential of light shelf over the world for different needs under different sky conditions; different aspects of light shelf configurations; and light shelf design consideration. The last part highlights critical findings from literature review. The methodology for simulation studies and field investigation are discussed in the next chapter (Chapter 3), developed with respect to the outcomes of this chapter.

2.2 Learning space and daylight

Learning environments and especially schools have always been of great interest for architects mainly because through design learning spaces can influence children's education and future. A school is not just a building to accommodate students and teachers, and it must not be seen as such. Architects and scientists named school environments as the "3rd teacher", and this is because the learning environment can play an important and significant role in students learning and academic performance (Heschong et al., 2002). The nucleus of a school is the classroom. In an everyday basis a student do certain activities in the classroom, e.g. reading, writing, drawing, solve mathematical problems, that are directly connected with the environment in which they perform. The learning environment if designed with consideration can be one of the most important components for successful learning and teaching.

Lack of appropriate environment of classroom can result physiological and psychological impacts on children. The most obvious effect of light on individuals is in enabling vision and performance of visual tasks. According to Boyce et al. (2003), the nature of the task—as well as the amount, spectrum, and distribution of the light—

determines the level of performance that is achieved. Performance on visual tasks gets better as light levels increase. A study by Santamaria and Bennett (1981) shows that, if the amount and distribution of light are controlled, most everyday visual tasks (such as reading and writing) can be performed under daylight conditions as similar to under artificial light sources (such as fluorescent light). Daylight is superior for tasks involving fine colour discrimination when it is provided at a high level without glare or any reduction in task visibility caused by veiling reflections or shadows (Boyce et al., 2003).

2.2.1 History of daylight use in learning environments

In 1874, Robson suggested in the book, *School architecture: practical remarks on the planning, designing, building, and furnishing of schoolhouses* that day-lighting of classrooms was merely important. He further suggested use of day-lighting through sunny windows or sourced from the north, and that south or south-west lighting should be avoided. This was widely implemented in United Kingdom schools. Robson further advised that the classroom is well lighted when it has about 20% glazed area to floor areas. It is worth mentioning that glare at this early period was already avoided. From the 1900s to 1930s, there had been emphasis on the use of daylight in schools. This was called the "open air school" and it was achieved with a complete opening to one side of the classroom with a garden site. This approach also achieved good ventilation of the classroom and also the facilitation of sunlight penetration into the classroom (Clay, 1929).

2.2.2 Quality of lighting

The light without glare which will be functional for the task of the space, comfortable, safe and also provide a pleasant and stimulating environment is quality lighting. Daylighting is preferable as the main source of lighting in schools, supplemented by electric light when light fades later in the day or during overcast weather. Students and teachers prefer natural lighting over artificial. They also actively dislike fluorescent lighting because of glare and flicker (BRANZ, 2007).

The main principles for daylighting design for classrooms are: avoid direct sunlight; avoid over-glazing which can create excessive solar heat gain in summer; ensure

light sources are balanced to give even but interesting lighting; provide windows with a view; eliminate glare; and to give users control when needed (BRANZ 2007).
Direct sunlight is an extremely strong source of light and heat; however, it has no place in classroom daylighting design and should be avoided. Because direct sunlight can cause, visual discomfort, solar heat gain that can cause thermal discomfort and glare.

2.2.3 Benefits of daylighting

Implementing natural light in a learning environment is of a great importance. Learning performance and health of students can be affected positively if the daylight design of a learning environment is correct and negatively impacted with its absence. Furthermore the correct implementation of natural light prove beneficial for the building's energy efficiency.

Natural light can illuminate a space by connecting with the outdoor environment and improve the users' health and academic performance. Successful implementation of natural light in a learning environment can be achieved with the correct use of daylight systems and principles. In design phase with the advances in computer technology, the interior illumination level can be predicted and further design decision can be taken (Sharmin and Ahmed, 2012).

a) Lighting and learning outcome

Researchers indicated that adequate natural lighting promotes student performance. In the United States of America, a number of studies have investigated the effects of natural lighting on student performance. The results show a strong correlation between daylighting variables, such as window size, sky conditions, tint, and level of anticipated daylight, and students' performance (Heschong et al., 2002).

Colorado, and California found that students in rooms with the most diffuse and glare-free daylight improved their performance on standardized tests by up to 26%. The study analyzed test score results for over 21,000 students (Creating quality cities, 2004). The Heschong Mahone Group examined the math and reading scores of students exposed to different lighting conditions and found that a 21% increase in performance from students exposed to the most daylight when compared with those exposed to least daylight. In another long-term study, it was found that an average of

14% difference in test performance of students in daylit against non-day lit school facilities (Nicklas and Bailey, 1996). Similar research is being carried out in New Zealand (Jackson and Donn, 2006).

b) Health and wellbeing

The benefits of supplying substantial light for free, natural light provides great physical and psychological benefits to the building's occupants (Kibert, 2016). Boyce and colleagues (2003) describe studies that clearly show that people’s moods are affected by different types of lighting conditions.

Daylighting promotes a healthy teaching environment, specifically through vitamin D generation and circadian regulation. The level of daylight is important for the student's vision and it limits the effect of harmful electrical light (Baker and Steemers, 1998). The level of illumination has a special psychological function in schools. Other researchers indicated that daylighting enhances mental performance, decreases violent behaviour, decreases depression, and improves sleep (Gelfand, 2010).

The lack of good environment of classroom can make student stressed. High school students in particular are experiencing unprecedented school-related stress (Ainslie et al., 1996; Byrne, Davenport, and Mazanov, 2007; Stuart, 2006). A US nationwide survey conducted by the Kaiser Family Foundation (2005) found that 63% of teenagers between fourteen and eighteen years of age felt that school was the greatest cause of stress, and that 27% of teenagers reported they had frequently suffered stress in their daily lives. Chronic stress has been consistently associated with negative outcomes, such as physical illness, anxiety, depression, decreased academic performance, social withdrawal and drug or alcohol experimentation. Another study concluded that people with depression symptoms who moved in more brightly lit buildings reduced their symptoms of depression by 19% (Scientific American, 2011).

c) Energy savings

Good daylighting can save electricity as long as electric lights are turned off or dimmed when natural light is adequate. Much of a school’s energy budget is for lighting (USDoE, 2002). This can be greatly reduced with well-designed natural lighting provided. Daylight can be related with economy as it gives some financial benefits. According to a report by the National Center for Education Statistics, 72% of the cost of energy in education buildings goes towards electricity, with the majority (56%) going toward lighting. Making a significant cut in electricity costs through daylighting can amount to substantial savings for other school expenses (SPM, 2000).

A series of schools built in Johnston County, N.C., replaced artificial lights with natural light, which resulted in between 22% and 64% energy savings as compared to typical neighboring schools. Since the construction, the schools have saved Johnson County Schools in excess of $500,000 in energy bills. The daylighting measures cost less than 1% of the construction budget and achieved a payback in less than three years (EDC, 1998; USDoE, 2002).

Daylight can be considered as one of the main factors of sustainable architecture. Light is one of the effective strategies in building energy optimization. Using a developed system of daylight designing decreases building's electrical consumption significantly. Using daylight has many economic and bio-environmental advantages (Chan and Tzempelikos, 2013). Electric energy consumption is the most important effective factor in buildings' carbon emission (USGBC, 2014), which consist 30–40 percent of the total energy consumed in commercial buildings (O'Connor, et al. 1997). By the developed designing of daylight, cooling load decreases significantly (EE, 2002).

2.2.4 Window and glare

During midday the sun hitting the ground can be more than 10,000 lux in tropical countries. For most people the tolerable amount of sunlight while reading a book outside is around 40,000 lux. There are large variation between the outside tolerable daylight from inside for reading. For a typical classroom the amount of light tolerable for reading is around 500 lux. In some field studies desktop illuminances of around 1500 lux to 2000 lux have been found to be too bright not because of the amount of illuminance but because of direct glare and glossy reflections. Care must be taken to avoid large variation of brightness between surfaces at the far end of the room and those close to windows (Tregenza and Wilson, 2011).

Glare can be defined as a very harsh, bright, dazzling light and separated in two categories, the disability glare and the discomfort glare. "Disability glare is defined as the effect of stray light in the eye whereby visibility and visual performance are reduced" (Jakubiec & Reinhart 2012). Discomfort glare is defined as glare that produces discomfort and it does not necessarily influence visual performance or visibility. A representative example of disability glare is the sensation that a person experiences on a sunny day surrounded by snow. The overall luminance levels of the environment is too great and bright for the eyes. An example of discomfort glare is what a person experiences when working on a computer screen and direct sunlight is falling in his field of view. It makes difficult to read what is on the screen because of the high luminance levels of the direct sunlight (Jakubiec & Reinhart 2012).

Studies on people reactions have shown that the discomfort from a small bright light depends on four factors (Jakubiec & Reinhart 2012): the luminance of the light source, the size of the source, the luminance of the background and the angle of the source from the subject's line of vision. The luminance and size of the light source have a direct connection with visual discomfort, as the light source luminance increases so does the discomfort. The luminance of the background and the angle of the source from the subject's line of vision reduce discomfort as they increase. This points to the fact that the discomfort glare is the result of excessive contrast within our visual field.

2.3 Illumination standards for classroom

Classrooms, learning environments and studying areas within a school are based on desk based activities. The users which are mainly the students and the teachers have to carry a variety of visual task in two and three dimensions, focusing on reading and writing on computers, on paper and black or whiteboard. To carry out visual tasks in a learning environment the user must adjust his vision from the board to the desk and from the desk to the board. It is important when designing a learning environment that the users may remain in the same position for long periods of time, an hour even more, and they may not have the choice to change position in the classroom (Tregenza and Wilson, 2011).

This section presents different international and Bangladeshi standards on illumination condition of classroom design.

2.3.1 International standard

Study show that, buildings e.g. office, school and industry use 40% of the total consumed energy for lighting (Lechner, 2001). Local authorities of different countries are trying to address legislation focusing on standards of proper lighting to reduce the energy consumption. Daylighting standards vary from one country to another (Julian, 1998), based on the requirements of different aspects necessary for a building design such as quality of indoor illumination inside a room, windows and their sizes. The most frequently used legislation that relates to daylighting is the requirement for specific window sizes for various types of spaces (Boubekri, 2008). When it comes to the standards for daylight in schools, most conventional codes prescribe minimum or maximum levels for window properties or allow the designer to meet performance goals (Sharmin, 2011).

The Illuminating Engineering Society of North America (IESNA) has recommended a design procedure which incorporates four steps: defining visual tasks in the proposed design, selection of illuminance category, determining the amount of lighting required, and establishing a target illuminance value for design (IESNA, 2000). It has established a set of minimum recommended illuminance levels for a variety of visual tasks and space functions. In 1979, IESNA established nine illuminance categories. Those have later been reduced to seven categories and organized into three sets of visual tasks with a set of minimum recommended illuminance levels (IESNA, 2000). Table 2.1 presents the IESNA recommended target light levels for three sets of visual tasks.

Table 2.1: Three sets of visual tasks and their recommended illuminances established by IESNA (Source: IESNA, 2000; cited from Iqbal, 2015).

Categories			Illumination
Orientation and simple visual task	A	Public spaces	30 lux (or 3fc)
	B	Simple orientation for short visit	50 lux (or 5 fc)
	C	Working space where simple visual task are performed	100 lux (or 10 fc)
Common visual task	A	Performance of visual task of high contrast and large size	300 lux (or 30 fc)
	B	Performance of visual task of high contrast and medium size	500 lux (or 50 fc)
	C	Performance of visual task of low contrast or small size	1000 lux (or 100 fc)
Special visual task	A	Performance of visual task near threshold	3000-10,000 lux (or 300-1000 fc)

The following Table 2.2 displays the minimum recommenced illuminance values for a variety of tasks in a school environment, according to data from the American National Standard Guide for School Lighting (IES, 1962).

Table 2.2: Minimum recommenced illuminance values for school environments. (American National Standard Guide for School Lighting; IES, 1962)

Area	Task	Illumination	
		Footcandle	Lux
Classrooms	Reading printed material	30	300
	Reading pencil material	70	700
	Duplicate material (good)	30	300
	Duplicate material (poor)	100	1000
	Drafting, bench work	100	1000
	Up reading, chalkboards, sewing	150	1500
Art room		70	700
Drafting room		100	1000
Home economics room	Sewing	150	1500
	Cooking	50	500
	Ironing	50	500
	Sink activities	70	700
	Note-taking areas	70	700
Laboratories		100	1000
Lecture room	Audience area	70	700
	Demonstration area	150	1500
Music room	Simple scores	30	300
	Advanced scores	70	700
Corridors and stairways		20	200

The European norm (EN, 2002) provides guidelines for illuminations need for all different types' activities at schools buildings are illustrated in Table 2.3.

Table 2.3: Overview of tasks in a classroom together with the requirements for the luminance by (EN, 2002, cited from Iqbal, 2015).

The Teacher	The Student	Standard Illuminance	
		In the class	In general
Writing on blackboard	Reading on blackboard	500 lux (vertical)	200 lux
Talking to students	Paying attention to the teacher	300 lux	300 lux
Showing presentations (slide, PowerPoints, television program, etc.)	Looking at the screen	300/10 lux	10 lux
Paying attention to working students	Writing, reading, drawing, etc.	300 lux	300 lux
Coaching computer activities	Looking to the computer screen and the paper	50 lux	300 lux above the computer
Preparing lessons	Not present	300 lux	50 lux

2.3.2 Local standard

The 'Bangladesh National Building Code 2006 (BNBC) is a national level legally binding document which forms the basis for standards of design, construction and maintenance of buildings in the country. For the capital city of Dhaka, the ‘Rajdhani Unnayan Kartripakhya’ (RAJUK) is the planning authority which specifies regulations set forth in a document titled ‘Bangladesh Gadget 2008’, regarding different types of buildings based on the BNBC (Sharmin, 2011). Exterior window area, in a room used for residential or commercial purposes, shall not be less than 15 percent of the floor area for proper daylighting and natural ventilation (BG, 2008). On the other hand, Bangladesh National Building Code 2006 (BNBC) follows a set of minimum recommended illuminance levels for a variety of visual tasks and space functions for educational buildings (Table 2.4). The guidelines for consideration of the brightness ratio in classrooms are illustrated in Table 2.5.

Table 2.4: Recommended values of illumination for Educational Building (BNBC, 2006; cited from Sharmin, 2011).

Area of Activity	Illumination [lux]
Class and Lecture Rooms	
Desks	300
Black boards	250
Art Rooms	400
Assembly Halls	
Examination	300
Corridors	70
Stairs	100

Table 2.5: Recommended brightness ratio at table top between task, adjacent source and surroundings (BNBC, 2006, Section 3.2.1).

Recommendation	Requirement	Reference
Recommended brightness	100 cd/m^2	(BNBC 2006:3.2.1,p.11207)
Brightness ration: for high task of work brightness	3 to 1	(BNBC 2006:3.2.1,p.11207)
Maximum ratio between work area and any remote area	10 to 1	(BNBC 2006:3.2.1,p.11207)
Overall average illumination level	150 lux	(BNBC 2006: Table 1.3.2)

2.3.3 Daylight factor-based standards

Commonwealth Association of Architects recommended a minimum Daylight Factor (DF) of 2% in 75% of all spaces occupied for critical visual tasks (Ahmed, 2011; CSIR, 2006). DF-based legislation does not target a specific daylight illuminance level in a room because of constantly changing outdoor conditions; rather, it is based on a percentage of whatever daylight is available outside and therefore is more practical than illuminance-based legislation. An example of such legislation can be found in a few countries (Boubekri, 2008). In France, the Cahier des Recommendations Techniques de Construction (Ministere of Education) recommends a minimum DF in classrooms of 1.5% under overcast sky conditions (MoE, 1977). Table 2.6 summarizes the important codes and standards for lighting in classrooms that have been developed over the years. The chronology suggests that daylighting regulations and standards have evolved more quickly since the early 1980s (Sharmin, 2011).

Table 2.6: Chronology of important codes and standards (Source: Jackson and Donn, 2006).

Code	Year	Country	Recommendations for Daylighting in Classrooms (Wu & Ng, 2003, pp.111)
The London Building Act	1894	Britain	One-fifth the floor space for vertical lights in classrooms. Recommended illuminances in classrooms is 91 Lux.
British Standards Codes of Practice	1945	Britain	Minimum 2% daylight sky factor in classrooms, and 5% sky factor where possible.
IES Lighting code	1955	Britain	The level of maintained illuminance and the daylighting factor In classrooms should not be less than 100 Lux and 2%, respectively.
Statutory Instrument	1959	Britain	2% minimum daylight factor in any area normally used as teaching accommodation (Boyce, 1981).
CIBS Lighting Code	1977	Britain	Minimum illuminance on the working plane should not be less than 300 Lux.
The Education (School Premises) Regulations	1981	Britain	Daylight illuminance of not less than 300 Lux, for it to be adequate for the task. With a combination of artificial and natural lighting a minimum of 350 Lux should be achieved.
Building Code of Australia	1990	Australia	Windows must be provided with a total area that is not less than 10 percent of the floor area of the room (Osterhaus and Donn, 1998, pp. 3).
Australian Standard 1680.1	1990	Australia and New Zealand	Maximum glare index value of 19. Standard. Where it is possible to provide daylight through the working hours, should provide no less than 200 Lux (Standards Australia, 1990, pp. 37 & 60)
Guidelines for Environmental Design in School	1997	Britain	School premises should have a minimum of 300 Lux on the working plane. Whenever possible, a daylight in School factor of 4-5% should be reached in a daylit space.

2.3.4 Design illumination level for primary school classroom

The comparison between different international and national standards on illumination level in Elementary school classroom is presented in Table 2.7.

Table 2.7: Comparison between national and international standards on illumination level in Elementary school classroom.

Standards	International Standards (IESNA, 2000)	Local Standards (BNBC, 2006)
Minimum illumination level at work plane (lux)	300	300
Maximum illumination level at work plane (lux)	500	-

For this research, the preferred illumination level at classroom work plane is considered as 300 lux (BNBC, 2000) and the illumination level on work plane should not exceed 500 lux (Sharmin, 2011).

The consideration about the quantity of natural light and the user’s visual comfort is a very important aspect when designing a learning environment with natural light and it depends on several parameters such as the usage of every space within a school and also on the activities and the tasks that have to be performed in every space.

Despite considering each space separately, for the light design, the school building must be considered as a whole in order to create spaces that the user will not experience any discomfort when moving from one space to another because of the difference between the illumination levels.

2.4 Light Shelf for Indoor Lighting

2.4.1 Light shelf

Light shelves are horizontal projections placed below a window lintel to reflect sunlight further into the interior. It is typically placed above eye level to reflect daylight to the deeper part of a room. The light shelf uses interior ceiling as a reflector instead of a typical shaded interior ceiling (A.G.S., 2000). In addition, the light shelf shade the lower portion of any window and reduce the amount of light near the window, where, generally has much higher illumination experienced than the deeper parts of spaces and help projecting the light towards the back. Thus it results a balanced luminous environment with less contrast and glare. A light shelf also divides a window into a view area below and a clerestory area above.

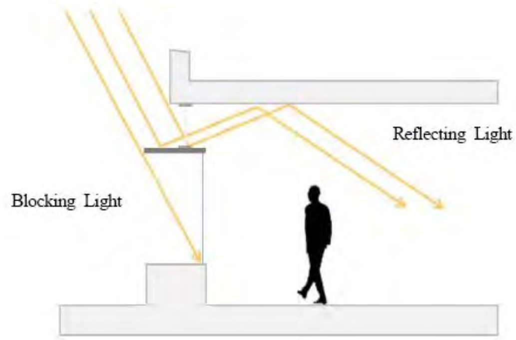


Figure 2.1 Light shelf reflects light deeper part into indoor area (source: Slide share, Introduction to Lighting; accessed in Nov. 2018)

a) Light shelf in early days

The use of mirrors as a means to redirect sunlight has been known since antiquity. Anthemius of Tralles and Isidore of Miletus designed an early type of the light shelf for Hagia Sophia in Constantinople (present day Istanbul, Turkey) in the 6th century AD. In the initial design, Anthemius used reflective window sills, which were located around the dome (Figure 2.2) so that sunlight was reflected to the interior surface of the dome in an effort to increase its brightness (Wassim, Potamianos, 2007; Potamianos, 1996). Although in late nineteenth century reflectors were in production to increase indoor illuminances e.g. the Tageslicht reflector form W. Hanifch and Co. which was presented in Berlin trade fair during 1889.

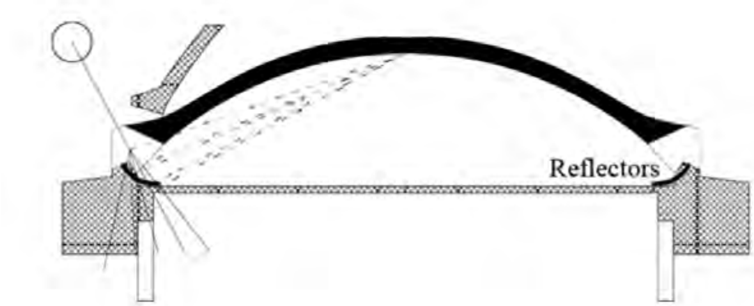


Figure 2.2 Schematic representation of the parapet of Hagia Sophia (Wassim and Potamianos, 2007).

It is not quite clear when the term “light shelf” started to be used. An early study for the use of light shelves in hospitals was carried out by Hopkinson during the 1950s (Hopkinson, 1952). Since the light shelf represents one of the simplest systems which reduces solar gains and redistributes daylight into the building interior, a large number of papers have been written in an effort to examine all related parameters affecting their performance. Focused research on the performance of light shelves begun during the 1980s.

b) Technical description

A light shelf is generally a horizontal or nearly horizontal baffle positioned inside and/or outside of the window facade. The light shelf can be an integral part of the facade or mounted on the building.

Material

Light shelves are commonly made from; timber, glass, plastics, metal panels, RCC, acoustic panels and so on. The choice of material may be determined by considerations regarding the design of the rest of the building, structural strength, ease of maintenance, cost, durability and so on.

Many light shelves' are made of extruded aluminum and aluminum composite material (ACM). Extruded aluminum, which is forced through a die during manufacture, is known for producing high-quality surfaces. ACM, a combination of aluminum and plastic, is known for its durability and versatility in commercial construction. The aluminum gives light shelves their conductive and lightweight properties. Additionally, aluminum and ACM provide a metallic surface that is easy to paint or coat with protective finishes. Frosted glass has also been used for light shelf materials.

Production

Light shelves are not standard, off-the-shelf products. They must be made to fit the architectural situation in which they are used.

Location

In window system a light shelf is usually positioned above eye level. It divides a window into a view area below and a clerestory area above. The light shelf is typically positioned to avoid glare and maintain view outside; its location will be dictated by the room configuration, ceiling height, and eye level of a person standing in the space.

c) Types

According to the placement, traditional flat light shelf can be divided by two types: Exterior light shelf and Interior light shelf.

Exterior light shelf

Exterior light shelves can be combined with shading devices, installed at the same height as the light shelves, which is below the tops of the windows. The system keeps direct sunlight from entering the portions of the windows below the light shelves. It can increase daylighting by reflecting more light farther into the space. The exterior shade needs a reflective upper surface and the window should extend well above the exterior shade. External light shelf can be preferred due to the reason that they prevent heat gain into the space to great extent.

Interior light shelf

Internal light shelf can be preferred owning to the minimized maintenance as it's easily accessible. Interior light shelves are available in various materials and in fixed and operable configurations. Tilting a light shelf makes the top surface easier to clean. A small amount of tilt may also improve performance. Tilting the shelf downward increases penetration of light into the space, but introduces the possibility of increasing glare. Tilting the shelf upward may avoid glare and increase daylighting at low sun angles.

Light shelves can be categorized according to their geometrical form. Therefore, in different research the following type of light shelves has been used- (a) horizontal, (b) flat tilted, (c) curved and finally, (d) active light shelves (Kontadakis et al, 2018).

According to the detail design and configuration light shelf can be categorized in many other names. Some of them are discussed below.

Conventional Light Shelf

A light shelf is usually a fixed, solid system, but some fixed external light shelves can incorporate slatted baffle systems with reduced upward reflection. The finish of a light shelf influences the “efficiency” and direction of light redirected from its top to the ceiling. A matte finish produces diffuse reflection with no directional control, in contrast to a specular reflection where the angle of incidence is (almost) equal to the angle of reflection. For a perfectly diffusive surface (Lambertian), only half of the reflected light will be distributed into the room, but for an interior light shelf, some of the “lost” light is reflected towards the interior from the clerestory glass surface. A highly reflective surface (e.g., a mirror, aluminium, or a polished material) reflects more light to the ceiling than a diffuse surface but may reflect onto the ceiling an image of any dirt pattern on it (Lam, 1986). A semi-specular finish for the top of the light shelf may be better. Another possibility is a reflecting prismatic film to throw light further into the room (Ruck et al. 2000; Littlefair, 1996).

Optically Treated Light Shelf

Optically treated light shelves (Figure 2.3) geometry is curved and segmented to passively reflect sunlight for specific solar altitudes. The light shelf design consists of a main lower reflector and a secondary upper reflector. The lower segmented reflector consists of inclined surfaces that are finished with a daylight film. The film has linear grooves that reflect sunlight within a 12–15° outgoing angle at normal incidence to the grooves. The segments are inclined to reflect sun to the ceiling plane up to 10 m from the window wall for noon solstice and equinox sun angles (south-facing facades in the northern hemisphere). The upper reflector is placed above the main reflector at the ceiling plane near the window to intercept incoming low winter sun angles and to reflect these rays to the lower main reflector. This reflector is surfaced with a highly reflective specular film and may be a small-area source of glare (Ruck et al, 2000).

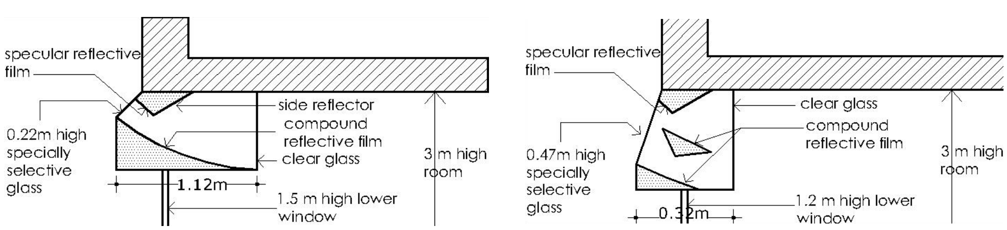


Figure 2.3 Section of light shelf: (left) single-level light shelf, (right) bi-level light shelf (cited from: Ruck et al, 2000)

Sun-Tracking Light Shelf

A variable area light reflecting assembly (VALRA) is a tracking light shelf system (Figure 2.4) that reflects light into a building (Howard et al. 1986). The system uses a reflective plastic film surface over a tracking roller assembly within a fixed light shelf. This system extends the projection capabilities of a fixed light shelf so that it functions for different sun angles. It has not been installed in a building to date. A simpler version of a light shelf that can be adjusted according to sun position or the sky luminance is the movable (pivotable), external light shelf. Figure 2.4 shows a case of monitored results from Denmark (Ruck et al, 2000).

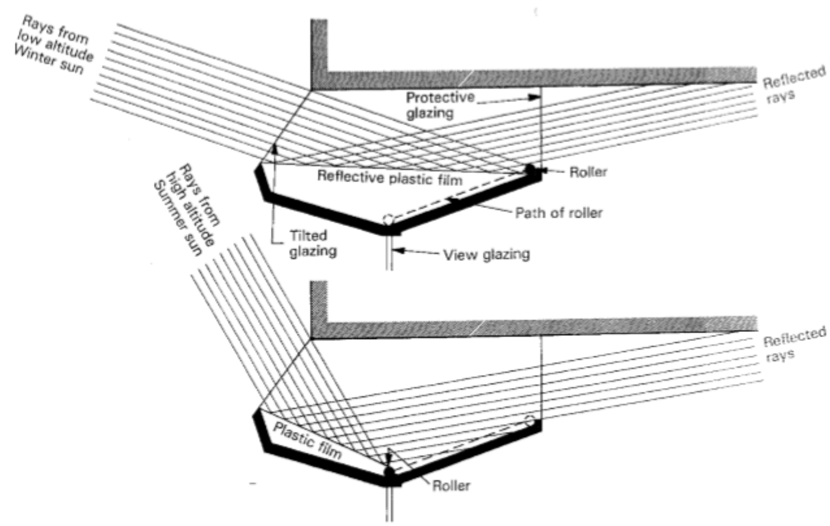


Figure 2.3 Winter and summer operation of the VALRA (Variable Area Light Reflecting Assembly. (source: Littlefair, 1996; Howard et al. 1986), cited from: Ruck et al, 2000.

d) Application

Light shelf applications is above eye-level for both tall conventional windows and clerestory windows. Installed on south side of a building, where maximum amount of sunlight is typically found. Light shelf systems are often misunderstood or improperly addressed in the initial design stages of a project. There are several key factors that must be addressed in effective light shelf system design. Four key components (window system, light shelf, interior ceiling and shading systems) make up a properly designed light shelf system.

Window system

A daylighting window system is horizontally divided into two parts, the view portion and the daylighting portion (Figure 2.5a). Light must be allowed to enter the upper (daylighting) portion of the window. Tinted or reflective glazing should be avoided, and can reduce the amount of light by 70% - 80%.

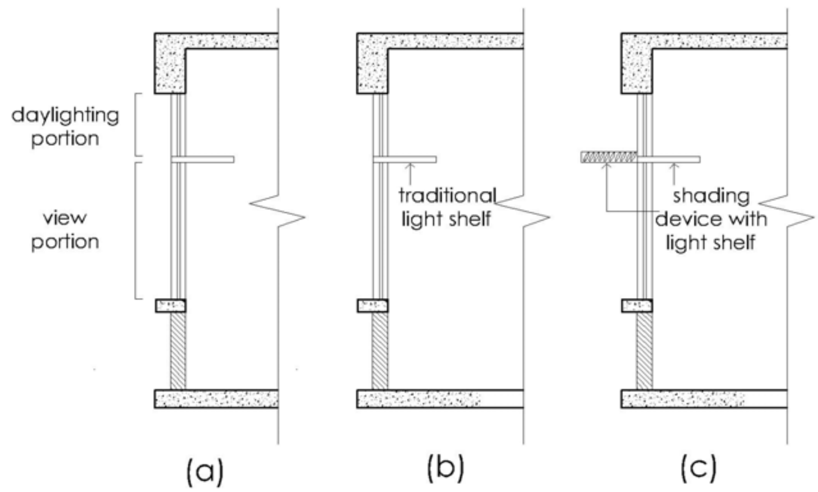


Figure 2.4 (a) Window system for light shelf, (b) Traditional light shelf and (c) Shading device with light shelf

Light shelf

Traditional light shelves are a flat horizontal projection. The amount of the projection is typically 250 mm (10 inch) to 750 mm (30 inch) but is also dependent on factors such as latitude and vertical daylight window height (Figure 2.5b).

Ceiling

Ceilings are usually made from painted drywall or acoustical tile. White or reflective colors are key to increasing luminance in the room. Ceilings may be at heights just above the window level or, to achieve deeper light penetration, higher ceiling levels or ceilings that slope upwards from the window system can be used.

Shading Devices

The fourth key component is a shading device. This can be in the form of an exterior mounted aluminum sunshade system, a roller shade, or mini blind systems. These systems shade the light from entering the view portion of the system (Figure 2.5c).

e) Maintenance

Light shelves require regular cleaning. An internal shelf collects dust, and an external shelf can become dirty and provide nesting places for birds or insects. A specular surface requires maintenance to maintain its reflective properties. Optically treated light shelves are completely sealed from the interior and exterior environment and protected from dirt and occupant interference. They require no routine maintenance other than cleaning of the exterior and interior glass.

f) Benefits

Architectural light shelves have been proven to reduce the need for artificial lighting in buildings. Since they can reflect light deeper into a space, the use of incandescent and fluorescent lighting can be reduced or completely eliminated during daylight hours, depending on the space. Light shelves make it possible for daylight to penetrate the space up to 2.5 times the distance between the floor and the top of the window (Penny, 2017). Now-a-day, advanced light shelf technology makes it possible to increase the distance up to 4 times (Penny, 2017). Furthermore, incorporating light shelves in a building design is admissible for the LEED point system, under the "Indoor Environment Quality: Daylight & Views" category (Penny, 2017). Using electric light, increases the carbon footprint. But light shelf optimizes the use of daylight and by controlling the amount of light, carbon emission can be reduced.

Light shelves on the south facing façades of building remarkably increase the daylighting quality and quantity. The main advantages of light shelves are following (Almsaad and Almusaed, 2014; Claros and Soler 2001; Littlefair 1996).

- *Increased sunlight penetration:* Since light falling on the surface of light shelf is reflected into the space, this property allows deeper sunlight penetration.
- *Reduced glare:* Through this passive technique, glare through the window is significantly reduced with the help of the light shelf.
- *Decreased heat gain:* Through reduction of glare near the window, the heating of space is reduced through the light shelf.
- *Decreased cooling charges:* Since heating is reduced, the amount of money spent on cooling the space through artificial means, is reduced.

- *Decreased energy consumption:* Light shelves can yield to a reduction in monthly demand charges due to reduced lighting energy during peak hours.
- *Enhance Indoor Environmental Quality (Daylighting):* Achieve a minimum daylight factor of 2 percent in 75 percent of all space occupied for critical visual tasks.
- *Optimize Energy Performance (Energy Efficiency):* Reduce the energy use by 30 percent compared to the baseline building performance rating per ASHRAE Standard 90.1-2007.

g) Limitations

Performance of light shelf may vary according to the sun's direction. When Light shelf is used in north/south directions, it allows deeper penetration of sunlight into the space. It will also shade the space near the window. If light shelf used in east/west directions, it will lower the heat gain, but do not allow deeper penetration.

Light shelves also increase maintenance requirements and window coverings must be coordinated with light shelf design. Dust can settle on a light shelf to degrade illumination; therefore, light shelves need to be cleaned on a regular basis. Internal light shelves however may be easier to maintain as they can be more accessible and less exposed.

An external light shelf has an external projection, a device attached to the outside of a building. The light shelf can be damaged by strong winds when used in high-rise buildings (Lee et al, 2017). Again the security grill can hamper the manual control of the light shelf.

In winters, the light shelf may cause an increase in the consumption of heating energy by blocking incoming solar radiation from the outside (Jeon et al, 2016). On the other hand R-value and U-value of material of light shelf have influence on the heat gain in indoor, and could be chosen appropriately to ensure comfort during summer.

2.4.2 Potential of light shelf

Daylight strategies and systems have not always lived up to their promise as energy efficiency strategies that enhance occupant comfort and performance. One reason is the lack of appropriate, low-cost, high-performance daylighting systems, simple tools to predict the performance of these advanced daylight strategies, and techniques to integrate daylight planning into the building design process.

Common barriers that have hindered the integration of daylight in buildings in the past are (Daylight in Building, 2000):

- lack of knowledge regarding the performance of advanced daylighting systems and lighting control strategies;
- lack of appropriate, user-friendly daylighting design tools; and
- lack of evidence of the advantages of daylighting in buildings.

Light shelves are possibly the simplest among daylighting systems. Light shelves represent one of the most popular design choices in contemporary buildings and are often suggested in literature as effective devices that can improve the lighting quality of a space and offer energy savings especially when daylight controls are used.

Some other options such as, smart glass/window, low-e-glass that could be used to restrict excessive daylight penetration similar to light shelf, is not so popular because of their cost, maintenance and operating system.

Smart glass or switchable glass is a glass or glazing whose light transmission properties are altered when voltage, light, or heat is applied. In general, the glass changes from transparent to translucent and vice versa, changing from letting light pass through to blocking some wavelengths of light and vice versa. When the electrical supply is switched on, the liquid crystal molecules align, incident light passes through and the privacy glass panel instantly clears. When the power is switched off the liquid crystal molecules are randomly oriented, thus scattering light and the privacy glass becomes opaque (private). Active smart glass technology allows for the control of various forms of light (visible, IR, UV) with electricity. With electricity, glass is switched from opaque to transparent, allowing for dynamic light control. It limits UV rays, reduces energy bill, prevents furniture from fading, reduces sound levels. But more costly than regular glass, slight haze to windows, no manual control, no control over visible light (Malins, 2014).

Low-e windows are windows that block the heat and certain types of light from coming through. Low-e stands for 'low-emittance,' which means that it does not allow as much to pass light and heat through the glass. One of the biggest advantages of this type of window is that it limits the amount of UV rays that come through. Another advantage of this type of glass is that it helps keep heat and cool inside building. It reflects the heat or cool back and does not allow it to escape outside. One of the disadvantages of low-e glass is that it is more expensive than regular glass. Another potential disadvantage is there is a slight haze in the window (Malins, 2014).

Several studies have been conducted on the effectiveness of light shelves. For example, Aghemo et al. (2008) present a case study for the comparison of lighting performance of different traditional shading devices and light shelves. Scaled models were tested for simulating the building performance under different sky conditions. Claros and Soler (2002) define the efficiency of light shelf as the ratio between illuminance inside the model equipped with the light shelf and a reference model without light shelf. They state that for light shelves with mirror and methacrylate surfaces, the efficiency is more than 1.0, implying that the lightshelf produces higher illuminance compared to the case without light shelf. Another important observation from this study is that when the walls and ceilings have realistic reflectance values that are possible in normal buildings, the efficiency is less than 1.0, implying that the lightshelf produces less illuminance compared to the reference model. There are many other studies on light shelves installed in classrooms (Meresi, 2016), and offices (Berardi and Anaraki, 2015; Atzeri et al. 2014).

Many studies have been done about light shelf performance in literature. Meresi 2016, studied on evaluating the daylight performance of light shelves combined with external blinds in south-facing classrooms in Athens, Greece. Soler and Oteiza (1997) investigate the light shelf performance in Madrid, Spain. The performance of a light shelf with a reflectance of 91% is studied in Madrid using two scale models with rectangular openings facing south, one taken as a reference and the other equipped with the light shelf. Edmonds and Greenup (2002) studied many innovative systems that provide shading and daylighting. They showed that the light shelf is an effective shading device and a daylighting system. Soler and Oteiza (1996) and Claros and

Soler (2002) studied the dependence of the light shelf performance on solar geometry and surfaces' reflectance.

a) Light shelf for different functions

Firstly light shelf was started to use only in the high-rise buildings. But day by day it has been started to use in different types of buildings, for example, institutions, hospitals, residential and many other functions.

i) Office buildings

For minimizing the energy load and for the productivity of the workers, daylight is a great concern for office building. Again office time matches to the daylighting time. The open plan of a working zone can be lighted by the light shelf to a deeper part.

A study has been done in the Prasetiya Mulya office, Jakarta. With the case study model a simulation was done with three different widths (0.3m, 0.6mand 0.9m) of light shelf. The result shows that with the use of 0.6m width light shelf works best. The visual comfort area increases to 52% from 42%. There is no glare area on the north and south sides. While the East side decreased glare, and lighting energy consumption decreased approximately to 26.6 kWh/m²/Year and 24.2 kWh/m²/Year. Again 0.6 meter light shelf gives a significant increase in energy saving (average 22 %). With right design of light shelves, daylighting area can be extended that meet visual comfort, minimize glare and increase energy saving in the office (Apritasari, 2017).

In a research by Berandi and Anaraki, the benefits of light shelves over the illuminance levels in office buildings in Toronto are evaluated. Annual simulations for buildings with different window-to-wall ratios were compared. Moreover, the effects of different window shapes, facade orientation and external obstructing elements were investigated (Figure 2.6). Results show that in the context of analysis, light shelves increase the useful daylight illuminance values mainly in the first 6m from the windows and provide a more homogeneous distribution of the daylight. Window-to-wall ratios above 35% consistently result in increasing glare risks. (Berardi and Anaraki 2016).

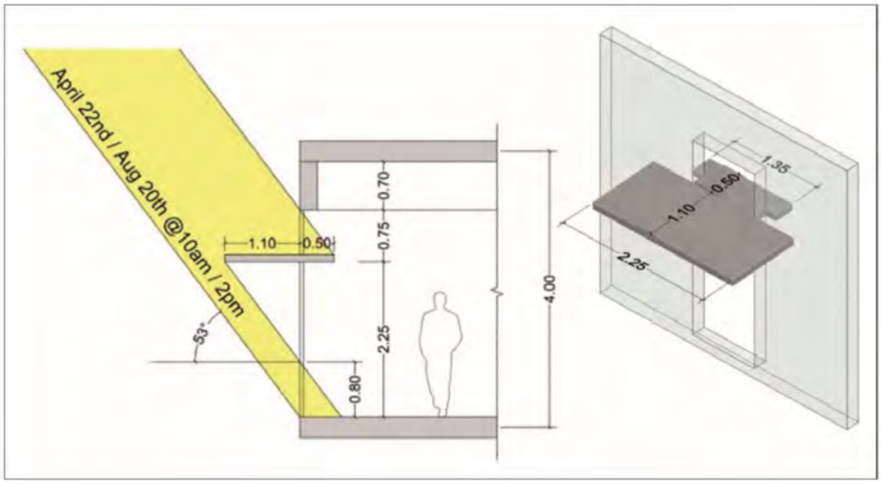


Figure 2.6 Room cross section dimensions (left) and light shelf geometry (right). (Berardi and Anaraki 2016).

Another research conducted by Joarder et al. (2009) aim to determine the most suitable height of mid positioned, fixed sized (1m width) light shelf for a typical office building in Dhaka, Bangladesh (Figure 2.7). Daylight simulation was performed by using Ecotect and Radiance software. 2m height of light shelf from the floor performs better results other than the six light shelf height variations for 3m office height at the end.

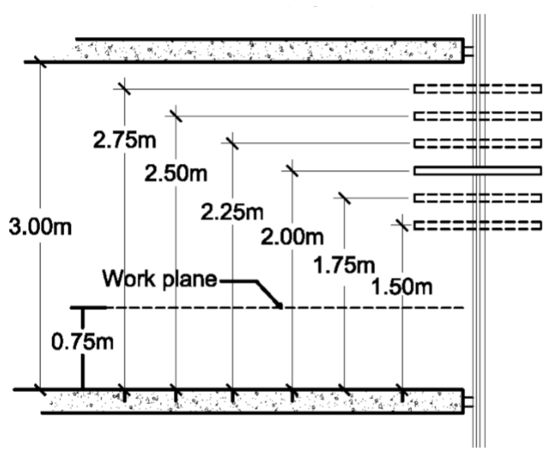


Figure 2.7 Section showing varying light shelf heights investigated by Joarder et al. (2009).

In Malaysia daylighting performance of various internal light shelves was studied using Radiance-based simulation for high-rise office buildings. The simulation results were validated against physical scaled model experiment and the results indicated significant Pearson correlations which ranged from 0.826 to 0.985. This study proved that high-rise office without any shading had poor daylighting quality with average illuminance as high as 11,193 lux and uniformity ratio below 0.1. Light Shelf (LS) 6 and LS 4 exhibited the best performance under intermediate sky, whereas LS 2 was the best under overcast sky (Figure 2.8). Although there was a decrease in illuminance level when comparing the optimum cases to the Base Case (ranging from 62.0% to 34.1%), the optimum cases showed a significant increase in uniform distribution uniformity which was up to 178.6%. The finding has proposed a dynamic internal light shelf which could provide optimum daylighting performance for different sky conditions, times, months and orientations under tropical sky (Lim and Heng, 2016).

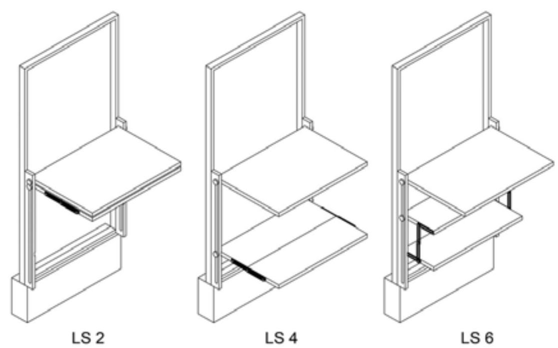


Figure 2.8 Dynamic internal light shelf which for optimum daylighting performance of different sky conditions under tropical sky (Lim and Heng, 2016).

Cüneyt and Esen have researched to explore the effect of location on earth to the light shelf size and position and the correlation between latitudes with light shelf placements for three different office heights (3m, 3.9m, and 4.8m). Determination of the suitable light shelf size and position according to 6 latitudes (0°, 15°, 30°, 45°, 60°, 75°) for 3 different office heights. Obtained a new curve pairs by joining the endpoints named as “CUN-OKAY light shelf curves” of the suitable light shelves according to latitudes for each office height condition (Figure 2.9). Creation of a new method to determine the light shelf size and position practically from new curve pairs for a random office height and a random latitude is another aim of the study. The results are significant for guiding to determine the suitable light shelf size and position practically without making any calculations (Kurtaya and Esenb, 2017).

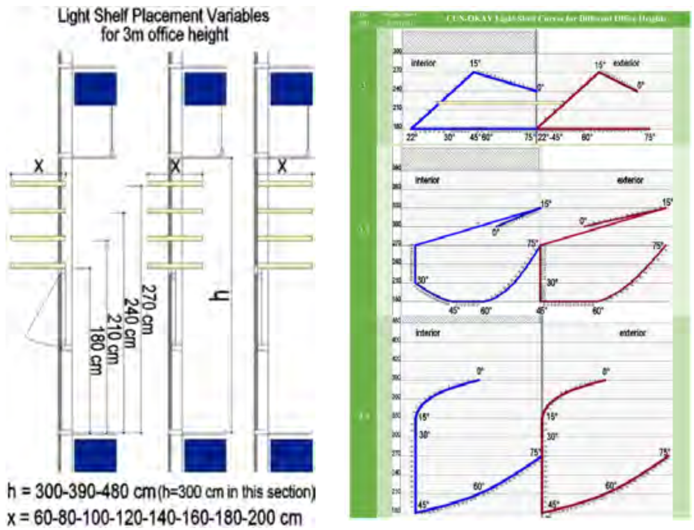


Figure 2.9 Placement variation of light shelf for study and CUN-OKAY light shelf curves (Kurtaya and Esenb, 2017).

ii) Institutional buildings

A study has been done in an educational building in Tehran aimed to investigate the impact of light shelf geometry parameters on daylight efficiency and visual comfort in different orientations. They used annual and advanced analysis and simulation, in order to obtain visual comfort and a suitable daylight distribution (Figure 2.10). The result shows that light shelves are most efficient in the southern orientation. They increase suitable daylight by 2%–40% and reduce 330 hours of annual glare compared to the shelf-less case. It does not perform well at other orientations either. At the northern orientation, light shelves are not efficient because of less direct sunlight. The light shelf can have optimum efficiency in eastern and western orientations (Moazzeni and Ghiabaklou, 2016).

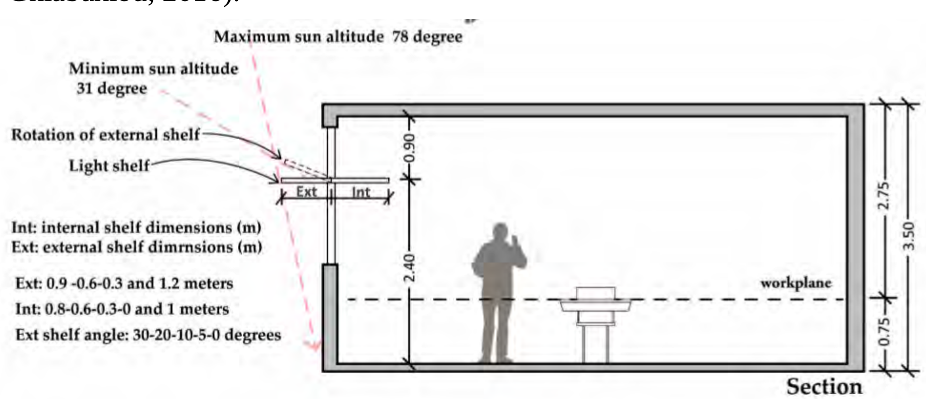


Figure 2.10 Classroom height, work plane and shelf location. Cited from: Moazzeni and Ghiabaklou (2016).

In a study by Aik Meresi in Athens, Greece light shelf was used to utilize daylight efficiently in a typical classroom. The paper evaluated different cases of a combination of light shelves and movable semi-transparent external blinds to efficiently exploit daylight in a typical Greek classroom with south orientation. The study included the simulation of many cases under the conditions of both overcast and clear skies using Athens climate data. From the results in the six analysis stages, a combination of a light shelf and semi-transparent movable external blinds can increase daylight exploitation in classrooms by providing shade and uniform distribution of daylight (Figure 2.11). It was proved that an external light shelf, positioned at 2.1m from the floor, with a width of 0.80 m ± 0.20 m, inclined at between 10° and 20° (external part higher), with a reflection index of 90% , in combination with movable external semi-transparent blinds, performed best in both improving the daylight distribution and protecting from glare (Meresi, 2016).

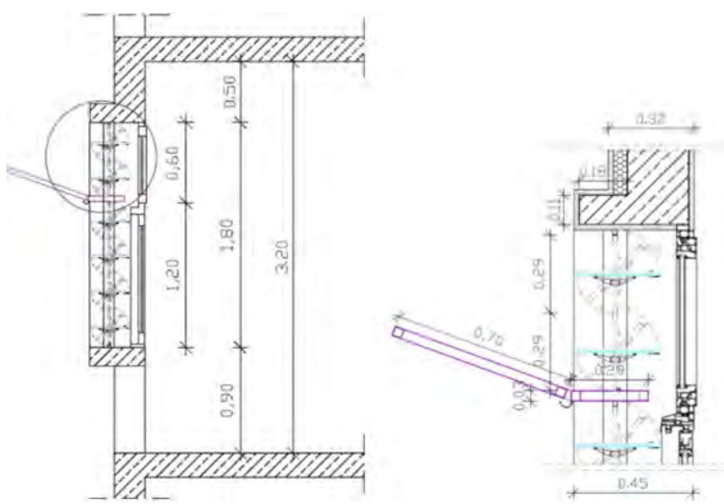


Figure 2.11 Indicative wall section and detail of a combination of light shelf and movable external blinds.

b) Light shelf for different sky conditions

As a general daylighting device for a room, the light shelf should ideally produce an improved daylight distribution at the back of a room for any sky condition (Claros and Soler, 2001; Soler and Oteiza, 1996). However, Freewan et al. (2008) state that there is a controversy over the potential of light shelves to increase illuminance levels in the rear of a room (Littlefair, Aizlewood, and Birtles 1994). Improvements in illuminance and energy savings are not always achievable. However, it is believed that light shelves are not efficient in terms of light penetration under overcast sky conditions and reduce the amount of daylight reaching the interior space (Eagan et al., 2002; Littlefair, 1996; Christoffersen, 1995; Aizlewood, 1993). They are more efficient under clear sunny skies typical of hot and arid regions.

Clear sunny skies

A study has been done under typical sky conditions of Biskra (Latitude 34.48 N, Longitude 5.44 N, Alt. 128 m above sea level). Biskra is a main town in Algeria situated in the south east on the border of the Sahara desert. In addition the microclimate of Biskra is characterized with sunny skies, little rainfall and high air temperatures. Research has done to choose the most appropriate configuration of light shelf system for the town of Biskra optimized according to orientation position material and design. According to the results of the simulations and measurements, it is possible to conclude that different tilting angles, configuration and a position of light shelves can contribute effectively to better results in natural lighting design in hot and arid regions (Safa et al. 2013).

Tropical sky condition

Tropical climate has a dynamic sky condition where the cloud formation differs in a matter of seconds. According to Zain-Ahmed et al. (2002), the hourly Nebulosity Index (NI) data indicated that 85.6% of the time, the sky is predominantly intermediate (2.3% intermediate overcast, 66.0% intermediate mean, 16.3% intermedi-ate blue, 14.0% overcast and 0% blue) at Subang, West Malaysia. On the similar findings, Djamila et al. (2002) proved that roughly 70-90% of the time, intermediate sky is exhibited in Kota Kinabalu, East Malaysia by using cloud cover ratio method. In contrast, by using NI method, the sky is 100% predominantly intermediate for the whole year. Clear skies are non-existence in Malaysia and thus, daylighting studies in the tropics shall consider inconsistent cloud formations of intermediate skies.

To obtain the global illuminance in tropical regions, irradiance data and proposed luminous efficacy constant were used. The global illuminance at noon time exceeds 80,000 lux in the month of March and achieves less intensity of 60 k lux in December (Zain-Ahmed et al., 2002). Previous research also shows that the global illuminance could be more than 100,000 lux (Lim et al. 2014 and Zain-Ahmed et al. 2002). Furthermore, the global illuminance acquired within the period of office working hour (9 am - 5 pm) exceeds 20,000 lux. These findings are similar to the data collected by researchers in other tropical regions in South East Asia and Africa (Pattarapanitchai et al., 2015; Fakra et al., 2011). Thus, the estimated value of 20,000 lux global illuminance can be employed for daylight factor (DF) analysis under overcast sky in tropical climate (Lim et al. 2013).

To bounce daylight by light shelf to the deepest part of a room suites well to most of the climates (IEA-ECBCS, 2010). The performances have been studied in various climates and sky conditions. Clear sky is the favorable condition to provide high average indoor illuminance level with even distribution. A Lightscape simulation based study, which was validated by field measurements (Wong and Istiadji, 2004) proved, however, that lightshelves could improve the indoor illuminance under a partly cloudy sky in Singapore. Another study on light shelf in warm tropics has been conducted under clear sky and overcast sky conditions in Yogyakarta, Indonesia based on Radiance simulations. In case of side windows with overhang, substitution of overhang with light shelf could improve the classroom’s visual uniformity (Binarti, 2005). To increase the effectiveness, Lim and Heng (2016) employed scaled physical models and computational simulation methods to examine the daylighting performance of lightshelves under several tropical sky conditions in Subang, Malaysia, i.e., intermediate sky with direct sunlight, intermediate sky without direct sunlight and overcast sky. Under clear sky conditions, daylighting performance of light shelf depends on the dynamic movement of solar position. Franco (Franco, 2007) proposed tilted and automatic light shelves to solve daylighting problems in hot tropics by adjusting the elevation of the internal shelf to the dynamic movement of solar position.

In the dense humid tropical urban area under clear and overcast sky conditions, light shelf created the most uniform daylight distribution in wide rooms (9m to 12m) with

North-facing windows in the Southern hemisphere and South-facing windows in the Northern hemisphere (Figure 2.12). The Daylight Autonomy (DA) of the room with light shelf was better than the DA of the other fenestrations. Under overcast sky conditions with south-facing windows in the Southern hemisphere and north-facing windows in the Northern hemisphere, the DA of the rooms with light shelf was lower than that of without shading device (Binarti and Dewi, 2016).

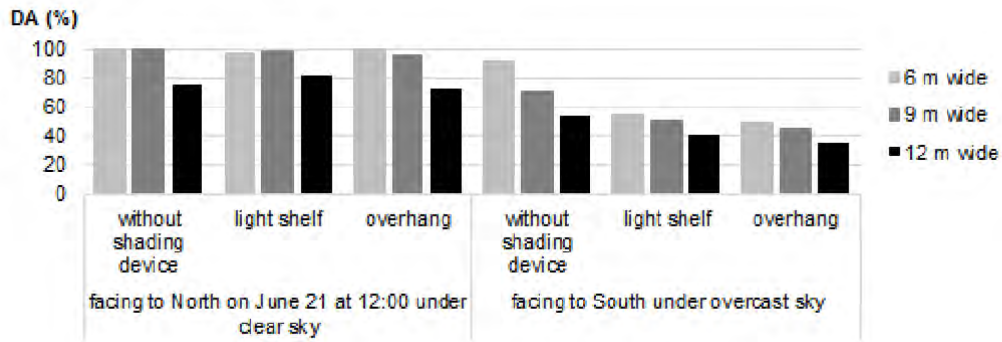


Figure 2.12 Percentage of the DA of 6 m, 9 m, and 12 m wide rooms with 3 variations in fenestration model on the first floor in an urban area. Cited from: Binarti and Sinta, 2016.

The Arhus city in Denmark is distinguished by shorter days in winter and longer days in summer. Because of the position of the sun is lower in general, they are subject to deficiencies in (sun) light and heat in the winter especially. For that reason, maximizing the influx of daylight is of utmost importance at these latitudes. For improved daylight penetration in light shelf systems using of a clearer glass in the part above the shelves for high daylight admission is needed. Using a tinted glass below for glare control and reduced glare will be helpful. Practical testing shows that the external light shelf system is more efficient in deeply recessed habitat space compared to internal light shelves (Figure 2.13) but the use of both systems would work best for optimal year round light distribution. An efficient design would need to consider and optimize the best possible arrangement of indoor and outdoor physical devices for best indoor illumination. Under these particular conditions, the external light shelves mounted on a normal window had a higher level of illumination than the internal system because of its position and geometry, with respect to the sun moving trajectory (Almsaad and Almusaed, 2014).

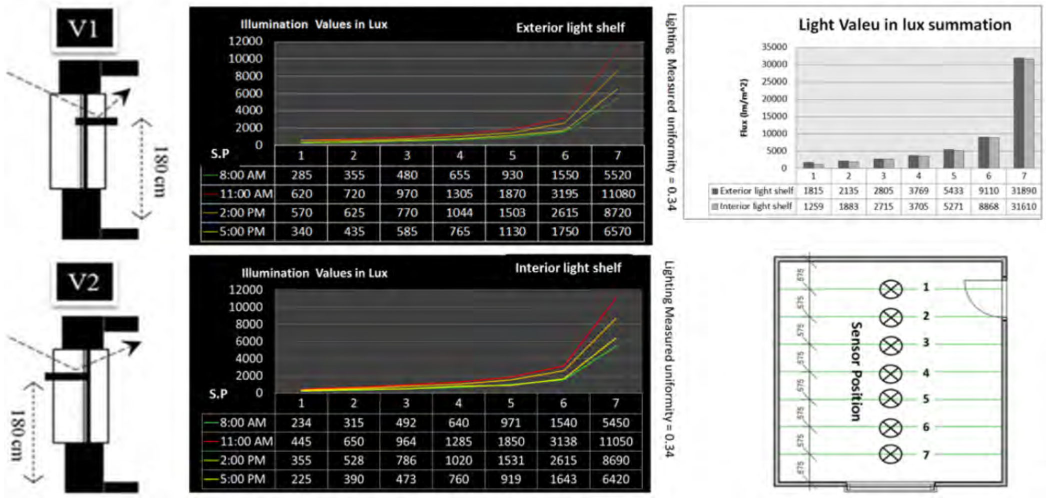


Figure 2.13 External and internal light shelf study result in Denmark (Almssad and Almusaed, 2014).

2.4.3 Different aspects of light shelf configuration

The light-shelf mechanism depends on receiving the direct sun light, and reflecting it to the ceiling and from there to the back of the room. Therefore, the light shelf's dimensions, location, reflectance, and room's surfaces reflectance and ceiling geometry are significant factors which affect the performance of the light shelf. In most of the studies, light shelf's performance was evaluated according to the illuminance levels on the working surface of a room or the luminance distribution on its surfaces. Since room dimensions used by various research teams varied widely, optimized designs varied as well.

Therefore, the criteria used for the performance evaluation of a light shelf, which are common among daylighting systems, are the following (Kontadakis et al., 2018).

1. Increase in illuminance especially in non-daylit areas.

2. Increase in uniformity.

3. Improvement of visual comfort.

4. Provision of sufficient shading.

The configuration of a light shelf varies to a great extent. As the performance of a light shelf depends on different aspects. Some aspects are discussed below.

a) Geometry and of light shelf

The performance varies as light shelves control diffuse and direct illuminance differently according to the shelf's geometry and the material used in its upper surface. The depth can significantly affect illuminance levels. An example is presented in Figure 2.14 (Kontadakis et al., 2018) of various interior radiance renderings of a south oriented room with dimensions 4×6×3 m and a window to floor ratio equal to 20% equipped with six different types light shelf.

The orientation, position in the facade (internal, external, or combined), and depth of a light shelf will always be a compromise between daylight and shading requirements. An internal light shelf, which redirects and reflects light, will reduce the amount of light received in the interior. For south-facing rooms (in the northern hemisphere), it is recommended that the depth of an internal light shelf be roughly equal to the height of the clerestory window head above the shelf. Moving the light shelf to the exterior creates a parallel movement of shaded area towards the window facade, which reduces daylight levels near the window and improves daylight uniformity. According to Littlefair (1995) the recommended depth of an external light shelf is roughly equal to its own height above the work plane. Glazing height and light shelf depth should be selected based on the specifics of latitude and climate.

Modifying light shelf geometries will change the way that the light collected and distributed. Therefore, the light shelf will collect more or less light and redistribute it deep into a space or near the window side. Consequently, the illuminance level increased or decreased based on the light shelf geometry.

b) Ceiling

The ceiling is an important secondary part of the light shelf system because light is reflected by the light shelf towards the ceiling and then reflected from the ceiling into the room. The characteristics of the ceiling that affect this process are surface finish, smoothness, and slope. Although a ceiling with a specular surface will reflect more light into the room, care should be taken to avoid glare from the ceiling reflections near the light shelf. To avoid glare, the ceiling finish is usually white diffusing or low-gloss paint. A study by (Al-Sallal, 2007) revealed that tilting the ceiling helped to reduce the difference in illuminance between the ceiling and the back and side walls in a tested space in a hot region.

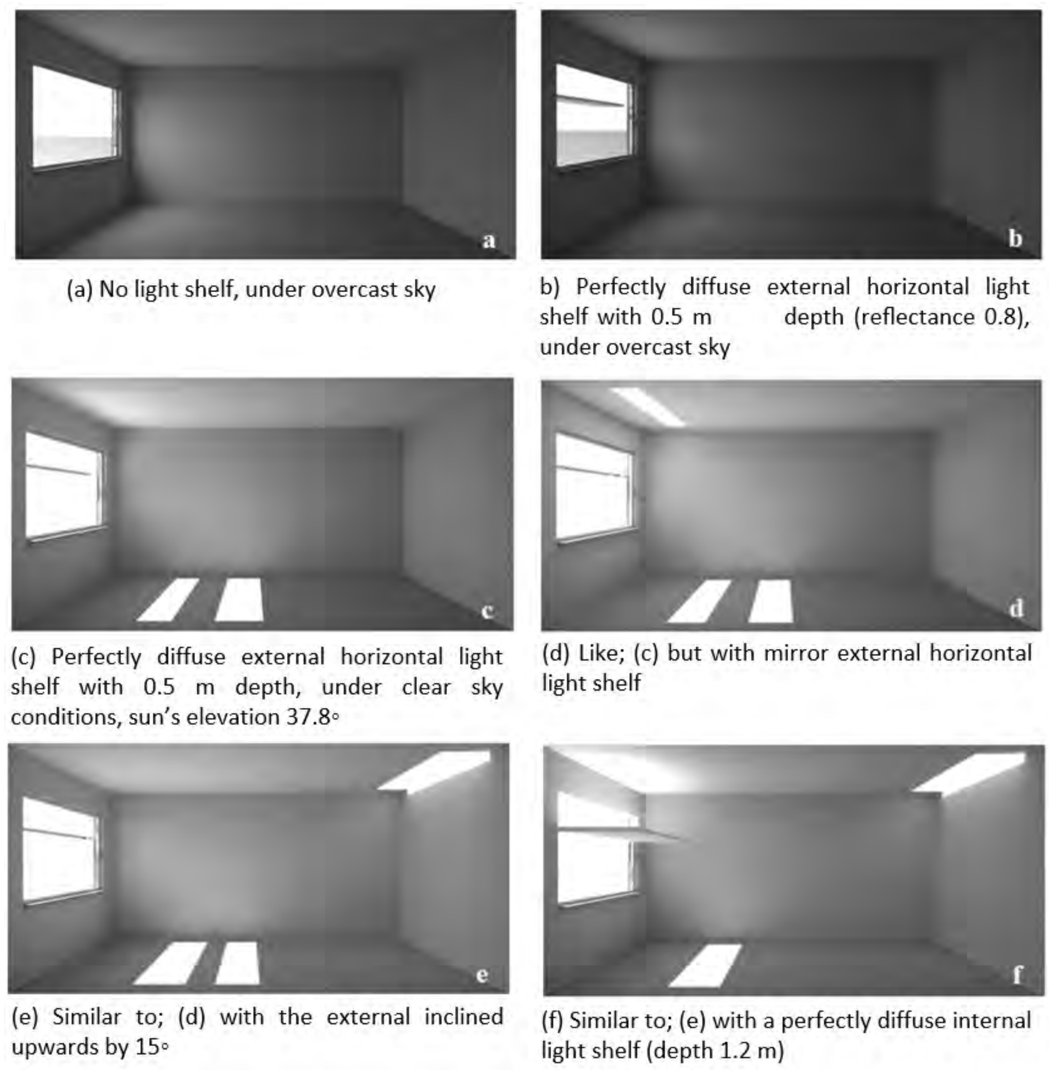


Figure 2.14 Various interior radiance renderings of a south oriented room with six different types light shelf (Kontadakis et al, 2018).

The penetration of light from a light shelf system depends on the ceiling slope. A gable style ceiling that slopes upwards from the window towards the center of the building will dramatically increase the depth to which light from the light shelf penetrates into the building. For a flat ceiling, light from the light shelf is mostly reflected into the space near the window, so penetration of light into the room is more modest. A study revealed that curved ceiling improved the performance of the light shelf. It helped to increase the illuminance level in the rear part and de-crease it in the front part and therefore improved the uniformity (Freewan et al. 2008).

c) Window and shading

The depth of the inner space has a direct effect on the intensity of illumination as well. If a space is modeled, keeping the floor-to-ceiling height and the area and location of the window constant, changing the room depth will cause a change in light intensity (Ander, 1995). For an efficient sustainable architecture, it is essential to understand that the quality and quantity of natural light that reach inner space depend on window orientation, form, height, and dimension. Orientation towards the east or west receives large amounts of solar energy in the morning period and in the same time in the afternoon. The westerly orientation for example, is disadvantages in the afternoon, where the sunlight becomes horizontal in the summer. The north direction in the northern hemisphere is totally different; it's without a direct sunlight, consequently the lighting in this position is very constant in light and temperature. The East and west parts of building get a little amount of sun light in autumn, spring and winter, but it is excessive in the period of summer (Scarazzato et al. 1996). A Well designed window improves optical comfort year round.

To prevent unwanted solar heating, a window must always be shaded from the direct solar component and often also from reflected components. It is generally agreed that the principle of thermal solar control is to let the sun's energy into the building during the winter and to intercept it in the summer. This simplified principle gained wide acceptance in architectural practice, prescribing overhangs according to the winter and summer solstice angles.

The seasonal positions of the sun are universally known in general terms. It is directly over the equator about March 21, the vernal equinox, and thereafter it appears farther north each day until it reaches its zenith above the Tropic of Cancer about June 21 (the summer solstice in northern latitudes). Then the sun appears a little more southerly each day, rising above the Equator about September 21 (the autumnal equinox) and reaching its most southerly point over the Tropic of Capricorn about December 21 (winter solstice). (Figure 2.15).

To know how the rays will strike a building and how far the rays will penetrate through the opening; to shade certain areas and irradiate others; to effectively use daylighting to reduce the use of artificial lighting; we must have the following information (Tarek et al., 2004):

1. The angle of the sun above horizon (altitude).
2. Azimuth of the sun, or its direction.
3. The angle of incidence of the sun relative to the surface being considered.

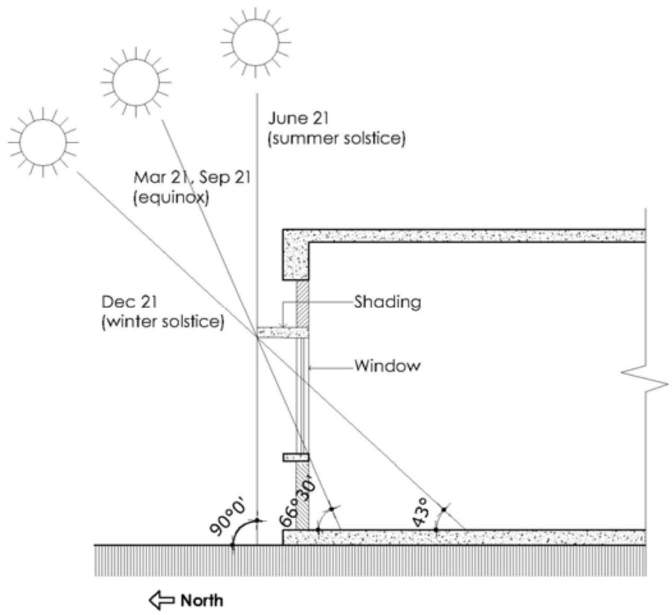


Figure 2.15 Solar solstice and equinox position for Dhaka, Bangladesh

The altitude angle is the angle of the sun above the horizon, achieving its maximum on a given day at solar noon. It is worthy to note that there is symmetry around solar noon. The azimuth angle is the directional angle of the sun's projection onto the ground "plane" relative to south. Altitude angles are high in the summer and low in the winter – with the difference between highest summer and lowest winter noon altitudes being roughly 47 degrees (ASHRAE, 2001).

The type, size and location of a shading device will therefore depend on solar angular relationships with the window in terms of solar altitude and azimuth.

By transmitting this information to scaled sectional and plan drawings, it is possible to determine the proper length and width of a shading device to completely shade the window during the overheated period, and let in solar radiation during the underheated period. The depth of a shading can be estimated with the help of some design chart (Saifelnasr, 2013; Brown & DeKay, 2001) prepared on the basis of solar path diagram. Therefore, some interactive computer program has been developed (A Kabre, 1999; Oh and Haberl, 1997; Bouchlaghem, 1996; Kensek et al., 1996) to establish the proper dimensions of horizontal and vertical shading devices.

d) Latitude of the building site

At low latitudes, the depth of internal light shelves can be extended to block direct sunlight coming through the clerestory window at different times (Figure 2.16). At higher latitudes and with east or west facing rooms, a light shelf may let some direct sunlight (low solar elevation) penetrate the interior, through the space between the light shelf and the ceiling, resulting in the need for additional shading devices. Increasing the depth of the shelf will reduce the problem but will also obstruct desired daylight penetration and outside view. Shading the window perimeter by tilting the shelf downward will reduce the amount of light reflected to the ceiling. Upward tilting will improve penetration of reflected daylight and reduce shading effects. A horizontal light shelf usually provides the best compromise between shading requirements and daylight distribution.

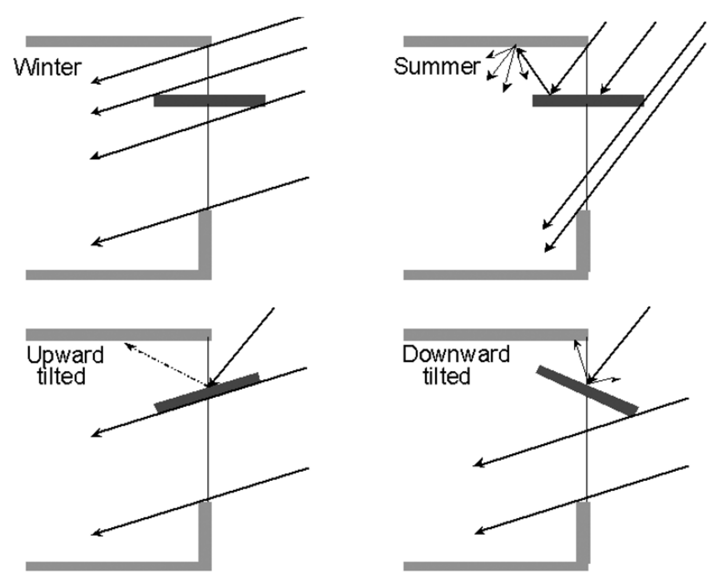


Figure 2.16 Light shelf with specular surface, showing the path of sunlight rays in two season; upward-downward tilted light shelf influences shading and daylight reflection

e) Season, solar altitude and angle of the sun

The illuminance penetrations through the window, varies significantly by season. Since the solar altitude is higher in summer, the penetration in summer is more tilted toward the window adjacent than in spring and fall. Extreme illumination was produced that touched the midpoint of the functional space in winter, probably because direct solar radiation incoming from below the light shelf is high in winter when solar altitudes are lower. The lighting environment in summer is consequently more reliable than that in other seasons (Beckett et al. 1974). The problems of day lighting involve the assessment of lighting generated from natural sources (sun and sky) at a certain reference point. It is therefore a matter of analyzing the light flux generated by these sources and the illumination they produce. Sky luminance varies according to a series of meteorological, seasonal, and geometrical parameters that are difficult to codify. In view of this problem some models of standard skies have been worked out, and simplified references can be made to some other limited conditions (Baker et al., 1993).

The level of daylighting on the floor of the habitat space in the building will vary throughout the day and around the year due to the angle of incidence of the sun on the building surface. An obvious characteristic of daylight is the quality in which it varies from season to season and even from minute to minute (Asaad and Amjad 2014)

As a general daylighting device for a room, the light shelf should ideally produce an improved daylight distribution at the back of a room for any sky condition (Claros and Soler, 2001; Soler and Oteiza, 1997). However detailed experimental studies shows that light shelf performance depends on the solar elevation, azimuth angle and, light shelf material reflectance (Carlos and Soler, 2002).

Although a light shelf is supposed to produce an improvement of illumination conditions and energy savings, this is not always the case. Light shelves have maximum efficiency when the sun shines directly over them (Ochoa and Capeluto, 2006). Claros and Soler (2002) and Soler and Oteiza (1996; 1997) studied the dependant of light shelf performance on solar geometry and surface reflectance. These studies revealed the need for careful light shelf's design in order to improve illuminance level in the back part of a room. The studies also demonstrated the dependence of light shelf on solar angle, time of year and day and model reflectance, yet illuminance level in the back of the room is not often improved.

2.5 Light Shelf Design Consideration

To ensure a well-designed and functional light shelf system, following considerations are necessary (Almusaed, 2010):

- A good treatment of windows. The lower part of the window under the light shelf system requires treatment to avoid the effect of glare.
- A precondition for an effective function of the light shelf system is orientation towards direct sunlight. The window has to be placed in direct sunlight in order to obtain an efficient system. However the lighting levels are still too unstable for any technical uses.
- The location is apparent for tall windows, where the light shelves can provide deeper penetration than daylighting that is modified by windows shades (Scarazzato et al., 2001).
- The operative system function of light shelf is offered by a modest reflecting surface, it could be made of a special form of aluminum foil.
- The distribution function of day lighting comes from the portion of the window that extends above the light shelf. The bottom portion of the window contributes daylight only to the narrow zone under the light shelf. The window must face towards the sun for a large part of the time, and outside objects cannot shade it. If the window glazing is tinted or reflective, the daylighting potential is reduced substantially (Almusaed, 2010).
- The ceiling is another vital part of the system that helps to distribute the sunlight, which is received from light shelves. In most cases, the ceiling should be highly reflective to save as much light as possible. The height and orientation of the ceiling and the diffusion characteristics of the ceiling distributes the daylight (Almusaed, 2010).
- Use of electric light has to be organized and calculated in accordance with the effects and positions of windows which can be improved by light shelves system.
- Exterior shelves are generally more effective shading devices than interior shelves. A combination of exterior and interior shelves will work best in providing an even illumination gradient (Almssad and Almusaed, 2014).

- A daylighting system cannot completely replace the need for electric lights. Daylight is only available during daylight hours. If a building is occupied during nighttime, a source of electric light is a must. An effective daylighting system should always include proper lighting controls to either dim or turn off electric lights. This system works best if it is designed to be automatic, as systems that require occupant intervention (dimmers, or switched banks) tend not to be used to their fullest potential, if at all.
- A light shelf system itself is a passive static system whereas the light that is incident is a dynamic source, constantly changing in altitude, azimuth, and intensity. It is almost not possible to have a perfect daylighting system that reflects 100% of the light 100% of the time. Because of the dynamic nature of the incident light, it is also extremely hard to predict exact lighting conditions or average expected luminance. There are a lot of factors associated with designing any daylighitng system. Some of these factors cannot be controlled, others have some control, and yet others have complete control. Again with these factors taken into account some can be predict well, and some are totally unpredictable.

The Factors that cannot be controlled but most are predictable.

- Project's location, specifically latitude. Latitude determines mainly solar altitude or the angle above horizontal that the sun is at in relationship to the project's position.
- Time of the year. The sun is at its lowest in the winter months and at its highest during the summer.
- Sky conditions such as cloud cover and pollution.
- Time of the day. The sun rises in the east and sets in the west.

Factors can be controlled:

- The orientation of the building.
- The design of the envelope, specifically location and size of windows
- The construction of the light shelf.
- Size (projection)
- Finishes

  - The ceiling construction.
  - The dimensions of the room to be lit.

- It is essential to consider light shelves at the beginning of the design process as they have an effect upon architectural design, but it also has the potential to improve existing building. They also require a relatively high ceiling in order to function effectively. Light shelves should be designed specifically for each window orientation, room configuration, and latitude.

- Light shelves are not operative utilizing north-facing glass. North-facing skies make available diffuse daylight relatively than direct sunlight for abundant of the year.

- They can be applied in climates with significant direct sunlight and are applicable in deep spaces on a south orientation in the northern hemisphere (north orientation in the southern hemisphere). Light shelves do not perform as well on east and west orientations and in climates dominated by overcast sky conditions.

- A curved profile of the reflecting surfaces of the light shelves can create a more effective and correct distribution of light, permitting deeper penetration of glare-free natural daylight.

- For avoiding of thermal bridges in the lighting system, attention when sun shades are joined to light shelves on the interior. A good design approach includes separation of these two mechanisms by independently attaching them to different framing, and a correct connection throughout the assembly is required to guarantee no thermal breaks occur.

2.6 Critical Findings from Literature Review

- Form above discussion, light shelf height 2 m is found (Section 2.4.2), better performs for 3 m height indoor space in Dhaka, Bangladesh.

- There are different opinions for the width of a light shelf (Section 2.4.2). The optimum width is varied depending on the season (Section 2.4.3).

- Firstly it was claimed that light shelf works only for clear sky condition (Section 2.4.2). Later different studies has done in different cities of different sky condition. So it proved that in different sky condition different types/width of light shelves performs better (Section 2.4.2).

- External light shelf system is more efficient in deeply recessed habitat space compared to internal light shelves. The external light shelves mounted on a normal window had a higher level of illumination than the internal system because of its position and geometry, with respect to the sun moving trajectory (Section 2.4.5).

- Southern orientation light shelves are most efficient. They increase suitable daylight in an educational building found from a study. (Section 2.4.2).

- The level of daylighting on the floor of the habitat space in the building will vary throughout the day and around the year due to the angle of incidence of the sun on the building surface. An obvious characteristic of daylight is the quality in which it varies from season to season and even from minute to minute (Section 2.4.2).

- Static horizontal light shelves should be employed only after careful design and performance evaluation. Adaptable light shelves and inclined ones are expected to have better performance (Section 2.4.3).

2.7 Summery

This chapter has achieved the first objective partially by mapping a chain of consequences of the potentiality of light shelf as strategy for daylighting in primary school classrooms. Within the scope of this thesis, benefits of daylighting, factors influencing illumination levels in every parts of a classroom, standard illumination for classroom have been discussed in this chapter, based on previous research and published sources. The findings of the chapter helped to select issues on which steps for the field survey and simulation study has been developed in Chapter 3.

3. CHAPTER THREE: METHODOLOGY

CHAPTER 3 METHODOLOGY

3.1 Preamble

In Chapter 2 the discussion was based on the outcomes of the literature review which is required as the background information on how field investigation and simulation study could be conducted. This chapter explains the detailed steps of the methodology of simulation exercise done during this research. The impact of lighting condition in different seasons with different widths of light shelf of a classroom can precisely be evaluated by simulation study. With advance lighting simulation tool, i.e. DAYSIM the amount of useful daylight inclusion and comfortable luminance conditions have been identified. The simulation parameters were derived from both literature study and field survey. The findings of this Chapter will assist to evaluate the performance of different widths of light shelf with the window of a classroom in Dhaka. This chapter consists the method of simulation tool selection, case room selection, and selection of different parameters for the case school building. Chapter 4 will compare the annual CBDM simulation results of different widths of light shelf based on the recommended methodology developed in this chapter.

3.2 Steps of daylight simulation

In this research, the prospective simulation study was chosen to identify the most feasible width of light shelf which can help to improve indoor luminous environment of classrooms. At first, field investigation was done to understand the present condition and selection of the case space. Then simulation tools were selected for measuring the performance of different widths of light shelf. The virtual 3D- case classroom was formed based on the field investigation data of the case building with the simulation tools. The selection of the test points and core test points were done and a measuring criterion was developed for the performance evaluation process. Figure 3.1 shows the flow diagram of the methodology for the simulation process of this research.

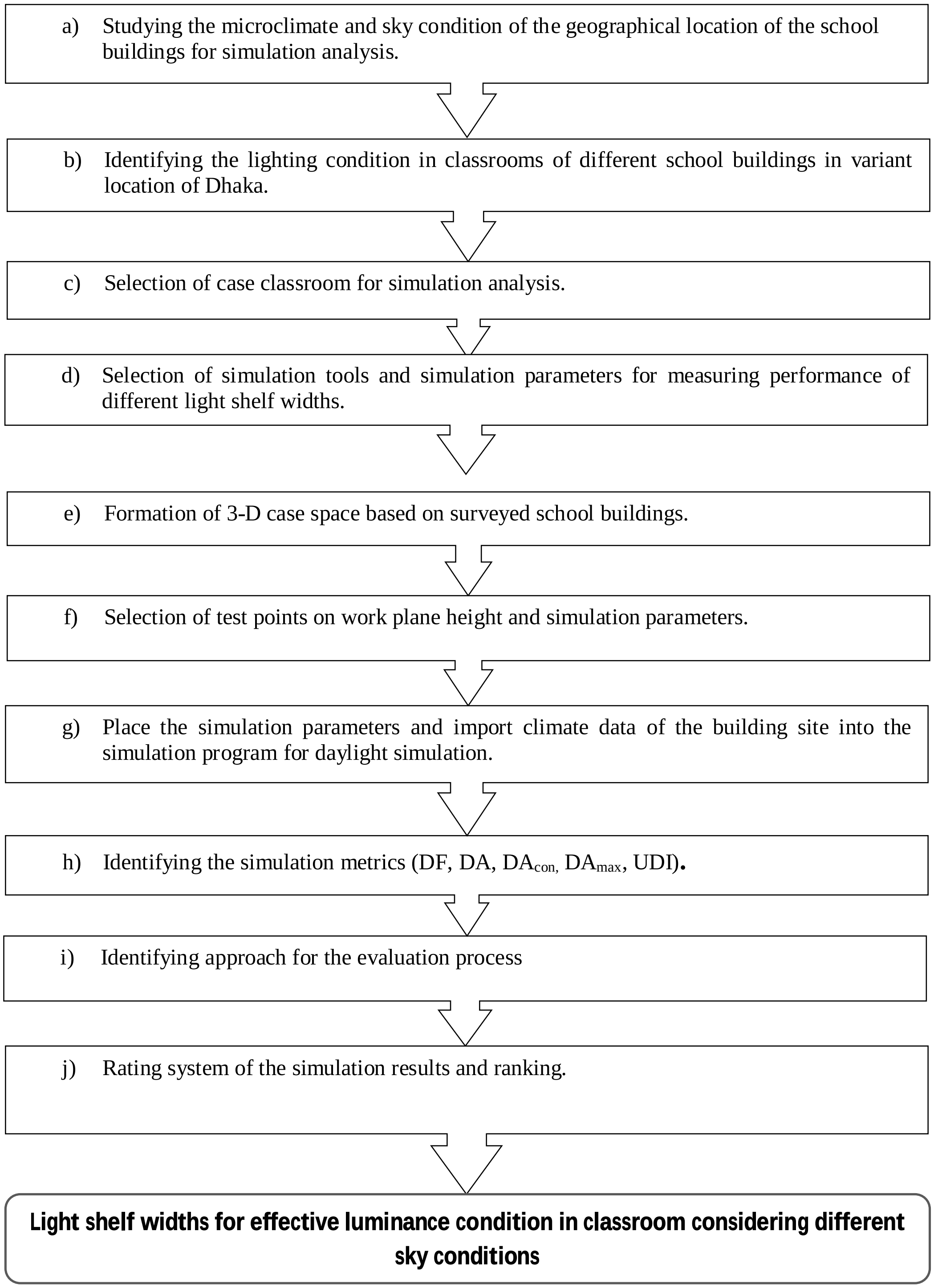


Figure 3.1 Flow diagram of the simulation process of the research. (after, Iqbal, 2015)

3.2.1 Microclimate of Dhaka

The location of Dhaka city is between longitude 90º20‘E and 90º30‘E and latitudes 23º40‘N and 23º55‘N. Dhaka faces a hot, wet and humid tropical climate. The city has a tropical savanna climate according to the Koppen climate classification. The city has a distinct monsoonal season, with an annual average temperature of 27.5°C (81.5°F) and monthly means varying between 19.5°C (67°F) in January and 32°C (90°F) in April .

The climate of Dhaka is tropical and has mainly three distinct seasons: – hot dry (March-May); hot humid (June-November); and cool dry season (December-February) (Ahmed, 1994).

The sky can be clear or overcast in different parts of the various seasons (Figure 3.2). During summer (March-May) the sky remains both clear (sunny with sun) and overcast. However, during the hot-humid (June-November) period, which includes the monsoons, the sky remains considerably overcast most of the time. It is only during the winter (December-February) that the sky mostly remains clear (U S D oE, 2008). So the designers face difficulties while designing considering it. The ways and means of tackling the two conditions are quite contrasting to each other (Ahmed, 1987).

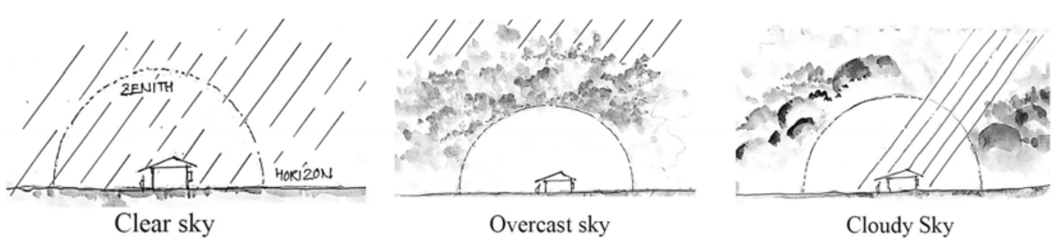


Figure 3.2 Various Sky Conditions (Source: Hossain, 2011)

In general, the cool dry season is short but the summer is long and wet. April is the hottest month with average maximum temperature that varies from 25.9ºC to 30.7ºC and January is the coldest month with average temperature ranging from 16.2ºC to 19.8ºC. Overheating is the major problem of Dhaka City, due to some associated factors. For example, it is noticed that from March to May there is high air temperature associated with high solar radiation (Joarder, 2007) (Figure 3.3).

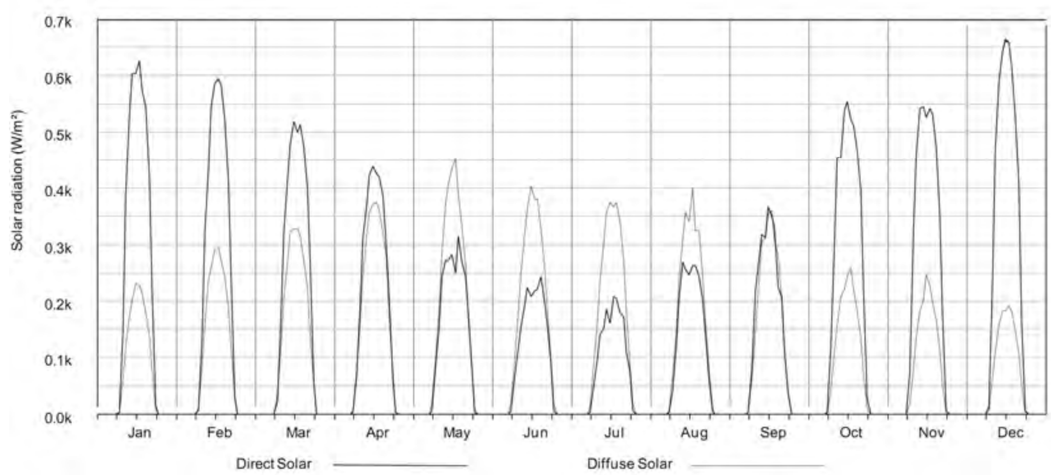


Figure 3. 3 Hourly solar radiation averaged by month for TRYs, Dhaka (source: U.S. Department of Energy, 2008).

From June to October, conditions with high humidity are associated with high air temperature. From March to May, minimizing the impact of solar radiation can potentially moderate the overheated condition, whereas from June to October maximizing wind flow can contribute to minimize the over-heating situation.

Table 3.1 shows the overall climatic condition of Dhaka related with thermal environment. The luminous environment of the city is related to the duration of sunshine hours and sky condition, two major climatic factors determining the quality and quantity of daylight. These two are discussed separately below.

Table 3.1: Climate data of Dhaka of the year- 2016 (Data source: Bangladesh Meteorological Department, Dhaka- 2017).

Climatic period	**Hot-dry**	**Warm -humid**	**Warm -humid**	**Cool-dry**
Month	Mar-may	Jun-Sep	Oct-Nov	Dec-Feb
Climatic Factors		(Monsoon)	(Post-Monsoon)	(Winter)
Air temperature (°c)				
a .Maximum	39.0°C	36.1°C	36.0°C	34.0°C
b. Minimum	18.2°C	22.8°C	14.9°C	10.0°C
c. Average	26.8°C	28.6°C	25.8°C	20.1°C
RH (%)	68.33	79.00	73.50	67.67
Rainfall (mm)	107.33	231.50	50.50	5.33
Sunshine hours	6.8	4.4	6.3	5.2
Cloud cover (octa)	4	6.3	3	1.3
Wind speed	3.0	2.4	2.25	2.4
Wind direction	S	S, E	W, NE	W

a. Sunshine hours and sun path diagram

Daylight availability of any locations is influenced by latitude and weather patterns (A.G.S. 2000). In the hot-dry period Dhaka has near to 9 hours of sunshine per day but during monsoon months (warm-humid season) this decreases to 5 hours per day due to cloud cover. Again it increases after September (Joarder 2007). Figure 3.4 shows the monthly average sunshine hours of 2015 for Dhaka city.

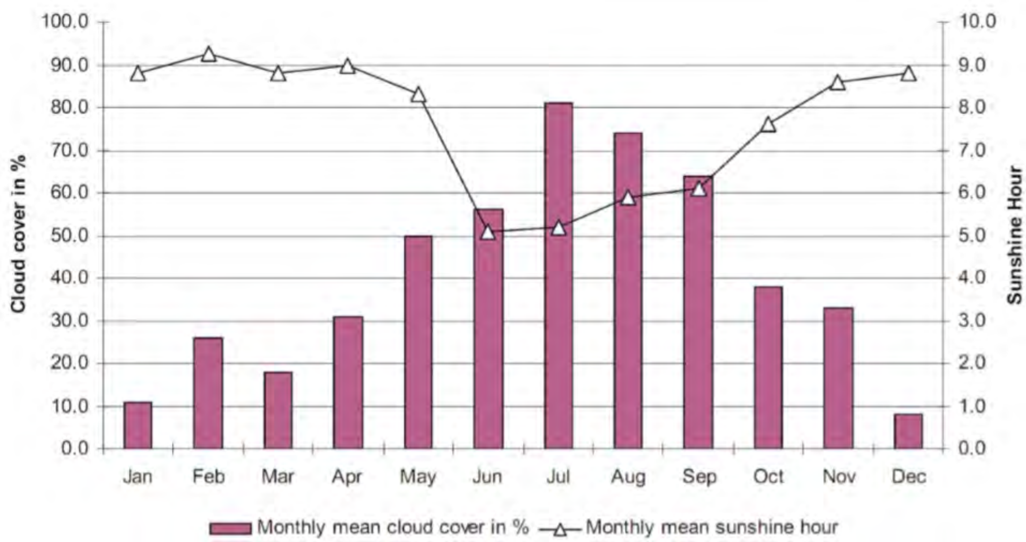


Figure 3.4 Monthly average cloud cover and sunshine hours in Dhaka (Data source: Bangladesh Meteorological Department, Dhaka- 2015; cited from Rahman, 2005).

The atmospheric condition during the month of June to September period is cloudy. As a consequence, the diffused component of the daylight is considerably high. The deviation in sunshine hours during June to September is wide. Figure 3.5 shows the sun path diagram of Dhaka, Bangladesh.

b. Sky condition

Direct sunlight is intense and fluctuates substantially as the sun's position changes throughout the day (up to 1,00,000 lux). Daylight from a clear sky can be 10% to 25% of the intensity of direct sunlight (10000-25000 lux). Daylight under partly cloudy conditions can be highly variable; daylight under full overcast conditions can be 5% to 10% of sun conditions (5000- 10000 lux) (AGS, 2000; Joarder, 2007). In context of Dhaka city the sky remains clear and overcast in different parts of various seasons (Figure 3.4). In summer (Hot Dry) the sky remains both clear (sunny with sun) and overcast. During the warm-humid (March-November) period, the sky remains overcast considerably. During monsoon (June-September) which is one third of the whole year the sky remains significantly overcast. During the winter (DecemberFebruary) the sky mostly remains clear. While during the rest of the year, both clear and overcast conditions are observed (Joarder et al., 2010; Joarder, et al., 2009). Table 3.2 shows sky condition with respect to cloud cover over a year round.

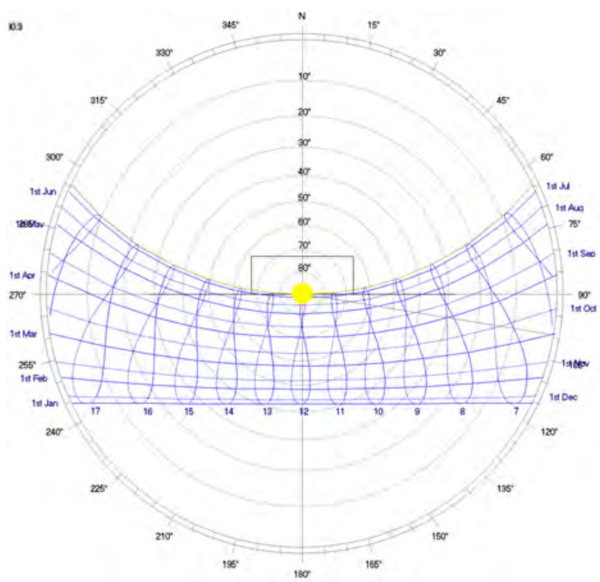


Figure 3.5 The sun path diagram of Dhaka, Bangladesh (Source: SUNTOOL - Solar Position Calculator, 1998; cited from Iqbal, 2015).

Table 3.2: Sky condition over a year round (Data source: Bangladesh Meteorological Department, Dhaka- 2005; cited from Iqbal, 2015).

Type of sky	Pre-monsoon (March-May)	Monsoon (Jun-Sept)	Post-Monsoon (Oct-Nov)	Cool Dry (Dec-Feb)	Total (day)
Clear sky	62	38	39	77	215
Overcast sky	30	84	22	14	150
Total sky	92	122	61	90	365

By use of statistical evaluation of long-term illumination records as 'design sky' illumination value can be established for a particular location. Suggested values for 'design sky' in the different latitudes are given in Table 3.3.

Published data on outdoor design sky illuminance specifies a value of approximately 10,000-12,000 lux for Dhaka latitudes (Hossain, 2011; Evans, 1980). Again in warm-humid climatic context with special reference to Dhaka, shows that eight-hour daylit time frame, an average of about 16,500 lux can be considered as outdoor design sky illuminance (Khan, 2005; cited from Joarder, 2007).

Table 3.3: Illumination from a design sky on a horizontal unobstructed surface on different latitude and solar altitude (Evans, 1980; Hossain, 2011).

Suggested values for overcast sky	**lux (lumen/m^2)**
Latitude 50-60^0	5,000
Latitude 40-50^0	5,000-6,000
Latitude 30-40^0	5,000- 8,000
Latitude 20-30^0	8,000-10,000
Latitude 10-20^0	10,000-15,000
Suggested values for overcast sky	
All latitude	5,000
Solar altitude 15^0	14,000
Solar altitude 30^0	36,000
Solar altitude 45^0	58,000
Solar altitude 60^0	75,000
Solar altitude 75^0	83,000
Solar altitude 90^0	94,000 to 110,000

3.2.2 Field investigation

Daylighting analysis is carried out through a study of selected school buildings and different window configurations of Dhaka. The process of selection is described in the following sections.

a) Significance of primary section classrooms in education system

The primary education system in Bangladesh is one of the largest systems in the country. The country has undertaken a number of measures to improve primary education since its independence. With a view to improve the quality of primary education, the Government of Bangladesh has undertaken an integrated sub-sector wide programme known as Primary Education Development Programme (PEDP) since 2005 in assistance with development partners. The Third Primary Education Development Programme (PEDP 3) for 2011-2016 (extended) is running to improve the quality at different levels of the primary education sub sector (BESR, 2015).

A large number of students are enrolling in the primary education level and it is the highest group of population. According to Bangladesh Education Statistics Report (2015) by Bangladesh Bureau of Educational Information and Statistics (BANBEIS) the total number of primary school is 80,397 and the enrolling student number is

16,225,658; which is a large number and the sector demands attention. This children group starts their first learning in a primary level school. The situation is more or less same in most of the schools in Bangladesh.

So when it comes to study the lighting condition of classroom it comes to the primary section as it is the largest group and first enrolled group of education.

b) The Prototype design of primary school by LGED

LGED is working on PEDP since 2003. There are several projects for example; reconstruction, renovation and new school building construction, that are completed and under construction. For these projects Design Section of LGED developed a prototype school building which started to construct schools in the new or old site in Dhaka and other parts of Bangladesh (EMR, LGED; April 2016).

The plan and section of primary school building designed by LGED are shown in Figure 3.6.

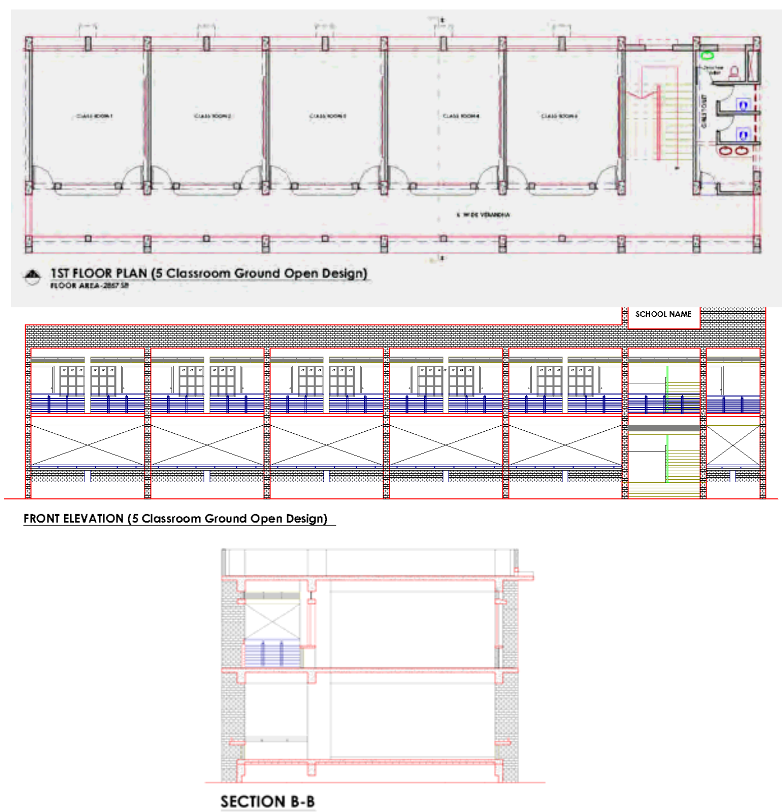


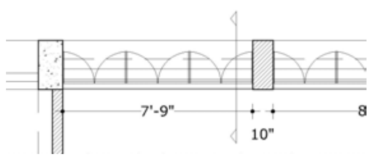
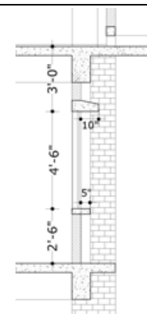
Figure 3.6 Plan, Elevation and Section of primary school building.

This design is customized during construction according to the need, site area and surroundings of the particular school. From the field survey it is noticed that the design is customized on the window size and type, in most of the cases and which is the major concern for daylighting situation.

c) Present situation of primary school classrooms

Existing classrooms of six different primary schools designed by LGED and located in Dhaka were surveyed priliminary to understand the physical characteristics of the windows and lighting condition. Table 3.4 – 3.9 shows the window configurations which are used in classrooms in different school buildings.

Table 3.4: Window configurations of Shahid Buddhijibi Dr. Amin Uddin Government Primary School

Plan of exterior wall window	**Section of exterior wall window**
	
Exterior view of the school	**Interior view of the classroom**
	

d) Different window categories

The windows on the exterior wall of the classroom are found two types. One is segregated viewing window and the other is continuous viewing window. The elevation of the two type windows are shown in Figure 3.7.

Table 3.5: Window configurations of Darussalam Government Primary School

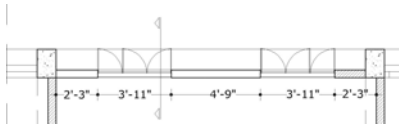
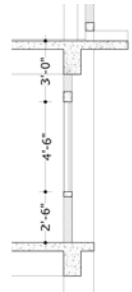
Plan of exterior wall window	**Section of exterior wall window**
	
Exterior view of the school	**Interior view of the classroom**
	

Table 3.6: Window configurations of Dorgah Government. Primary School

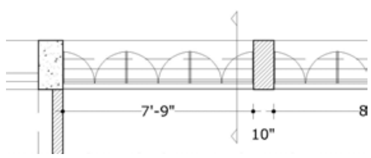
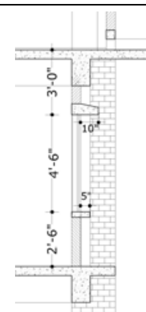
Plan of exterior wall window	**Section of exterior wall window**
	
Exterior view of the school	**Interior view of the classroom**
	

Table 3.7: Window configurations of Lalmatia Government Primary School

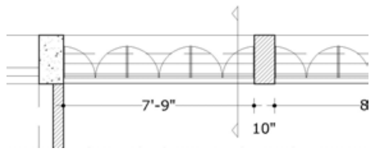
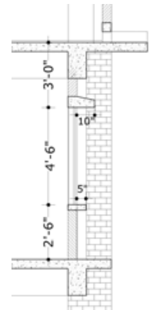
Plan of exterior wall window	**Section of exterior wall window**
	
Exterior view of the school	**Interior view of the classroom**
	

Table 3.8: Window configurations of Mohammadpur Government Primary School

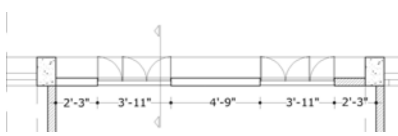
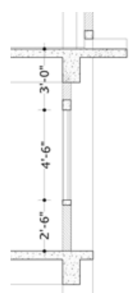
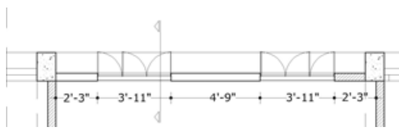
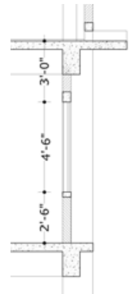
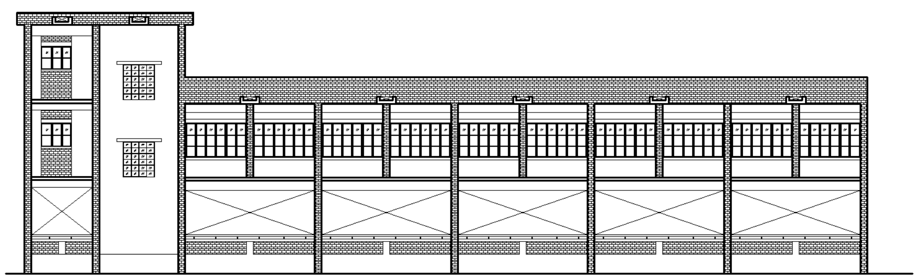
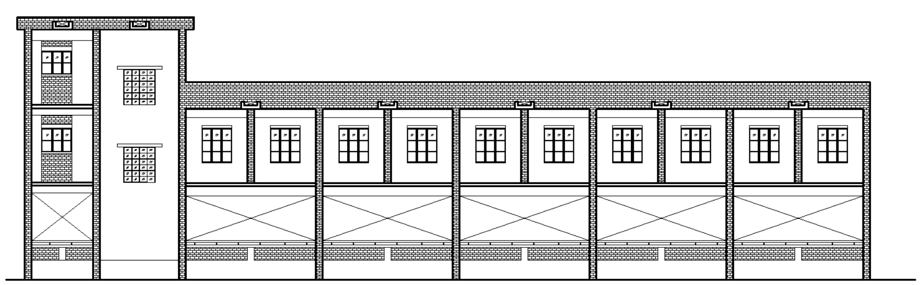
Plan of exterior wall window	**Section of exterior wall window**
	
Exterior view of the school	**Interior view of the classroom**
	

Table 3.9: Window configurations of Paikpara Government Staff Quarter Primary School

Plan of exterior wall window	**Section of exterior wall window**
	
Exterior view of the school	**Interior view of the classroom**
	



BACK ELEVATION of Window Type 01



BACK ELEVATION of Window Type 02

Figure 3.7 Elevation of the primary school building

From the primary survey it was found that the old buildings have the segregated windows. In the typical prototype plan LGED designed with the continuous window as the old ones did not get adequate light in the classroom. Some schools are constructed segregated window with the new plan as the continuous window causes glare problem.

e) Daylighting conditions of the selected school classrooms

In six different schools the context and site surroundings are different. The classrooms with small window apparently do not get adequate light upon every desk, i.e. in the corners of the room. The continuous window can bring a lot of light and the condition is better than the small window. But it creates glare problem. Again the condition of the classroom with both type widows vary with the sky condition and the time of the day. Especially in the Monsoon season the amount of the light varies in every single minute. Figure 3.8 shows the illuminance reading in a same classroom one near the window (446 lux) and the other opposite of the window (48 lux).

f) Observations from field investigation

The observations from the field survey are summarized below:

- Maximum illumination levels in the classrooms were much higher (i.e. 1260 lux) than the recommended maximum illumination level (500 lux), while minimum values (i.e. 105 lux) were well below than the illumination threshold (300 lux). (Table 4.66)
- The standard of uniformity ratio between the daylight levels in the front and back are not maintained in most of the classes.
- Except for the places near openings, daylight conditions in the classes are poor, especially at the rare parts. Students and teachers are dependent on artificial lighting most of the time and it became worse on the cloudy days.
- Large windows at exterior walls allow excessive daylighting, which cause glare in some classes. Closing the window and using the artificial light is a common practice in such situation.

Figure 3.8 Illuminance reading on the desk of the classroom

3.2.3 Selection of the case classroom for simulation analysis

For simulation study, the case school building was selected on the basis of following criteria to analyze the daylighting performance with light shelf (Sharmin, 2011).

a) Location of the school building would be in the urban context of Dhaka.
b) The case building should be a typical designed school building.
c) The building should be built in accordance with the Building Construction Regulations of the City Authority
d) Year of completion of the building should be within last 05 years (i.e. 2014 - 2019).
e) Classrooms must have the provision for significant daylight inclusion and distribution.
f) Exterior window on north/south wall for placement of light shelf.
g) Minimum three storey building to select a classroom in the middle of the building.

The Mohammadpur Government Primary School and Lalmatia Government Primary School are not selected for the second phase of survey as the buildings are old and the provision of daylight in classrooms ar not very well. Again Shahid Buddhijibi Dr. Amin Uddin Government Primary School also omitted from the selection as the building is one storey though it is a new building. The rest of three schools of three different places were selected for detail study based on the above criteria. The investigation covered a broad area through observation about the physical characteristics of the classrooms. As the choice of the case classroom was based on basic consideration that it has to be newly constructed according to the design of

LGED. A check was done to see that other criteria that are relevant in this study have been covered in the selection process (Table 3.10).

Table 3.10: Primary selection of the schools for detail study

Case no.	Name of the School	Number of Storey	Each classroom area	Student capacity per classroom	Exterior window openings	Location
01	Darussalam Government Primary	2	29.68 m^2	40	West	Mirpur Road, Mirpur, Dhaka.
02	Dorgah Government. Primary School	2	29.68 m^2	36	West	Mazar Road, Mirpur, Dhaka.
03	Paik para Government Staff Quarter Primary School	3	29.68 m^2	40	North	Paik Para Staff Colony, Mirpur, Dhaka.

Table 3.11, 3.12 and 3.13 presents data and plan of the shortlisted school buildings. Discussions of this section are aimed to select one of the school building among the three buildings as case building considering the orientation, provision of direct sunlight penetration height and site surroundings features. Items such as interior materials, finishes, and functions were excluded in the discussions, as these parameters were fixed in simulation study only for the selected case classroom.

Table 3.11: Field survey data of case 01: Darussalam Government Primary School

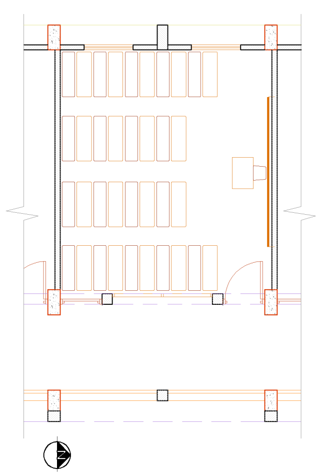
Name of the School	Shape of the room	Obstacle to Direct sunlight	Provision of effective windows	Depth (m)	Floor area	Direction of classroom arrangement
Darussalam Government Primary School	Regular	Corridor on East	On East and West wall	5.85	29.68 m^2	North - South direction
Plan of the classroom				**Existing condition (without electric lighting)**		
						

Table 3.12: Field survey data of case 02: Dorgah Government. Primary School

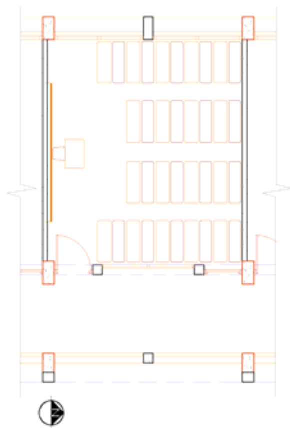
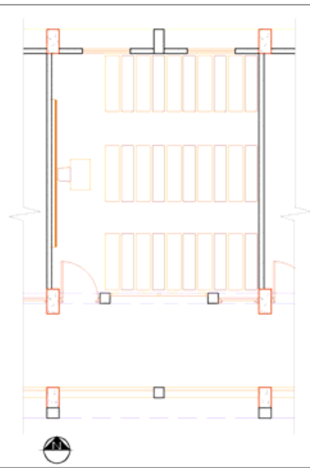
Name of the School	Shape of the room	Obstacle to Direct sunlight	Provision of effective windows	Depth (m)	Floor area	Direction of classroom arrangement
Dorgah Government. Primary School	Regular	Corridor on East	On East and West wall	5.85	29.68 m^2	North - South direction
Plan of the design studio				**Existing condition (without electric lighting)**		
						

Table 3.13: Field survey data of case 03: Paikpara Government Staff Quarter Primary School

Name of the School	Shape of the room	Obstacle to Direct sunlight	Provision of effective windows	Depth (m)	Floor area	Direction of classroom arrangement
Paik para Government Staff Quarter Primary School	Regular	Corridor on South	On North and South wall	5.85	29.68 m^2	East - West direction
Plan of the design studio				**Existing condition (without electric lighting)**		
						

From the above three case school buildings the case 03 (Paikpara Government Staff Quarter Primary School) is selected on the basis of 'Convenience Sampling Method' for simulation modelling as it fulfill all the criteria for selection (Table 3.14). Convenience sampling (also known as Haphazard Sampling or Accidental Sampling) is a type of nonprobability or nonrandom sampling where members of the target population that meet certain practical criteria, such as easy accessibility, geographical proximity, availability at a given time, or the willingness to participate are included for the purpose of the study (Dörnyei, 2007). The main objective of convenience sampling is to collect information from participants who are easily accessible to the researcher (Given and Lisa, 2008).

Table 3.14: Selection criteria of the school building for simulation study

Selection criteria	**In urban context of Dhaka**	**Typical designed school building**	**Built in accordance the construction regulation**	**Built within last five years**	**Provision for significant daylight**	**Exterior window on North/South wall**	**Three storey building**
Shahid Buddhijibi Dr. Amin Uddin Government Primary School	√	√	√	√	√	×	×
Darussalam Government Primary School	√	√	√	√	√	×	×
Dorgah Government. Primary School	√	√	√	√	√	×	×
Lalmatia Government Primary School	√	√	√	×	×	√	×
Mohammadpur Government Primary School	√	√	√	×	×	×	√
Paik para Government Staff Quarter Primary School	√	√	√	√	√	√	√

Paik para Government Staff Quarter Primary School building is a three storey structure and north-south oriented building (Figure 3.9). The construction is completed in 2015 (Figure 3.10). The building is surrounded by a number of trees (Figure 3.11). There are three classrooms in each floor and a toilet block at the east side (Figure 3.12). The classroom at the middle of the building on the first floor was selected for the simulation study.

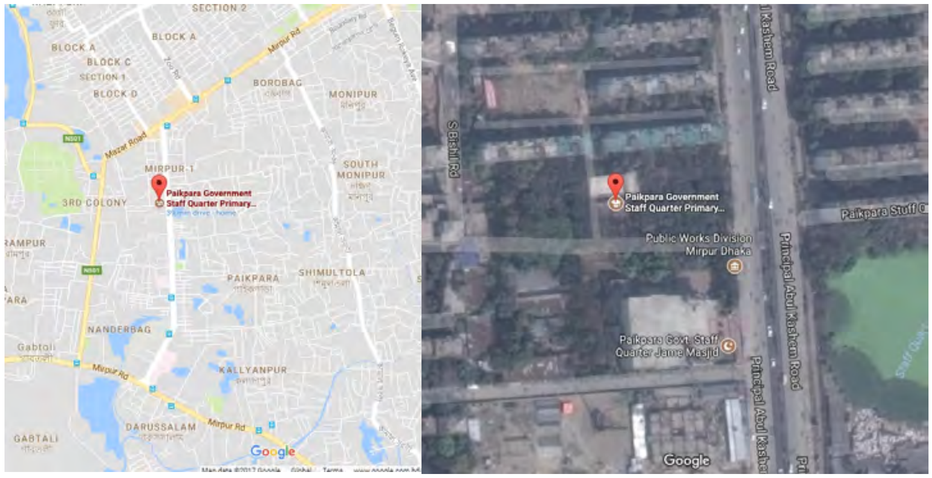


Figure 3.9 Location of the case study building Paik Para Staff Govt. Quarter Primary School

Figure 3.10 Case school building Paikpara Government Staff Quarter Primary School

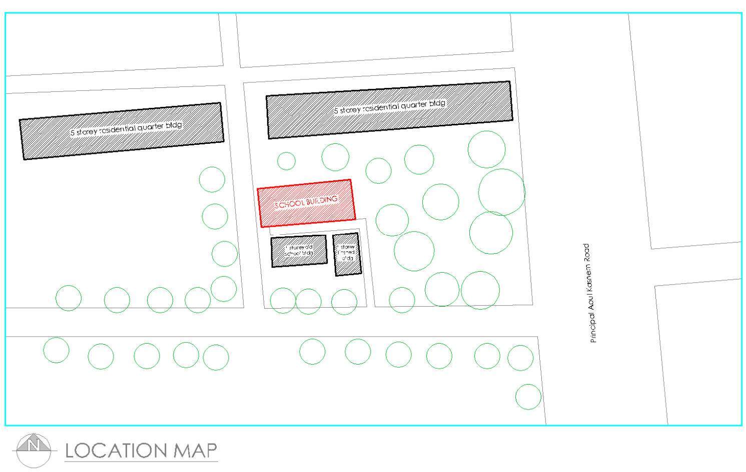


Figure 3.11 Site Plan of case school building Paikpara Government Staff Quarter Primary School

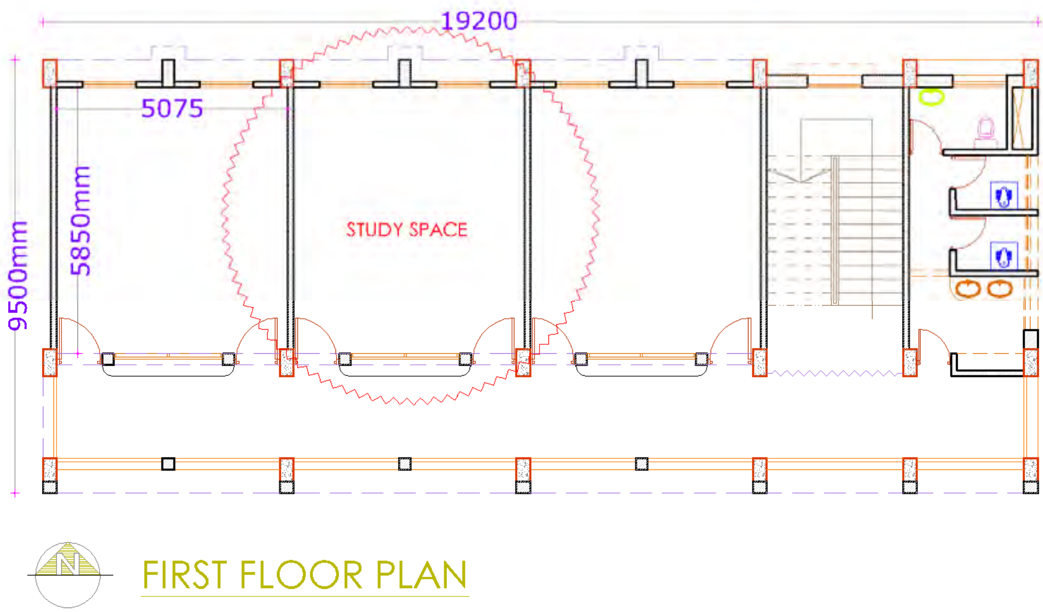


Figure 3.12: Floor Plan of case school building Paikpara Government Staff Quarter Primary School

The exterior windows of the case school building are on the north wall. As the light shelf work better on the south façade, during modelling of the building orientation was changed and the exterior façade modelled as the south. The window type also changed to continuous window as most of the cases the continuous window is constructed in the new structure. For the validation of the simulation reading, another model with exact same orientation and window type with the surroundings of the case study was modelled and run the simulation to compare the physical survey with the simulation result (Section 4.6).

3.2.4 Selection of daylighting simulation tools

There are a large number of simulation tools available concerning lighting and thermal simulation in buildings. Dubois *et al.* reviewed the existing computer tools widely used by architects today, covering a total of 56 computer programs which were classified into three categories: CAAD (computer-aided architectural design) tools, Visualization tools, and simulation tools (Kanters, 2014). For the evaluation of the daylighting concept, a suitable simulation tool was required, which (Joarder, 2011)

- has high prediction capability for indoor daylight distribution;
- can model simple to complex geometry with surrounding environments; and
- can provide climate based daylight metrics as output (e.g. DA and UDI).

In this research, the initial simulation model of the case classroom was constructed by ECOTECT V5.20 simulation program to analyze the lighting performance of different light shelf configurations. Among the RADIENCE based ray tracer, a limited number of software are able to calculate climate based metrics as final output, such as 3D SOLAR, GENELUX, LIGHTSWITCH WIZARD, S.P.O.T, LIGHT SOLVE and DAYSIM.

For daylight simulation analysis, DAYSIM 2.1.P4 (Appendix-F) was selected for simulation which satisfied the above mentioned three criteria. DF, DA, UDI>2000, DA_{max} above 5% and illumination on a specific point can be calculated by using DAYSIM simulation program. DAYSIM uses RADIANCE (backward) raytracer combined with a daylight coefficient approach (Tregenza, 1983). DAYSIM considers Perez all weather sky luminance models (Perez, 1990; 1993) and can provide more than 365 x 24 = 8760 hours' data for each sensor point. DAYSIM have been validated comprehensively and successfully for daylighting analysis (Reinhart, 2006).

3.2.5 3-D model of the case classroom for daylight simulation

For daylight simulation, the classroom was modelled in ECOTECT V5.5 (Appendix-D). The classroom at Paik para Government Staff Quarter Primary School is a rectangular room of 29.68 m^2 (5.075 m x 5.850 m), designed for 40 students which consists of exterior window openings on north façade. Two doors, one window and a continuous high window on south façade (Figure 3.13). A corridor runs through the floor in front of the room on south side. There are two windows of 1.55 m^2 (1.15m x 1.35m) each in the classroom at north side (Figure 3.13). The bottom level of the window was at 750 mm and the top level was at 2100 mm.

While modelling in ECOTECT V5.5 the whole plan of the building was rotated to 180° and made the North sign to downward. The exterior window was modelled on the south façade, as light shelf works better on south side and the corridor on the north side. The window on exterior façade modelled as per typical design of 3.14 m^2 (2.325m x 1.35m). The other dimensions interior and exterior environment was kept same as the case classroom. The existing classroom and the modelled classroom plan are shown in Figure 3.14.

Indoor and outdoor conditions were kept constant, as found in the physical survey, i.e. window size, sill height, work plane height and different material reflectance. The interior space was modelled as vacant, devoid of any partitions or furniture, to avoid the effects of such surfaces, which may block and reflect daylight and may hide the actual difference of the impacts of the different light shelf configurations being assessed (Joarder et al.,2009). Table 3.15 shows the modelling parameters for simulation study.

Figure 3.13 Interior view and corridor of the classroom at Paik para Government Staff Quarter Primary School

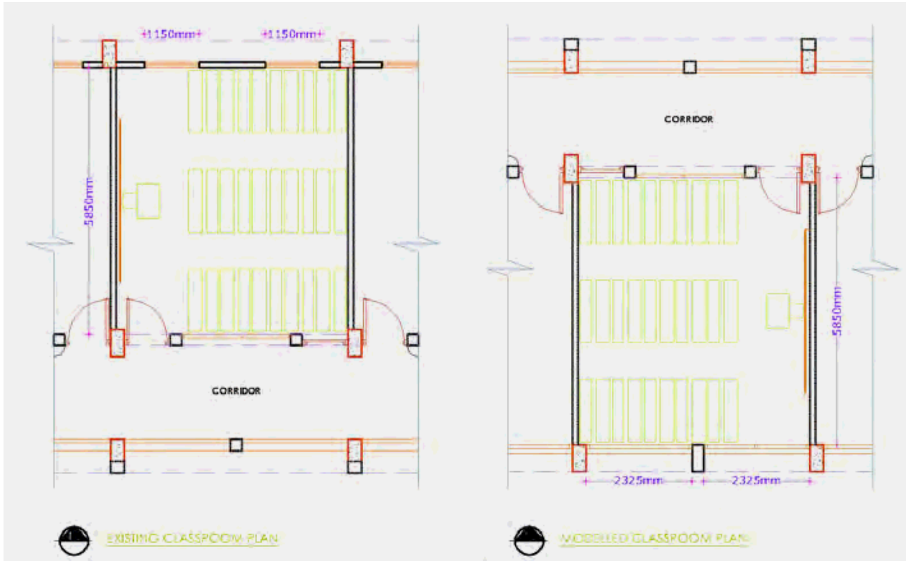


Figure 3.14 Plan of existing and modelled classroom at Paik para Government Staff Quarter Primary School

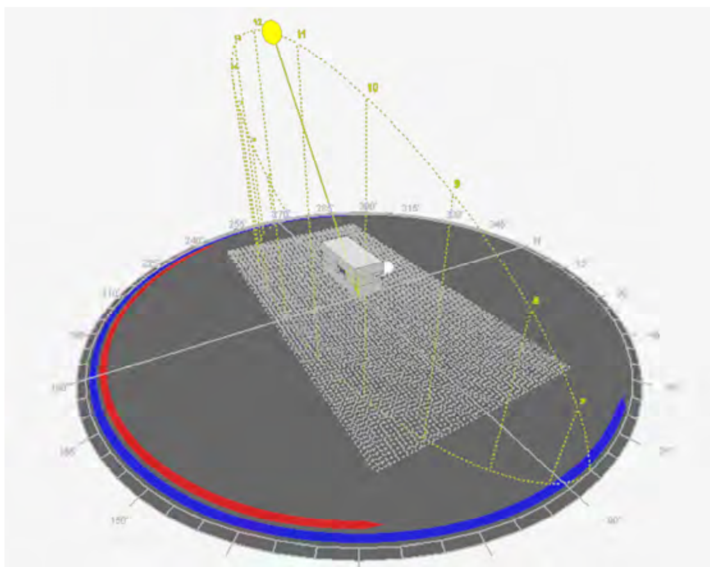


Figure 3.15 3-dimensional exterior view of the classroom at Paik para Government Staff Quarter Primary School

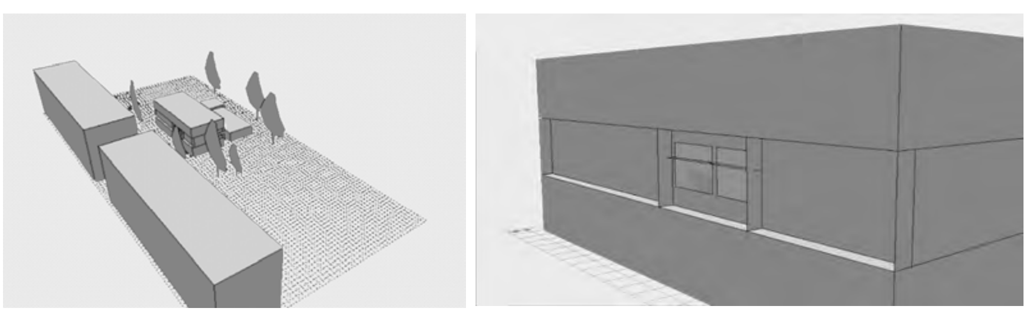


Figure 3.16 3-dimensional exterior view of the classroom at Paik para Government Staff Quarter Primary School with surrounding environment

Table 3.15: Modelling parameters of the classroom at Paik para Government Staff Quarter Primary School for daylight and simulation

Sl.	Parameters	Specification
1	Classroom floor dimension	5.075 m x 5.850 m
2	Classroom floor area	29.68 m^2
3	Window to floor area ratio	0.31%
4	Window size	3.14 m^2
5	Number of windows	3 nos.
7	Work plane height	0.75m
8	Window top level	2.1m
9	Window bottom height	0.75m
10	Ceiling	Height: 2.85m, Concrete, White painted
11	Average work plane height of studio table	0.75m
12	Floor	400mm x 400mm glazed tiles
13	Wall	North and East: Cream White colour painted on plaster West and South: Light Pastel colour painted on plaster
14	Window glazing	Single panel of glass with Wrought Iron frame with grill
15	Roof material	Concrete, white painted.

Material Properties for daylight simulation

For daylight simulation, material properties of the models were set according to the most common conditions found in the field surveys (Table 3.16)

Table 3.16: Material properties of the classrooms used for simulation study

Building element	Material description	Material properties
Ceiling	Concrete slab with plaster	80% diffuse reflectance
	North: Brick with plaster and White colour paint	50% diffuse reflectance
Walls	East: Brick with plaster and White colour paint	50% diffuse reflectance
	South: Brick with plaster and Light Pastel colour paint	40% diffuse reflectance
	West: Brick with plaster and Light Pastel colour paint	40% diffuse reflectance
Floor	Concrete slab on ground plus ceramic tiles	30% diffuse reflectance
Window	Single glazed with Wrought Iron frame	90% visual transmittance
Grill	Wrought Iron	50% diffuse reflectance

3.2.6 Test sensor points in 3-D space

With the reference of the furniture arrangements (desk), entire floor of the classroom at Paik Para Govt. Staff Quarter Primary School was divided into 56 sensor points for simulation purpose (Figure 3.17). These sensor points were set into the work plane height at 0.75m from the floor level, representing the average height of the desk.

Intersection points in the plan were coded according to the letter and number system shown in the Figure 3.17 and Table 3.17. A total of 7 test sensor axis lines were placed in XX' direction and 8 in YY' direction, in an equal distance of 700mm and 750mm from center to center.

For dynamic daylight simulation which considers all possible sky models throughout the year, eight points on the CC axis were selected as core sensor points (Figure 3.18). The calculations consider both daylight factor (DF) concepts under overcast sky conditions when there is no direct sunlight and dynamic metric concept under all possible sky conditions.

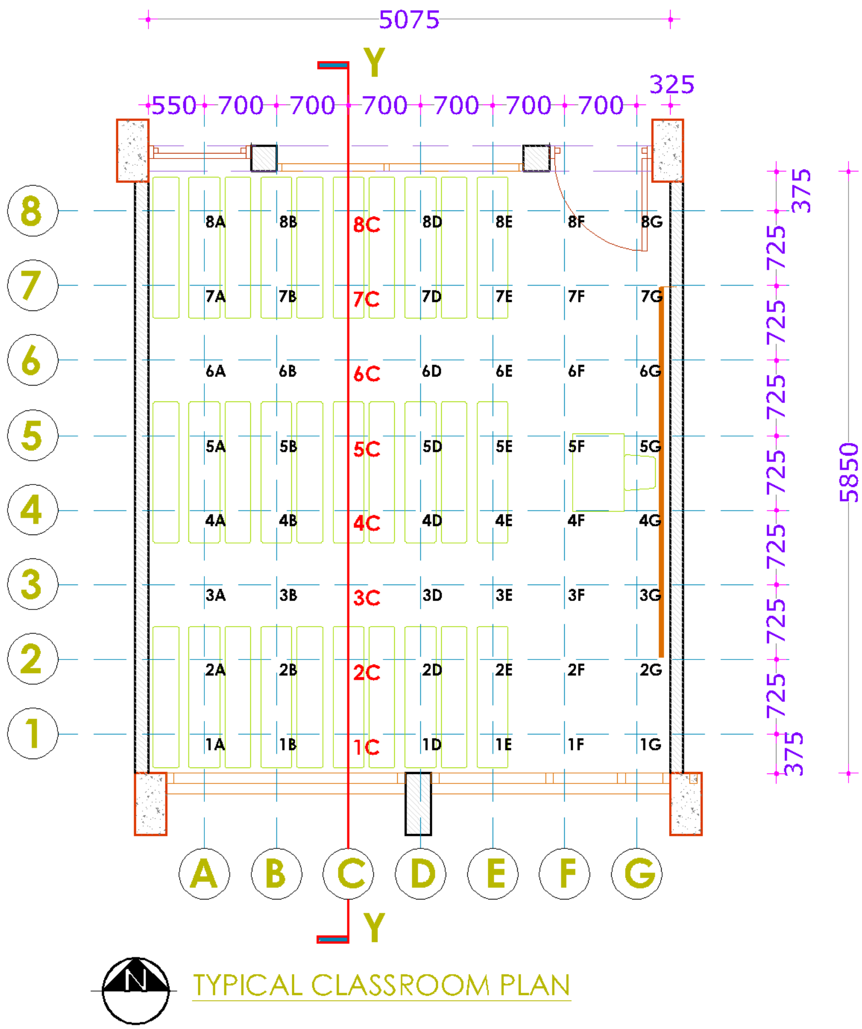


Figure 3.17 Classroom at Paik Para Govt. Staff Quarter Primary School showing the sensor point grids.

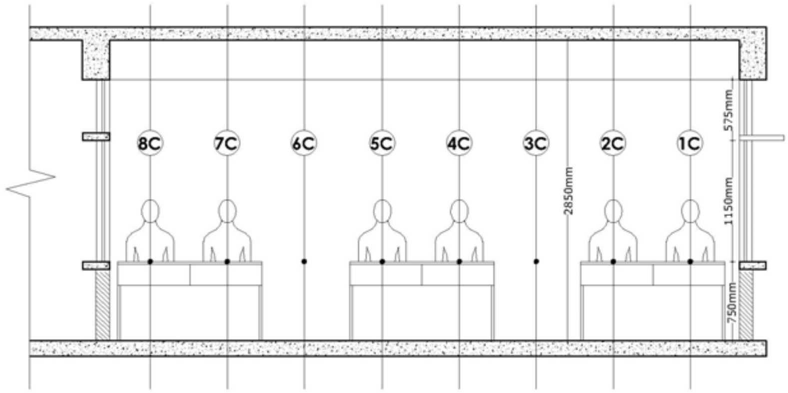


Figure 3.18 Cross section of the classroom at Paik Para Govt. Staff Quarter Primary School showing core sensor points.

Table 3.17: Intersection points for simulation study

	A	*B*	*C*	*D*	*E*	*F*	*G*
8	8A	8B	8C	8D	8E	8F	8G
7	7A	7B	7C	7D	7E	7F	7G
6	6A	6B	6C	6D	6E	6F	6G
5	5A	5B	5C	5D	5E	5F	5G
4	4A	4B	4C	4D	4E	4F	4G
3	3A	3B	3C	3D	3E	3F	3G
2	2A	2B	2C	2D	2E	2F	2G
1	1A	1B	1C	1D	1E	1F	1G
Visible node : 56							
Core sensor points: 1C, 2C, 3C, 4C, 5C, 6C, 7C, 8C.							

3.2.7 Simulation parameters

a) Time basis for daylight simulations

Calculation of hourly illumination was done for the whole year at intersecting grid points for dynamic daylight simulation. Each point provides 8760 (365 x 24) illumination data, considering 24 hours of the day and 3285 (365 x 09) data considering 09 hours of daylight time from 7:00 AM to 4:00 PM in 6 days a week.

Table 3.18 shows the parameters, considered for dynamic daylight metrics (Iqbal, 2015).

Table 3.18: Daylighting simulation parameters

Parameters	Specifications
Location	Dhaka, Bangladesh
Longitude	90.40˚N
Latitude	23.80˚E
Sky illuminance design	16,500 Lux (Khan, 2005)
Time zone	+6 GMT
Hours of operation	6 days a week, 7:00 AM to 4:00 PM
Simulation time	7:00 AM to 4:00 PM
Building construction type	ASHRAE 90.1 non Res.
Occupancy	40 persons
Date	For dynamic daylight metrics: whole year For Radiance simulation: 20 March, 21 June, 22 September, Awwwww21 December 2017
Sky illumination model	Perez all possible sky model round the year (Appendix-E).
Unit of dimension	SI, metric (m, cm, mm) Photometric dimension: SI (lux, cd/m2)
Daylight properties of sky window glaze portion	Transmission: 90% Pollution factor: 0.70 Framing factor: 0.90 Maintenance factor: 0.85

b) Climate database for daylight simulations

Hourly weather data 'BGD_Dhaka.419230_SWERE.epw, originated from the US Department of Energy for Dhaka/Tejgaon was used to give input in DAYSIM (USDoE, 2008).

c) Dynamic daylight simulation engine parameters

DAYSIM uses the same Raytracer used to generate RADIANCE rendering. As DAYSIM calculate illuminances at discrete sensors, the simulation parameters needed to be modified slightly. Higher parameter settings will result in longer process time. Therefore, the art is to use parameters that are “sufficiently high but not too high” (Joarder, 2011). Table 3.19 summarizes the non-default RADIANCE simulation parameters for the simulation analysis for complex geometry. Appendix-C provides the definition of terms used in Table 3.19.

Table 3.19: Utilized simulation parameters in DAYSIM (Reinhart, 2006)

Ambient bounces	Ambient division	Ambient sampling	Ambient accuracy	Ambient Resolution	Specular threshold	Direct sampling
5	1000	20	0.01	300	0.15	0.0

3.2.8 Metrics for simulation performance evaluation

Criteria were chosen which determine whether the daylight situation at a sensor is ‘adequate’ at a particular point in time. Several criteria have been suggested as following. Appendix-C provides the detailed lighting terminology.

1. **DF** is the ratio of internal light level to external light level and is defined as follows: DF = (Ei / Eo) x 100%

Where, E_i = illuminance due to daylight at a point on the indoor working plane
E_o = simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky.

2. **DA [%],** the percentage of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight alone (Reinhart and Walkenhors, 2001). For this simulation analysis the minimum illuminance requirement at work plane height is set as 300 lux (Perez et al, 1993). If arrival time is 8:00 AM and departure time is 5:00 pm, it means 9 hour of a day x 365 days = 3285 luminous hours round the year.

3. **UDI [%]** is hourly time values based upon three illumination ranges, 0-100 lux, 100-2000 lux, and over 2000 lux (Nabil, 2006). Below 100 lux is not considered as working light. It provides full credit only to values between 100 lux and 2,000 lux. This range is regarded as useful daylight illumination range. Horizontal illumination values above 2,000 lux range are not useful. 2000 lux is the upper threshold, above which daylight is not wanted due to potential glare or overheating. So, less value of UDI<2000 means good indoor luminous environment.

4. **DA_{max} [%]** is an illuminance-based glare analysis metrics. The idea is to calculate DA_{max} using an illuminance threshold which is 10 times the design illuminance. For example, if 300 lux is the threshold then over 300 x 10= 3000 lux will be counted as DA_{max} value. DA_{max} must not exceed 1%, for more than 5% of a critical working plane area (Iqbal, 2015).

3.2.9. Identifying approach for the evaluation process

In this research, Static daylight simulation (SDS) was done at first. A single sky model was considered for this simulation and identified illumination levels for all the sensor points. Performance evaluation of different light shelf during different seasons of the year and SDS have been evaluated according to the following criteria.

- Minimum Illumination
- Maximum Illumination
- Average Illumination
- No. of Points <300 lux
- No. of Points 300-500 lux
- No. of Points 501-900 lux
- No. of Glare Points (>900 lux)
- No. of Glare Points (>1500 lux)

Dynamic Daylight Simulation (DDS) of the case classroom generates the result of performance metrics for individual sensor points and it can be presented through graphical presentations as contour plots and false colour maps. These graphical presentations show how daylight is distributed throughout a space. However, it is necessary for a rating system to come up with single metric for a space.

For the dynamic performance metrics, different overall rating procedures have been proposed in the past. One approach is to concentrate on central core work plane sensors. Generally, sensor points on the central axis towards north-south direction are called central core work plane sensors. This is the approach that has been used for the daylight autonomy calculations (Reinhart, 2006). In this study, the sensor points are also set through the whole classroom layout plan to check the performances. Eight points on the CC axis were selected as core sensor points (Figure 3.18).

In dynamic daylight simulation has also done in this research. DA, DAmax, UDI<100, UDI100-2000, UDI>2000 and annual daylight exposure were measured. Dynamic metric simulation can consider all possible sky models throughout the year. The overall illumination level condition for the configurations have been evaluated in DDS according to the following criteria.

- Daylight autonomy [DA] [%]
- Maximum DA mean [DA max] [%]
- UDI<100 [%]
- UDI 100-2000[%]
- UDI> 2000 [%]

3.2.10. Rating system of the simulation results and ranking

Performance metrics can be used for comparative studies to guide building design or to benchmark a building against a pool of other buildings. Performance metrics range from being rather specific, e.g. it can be used to benchmark a light shelf configuration for primary school classrooms in Bangladesh against a pool of available light shelf configuration types used in the designed or renovated classrooms. These metrics usually combines several individual sub metrics into a single overall rating, stipulating a pass or fail criteria for each sub metric (Reinhart et al. 2006).

Dynamic Daylight Simulation (DDS) involve a pre-processing step during which a set of daylight coefficient is calculated for each sensor points and a post-processing step during which the daylight coefficient are coupled with the climate data to yield the annual time series of interior illuminance and luminance. On the other hand, dynamic simulation processes in this context meaning variable with time due to changing sky conditions and shading device settings, in contrast to static modelling concepts such as daylight factors.

Rating between different configurations simulated results is easier to interpret using the dynamic metrics e.g. DA, DAmax, UDI<100, UDI100-2000, UDI>2000 and annual daylight exposure metrics. In the rating of the different light shelf configurations according to the different metrics (Table 4.7), the highest value was considered as a rating of 4 points. When the values of the configuration types were decreased the rating point was also decreased respectively. The lowest value in any performance metric counted as '0' rating points. When all the studied configurations have got the ratings for each of the performance parametric, the total rating has been counted for each configuration individually. By comparing these individual performances total ratings, a ranking has been done (Table 4.7) to know which one secured the first position.

3.3 Summary

This chapter has achieved the first objective partially by highlighting the usefulness of light shelf as strategy for daylighting in classrooms. From field investigation it is found that the standard of uniformity ratio between the daylight levels in the front and back are not maintained in the classrooms in Dhaka due to different orientations, locations and contexts. Therefore, light shelf can be an effective solution in this condition as light shelf is supposed to reflect daylight to the inner part of a room.

This chapter also explains the methodology for simulation study and selection criteria of case classroom. The detail simulation study of different light shelf configurations placed in case classroom with respect to daylighting condition, is analyzed and presented in the next Chapter 4.

4. CHAPTER FOUR: SIMULATION STUDY AND RESULTS

CHAPTER 4 SIMULATION STUDY AND RESULTS

4.1 Preamble

Chapter 2 describes the basic information required to identify on which simulation could be conducted. Chapter 3 presents detail steps of the methodology of simulation study. This chapter contains the descriptions and outcomes of simulation exercise based on the information of previous two chapters. This chapter consists of three major parts. The first part describes the outcomes of static metrics which consider one sky model (overcast). The second part presents the results of dynamic metrics which considers all possible sky models in a year. The third part describes the findings of the experiment which was done to verify the results of simulation analysis with actual field measured data. The strategies based on the activities and key findings have been presented in concluding Chapter 5.

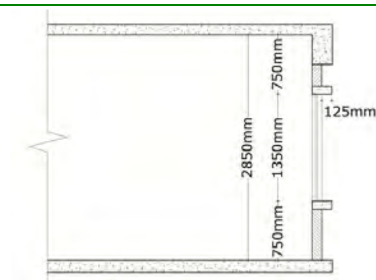
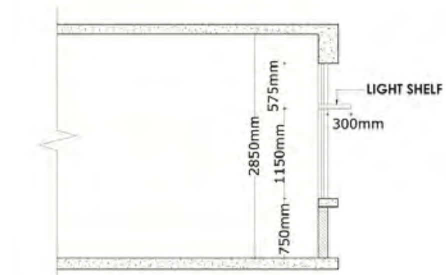
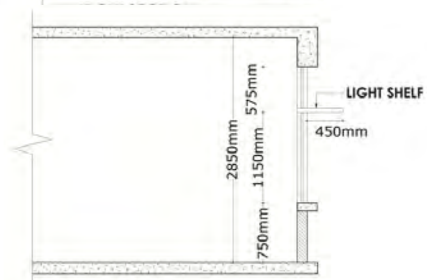
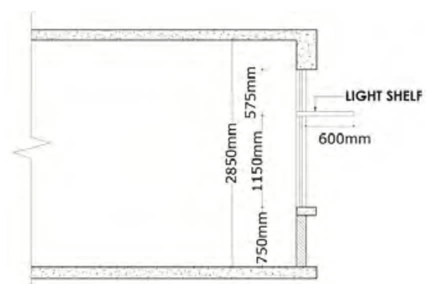
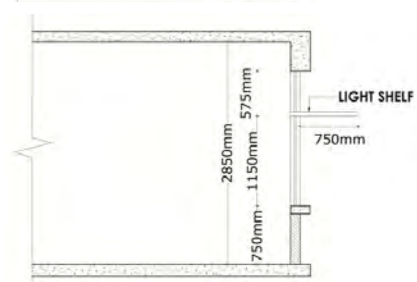
4.2 Evaluation of light shelf configuration performance

To start with, three case classroom window with five types of light shelf categories i.e. with no light shelf, 300mm width light shelf, 450mm width light shelf, 600mm width light shelf and 750mm width light shelf (Table 4.1) were modelled in ECOTECT V5.0 and transported to DAYSIM V2.1.P4 simulation software to analyze static and dynamic performance daylighting situations. The first segment was selected 300mm as found very common width in field survey as shading the window. The next segment was selected multiple of 150mm and the last width is limited to 750mm according to the shading width and set back rules of Building Construction Regulations.

Outdoor and indoor conditions and parameters were kept constant as found in field investigation and described in previous Chapter 3.

Five type light shelf configurations were coded as LSW 00, LSW 300, LSW 450, LSW 600, and LSW 750 (Table 4.1) and simulated in two metrics as following:
- Static metrics which considers overcast sky model.
- Dynamic metrics, which considers all possible sky models of 8760 hours of a year. For this research, 9 hours of a day was considered from 7:00AM to 4:00 PM.

Table 4.1: Light shelf configurations with dimensions.

<table>
<tr><th>Name</th><th>Width</th><th>Length</th><th>Height</th><th>Window section</th></tr>
<tr><td>LSW 00</td><td>No light shelf</td><td>2325mm</td><td>1900mm</td><td>
</td></tr>
<tr><td>LSW 300</td><td>300mm</td><td>2325mm</td><td>1900mm</td><td>
</td></tr>
<tr><td>LSW 450</td><td>450mm</td><td>2325mm</td><td>1900mm</td><td>
</td></tr>
<tr><td>LSW 600</td><td>600mm</td><td>2325mm</td><td>1900mm</td><td>
</td></tr>
<tr><td>LSW 750</td><td>750mm</td><td>2325mm</td><td>1900mm</td><td>
</td></tr>
</table>

Material properties and simulation parameters (e.g. intensity, timing and duration) were kept same as illustrated on previous chapter for both static and dynamic metric simulation process. The goal of the simulation analysis was to provide minimum 300 lux daylight illumination at each sensor points at work plane height, for duration of 9 hours in a day from 7:00 AM to 4:00 PM.

4.3 Static daylight simulation results

Static daylight simulations were done by considering single sky condition on a fixed time of a year. Simulation time was fixed at 1st April at 12:30 PM. For studied classrooms sky condition is overcast condition and design sky illumination level is 16500 lux for Dhaka (Khan, 2005).

In Paik para Govt. Staff Quarter Primary School classroom, simulation results were taken on the 56 sensor points on the work plane (750mm from floor level as described in Section 3.2.6). For cross checking another two classrooms from high schools and university was selected based on convenience sampling method for analysis: Government Laboratory High School classroom; and BUET- ECE Building classroom. In Government Laboratory High School classroom, simulation results were taken on the 110 sensor points on the work plane (Section 4.3.2). In BUET- ECE Building classroom simulation results were taken on the 180 sensor points on the work plane (Section 4.3.3)**.**

4.3.1 Static simulation result of Paik Para Govt. Staff Quarter Primary School

In Table 4.2 to 4.6, the static daylight simulation results are shown: average illumination level 639 lux with illumination range of 418 lux - 1489 lux for LSW 0; average illumination level 686 lux with illumination range of 509 lux - 1231 lux for LSW 300; average illumination level 667 lux with illumination range of 509 lux - 1166 lux for LSW 450; average illumination level 653 lux with illumination range of 508 lux - 1107 lux for LSW 600; and average illumination level 645 lux with illumination range of 506 lux – 1156 lux for LSW 750.

LSW 300 showed the highest average illumination level and LSW 0 showed lowest average illumination level. Appendix-G presents the detailed static daylight simulation data. With the use of light shelf the lowest illumination level increases 418 to 509 for both LSW 300 and LSW 450, but after that with the increase of light shelf width a small decrease on the lowest level illumination. The highest illumination level is 1489 for LSW 00 and it decreases with the increase of light shelf width.

Table 4.2: Static simulation result of LSW 0

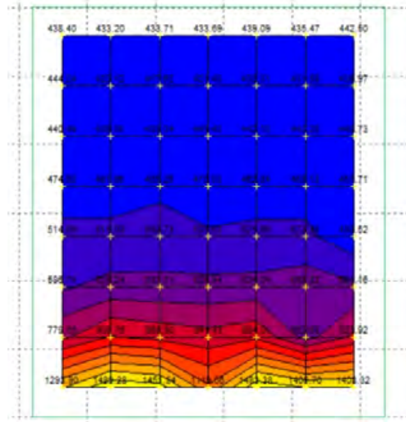
Name	Simulation result				Illumination level		
LSW 0					Average illumination level=639 lux Min. 418 lux Max. 1489 lux		
	A	**B**	**C**	**D**	**E**	**F**	**G**
1	*1294*	*1489*	*1452*	*1120*	*1483*	*1406*	*1408*
2	780	*909*	869	841	884	663	822
3	587	635	631	630	634	659	621
4	515	511	531	508	522	523	**431**
5	**475**	**482**	**485**	**470**	**462**	**458**	**458**
6	**440**	**438**	**433**	**443**	**442**	**442**	**441**
7	**444**	**423**	**418**	**421**	**432**	**432**	**439**
8	**438**	**433**	**434**	**434**	**439**	**435**	**442**

Table 4.3: Static simulation result of LSW 350

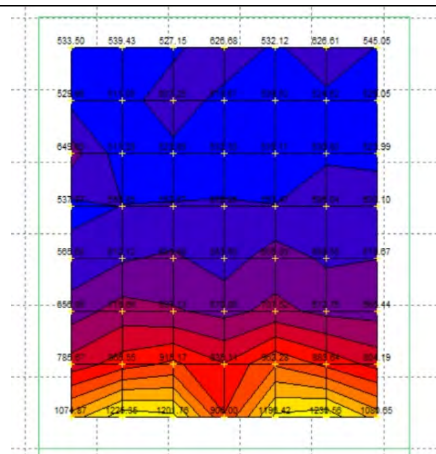
Name	Simulation result				Illumination level		
LSW 300					Average illumination level=686 lux Min. 509 lux Max. 1231 lux		
	A	**B**	**C**	**D**	**E**	**F**	**G**
1	*1075*	*1225*	*1202*	*906*	*1196*	*1231*	*1081*
2	786	866	*915*	835	*962*	884	804
3	657	720	697	671	708	673	665
4	566	612	632	584	656	609	620
5	537	551	553	553	550	587	600
6	649	511	524	532	535	539	524
7	530	511	607	516	509	525	529
8	534	539	527	627	532	627	545

Table 4.4: Static simulation result of LSW 450

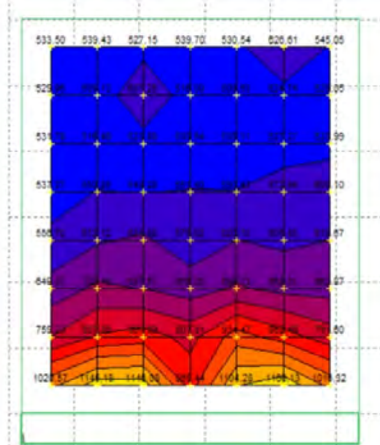
Name	**Simulation result**				**Illumination level**		
LSW 450					Average illumination level=667 lux Min. 509 lux Max. 1166 lux		
	A	**B**	**C**	**D**	**E**	**F**	**G**
1	*1021*	*1145*	*1146*	*869*	*1104*	*1166*	*1016*
2	759	837	862	808	*934*	862	792
3	649	703	688	656	699	668	663
4	557	612	632	576	621	605	620
5	537	551	549	551	550	573	600
6	532	516	524	531	535	527	524
7	530	509	607	516	509	525	529
8	534	539	527	540	531	627	545

Table 4.5: Static simulation result of LSW 600

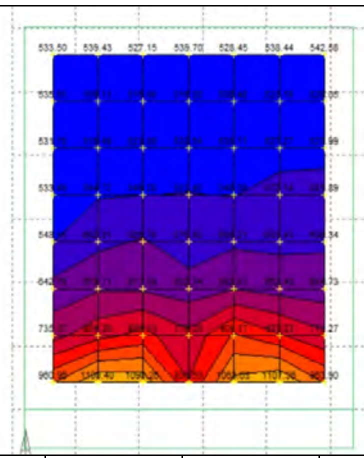
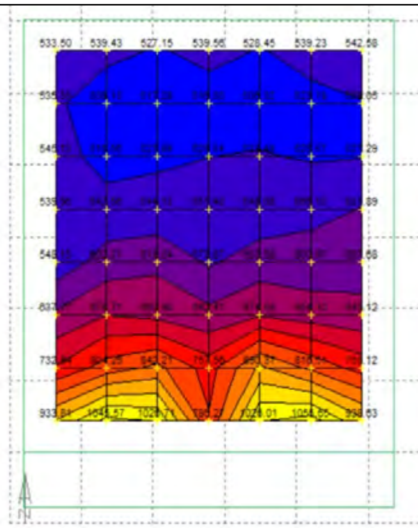
Name	***Simulation result***				***Illumination level***		
LSW 600					Average illumination level=653 lux Min. 508 lux Max. 1107 lux		
	A	***B***	***C***	***D***	***E***	***F***	***G***
1	*961*	*1100*	*1090*	*832*	*1064*	*1107*	*964*
2	735	804	854	778	*910*	837	771
3	643	680	678	652	683	662	655
4	548	602	627	576	608	603	608
5	533	545	549	551	548	572	582
6	532	516	524	531	535	527	524
7	536	509	516	516	508	523	529
8	534	539	527	540	528	538	543

Table 4.6: Static simulation result of LSW 750

Name	**Simulation result**				**Illumination level**		
LSW 750					Average illumination level=645 lux Min. 506 lux Max. 1056 lux		
	A	**B**	**C**	**D**	**E**	**F**	**G**
1	*934*	*1046*	*1027*	786	*1026*	*1056*	*939*
2	733	804	842	758	890	817	759
3	638	680	664	642	675	654	645
4	548	602	619	574	604	601	608
5	540	543	544	551	548	566	582
6	545	517	524	530	533	526	527
7	536	509	517	516	506	523	529
8	534	539	527	540	528	539	543

Rating system of the simulation results

To find out the preferable light shelf, rating has been done between the different light shelf widths simulated results. Table 4.7 shows the rating of the five types of light shelf configurations according to the different factors (minimum, maximum and average illumination level; no. of points less than 300 lux; no. of points 501-900 lux; no. of points greater than 900 lux; and no. of points greater than 1500 lux). From 1st to 5th place rating points were considered as 4points-0 point respectively (Reinhart et al., 2006).

After summing all the rating points achieved by the light shelf configurations, LSW 450 was found as superior with 22 points than other light shelf configuration types (Table 4.7). On the other hand, LSW 00 was found as lowest as it achieved only 11 points.

Table 4.7: Summery result and rating distribution of static simulation of different light shelf width for the window of Paik Para Govt. School classroom

Code of Light Shelf Widths		Min Illumination	Max Illumination	Average Illumination	**No. of points 300-500 lux**	No. of points 501-900 lux	*No. of glare points (>900)*	***No. of glare points (>1500)***	Total Rating Points	**Rank**
LSW 00	*Value*	*418*	*1489*	*639*	*29*	*19*	*8*	*0*	11	5th
	Rating point	0	0	0	4	0	3	4		
LSW 300	*Value*	*509*	*1231*	*686*	*0*	*47*	*9*	*0*	17	4th
	Rating point	4	1	4	3	1	0	4		
LSW 450	*Value*	*509*	*1166*	*667*	*0*	*48*	*8*	*0*	22	**1st**
	Rating point	4	2	3	3	3	3	4		
LSW 600	*Value*	*508*	*1107*	*653*	*0*	*48*	*8*	*0*	20	3rd
	Rating point	2	3	2	3	3	3	4		
LSW 750	*Value*	*506*	*1056*	*645*	*0*	*50*	*6*	*0*	21	2nd
	Rating point	1	4	1	3	4	4	4		

4.3.2 Static simulation result of Government Laboratory High School

The building of Government Laboratory High School Dhaka is a two storey structure and north-south oriented building (Figure 4.1). On the south side of the building there are some trees and there is a playground on the north side. There are six classrooms with a double loaded corridor. One classroom on first floor with south window was selected for simulation study (Figure 4.2, 4.3).

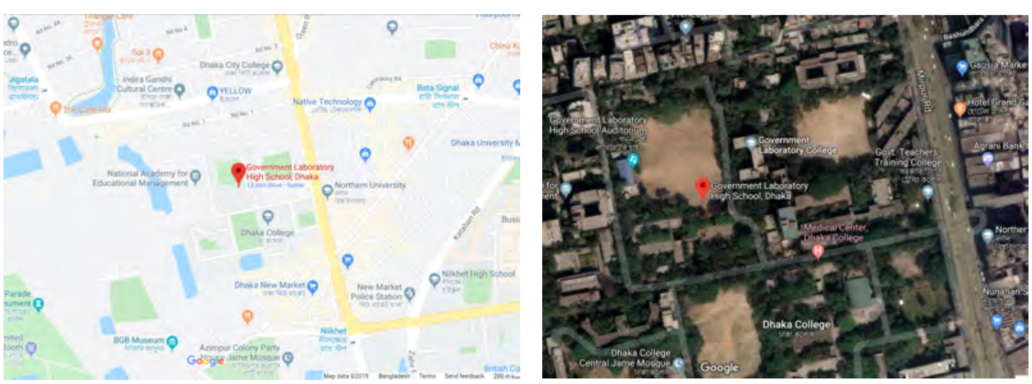


Figure 4.1 Location of the case study building of Govt. Laboratory High School

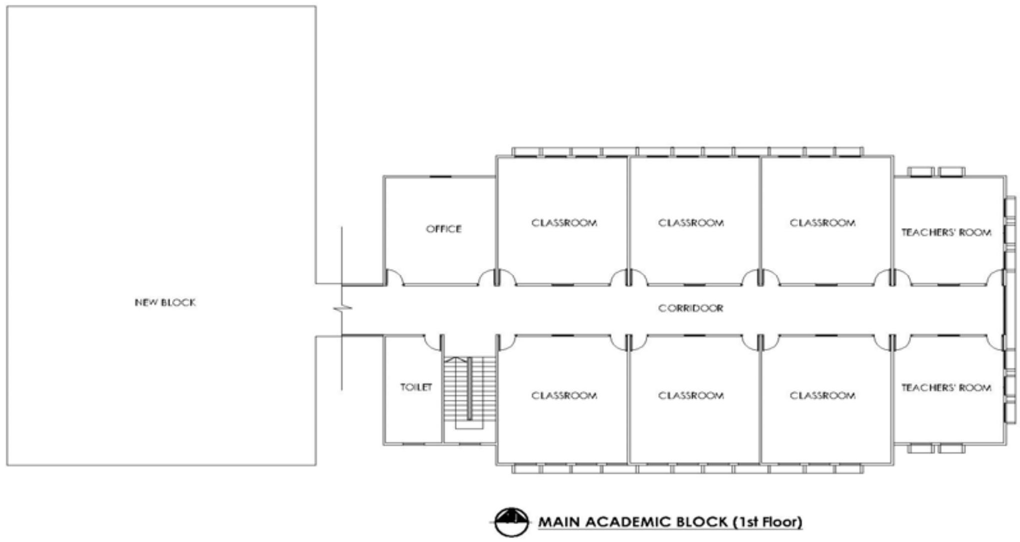


Figure 4.2 Floor plan of Govt. Laboratory High School (main academic block)

Figure 4.3 Exterior façade of Govt. Laboratory High School

The classroom at Govt. Laboratory High School is a rectangular room of 53.82 m^2 (6.9 m x 7.8 m), designed for 72 students which consists of exterior window openings on south façade. Four segregated windows with high windows on exterior wall (Figure 4.3). A corridor runs through the floor in front of the room on north side. The window area is 2.194 m^2 (1.125m x 1.950m) each in the classroom at south side (Figure 4.4). The bottom level of the window was at 750 mm and the top level was at 2700 mm.

Figure 4.4 Interior view of the classroom at Govt. Laboratory High School

Indoor and outdoor conditions were kept constant, as found in the physical survey, i.e. window size, sill height, work plane height and different material reflectance. The interior space was modelled as vacant, devoid of any partitions or furniture, to avoid the effects of such surfaces, which may block and reflect daylight and may hide the actual difference of the impacts of the different light shelf configurations being assessed (Joarder et al., 2009). Table 4.8 shows the modelling parameters for simulation study.

Table 4.8: Modelling parameters of classroom at Govt. Laboratory High School for daylight simulation

Sl.	Parameters	Specification
1	Classroom floor dimension	6.9 m x 7.8 m
2	Classroom floor area	53.82 m^2
3	Window to floor area ratio	0.163%
4	Window size	2.194 m^2
5	Number of windows	4 nos.
7	Work plane height	0.75m
8	Window top level	2.7m
9	Window bottom height	0.75m
10	Ceiling	Height: 3.55m, Concrete, White painted
11	Average work plane height of studio	0.75m
12	Floor	Cement finish on concrete
13	Wall	Light Yellow colour painted on plaster
14	Window glazing	Single panel of glass with Wrought Iron frame with grill
15	Roof material	Concrete, white painted.

The classroom at Government Laboratory High School, Dhaka was also divided into 110 sensor points for simulation purpose with the reference of the desk arrangements (Figure 4.5). These sensor points were set into the work plane height at 0.75m from the floor level, representing the average height of the desk.

Figure 4.5 Plan of existing classroom at Govt. Laboratory School

Intersection points in the plan were coded according to the letter and number system shown in the Figure 4.6. A total of 10 test sensor axis lines were placed in XX' direction and 11 in YY' direction, in an equal distance of 700mm and 675mm from center to center.

In table 4.9 to 4.13, the static daylight simulation results are shown: average illumination level 536 lux with illumination range of 268 lux - 1346 lux for LSW 00; average illumination level 637 lux with illumination range of 478 lux - 1278 lux for LSW 300; average illumination level 624 lux with illumination range of 478 lux - 1199 lux for LSW 450; average illumination level 613 lux with illumination range of 476 lux - 1149 lux for LSW 600; and average illumination level 604 lux with illumination range of 476 lux – 1085 lux for LSW 750.

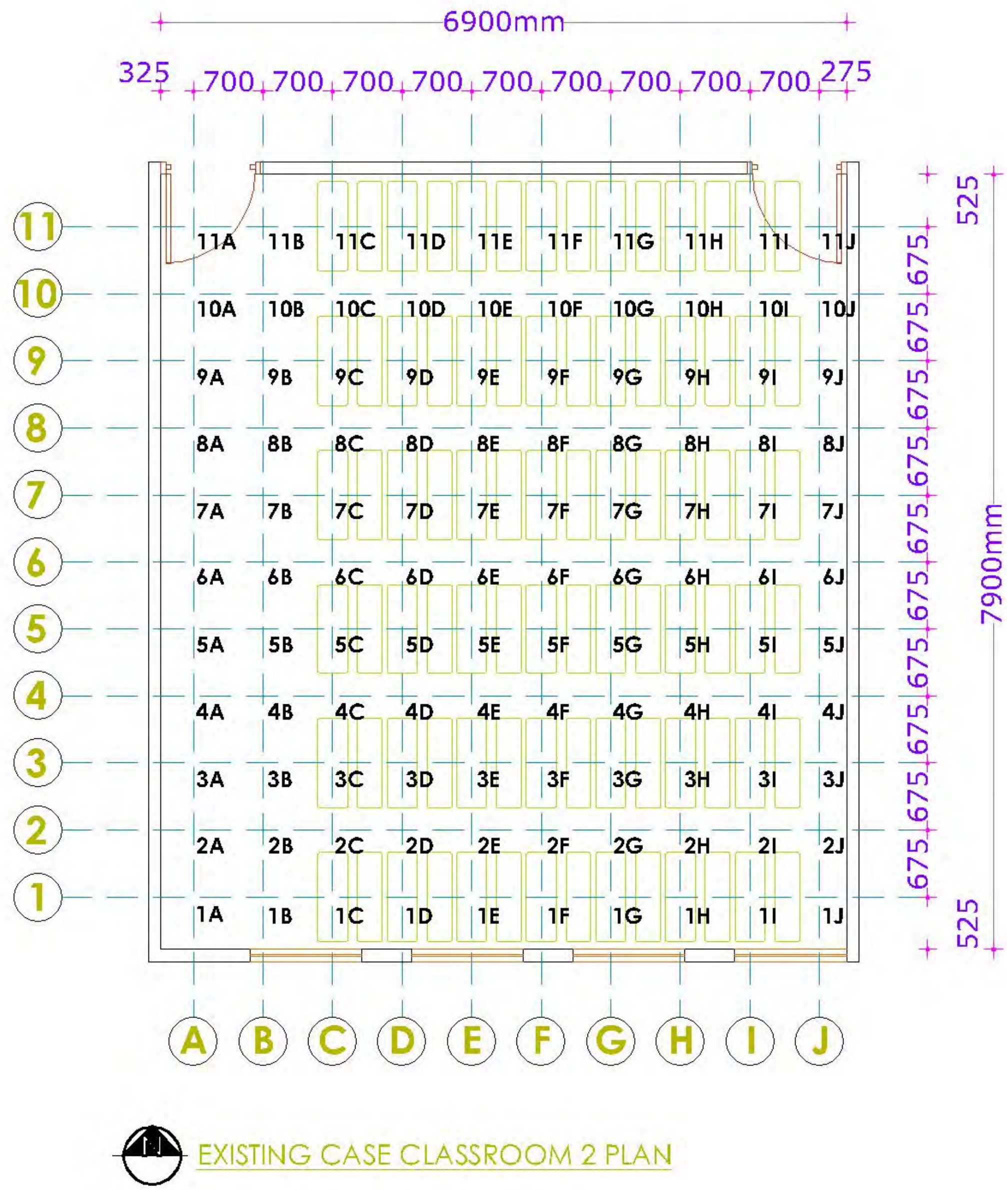
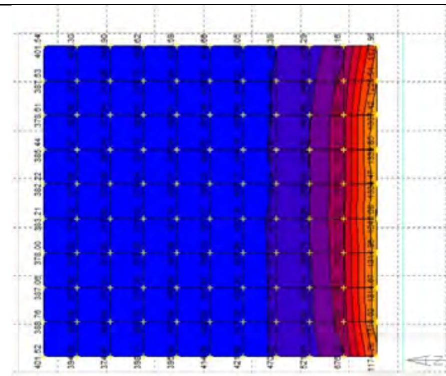


Figure 4.6 Classroom at Government Laboratory High School showing the sensor point grids.

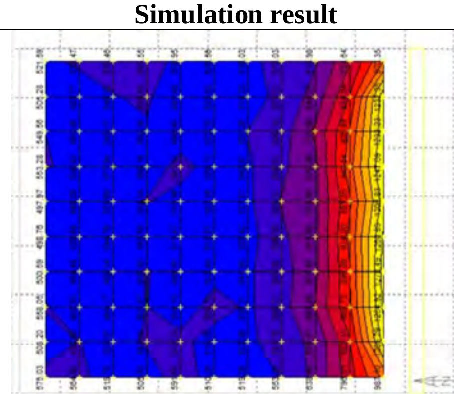
LSW 300 showed the highest average illumination level and LSW 00 showed lowest average illumination level. Appendix-G presents the detailed static daylight simulation data. With the use of light shelf the lowest illumination level increases 268 to 478 for both LSW 300 and LSW 450, but after that with the increase of light shelf width a small decrease on the lowest level illumination. The highest illumination level is 1376 for LSW 00 and it decreases with the increase of light shelf width.

Table 4.9: Static simulation result of LSW 00 at Govt. Laboratory High School classroom

Name	Simulation result	Illumination level
LSW 00		Average illumination level=536 lux Min. 268 lux Max. 1346 lux

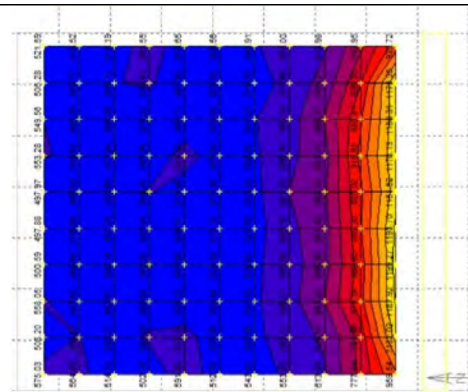
	A	B	C	D	E	F	G	H	I	J
1	*1174*	*1310*	*1315*	*1315*	*1346*	*1334*	*1340*	*1337*	*1226*	*1128*
2	676	732	754	763	773	755	759	753	722	646
3	522	552	552	567	573	567	576	562	546	516
4	**470**	**473**	**472**	**473**	**474**	**464**	**469**	**465**	**470**	**459**
5	**422**	**428**	**428**	**430**	**430**	**430**	**435**	**436**	**416**	**433**
6	**415**	**403**	**398**	**396**	**397**	**399**	**405**	**398**	**409**	**415**
7	**396**	**387**	**387**	**381**	**382**	**392**	**386**	**390**	**391**	**404**
8	**398**	**381**	**377**	**375**	**374**	**375**	**382**	**381**	**379**	**401**
9	**375**	**385**	**373**	**371**	**373**	**372**	**368**	**378**	**380**	**399**
10	**394**	**384**	**373**	**377**	**374**	**378**	**372**	**380**	**381**	**402**
11	**402**	**389**	**387**	**378**	**383**	**382**	**385**	**379**	**388**	**402**

Table 4.10: Static simulation result of LSW 300 at Govt. Laboratory High School classroom

Name	Simulation result	Illumination level
LSW 300		Average illumination level=637 lux Min. 478 lux Max. 1278 lux

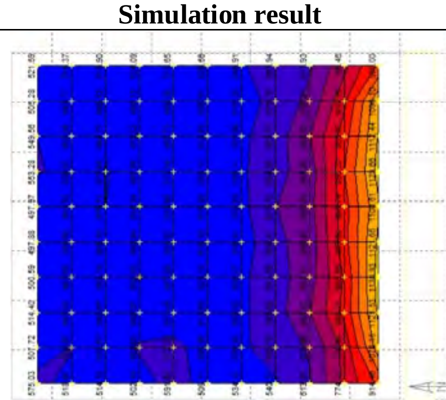
	A	B	C	D	E	F	G	H	I	J
1	*987*	*1205*	*1265*	*1278*	*1261*	*1207*	*1248*	*1232*	*1232*	*970*
2	796	822	890	896	*914*	891	*941*	*906*	835	752
3	639	636	694	677	672	679	670	702	645	613
4	553	592	596	592	607	625	607	590	573	572
5	519	533	539	542	525	538	543	551	514	536
6	510	511	585	522	514	522	509	523	504	527
7	592	572	504	**499**	512	511	582	500	**498**	529
8	506	563	552	556	**493**	554	**498**	542	559	582
9	520	503	**484**	**492**	545	534	**477**	540	547	576
10	565	553	**484**	**484**	540	**498**	539	**491**	**484**	572
11	575	508	558	501	**499**	**498**	553	550	505	522

Table 4.11: Static simulation result of LSW 450 at Govt. Laboratory High School classroom

Name	Simulation result	Illumination level
LSW 450		Average illumination level=624 lux Min. 478 lux Max. 1199 lux

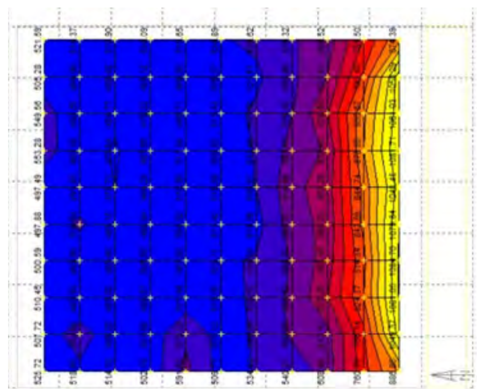
	A	B	C	D	E	F	G	H	I	J
1	*960*	*1132*	*1188*	*1199*	*1194*	*1152*	*1170*	*1158*	*1175*	836
2	778	782	873	863	889	885	*919*	889	826	743
3	613	630	691	667	661	683	662	696	645	613
4	553	589	596	591	607	621	607	590	578	567
5	543	533	541	539	521	532	539	547	514	547
6	513	510	502	522	510	517	508	515	504	527
7	592	572	504	**498**	**500**	511	582	**496**	**498**	516
8	502	563	**490**	556	**491**	554	**498**	**479**	559	582
9	514	503	**483**	**492**	**492**	534	**478**	**487**	547	515
10	565	553	**484**	**483**	540	**496**	539	**492**	**484**	516
11	575	508	558	501	**498**	**498**	553	550	505	522

Table 4.12: Static simulation result of LSW 600 at Govt. Laboratory High School classroom

Name	Simulation result	Illumination level
LSW 600		Average illumination level=613 lux Min. 476 lux Max. 1149 lux

	A	B	C	D	E	F	G	H	I	J
1	*914*	*1078*	*1122*	*1139*	*1122*	*1101*	*1130*	*1112*	*1096*	*909*
2	774	776	849	836	868	866	896	866	814	739
3	613	626	686	663	650	666	645	686	636	612
4	540	593	590	592	604	618	604	587	576	568
5	534	536	539	538	516	532	539	538	515	547
6	510	509	513	525	510	515	503	513	507	527
7	592	572	501	**498**	505	511	511	**496**	**498**	516
8	502	563	**487**	556	**491**	554	**498**	**479**	**495**	524
9	514	503	**483**	**492**	**489**	**480**	**476**	**485**	**488**	513
10	519	553	**484**	**483**	540	**494**	539	**492**	**484**	514
11	575	508	514	501	**498**	**498**	553	550	505	522

Table 4.13: Static simulation result of LSW 750 at Govt. Laboratory High School classroom

Name	**Simulation result**	**Illumination level**
LSW 750		Average illumination level=604 lux Min. 476 lux Max. 1085 lux

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
1	887	*1049*	*1082*	*1085*	*1080*	*1048*	*1082*	*1061*	*1058*	874
2	761	766	824	814	843	845	879	866	790	732
3	608	613	677	655	648	657	637	679	631	609
4	540	590	590	584	604	615	597	579	570	574
5	534	536	539	534	515	531	533	538	522	540
6	510	507	513	524	511	515	501	511	506	525
7	592	572	501	**498**	505	511	511	**496**	**498**	516
8	502	502	**487**	506	**491**	**494**	**498**	**479**	**495**	524
9	514	**499**	**486**	**485**	**489**	**480**	**476**	**485**	**488**	513
10	519	553	**484**	**483**	540	**492**	**492**	**492**	**484**	514
11	526	508	510	501	**498**	**497**	553	550	505	522

Rating system of the simulation results

Same as the previous school classroom, rating has been done between the different light shelf widths simulated results. Table 4.14 shows the rating of the five types of light shelf configurations according to the different factors (minimum, maximum and average illumination level; no. of points 501-900 lux; no. of points greater than 900 lux; and no, of points greater than 1500 lux). From 1st to 5th place rating points were considered as 4points-0 point respectively (Reinhart et al., 2006).

After summing all the rating points achieved by the light shelf configurations, LSW 450 was found as superior with 20 points than other light shelf configuration types (Table 4.14). On the other hand, LSW 00 was found as lowest as it achieved only 11 points.

Table 4.14: Summery result and Rating point distribution of static simulation of different light shelf width for the window of Govt. Laboratory School classroom

Code of Light Shelf Widths		Min Illumination	Max Illumination	Average Illumination	**No. of points 300-500 lux**	No. of points 501-900 lux	*No. of glare points (>900)*	***No. of glare points (>1500)***	Total Rating Points	**Rank**
LSW 00	*Value*	*268*	*1346*	*536*	*80*	*20*	*10*	*0*	11	5th
	Rating point	0	0	0	4	0	3	4		
LSW 300	*Value*	*477*	*1278*	*637*	*14*	*83*	*13*	*0*	16	4th
	Rating point	3	1	4	0	4	0	4		
LSW 450	*Value*	*478*	*1199*	*624*	*20*	*80*	*10*	*0*	20	1st
	Rating point	4	2	3	1	3	3	4		
LSW 600	*Value*	*476*	*1149*	*613*	*22*	*78*	*10*	*0*	18	3rd
	Rating point	2	3	2	2	2	3	4		
LSW 750	*Value*	*476*	*1085*	*604*	*25*	*77*	*8*	*0*	19	2nd
	Rating point	2	4	1	3	1	4	4		

4.3.3 Static simulation result of BUET ECE Building Classroom

The third case study building is BUET ECE building at Palashi, Dhaka. It is a twelve storey structure and north-south oriented building (Figure 4.7). On the south side of the building there is a garden and a road on the north side. There are ten classrooms with a double loaded corridor. One classroom on second floor with south window have selected for simulation study (Figure 4.8, 4.9).

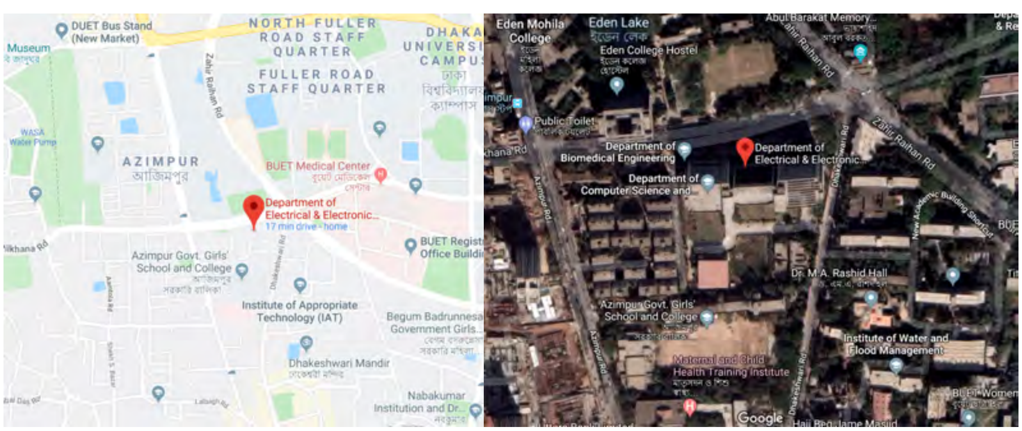


Figure 4.7 Location of the BUET ECE building

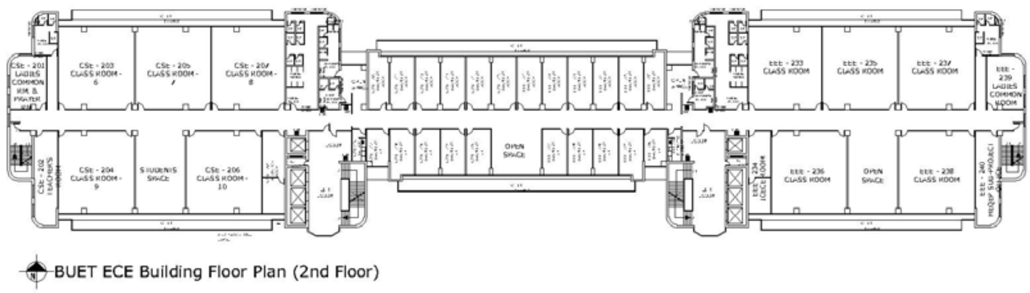


Figure 4.8 BUET ECE Building Floor plan (2nd Floor)

Figure 4.9 BUET ECE building

The classroom at BUET-ECE building is a rectangular room of 102.6m^2 (9.0m x 11.4m), designed for 98 students which consists of exterior window openings on south façade. Two continuous windows with high windows on exterior wall (Figure 4.9). A corridor runs through the floor in front of the room on north side. The window area is 16m^2 in the classroom at south side (Figure 4.10). The bottom level of the window was at 750mm and the top level was at 2700mm.

Figure 4.10 Interior view of the BUET ECE building classroom

Indoor and outdoor conditions were kept constant, as the previous case classroom condition. Table 4.15 shows the modelling parameters for simulation study.

Table 4.15: Modelling parameters of BUET ECE building classroom for daylight simulation

Sl.	Parameters	Specification
1	Classroom floor dimension	9.0 m x 11.4 m
2	Classroom floor area	102.6 m^2
3	Window to floor area ratio	0.16%
4	Window size	16.0875 m^2
5	Number of windows	1 no (continuous)
7	Work plane height	0.75m
8	Window top level	2.7m
9	Window bottom height	0.75m
10	Ceiling	Height: 3.6m, Concrete, White painted
11	Average work plane height of studio	0.75m
12	Floor	Cement finish on concrete
13	Wall	Cream White colour painted on plaster
14	Window glazing	Sliding glass with aluminum frame with grill
15	Roof material	Concrete, white painted.

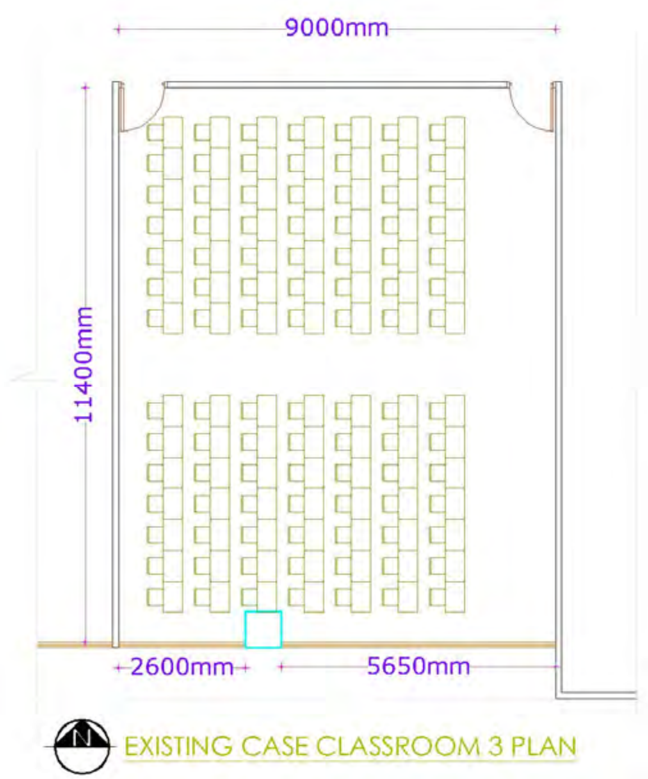


Figure 4.11 Existing BUET ECE Building classroom plan

The classroom at BUET-ECE Building was also divided into 180 sensor points for simulation purpose with the reference of the desk arrangements (Figure 4.11). These sensor points were set into the work plane height at 0.75m from the floor level, representing the average height of the desk.

Intersection points in the plan were coded according to the letter and number system shown in the Figure 4.12. A total of 10 test sensor axis lines were placed in XX' direction and 18 in YY' direction, in an equal distance of 975mm and 650mm from center to center.

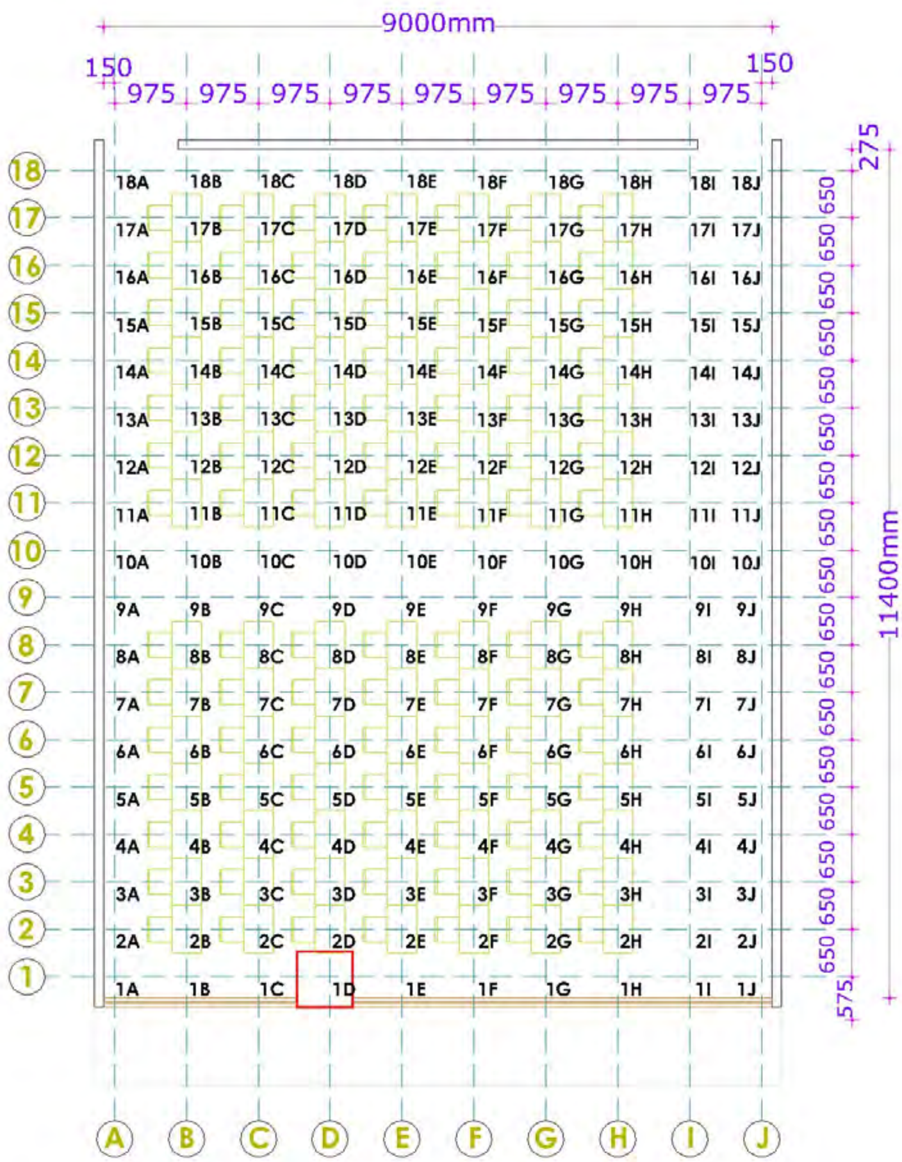


Figure 4.12 Classroom at BUET-ECE Building showing the sensor point grids.

In Table 4.16 to 4.20, the static daylight simulation results are shown: average illumination level 389 lux with illumination range of 242 lux - 1644 lux for LSW 0; average illumination level 444 lux with illumination range of 315 lux - 1366 lux for LSW 300; average illumination level 439 lux with illumination range of 316 lux - 1325 lux for LSW 450; average illumination level 437 lux with illumination range of 316 lux - 1289 lux for LSW 600; and average illumination level 434 lux with illumination range of 318 lux – 1276 lux for LSW 750.

LSW 300 showed the highest average illumination level and LSW 0 showed lowest average illumination level. Appendix-G presents the detailed static daylight simulation data. With the use of light shelf the lowest illumination level increases 242 to 318 for LSW 750. The highest illumination level is 1644 for LSW 00 and it decreases with the increase of light shelf width.

Table 4.16: Static simulation result of LSW 00 at BUET ECE building classroom

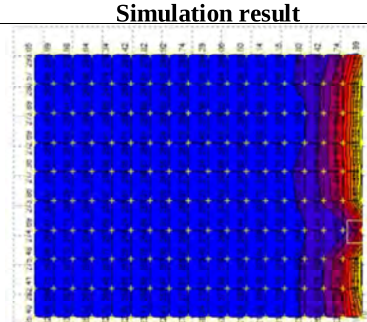
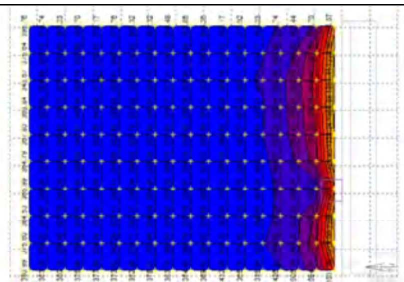
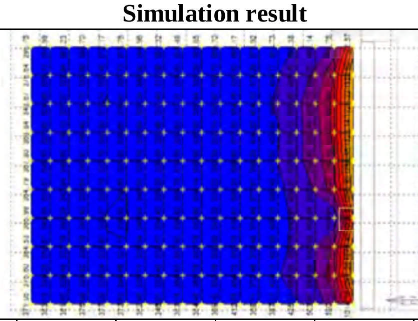
Name		**Simulation result**						**Illumination level**		
LSW 00								Average illumination level=389 lux Min. 242 lux Max. 1644 lux		
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
1	*1312*	***1596***	***1584***	815	***1637***	***1571***	***1644***	***1612***	***1589***	*1185*
2	723	799	789	**402**	800	861	899	862	820	644
3	**457**	510	**498**	**422**	519	551	562	547	524	**438**
4	**384**	**384**	**381**	**365**	**394**	**410**	**371**	**337**	**410**	**388**
5	**331**	**338**	**332**	**333**	**338**	**346**	**349**	**352**	**343**	**338**
6	**321**	**309**	**308**	**306**	**304**	**316**	**311**	**320**	**315**	**317**
7	**301**	290	283	282	289	**302**	296	297	293	**304**
8	293	278	279	285	248	281	281	279	279	299
9	298	271	270	273	270	271	274	273	275	294
10	288	272	266	268	270	270	262	268	269	294
11	283	253	268	258	263	262	261	262	264	285
12	283	267	259	255	257	257	266	258	262	280
13	282	259	257	254	256	259	251	256	260	281
14	283	265	258	258	252	260	252	254	242	278
15	286	264	257	254	255	257	259	262	264	282
16	283	261	258	256	256	258	258	253	265	277
17	282	267	263	261	265	260	264	261	263	282
18	295	282	275	275	274	277	273	274	281	294

Table 4.17: Static simulation result of LSW 300 at BUET ECE building classroom

Name	Simulation result	Illumination level
LSW 300		Average illumination level=444 lux Min. 315 lux Max. 1366 lux

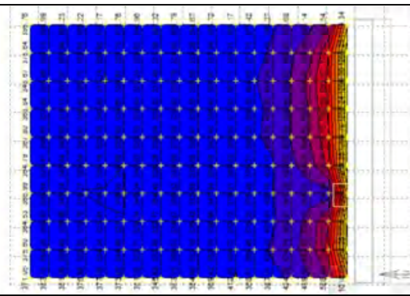
	A	B	C	D	E	F	G	H	I	J
1	1032	1319	1302	1067	1323	1328	1366	1361	1339	1150
2	595	737	678	506	722	769	810	813	784	565
3	506	541	528	502	553	594	605	631	560	482
4	427	465	454	445	484	507	508	510	483	440
5	376	427	397	408	400	431	420	447	425	393
6	366	375	371	425	380	402	407	406	425	378
7	413	405	354	380	366	369	376	364	354	365
8	369	391	339	381	351	380	354	336	391	403
9	354	369	333	335	334	336	335	337	334	354
10	354	369	358	357	370	371	359	337	324	354
11	378	333	334	354	326	328	349	354	361	381
12	353	326	352	346	347	321	332	325	342	343
13	374	342	321	340	320	326	340	340	346	374
14	377	324	324	339	335	323	341	315	326	372
15	376	329	339	340	346	344	346	329	353	381
16	350	329	328	343	343	341	319	337	354	367
17	353	354	351	349	332	346	328	325	351	375
18	391	376	365	366	365	368	364	344	376	396

Table 4.18: Static simulation result of LSW 450 at BUET ECE building classroom

Name	Simulation result	Illumination level
LSW 450		Average illumination level=439 lux Min. 316 lux Max. 1325 lux

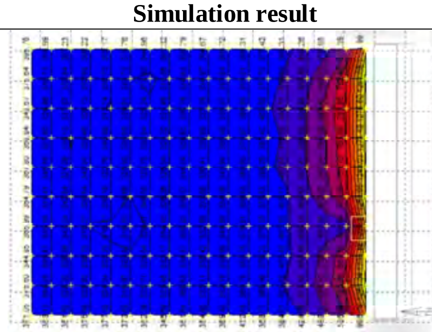
	A	B	C	D	E	F	G	H	I	J
1	1015	1291	1276	1070	1297	1299	1322	1325	1323	1123
2	590	731	677	455	713	758	802	804	773	560
3	504	543	540	456	553	599	601	630	560	480
4	425	465	452	443	484	508	509	510	486	437
5	387	424	402	408	399	432	421	443	425	402
6	369	372	378	375	378	398	404	404	373	378
7	413	405	353	380	365	369	372	364	356	365
8	369	352	339	381	351	380	354	336	350	366
9	354	369	333	333	334	336	335	336	333	354
10	354	369	358	357	370	371	329	337	325	354
11	347	333	332	354	326	326	320	331	331	381
12	353	326	329	346	347	321	331	325	341	345
13	374	344	321	317	320	326	340	340	321	374
14	377	324	324	316	335	323	341	318	326	372
15	376	329	339	340	326	344	346	327	353	381
16	352	329	328	343	343	341	319	337	354	367
17	353	354	351	349	332	346	328	325	351	355
18	371	376	365	366	365	368	364	344	376	396

Table 4.19: Static simulation result of LSW 600 at BUET ECE building classroom

Name	Simulation result	Illumination level
LSW 600		Average illumination level=437 lux Min. 316 lux Max. 1289 lux

	A	B	C	D	E	F	G	H	I	J
1	1011	1268	1250	1070	1269	1270	1292	1288	1289	1114
2	588	724	673	455	708	756	789	794	770	555
3	499	543	539	457	552	597	597	628	560	480
4	424	475	452	441	483	508	508	507	486	438
5	387	424	401	408	403	431	421	441	431	399
6	369	369	379	375	379	398	399	404	372	377
7	413	405	353	380	369	369	372	368	355	365
8	369	352	340	348	354	342	356	336	358	366
9	355	333	336	333	334	336	335	339	333	355
10	354	369	335	357	339	371	329	336	325	356
11	346	333	332	354	326	326	320	331	331	381
12	351	326	329	346	347	321	331	325	340	345
13	374	344	321	317	320	326	340	340	321	374
14	377	324	324	316	335	323	341	318	327	372
15	376	329	339	319	326	344	346	327	353	356
16	352	329	326	343	343	341	319	337	354	367
17	353	354	351	331	331	346	328	325	351	355
18	371	376	365	366	365	368	364	344	376	396

Table 4.20: Static simulation result of LSW 750 at BUET ECE building classroom

Name	Simulation result	Illumination level
LSW 750		Average illumination level=434 lux Min. 318 lux Max. 1276 lux

	A	B	C	D	E	F	G	H	I	J
1	997	1251	1232	1070	1252	1249	1273	1276	1262	1105
2	586	720	668	455	702	752	782	788	762	555
3	499	546	537	461	552	595	594	627	560	480
4	424	473	455	438	483	507	506	505	484	440
5	385	422	401	408	403	431	418	440	429	398
6	369	369	379	375	379	398	397	404	372	377
7	413	361	353	380	369	369	371	367	355	365
8	369	352	340	345	354	344	356	335	358	366
9	355	333	336	333	334	336	340	337	335	355
10	352	369	335	357	339	344	329	336	325	356
11	346	333	332	354	326	326	320	331	331	381
12	352	326	329	321	347	321	331	325	318	345
13	374	320	321	317	320	326	340	340	321	374
14	377	324	323	316	335	323	341	318	327	372
15	376	329	339	319	326	344	325	327	353	356
16	352	328	326	343	343	321	319	337	354	367
17	353	354	351	331	331	346	328	325	351	355
18	371	376	345	366	365	368	364	344	376	396

Rating system of the simulation results

Same as the previous school classroom, rating has been done between the different light shelf widths simulated results. Table 4.21 shows the rating of the five types of light shelf configurations according to the different factors (minimum, maximum and average illumination level; no. of points less than 300 lux; no. of points 501-900 lux; no. of points greater than 900 lux; and no, of points greater than 1500 lux). From 1st to 5th place rating points were considered as 4points-0 point respectively (Reinhart et al., 2006).

After summing all the rating points achieved by the light shelf configurations, LSW 450 was found as superior with 26 points than other light shelf configuration types (Table 4.21). On the other hand, LSW 00 was found as lowest as it achieved only 4 points.

Table 4.21: Summery result and rating point distribution of static simulation of different light shelf widths for the window of BUET ECE building classroom

Code of Light Shelf Widths		Min Illumination	Max Illumination	Average Illumination	No. of points (<300 lux)	**No. of points (300-500 lux)**	No. of points (501-900 lux)	*No. of glare points (>900 lux)*	***No. of glare points (>1500 lux)***	Total Rating Points	**Rank**
LSW 00	*Value*	*242*	*1644*	*389*	*117*	*38*	*16*	*2*	*7*	4	5th
	Rating point	0	0	0	0	0	0	4	0		
LSW 300	*Value*	*315*	*1366*	*444*	*0*	*148*	*22*	*10*	*0*	22	4th
	Rating point	1	1	4	4	1	4	3	4		
LSW 450	*Value*	*316*	*1325*	*439*	*0*	*150*	*20*	*10*	*0*	26	1st
	Rating point	3	2	3	4	4	3	3	4		
LSW 600	*Value*	*316*	*1289*	*437*	*0*	*149*	*19*	*10*	*0*	24	3rd
	Rating point	3	3	2	4	3	2	3	4		
LSW 750	*Value*	*318*	*1276*	*434*	*0*	*149*	*19*	*10*	*0*	25	2nd
	Rating point	4	4	1	4	3	2	3	4		

4.3.4 Comparison of the rating points and ranks from static simulation of three different classrooms

The result from the static simulation for three different classrooms are compared and showed in Table 4.22.

Table 4.22: Comparison of the rating point and rank from static simulation of three different classrooms

	Paik Para Govt. Staff Quarter Primary School classroom		**Government Laboratory School classroom**		**BUET ECE Building classroom**	
Code of Light Shelf Widths	Total Rating Points	Rank	Total Rating Points	Rank	Total Rating Points	Rank
LSW 00	11	5th	11	5th	4	5th
LSW 300	17	4th	16	4th	22	4th
LSW 450	22	1st	20	1st	26	1st
LSW 600	20	3rd	18	3rd	24	3rd
LSW 750	21	2nd	19	2nd	25	2nd

The static result (Table 4.22) shows the width of the light shelf of different classrooms got the same rank. The LSW 450 (width 450mm) stood first among all other depth. LSW 750 light shelf (width 750mm) got the second position and LSW 600 (width 600mm) got the third position. LSW 300 (width 300mm) stood fourth and LSW 00 (no light shelf condition) was fifth among all light shelf

As in static metric simulation overcast sky is considered only and different condition of sky is not considered, dynamic simulation has been done for better understanding. Though the result is same for all classroom in static simulation only Paik Para Govt. Staff Quarter Primary School classroom is considered as case classroom and selected for further dynamic simulation for detail analysis.

4.4 Dynamic daylight simulation findings

Summary Results of annual dynamic metric simulations are described in this Section, considering core work plane sensor approach (described in Section 3.2.6), which was introduced by Reinhart et al. (2006). Table 4.1 shows the ECOTECT modelling of the case classroom with different light shelf modelled in ECOTECT. Appendix-H presents the detailed dynamic daylight simulation data.

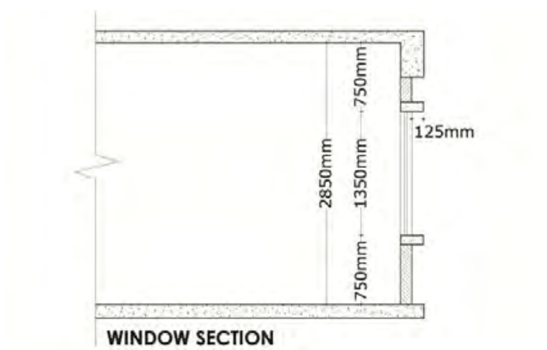
4.4.1 Dynamic daylight simulation with different widths

Dynamic daylight simulation of LSW 00

Annual CBDM simulation result of case classroom with no light shelf (LSW 00) on south façade is presented in Table 4.23. The dynamic result on the core sensor points of the classroom grid are analyzed. It was observed from the table that core sensor point 1C yielded highest DA of 95%. Lowest 82% DA was found at 6C sensor point. 6C and 7C sensor points yielded the best UDI value among other sensor points with highest 81% $UDI_{100-2000}$ and lowest 13% $UDI_{>2000}$ metric value. 1C sensor point provided the worst UDI value among other sensor points with lowest 19% $UDI_{100-2000}$ and highest $UDI_{>2000}$ of 78%.

Table 4.23: Annual CBDM simulation result of LSW 0 on south facade

Type LSW 00 (No light shelf)



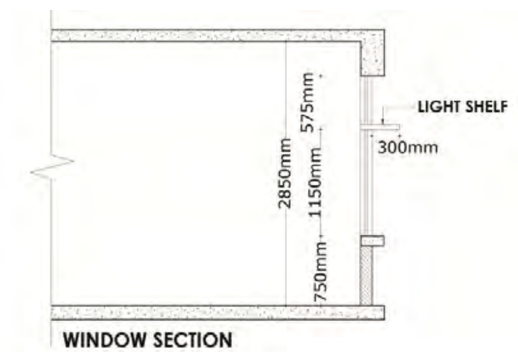
Core points	**1C**	**2C**	**3C**	**4C**	**5C**	**6C**	**7C**	**8C**	**AVG**
Daylight autonomy [DA] [%]	95	94	89	86	83	82	85	90	88
Maximum DA mean [DA_{max}] [%]	71	62	13	10	6	2	1	1	20.75
UDI<100 [%]	3	4	5	6	6	6	6	5	5.12
UDI 100-2000[%]	19	28	61	70	76	81	81	76	61.5
UDI> 2000 [%]	78	68	33	25	17	13	13	19	33.25

Dynamic daylight simulation of LSW 300

Annual CBDM simulation result of case classroom with 300 mm light shelf (LSW 300) on south façade is presented in Table 4.24. It was observed from the table that core sensor points 8C yielded highest DA of 85%. Lowest 63% DA was found at 1C sensor point. 6C, 7C and 8C sensor points yielded the best UDI value among other sensor points with highest 93%. Again 5C, 6C and 7C yielded lowest 0% $UDI_{>2000}$. 2C sensor point provided the worst UDI value among other sensor points with lowest 60% $UDI_{100-2000}$ and highest $UDI_{>2000}$ of 34%.

Table 4.24: Annual CBDM simulation result of LSW 300 on south facade.

Type LSW 300 (300 mm light shelf)



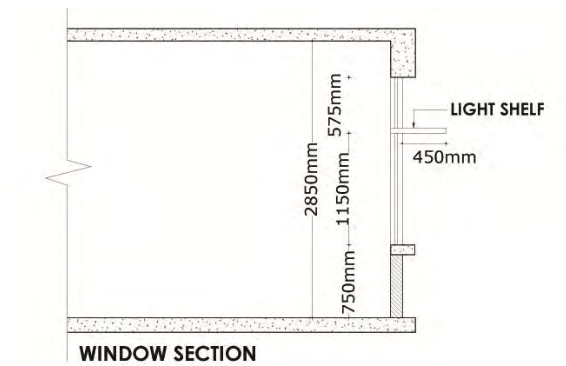
Core points	1C	2C	3C	4C	5C	6C	7C	8C	AVG
Daylight autonomy [DA] [%]	63	82	84	76	75	76	78	85	77.37
Maximum DA mean [DA_{max}] [%]	0	26	21	0	0	0	0	0	5.87
UDI<100 [%]	16	6	6	7	8	7	7	6	7.87
UDI 100-2000[%]	84	60	68	91	92	93	93	93	84.25
UDI> 2000 [%]	0	34	26	2	0	0	0	1	7.87

Dynamic daylight simulation of LSW 450

Annual CBDM simulation result of case studio with 450 mm light shelf (LSW 450) on south facade is presented in Table 4.25. It was observed from the Table that core sensor point 3C and 8C yielded highest DA of 80%. Lowest 53% DA was found at 1C sensor point. On the other hand, 8C sensor point yielded the best UDI value among all sensor points with highest 92% $UDI_{100-2000}$ and lowest 0% $UDI_{>2000}$. 2C sensor point provided the worst UDI value among other sensor points with lowest 65% $UDI_{100-2000}$ and highest $UDI_{>2000}$ of 26%.

Table 4.25: Annual CBDM simulation result of LSW 450 on south facade.

Type LSW 450 (450 mm light shelf)



Core points	**1C**	**2C**	**3C**	**4C**	**5C**	**6C**	**7C**	**8C**	**AVG**
Daylight autonomy [DA] [%]	53	78	80	70	68	66	71	80	70.75
Maximum DA mean [DA_{max}] [%]	0	18	18	0	0	0	0	0	4.5
UDI<100 [%]	23	8	8	11	12	14	11	8	11.87
UDI 100-2000[%]	77	65	70	89	88	86	89	92	82
UDI> 2000 [%]	0	26	22	0	0	0	0	0	6

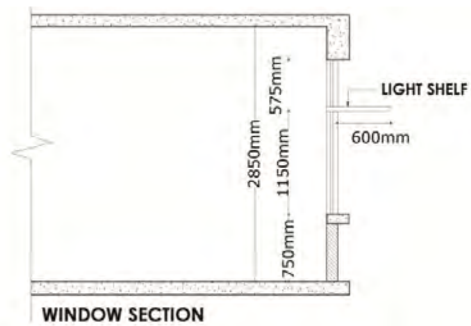
Dynamic daylight simulation of LSW 600

Annual CBDM simulation result of case studio with 600 mm light shelf (LSW 600) on south facade is presented in Table 4.26. It was observed from the table that core sensor point 8C yielded highest DA of 79%. Lowest 56% DA was found at 1C sensor point. 8C sensor point yielded the best UDI value among studied sensor points with highest 92% $UDI_{100-2000}$ and lowest 0% $UDI_{>2000}$. 2C sensor point provided the worst

UDI value among other sensor points with lowest 64% $UDI_{100-2000}$ and highest $UDI_{>2000}$ of 27%.

Table 4.26: Annual CBDM simulation result of LSW 600 on south facade.

Type LSW 600 (600 mm light shelf)



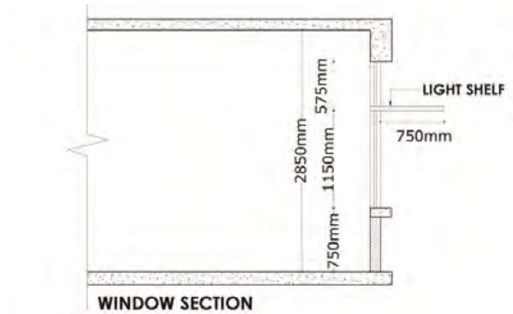
Core points	**1C**	**2C**	**3C**	**4C**	**5C**	**6C**	**7C**	**8C**	**AVG**
Daylight autonomy [DA] [%]	56	78	79	70	69	69	72	79	71.5
Maximum DA mean [DA_{max}] [%]	0	18	18	0	0	0	0	0	4.5
UDI<100 [%]	22	8	8	11	12	12	10	8	11.37
UDI 100-2000[%]	78	64	69	89	88	88	90	92	82.25
UDI> 2000 [%]	0	27	23	0	0	0	0	0	6.25

Dynamic daylight simulation of LSW 750

Annual CBDM simulation result of case studio with 750 mm light shelf (LSW 750) on south façade is presented in Table 4.27. It was observed from the table that core sensor point 8C yielded highest DA of 85%. Lowest 62% DA was found at 1C sensor point. On the other hand, 7C and 8C sensor point both yielded the best UDI value among other sensor points with highest 93% $UDI_{100-2000}$ and lowest $UDI_{>2000}$ value with 0% and 1% respectively. 2C sensor point provided the worst UDI value among other sensor points with lowest 60% $UDI_{100-2000}$ and highest $UDI_{>2000}$ of 34%.

Table 4.27: Annual CBDM simulation result of LSW 750 on south facade.

Type LSW 750 (750 mm light shelf)



Core points	**1C**	**2C**	**3C**	**4C**	**5C**	**6C**	**7C**	**8C**	**AVG**
Daylight autonomy [DA] [%]	62	81	84	76	75	75	77	85	76.87
Maximum DA mean [DA_{max}] [%]	0	26	22	0	0	0	0	0	6
UDI<100 [%]	17	6	6	7	8	8	7	6	8.125
UDI 100-2000[%]	82	60	68	91	92	92	93	93	83.87
UDI> 2000 [%]	0	34	27	2	1	0	0	1	8.12

4.4.2 Comparison of Dynamic Daylight Simulation Results

Table 4.28 presents summery result of annual CBDM simulation for different width of light shelf for the core sensor points in case classroom. The no light shelf condition is critical as the DA_{max} is much more than 5% which is 20.75 %. Again UDI metrics also worse for no light shelf. DA_{max} is better for LSW 450 and LSW 600 but UDI is best for LSW 300. Again for the value of DA, LSW 300 is second best option for light shelf width among all light shelf. In conclusion according to the DA and UDI metric, LSW 300 was found as superior among the studied light shelf options. LSW 600 scored average in all metrics concept. Again LSW 450 scored worse in DA metric and average in UDI metrics. Figure 4.13, 4.14, 4.15, 4.16 and 4.17 show comparison of different light shelf width performance with respect to different dynamic metrics.

Table 4.28: Summery result of annual CBDM simulation of different light shelf configuration for the window of primary school classrooms

Code	***LSW 0***	***LSW 300***	***LSW 450***	***LSW 600***	***LSW 750***
Light shelf width	No light shelf	300 mm	450 mm	600 mm	750 mm
Daylight autonomy [DA] [%]	88	77.37	70.75	71.5	76.87
Maximum DA mean [DA $_{max}$] [%]	20.75	5.87	4.5	4.5	6
UDI<100 [%]	5.12	7.87	11.87	11.37	8.12
UDI 100-2000[%]	61.5	84.25	82	82.25	83.87
UDI> 2000 [%]	33.25	7.87	6	6.25	8.125

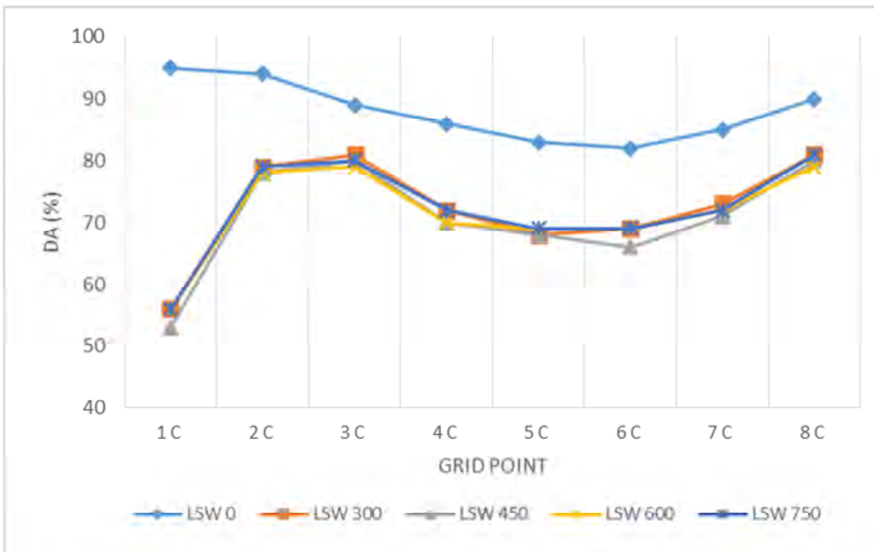


Figure 4.13 DA performance analysis of different light shelf configuration for the window of case classrooms.

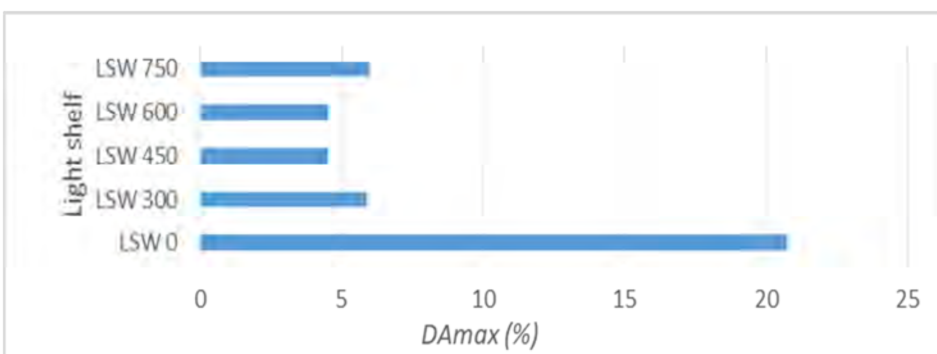


Figure 4.14 DA$_{max}$ metric performance analysis of different light shelf configuration for the window of case classrooms.

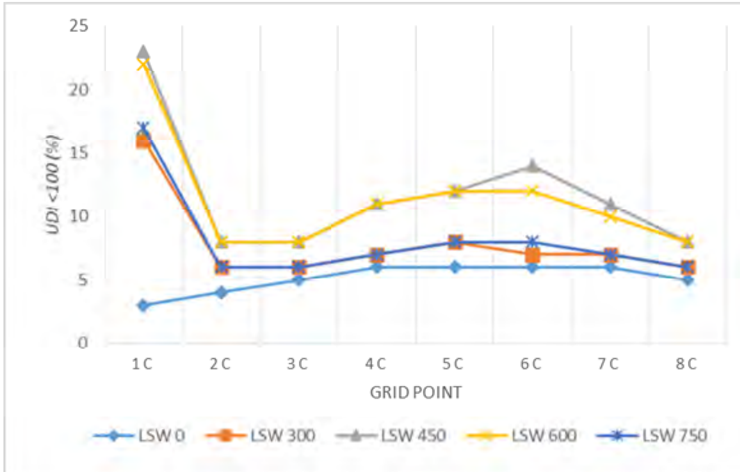


Figure 4.15 UDI <100 metric performance analysis of different light shelf configuration for the window of case classrooms.

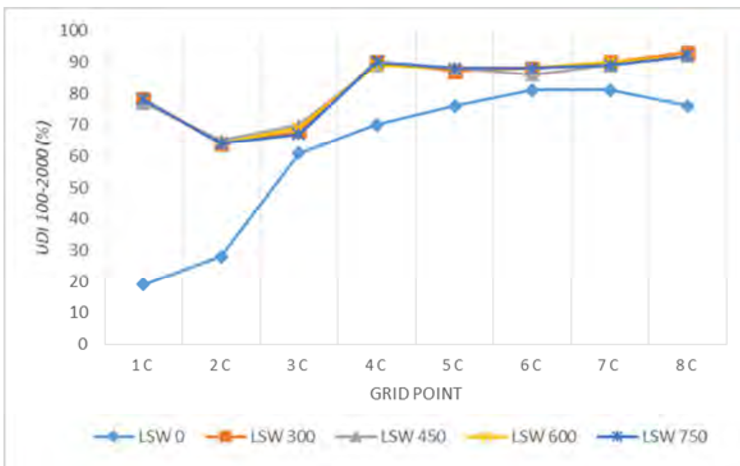


Figure 4.16 UDI 100-2000 metric performance analysis of different light shelf configuration for the window of case classrooms.

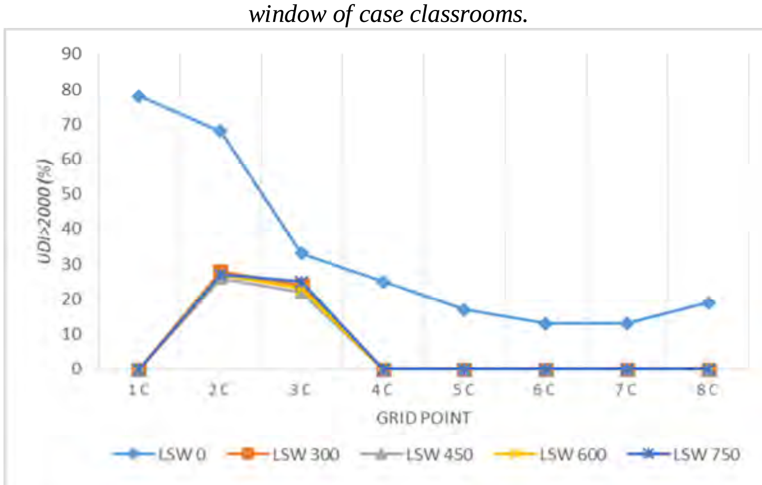


Figure 4.17 UDI>2000 metric performance analysis of different light shelf configuration for the window of case classrooms.

4.4.3 *Rating system of the simulation results and rankings*

Rating between the different light shelf width simulated results is easier to interpret using the dynamic metrics except DF; as DF consider only overcast sky (Reinhart et al. 2006). No light shelf (LSW 00) has been withdrawn from the comparison and ranking as DA_{max} is very high and UDI metric is not preferable for the lighting environment. Again the static simulation result proves that LSW 00 is the worst case and can removed from the further rating of dynamic simulation.

Table 4.29 shows the rating of the 4 type of light shelf configurations according to the different metrics. When a metric led to different rating for the CC axis (Figure 3.17 and 3.18) of the space, the mean result and the minimum to maximums range for core work plane sensors were compared.

From 1st to 4th place rating points were considered as 3points-0 point respectively (Reinhart et al., 2006). Rating was done considering the dynamic metric e.g. DA, DA max, UDI<100, UDI 100-2000, UDI>2000 range values and mean value of core sensor points for each light shelf configuration for primary school classroom.

After summing all the rating points achieved by the light shelf configurations, LSW 300 was found as superior with 11 points than other light shelf configuration types (Table 4.29). On the other hand, LSW 450 and LSW 750 both were found as lowest as it achieved only 6 points and most of the metrics and sub metrics it created over day lit condition in the interior of a classroom. LSW 600 is more feasible light shelf than LSW 450 and LSW 750 as it placed 2^{nd} position.

Table 4.29: Rating points distribution and ranking for different dynamic metrics of four light shelf width for case classrooms.

Code of Light Shelf Angles	***LSW 300***	***LSW 450***	***LSW 600***	***LSW 750***
Daylight autonomy [DA] [%]	3	0	1	2
Maximum DA mean [DA max] [%]	1	3	3	0
UDI<100 [%]	3	0	1	2
UDI100-2000[%]	3	0	1	2
UDI> 2000 [%]	1	3	2	0
Rating Points	11	6	8	6
Place	**1st**	**3rd**	**2nd**	**3rd**

4.5 Performance evaluation of different light shelf during different seasons of the year

The sun angle, cloud covers and sunshine hours differs on different times of the year, so the amount of light enter in a classroom will vary with the width of the light shelf. For finding the accurate width of a light shelf on different seasons analysis at particular date is needed. Four date have been selected to analyze according to different sky condition and sunshine time: 20 March, 21 June, 22 September and 21 December; which are the equinox and solstice dates for Dhaka. These particular dates were selected as the highest, lowest and equal length daytime of a year. As the sun position also changes on different parts of a day, three times of a day are selected for the accuracy of result. The times are 8:30am at morning, 12:30 at noon and 3:30 at afternoon.

4.5.1 Illumination level with light shelf on different date and time

Illumination level with different light shelf on 20th March at 08:30 am

On 20th March, the illumination is high due to the position of the sun. Simulation result on the core sensor points of five case types for case classroom on 20th March at 08:30 am on south facade is presented in Table 4.30. It was observed from the table that, without any light shelf it is creating glare and high range of illumination on the core sensor points especially very high near the window. The other light shelves cut down the illumination to an accepted level.

Table 4.30: Illumination level from DAYSIM on the core sensor points for different light shelf on 20th March at 08:30am

Code of Light Shelf Widths	1C	2C	3C	4C	5C	6C	7C	8C	AVG
LSW 300	**337**	*886*	***1058***	*672*	**489**	*528*	*620*	***921***	689
LSW 450	**306**	***943***	***970***	*604*	*512*	**431**	*586*	*864*	652
LSW 600	**369**	***918***	***970***	*603*	*537*	*517*	*615*	*834*	670
LSW 750	**376**	***1042***	***1002***	*704*	*538*	*530*	*608*	***911***	714

Note: ***No. of Glare Point*** are highlighted in ***Italic Bold***, **No. of Point 300-500 lux** are highlighted in **Bold** and *No. of Point > 500 lux* are highlighted in *Italic* style.

To identify the best width for 08.30 am on 20th March, some variables have been compared such as average illumination, number of glare point (above 900lux), number of point below 300 lux and number of points between 300-500 lux and above 500 lux which are shown in Table 4.31.

Table 4.31: Different parameters for different widths of light shelf on 20th March at 08.30 am

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point > 500 lux*
LSW 300	670	2	0	2	6
LSW 450	652	2	0	2	6
LSW 600	689	2	0	1	7
LSW 750	714	3	0	1	8

Table 4.32: Rating of different light shelf width on 20th March at 08.30 am

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point > 500 lux*	Total Points	Position
LSW 300	1	3	3	3	3	13	**1st**
LSW 450	0	3	3	3	3	12	2nd
LSW 600	2	3	3	1	1	10	3rd
LSW 750	3	0	3	1	0	7	4th

Table 4.32 shows the rating of the different width light shelf from the result found in Table 4.31. From the above comparison it is shown that 300 mm light shelf will create best luminous environment in the morning.

Illumination level with different light shelf on 20th March at 12:30 pm

Simulation result on the core sensor point of five case types in a classroom on 20th March at 12:30 pm on south facade is presented in Table 4.33.

Table 4.33: Illumination level from DAYSIM result on the core sensor points for different light shelf on 20th March at 012:30pm

Code of Light Shelf Widths	**1C**	**2C**	**3C**	**4C**	**5C**	**6C**	**7C**	**8C**	**AVG**
LSW 300	816	***2779***	***1806***	***1103***	***909***	***1015***	***1173***	***1635***	1405
LSW 450	725	**2633**	**1686**	**1009**	**905**	870	***1133***	***1548***	1500
LSW 600	***952***	***2849***	***1820***	***1121***	***1041***	***1007***	***1200***	***1515***	1438
LSW 750	***1006***	***2810***	***2030***	***1245***	***1027***	***1051***	***1197***	***1635***	1314

Note: ***No. of Glare Point*** are highlighted in ***Italic Bold***, **No. of Point 300-500 lux** are highlighted in **Bold** and *No. of Point > 500 lux* are highlighted in *Italic* style.

To identify the best width for 12.30 pm on 20th March, some variables have been compared such as average illumination, number of glare point, number of point below 300 lux and number of points between 300-500 lux and above 500 lux which are shown in Table 4.34 and 4.35.

Table 4.34: Different parameters for different widths of light shelf on 20th March at 12.30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point > 500 lux*
LSW 300	1405	7	0	0	8
LSW 450	1500	6	0	0	8
LSW 600	1438	8	0	0	8
LSW 750	1314	8	0	0	8

Table 4.35: Rating of different light shelf width on 20th March at 12.30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point >500 lux*	Total Points	Position
LSW 300	1	2	3	3	3	12	2nd
LSW 450	3	3	3	3	3	15	**1st**
LSW 600	2	1	3	3	3	12	2nd
LSW 750	0	1	3	3	3	10	3rd

From the above comparison it is shown that 450 mm light shelf will create best luminous environment at noon time.

Illumination level with different light shelf on 20th March at 03:30 pm

Simulation result on the core sensor point of five case type in a classroom on 20th March at 03:30 pm on south facade is presented in Table 4.36.

Table 4.36: Illumination level from DAYSIM result on the core sensor points for different light shelf on 20th March at 03:30pm

Code of Light Shelf Widths	**1C**	**2C**	**3C**	**4C**	**5C**	**6C**	**7C**	**8C**	**AVG**
LSW 300	**327**	***964***	*804*	*543*	**459**	*542*	*632*	***931***	650
LSW 450	297	*847*	782	*502*	**466**	**445**	*597*	*892*	604
LSW 600	**353**	***968***	*779*	*515*	*513*	*514*	*625*	838	638
LSW 750	**362**	*885*	*878*	*577*	*503*	*521*	*619*	***923***	659

Note: ***No. of Glare Point*** are highlighted in ***Italic Bold***, **No. of Point 300-500 lux** are highlighted in **Bold** and *No. of Point > 500 lux* are highlighted in *Italic* style.

To identify the best width for 03.30 pm on 20th March, some variables have been compared such as average illumination, number of glare point, number of point below 300 lux and number of points between 300-500 lux and more above 500 lux which are shown in Table 4.37 and 4.38.

Table 4.37: Different parameters for different widths of light shelf on 20th March at 03.30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point > 500 lux*
LSW 300	650	2	0	2	6
LSW 450	659	0	1	2	5
LSW 600	638	1	0	1	7
LSW 750	604	1	0	1	7

Table 4.38: Rating of different light shelf width on 20th March at 03.30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point >500 lux*	Total Points	Position
LSW 300	2	0	3	3	2	10	2nd
LSW 450	3	3	0	3	3	12	**1st**
LSW 600	1	2	3	1	1	8	3rd
LSW 750	0	2	3	1	1	7	4th

From the above comparison it is shown that 450 mm light shelf will create best luminous environment in the afternoon.

From the above three different times of 20^{th} March, it is found that 450 mm light shelf performs best both in noon and afternoon. But in the morning 300 mm light shelf will be best. So, 450 mm light shelf will be the best option for 20^{th} March and 300 mm will be a second option.

Illumination level with different light shelf on 21^{st} June at 08:30 am

On 21st June, the illumination is the low than the month March due to the cloud cover. But the sun position is straight high in the sky. Simulation result on the core sensor point of five case types in a classroom on 21^{st} June at 08:30 am on south facade is presented in Table 4.39.

Table 4.39: Illumination level from DAYSIM result on the core sensor points for different light shelf on 21th June at 08:30am

Code of Light Shelf Widths	1C	2C	3C	4C	5C	6C	7C	8C	*AVG*
LSW 300	**368**	***988***	***1071***	*749*	*609*	*687*	*822*	***1230***	816
LSW 450	**336**	***991***	***996***	*682*	*612*	*584*	*782*	***1186***	771
LSW 600	**353**	***948***	***980***	*657*	*636*	*642*	*800*	***1137***	769
LSW 750	**347**	***997***	***1003***	*750*	*621*	*661*	*799*	***1251***	804

Note: ***No. of Glare Point*** are highlighted in ***Italic Bold***, **No. of Point 300-500 lux** are highlighted in **Bold** and *No. of Point > 500 lux* are highlighted in *Italic* style.

To identify the best width for 8.30 am on 21st June, some variables have been compared such as average illumination, number of glare point, number of point below 300 lux and number of points between 300-500 lux and above 500 lux which are shown in Table 4.40 and 4.41.

Table 4.40: Different parameters for different widths of light shelf on 21st June at 08.30 am

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point > 500 lux*
LSW 300	816	3	0	1	7
LSW 450	771	3	0	1	7
LSW 600	769	3	0	1	7
LSW 750	804	3	0	1	7

Table 4.41: Rating of different light shelf width on 21st June at 08.30 am

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point >500 lux*	Total Points	Position
LSW 300	3	3	3	3	3	15	**1st**
LSW 450	1	3	3	3	3	13	3rd
LSW 600	0	3	3	3	3	12	4th
LSW 750	2	3	3	3	3	14	2nd

From the above comparison it is shown that 300 mm light shelf will create best luminous environment in the morning.

Illumination level with different light shelf on 21st June at 12:30 pm

Simulation result on the core sensor point of five case type in a classroom on 21st June at 12:30 pm on south facade is presented in Table 4.42.

Table 4.42: Illumination level from DAYSIM result on the core sensor points for different light shelf on 21st June at 12:30pm

Code of Light Shelf Widths	1C	2C	3C	4C	5C	6C	7C	8C	AVG
LSW 300	187	*720*	*650*	**390**	**308**	**352**	**427**	*644*	460
LSW 450	172	*691*	*623*	**358**	**315**	289	**398**	*621*	433
LSW 600	193	*709*	*610*	**349**	**336**	**329**	**418**	*583*	441
LSW 750	197	*676*	*677*	**410**	**332**	**346**	**412**	*641*	461

Note: ***No. of Glare Point*** are highlighted in ***Italic Bold***, **No. of Point 300-500 lux** are highlighted in **Bold** and *No. of Point > 500 lux* are highlighted in *Italic* style.

To identify the best width for 12.30 pm on 21st June, some variables have been compared such as Average illumination, number of glare point, number of point below 300 lux and number of points between 300-500 lux and above 500 lux which are shown in Table 4.43 and 4.44.

Table 4.43: Different parameters for different widths of light shelf on 21st June at 12.30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point > 500 lux*
LSW 300	2323	0	1	4	3
LSW 450	460	0	2	3	3
LSW 600	433	0	1	4	3
LSW 750	441	0	1	4	3

Table 4.44: Rating of different light shelf width on 21st June at 12.30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point >500 lux*	Total Points	Position
LSW 300	3	3	3	3	3	15	**1st**
LSW 450	2	3	0	0	3	8	4th
LSW 600	0	3	3	3	3	12	3rd
LSW 750	1	3	3	3	3	13	2nd

From the above comparison it is shown that 300 mm light shelf will create best environment.

Illumination level with different light shelf on 21st June at 03:30 pm

Simulation result on the core sensor point of five case type in a classroom on 21st June at 03:30 pm on south facade is presented in Table 4.45. It was observed from the table that without any light shelf it is creating glare and high illumination on the core sensor points especially near the window. Again after using the other light shelf cut it down the illumination level is very low on 1C similar to the morning condition.

Table 4.45: Illumination level from DAYSIM result on the core sensor points for different light shelf on 21st June at 03:30pm

Code of Light Shelf Widths	1C	2C	3C	4C	5C	6C	7C	8C	AVG
LSW 300	267	*761*	*730*	*531*	**453**	*532*	*649*	***997***	615
LSW 450	244	*696*	*703*	**494**	**452**	**443**	*601*	***976***	576
LSW 600	256	*724*	*678*	**472**	**484**	**486**	*634*	890	578
LSW 750	254	*683*	*728*	540	**476**	*511*	*622*	***988***	600

Note: ***No. of Glare Point*** are highlighted in ***Italic Bold***, **No. of Point 300-500 lux** are highlighted in **Bold** and *No. of Point > 500 lux* are highlighted in *Italic* style.

To identify the best width for 03.30 pm on 21st June, some variables have been compared such as average illumination, number of glare point, number of point below 300 lux and number of points between 300-500 lux and above 500 lux which are shown in Table 4.46 and 4.47.

Table 4.46: Different parameters for different widths of light shelf on 21st June at 3.30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point > 500 lux*
LSW 300	615	1	1	1	6
LSW 450	576	1	1	3	4
LSW 600	578	0	1	3	4
LSW 750	600	1	1	1	6

Table 4.47: Rating of different light shelf width on 21st June at 3.30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point >500 lux*	Total Points	Position
LSW 300	3	2	3	1	1	10	3rd
LSW 450	0	2	3	3	3	11	2nd
LSW 600	1	3	3	3	3	13	**1st**
LSW 750	2	2	3	1	1	9	4th

From the above comparison it is shown that 600 mm light shelf will create best luminous environment in the afternoon.

From the above three different times of 21st June, it is found that 300 mm light shelf performs better in the morning and noon and 600 mm performs best at afternoon. So, 300 mm light shelf is the best option for 21st June.

Illumination level with different light shelf on 22nd September at 08:30 am

On 22nd September, the illumination is the high due to the position of the sun. Again due to partly overcast sky the illumination level varies time to time. Simulation result on the core sensor point of five case type in a classroom on 22nd September at 08:30 am on south facade is presented in Table 4.48.

Table 4.48: Illumination level from DAYSIM result on the core sensor points for different light shelf on 22nd September at 08:30 am

Code of Light Shelf Widths	**1C**	**2C**	**3C**	**4C**	**5C**	**6C**	**7C**	**8C**	**AVG**
LSW 300	**371**	***1174***	***1209***	*741*	*565*	*623*	*739*	***1069***	811
LSW 450	**403**	***1453***	***1415***	*835*	*696*	*586*	*794*	***1156***	917
LSW 600	**361**	***1142***	***1101***	*644*	*599*	*589*	*719*	***977***	767
LSW 750	**354**	***1162***	***1170***	*748*	*588*	*602*	*708*	***1049***	798

Note: ***No. of Glare Point*** are highlighted in ***Italic Bold***, **No. of Point 300-500 lux** are highlighted in **Bold** and *No. of Point > 500 lux* are highlighted in *Italic* style.

To identify the best angle for 08.30 am on 22nd September, some variables have been compared such as average illumination, number of glare point, number of point below 300 lux and number of points between 300-500 lux and above 500 lux which are shown in table 4.49 and 4.50.

Table 4.49: Different parameters for different widths of light shelf on 22nd September at 08:30 am

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point > 500 lux*
LSW 300	811	3	0	1	7
LSW 450	917	3	0	1	7
LSW 600	767	3	0	1	7
LSW 750	798	3	0	1	7

Table 4.50: Rating of different light shelf width on 22nd September at 08:30 am

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point >500 lux*	Total Points	Position
LSW 300	2	3	3	3	3	14	2nd
LSW 450	3	3	3	3	3	15	**1st**
LSW 600	0	3	3	3	3	12	4th
LSW 750	1	3	3	3	3	13	3rd

From the above comparison it is shown that 450 mm light shelf will create best luminous environment in the morning.

Illumination level with different light shelf on 22nd September at 12:30 pm

Simulation result on the core sensor point of five case type in a classroom on 22nd September at 12:30 pm on south facade is presented in Table 4.51.

Table 4.51: Illumination level from DAYSIM result on the core sensor points for different light shelf on 22nd September at 12:30 pm

Code of Light Shelf Widths	**1C**	**2C**	**3C**	**4C**	**5C**	**6C**	**7C**	**8C**	**AVG**
LSW 300	201	*755*	*732*	**431**	**332**	**374**	**452**	*680*	473
LSW 450	545	***2391***	***1765***	*878*	*769*	*702*	***925***	***1296***	1159
LSW 600	207	*745*	*680*	**382**	**359**	**351**	**442**	*614*	495
LSW 750	206	*720*	*751*	**448**	**355**	**365**	**434**	*673*	494

Note: ***No. of Glare Point*** are highlighted in ***Italic Bold***, **No. of Point 300-500 lux** are highlighted in **Bold** and *No. of Point > 500 lux* are highlighted in *Italic* style.

To identify the best width for 12.30 pm on 22nd September, some variables have been compared such as average illumination, number of glare point, number of point below 300 lux and number of points between 300-500 lux and above 500 lux which are shown in Table 4.52 and 4.53.

Table 4.52: Different parameters for different widths of light shelf on 22nd September at 12:30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point > 500 lux*
LSW 300	473	0	1	4	3
LSW 450	1159	4	0	0	8
LSW 600	495	0	1	4	3
LSW 750	494	0	1	4	3

Table 4.53: Rating of different light shelf width on 22nd September at 12:30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point >500 lux*	Total Points	Position
LSW 300	0	3	2	3	3	11	3rd
LSW 450	3	0	3	0	0	6	4th
LSW 600	2	3	2	3	3	13	**1st**
LSW 750	1	3	2	3	3	12	2nd

From the above comparison it is shown that 600 mm light shelf will create a best luminous environment.

Illumination level with different light shelf on 22nd September at 03:30 pm

Simulation result on the core sensor point of five case type in a classroom on 22nd September at 03:30 pm on south facade is presented in Table 4.54.

Table 4.54: Illumination level from DAYSIM result on the core sensor points for different light shelf on 22nd September at 03:30 pm

Code of Light Shelf Widths	**1C**	**2C**	**3C**	**4C**	**5C**	**6C**	**7C**	**8C**	**AVG**
LSW 300	164	*531*	*506*	**313**	252	287	**347**	*511*	364
LSW 450	105	**361**	**342**	205	182	171	232	**353**	244
LSW 600	156	*510*	**465**	274	266	267	**337**	**464**	342
LSW 750	152	**489**	*505*	**316**	260	275	**330**	*502*	354

Note: ***No. of Glare Point*** are highlighted in ***Italic Bold***, **No. of Point 300-500 lux** are highlighted in **Bold** and *No. of Point > 500 lux* are highlighted in *Italic* style.

To identify the best width for 03.30 pm on 22nd September, some variables have been compared such as average illumination, number of glare point, number of point below 300 lux and number of points between 300-500 lux and above 500 lux which are shown in Table 4.55 and 4.56.

Table 4.55: Different parameters for different widths of light shelf on 22nd September at 3:30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point > 500 lux*
LSW 300	354	0	3	2	3
LSW 450	244	0	5	3	0
LSW 600	364	0	4	3	1
LSW 750	342	0	3	3	2

Table 4.56: Rating of different light shelf width on 22nd September at 3:30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point >500 lux*	Total Points	Position
LSW 300	2	3	3	0	0	8	4th
LSW 450	0	3	0	3	3	9	3rd
LSW 600	3	3	1	3	2	12	**1st**
LSW 750	1	3	3	3	1	11	2nd

From the above comparison it is shown that 600 mm light shelf will create best luminous environment in the afternoon.

From the above three different times of 22nd September, it is found that 600 mm light shelf performs better in the noon and afternoon than the others. But for morning 450 mm light shelf will be better among all light shelf width. So, preferably 600 mm will perform best and 450 mm light shelf will be other option for 22nd September.

Illumination level with different light shelf on 21st December at 08:30 am

On 21st December morning, the illumination is the lowest due to the position of the sun. In this phase of the year the sun angle is lower than the other time. Simulation result on the core sensor point of five case type in a classroom on 21st December at 08:30 am on south facade is presented in Table 4.57.

Table 4.57: Illumination level from DAYSIM result on the core sensor points for different light shelf on 21st December at 08:30 am

Code of Light Shelf Widths	**1C**	**2C**	**3C**	**4C**	**5C**	**6C**	**7C**	**8C**	**AVG**
LSW 300	124	**302**	**471**	**300**	202	215	242	**371**	278
LSW 450	117	**313**	**433**	269	218	154	236	**331**	259
LSW 600	123	295	**400**	252	221	201	241	**307**	255
LSW 750	142	**373**	**456**	**335**	243	233	259	**380**	303

Note: ***No. of Glare Point*** are highlighted in ***Italic Bold***, **No. of Point 300-500 lux** are highlighted in **Bold** and *No. of Point > 500 lux* are highlighted in *Italic* style.

To identify the best width for 8.30 am on 21st December, some variables have been compared such as average illumination, number of glare point, number of point below 300 lux and number of points between 300-500 lux and above 500 lux which are shown in table 4.58 and 4.59.

Table 4.58: Different parameters for different widths of light shelf on 21st December at 08:30 am

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point > 500 lux*
LSW 300	278	0	4	3	0
LSW 450	259	0	5	3	0
LSW 600	255	0	6	2	0
LSW 750	303	0	4	3	0

Table 4.59: Rating of different light shelf width on 21st December at 08:30 am

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point >500 lux*	Total Points	Position
LSW 300	2	3	3	3	3	14	2nd
LSW 450	1	3	1	3	3	11	3rd
LSW 600	0	3	0	0	3	6	4th
LSW 750	3	3	3	3	3	15	**1st**

From the above comparison it is shown that 750 mm light shelf will create best luminous environment in the morning.

Illumination level with different light shelf on 21st December at 12:30 pm

Simulation result on the core sensor point of five case type in a classroom on 21st December at 12:30 pm on south facade is presented in Table 4.60. The table shows the most critical condition among the selected dates and time as at this time highest level of illumination enters in the classroom. The cause is behind the situation is the sun position on the sky. The light shelf can cut it down except on the 3C.

Table 4.60: Illumination level from DAYSIM result on the core sensor points for different light shelf on 21st December at 12:30 pm

Code of Light Shelf Widths	1C	2C	3C	4C	5C	6C	7C	8C	AVG
LSW 300	***947***	***2380***	***19649***	***1391***	***1124***	***1145***	***1224***	***1559***	3677
LSW 450	*869*	***2321***	***19583***	***1299***	***1148***	***977***	***1172***	***1439***	3601
LSW 600	***1020***	***2449***	***19520***	***1333***	***1232***	***1128***	***1225***	***1414***	3665
LSW 750	***1024***	***2350***	***20366***	***1469***	***1215***	***1146***	***1192***	***1490***	3782

Note: ***No. of Glare Point*** are highlighted in ***Italic Bold***, **No. of Point 300-500 lux** are highlighted in **Bold** and *No. of Point > 500 lux* are highlighted in *Italic* style.

To identify the best width for 12.30 pm on 21st December, some variables have been compared such as average illumination, number of glare point, number of point below 300 lux and number of points between 300-500 lux and above 500 lux which are shown in Table 4.61 and 4.62.

Table 4.61: Different parameters for different widths of light shelf on 21st December at 12:30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point > 500 lux*
LSW 300	3677	8	0	0	8
LSW 450	3601	7	0	0	8
LSW 600	3665	8	0	0	8
LSW 750	3782	8	0	0	8

Table 4.62: Rating of different light shelf width on 21st December at 12:30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point >500 lux*	Total Points	Position
LSW 300	2	2	3	3	3	13	2nd
LSW 450	0	3	3	3	3	12	2nd
LSW 600	1	2	3	3	3	12	3rd
LSW 750	3	2	3	3	3	14	**1st**

From the above comparison it is shown that 750 mm light shelf will create best luminous environment in the noon time.

Illumination level with different light shelf on 21st December at 03:30 pm

Simulation result on the core sensor point of five case type in a classroom on 21st December at 03:30 pm on south facade is presented in Table 4.63.

Table 4.63 Illumination level from DAYSIM result on the core sensor points for different light shelf on 21st December at 03:30 pm

Code of Light Shelf Widths	**1C**	**2C**	**3C**	**4C**	**5C**	**6C**	**7C**	**8C**	**AVG**
LSW 300	154	**455**	**462**	294	253	**315**	**376**	*579*	361
LSW 450	142	**414**	**457**	278	266	248	**354**	*548*	338
LSW 600	150	**447**	**429**	265	280	288	**370**	*506*	342
LSW 750	179	**474**	*536*	**346**	**310**	**349**	**434**	*673*	413

Note: ***No. of Glare Point*** are highlighted in ***Italic Bold***, **No. of Point 300-500 lux** are highlighted in **Bold** and *No. of Point > 500 lux* are highlighted in *Italic* style.

To identify the best width for 3.30 pm on 21st December, some variables have been compared such as average illumination, number of glare point, number of point below 300 lux and number of points between 300-500 lux and above 500 lux which are shown in Table 4.64 and 4.65.

Table 4.64: Different parameters for different widths of light shelf on 21st December at 03:30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point > 500 lux*
LSW 300	361	0	3	4	1
LSW 450	338	0	4	3	1
LSW 600	342	0	4	3	1
LSW 750	413	0	1	5	2

Table 4.65: Rating of different light shelf width on 21st December at 03:30 pm

Code of Light Shelf Widths	Average Illumination	***No. of Glare Point***	No. of Point <300 lux	**No. of Point 300-500 lux**	*No. of Point >500 lux*	Total Points	Position
LSW 300	2	3	2	2	3	12	2nd
LSW 450	0	3	1	1	3	8	4th
LSW 600	1	3	1	1	3	9	3rd
LSW 750	3	3	3	3	0	12	**1st**

From the above comparison it is shown that 750 mm light shelf will create best luminous environment in the afternoon.

From the above three different times of 21st December, it is found that 750 mm light shelf performs best in the morning, noon and evening. Thus, it can be clearly said that 750 mm light shelf is the best option for 21st December.

The above all analysis with DAYSIM result on four particular dates shown that for different dates four different width light shelf creates preferable illumination condition in the classroom. Again the width may be vary in different time of that particular date. The analysis shows 450 mm will be best on 20th March, 300 mm for 21st June, 600 mm for 22nd September and 750 mm will be best on 21st December.

4.6 Validation

4.6.1 Existing illumination condition of the case reading space from physical survey

To validate the dynamic daylight simulation results of case classroom, illumination level was measured physically on the work plane height under overcast sky condition on 5th December, 2017 at 11.30pm. The outdoor illumination was 27000 lux. The measured data are placed on Table 4.66.

Table 4.66 Existing illumination level of case classroom measured with lux meter under overcast sky condition

	A	***B***	***C***	***D***	***E***	***F***	***G***
8	140	730	**700**	620	510	740	1260
7	190	300	**500**	420	450	400	495
6	180	260	**350**	340	318	340	280
5	200	290	**280**	275	250	248	190
4	200	260	**245**	230	215	198	150
3	170	250	**270**	224	180	200	165
2	250	500	**320**	180	220	250	200
1	350	780	**300**	140	418	400	105
Maximum: 1260 lux and Minimum: 105 lux							
Visible Nodes: 56, Average value of overall plane: 333 lux							
Core sensor points for simulation: 1C, 2C, 3C, 4C, 5C, 6C, 7C and 8C							

Lux reading were taken by Dr. Meter Digital Light Meter Model: LX1330B (Appendix E) on the 56 sensor points as described in Section 3.2.6. North window side sensor points showed slightly higher value than the south sensor points (Table 4.66). There is a corridor next to the door and regular window with high window on south façade, so the illumination are not low on that zone. But middle part of the classroom dose not receive enough light. Middle zone sensor points showed illumination level between 150 lux to 250 lux, while the illumination threshold is 300 lux (IESNA, 2000). Average illumination level of all 56 sensor points were found as 333 lux. On the other hand, illumination level at the window side sensor points were far more than the illumination level, since the illumination range is 300 lux-500 lux (Sharmin,2011).

4.6.2 Illumination condition of the case reading space from simulation

To validate the dynamic daylight simulation results, illumination level was generated from the same time and date on the model case classroom (Table 4.67).

Table 4.67 Existing illumination level from simulation on the same date of physical survey

	A	***B***	***C***	***D***	***E***	***F***	***G***
8	250	760	**680**	690	620	710	1040
7	245	330	**460**	465	490	410	455
6	220	280	**358**	362	370	350	275
5	190	290	**290**	290	255	254	198
4	210	270	**235**	243	235	210	160
3	180	350	**280**	248	210	217	168
2	265	600	**328**	210	260	258	223
1	450	820	**330**	240	420	460	125
Maximum: 1040 lux and Minimum: 125 lux							
Visible Nodes: 56, Average value of overall plane: 358 lux							
Core sensor points for simulation: 1C, 2C, 3C, 4C, 5C, 6C, 7C & 8C							

4.7.3 Comparison between measured daylight illumination and simulation findings

Physical measurement of the actual daylight level in the existing condition of case classroom were compared with the illumination values generated by RADIANCE dynamic metric simulation tool at 11:30 AM on 5th December, 2017 according to climate data collected from Bangladesh Meteorological Department. To validate the daylighting level outcome of existing and simulation findings, deviation at core sensor point values were compared (Table 4.68).

The average illumination value of core sensor points found in survey was 371 lux. On the other hand, average illumination value of core sensor points found in DAYSIM dynamic metric simulation tool was 370 lux. Therefore, according to Table 4.68, there is a deviation of 1 lux between actual condition and simulation tool results, which was approximately 0.27 % (<5%) deviation of actual condition.

Table 4.68: Comparison between existing illumination level and simulated illumination level of the case classroom.

Core sensor points	Daylight Illumination level [lux] (Field Survey)	Daylight Illumination level [lux] DAYSIM Output	Deviation	Percentage [%]
1C	300	330	30	10
2C	320	328	8	2.5
3C	270	280	10	3.7
4C	245	235	10	4
5C	280	290	10	3.6
6C	350	358	8	2.3
7C	500	460	20	4
8C	700	680	20	2.8
Average of 8 core sensor points	371	370	1	0.27

4.7 Summary

This chapter achieved the second and third objectives of the research.

The second objective of this research has been achieved by finding an effective light shelf width for distributing suitable daylight in the interior of classroom throughout the year for all sky conditions in Dhaka. The width was found 300 mm. Again it is found that a fixed depth is not effective for light shelf throughout the year as the sky condition differs time to time.

The third objective has been achieved by identifying four different widths for enhanced daylight inclusion, considering different sky conditions for classrooms in Dhaka from the result of daylight simulation. Result on four particular dates show that for different dates four different widths of light shelf creates preferable illumination condition in the classroom. Again the width may be vary in different time of that particular date. The analysis shows 450 mm wide external light shelf will be best on 20^{th} March, 300 mm wide external light shelf for 21^{st} June, 600 mm wide external light shelf for 22^{nd} September and 750 mm wide external light shelf will be best on 21^{st} December. Based on the observations made by simulation studies, it can be stated that, by careful selection of light shelf width, sufficient daylight can be efficiently included and glare can be controlled.

This chapter leads to the presentation of the achievement of the research objectives in next Chapter 5 with some indicative recommendations and suggestions for future work.

5 CHAPTER FIVE: RECOMMENDATION AND CONCLUSION

Preamble

Achievement of the objectives

Recommendations

Suggestion for future research

CHAPTER 5 RECOMMENDATION AND CONCLUSION

5.1 Preamble

Chapter 1 introduced the research, and Chapter 2 focused on the literature review for this research to provide a clear understanding of necessity of light shelf and different national and international standards of illuminance level in a classroom. Detailed steps of methodology for simulation study with field survey were discussed in chapter 3 and parameters of simulation model was selected. In Chapter 4, five types of light shelf was simulated in three classrooms by static simulation. Again on four dates with three particular times on each date were simulated and evaluated through dynamic daylight to find out the most feasible light shelf width under different sky conditions. This chapter summarizes the research, mentioning the achievement of the objectives which was mentioned in Chapter 1, and recommends some indicative suggestions that could be considered to improve the luminous environment in classrooms in context of Dhaka. It also concludes with highlighting areas of further research.

4.2 Achievement of the objectives

The achievements of the objectives of this research, developed in Chapter 1 (Section 1.3) are discussed in this section as following.

5.1.1 Necessities of light shelf

The first objective of the research was to rationalize the necessities of light shelf for efficient daylighting in classrooms. In order to achieve this objective literature review on light shelf for classrooms was conducted. Literature shows that 300 lux illumination level is required for reading and writing in a classroom. Light shelf can be an effective solution in this condition as it supposed to reflect daylight to the inner parts of a room. At the same time, the light shelf shades the lower portion of any window, reducing the amount of light near the window, which normally has much higher illumination than the deeper parts of spaces and projects the light towards the back. The result is a balanced luminous environment, with less contrast and glare. To upgrade the lighting condition in buildings in tropical area light shelf acts effectively if designed properly. Larger window areas will not result in significant increase in useful daylight in the room, therefore this is identified as the daylighting saturation for south-facing facades and should be taken into account when selecting glass ratio of a south-facing façade for daylight maximization. For warmer climates, results would tend to shift to smaller values for window-to-wall ratio and shading transmittance, with higher energy benefits.

Field investigation was done in different schools on different location of Dhaka city to found the existing condition of illuminance level in the classrooms. The standard of uniformity ratio between the daylight levels in the front and back are not maintained in most of the primary school classroom in Dhaka due to different orientation, location and context.

Light shelf is low-cost, high-performance daylighting systems which can enhance occupant comfort and performance. Light shelves are possibly the simplest among all daylighting systems. Light shelves represent one of the most popular design choices in contemporary buildings and are often suggested in literature as effective devices that can improve the lighting quality of a space and offer energy savings especially when daylight controls are used. Many studies have been done about light shelf performance in literature. Light shelf can be incorporate with the shading of a window. Installation and maintenance is also very easy. Moreover installation can be done in an old building if proper size and design is simulated. In all sky type and location light shelf can work effectively with the variation of width, size, angle and shape. So, to upgrade the condition of the illuminance level in the classroom light shelf will be a effective and feasible solution.

5.1.2 One effective light shelf width throughout the year in context of Dhaka.

To enhance useful daylight penetration, second objective of the research was to find out one effective width of light shelf under different sky conditions for classrooms in the climatic context of Dhaka. In order to achieve this objective, field survey was conducted at different schools in Dhaka to find out three case classroom for static and dynamic daylighting simulation study. Different simulation parameters and criteria were set and simulation performance metric were conducted on the five types of light shelves for classroom windows to identify the most feasible width of light shelf.

From static simulation 450 mm width light shelf was identified as the most effective width for a classroom. As in static simulation it does not consider different sky conditions another dynamic simulation was done. By analysing summery result of annual CBDM simulation of five type light shelves LSW 300 scored the highest. So if particular one width is preferred for the entire year 300 mm width light shelf will work best among the studied configurations.

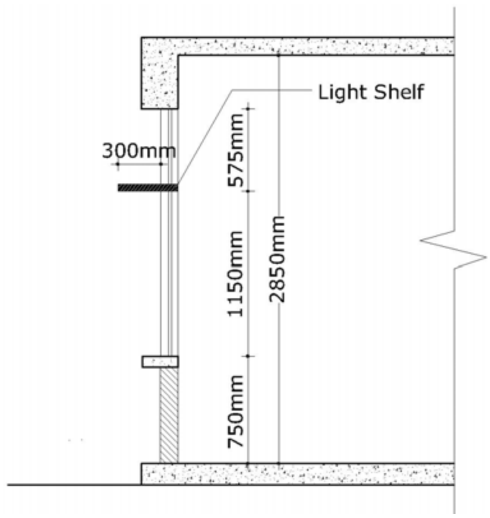


Figure 5.1 300 mm light shelf with window section for Dhaka, Bangladesh.

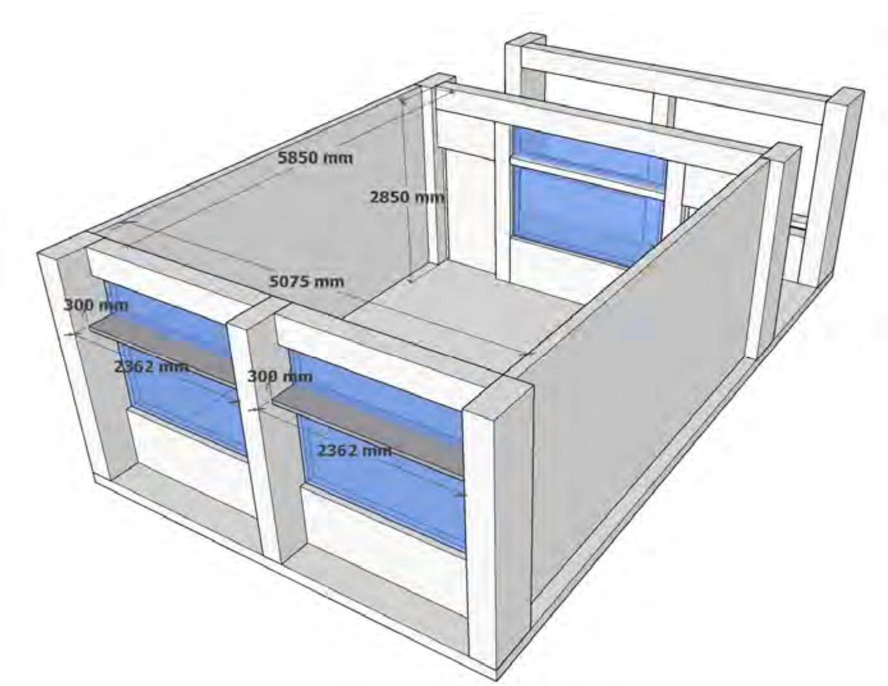


Figure 5.2 300 mm light shelf will work for a classroom throughout the year.

5.1.3 Effective light shelf widths for different parts of the year in context of Dhaka.

The third objective was to identify different light shelf widths to increase illuminance level at deeper parts of the classroom for different sky conditions on distinct parts of the year in context of Dhaka. Four dates have been selected to analyze according to different sky conditions and sunshine times. They were the 20th March, 21st June, 22nd September and 21st December; which are the equinox and solstice dates of Dhaka. As the sun position changes with time, three different times of a day were selected as such 8:30am at morning, 12:30 at noon and 4:30 at afternoon. The dynamic daylight simulations were done in order to find out the best width for a particular date. Table 5.1 shows recommended light shelf width for different dates for primary school classrooms. From the comparison of the results it was found that a fixed width is not feasible and the width not only differs by season but also in different times on the same date, for example on 22nd September 450 mm work well for morning and noon but it is not good for afternoon. At noon 300 mm width will work better. Although sun angles are similar in 20th March and 22nd September (Figure 2.18), due to the different cloud covers (Figure 3.6) different widths of light shelf performed effectively in these two dates. Appendix B shows the penetration of sun on the four dates for the simulated result.

Table 5.1: Recommended light shelf width for different dates for primary school classroom.

Date	Time	Code of Light Shelf Width	Best Light Shelf Width for the Date
20th March	8.30 am	LSW 300	450 mm
	12:30 pm	LSW 450	
	3:30 pm	LSW 450	
21st June	8.30 am	LSW 300	300 mm
	12:30 pm	LSW 300	
	3:30 pm	LSW 600	
22nd September	8.30 am	LSW 450	600 mm
	12:30 pm	LSW 600	
	3:30 pm	LSW 600	
21st December	8.30 am	LSW 750	750 mm
	12:30 pm	LSW 750	
	3:30 pm	LSW 750	

5.2 Recommendations

The sun angle changes not only in different seasons but in different times of a day. To found the effective width the study has done on three different times of a day. The best one was found, which works better more than one time of a day. The following general recommendations are drawn from this research for light shelf width for designing of classroom of schools in order to improve the luminous environment in climatic context of Dhaka.

From the research, it is evident that four different widths of light shelf work better on four different dates, which would represent the seasons that means four different parts of the year as summarized below.

- For February, March and April 450 mm wide external light shelf works skillfully in morning and afternoon.
- For May, June and July 300 mm wide external light shelf works best.
- For August, September and October 600 mm wide external light shelf can work effectively.
- For November, December and January 750 mm is preferable.

From the above result it could be recommended that adjustable light shelf of four segments with 150 mm each could be effective. For different seasons and time period it can be folded or extended. It can also be changed in different parts of a day if necessary. The light shelf can be adjusted manually or mechanically.

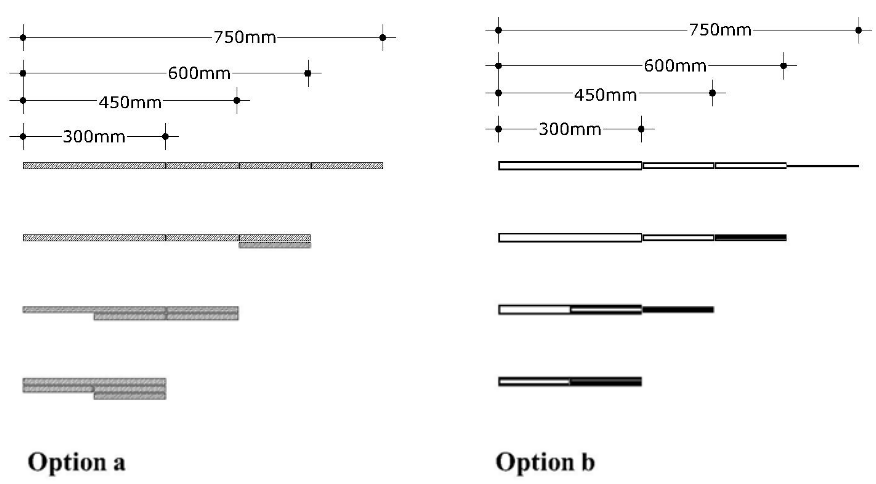


Figure 5.3 Two option for adjustable light shelf

5.3 Suggestions for further research

Some of the most important areas that need to be explored in future with light shelf to daylighting classroom are following.

- This study is based only on the performance of five types of light shelf width. Change of the parameters, or relationship among different geometrical elements of these configurations, may yield variation in the results generated in the simulation studies. Further research could be conducted to identify a more suitable width which may be better than the existing five options.
- In this research only external light shelf has been studied. Indoor light shelf also may be studied and further more a combination of indoor and outdoor light shelf may bring out more specific and precise width of light shelf.
- Different angles, materials and short segments of light shelf can also be analyzed for further research.
- The study concentrates only on institutional classrooms. Investigations of different building types need to be conducted before generalized application.
- Simulation studies of daylighting were based on the climatic context of Dhaka. Analysis in different case locations may yield different result.
- More analysis can be done to the effect of light shelf for daylighting on overall energy savings.
- Impact of daylighting with light shelf on heat gain, thermal comfort condition and ventilation aspects need to be explored.

It is expected that, the research will contribute to further research on daylighting and by helping architects and designers to investigate other aspects as described above for appropriate daylight distribution in classroom.

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APPENDICES

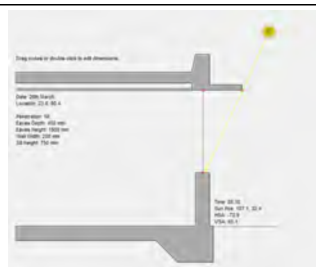
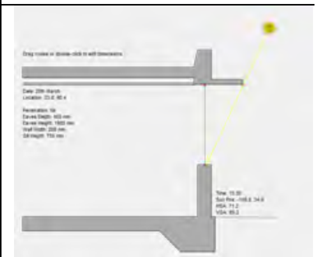
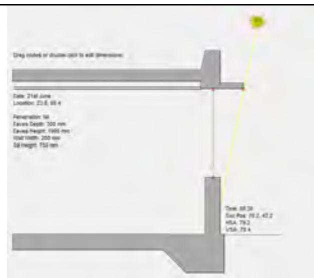
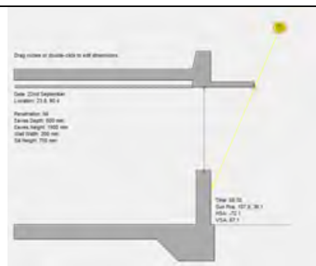
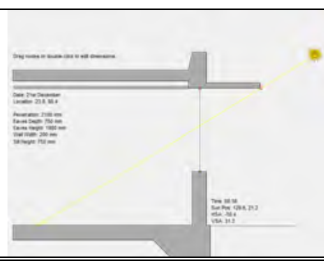
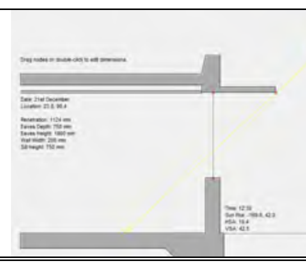
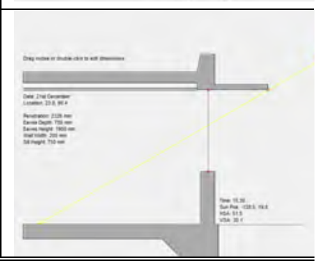
Appendix A: Summary of the key findings of the research

Table A1: Summary of the key findings of the research

Objective	Methods	Chapter	Key findings
Objective 1: To rationalize the necessities of light shelf for efficient daylighting in classroom.	Literature review	Chapter 2	Light shelf can be an effective solution as it supposed to reflect daylight to the inner part of a room. At the same time, the light shelf shades the lower portion of any window, reducing the amount of light near the window and projects the light towards the back. The result is a balanced luminous environment, with less contrast and glare. To upgrade the lighting condition in buildings in tropical area light shelf acts effectively if designed properly.
	Field Investigation	Chapter 3	The standard of uniformity ratio between the daylight levels in the front and back are not maintained in most of the primary school classroom in Dhaka due to different orientation, location and context.
Objective 2: To find out an effective light shelf width to increase illuminance level at deeper parts of the classroom throughout the year in context of Dhaka.	Static and Dynamic daylight simulation analysis	Chapter 4	300mm wide light shelf is effective to increase illuminance level at deeper parts of the classroom throughout the year in context of Dhaka.
Objective 3: To identify different light shelf widths to increase illuminance level at deeper parts of the classroom for different sky conditions on distinct parts of the year in context of Dhaka.	Static and Dynamic daylight simulation analysis	Chapter 4	Four different widths of light shelf were found as feasible for enhanced daylight inclusion considering different sky condition in classrooms in Dhaka. The analysis shows 450 mm wide external light shelf will be best on 20th March, 300 mm wide external light shelf for 21st June, 600 mm wide external light shelf for 22nd September and 750 mm wide external light shelf will be best on 21st December.

Appendix B: The penetration of sun at different time

Table B1: The penetration of sun at different time throughout the year with the simulated result

Date	Time		
	8:30 pm	**12:30 pm**	**3:30 pm**
20th March			
21st June			
22nd September			
21st December			

Appendix C: Key terms and concepts

LIGHTING TERMINOLOGY

DA (Daylight Autonomy) – is the percentage of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight alone.

DA_{con} (Continuous Daylight Autonomy) – is the percentage of the minimum illuminance requirement met by daylight alone at the sensor during the full occupied times of the year. The metric acknowledges that even a partial contribution of daylight to illuminate a space is still beneficial. For e.g. if the design illuminance is 300 lux on core work plane sensor, and 180 lux are provided by daylight alone at one sensor point during the whole office hours of the year; a partial credit of 180lux/300lux=0.6 (60%) is given to that sensor point.

DA_{max} (Maximum Daylight Autonomy) – is the percentage of the occupied hours when the daylight level is 10 times higher than design illumination; represents the likely appearance of glare.

Daylight factor (DF) – is the ratio of the daylight illuminance at an interior point to the unshaded, external horizontal illuminance of the building under a CIE overcast sky condition.

Diffuse radiation – is the total amount of radiation falling on a horizontal surface from all parts of the sky apart from the direct sun.

Direct radiation – is the radiation arriving at the earth's surface with the sun's beam.

Global radiation – is the total of direct solar radiation and diffuse sky radiation received by a horizontal surface of unit area.

Illuminance – is the quantitative expression for the luminous flux incident on unit area of a surface. A more familiar term would be “lighting level”. Illuminance is expressed in lux (lx). One lux equals one lumen per square meter (lm/m^2). In Imperial units the unit is the foot-candle which equals lumen per square foot (lm/ft^2).Other units are – metrecandle, phot, nox.

UDI (Useful daylight illuminance) – try to find out when daylight levels are ‘useful’ for the user and when they are not. Based on occupants’ preferences in daylit RMGs, UDI results in three metrics, i.e. the percentages of the occupied times of the year when daylight is useful (100- 2000lux), too dark (<100 lux), or too bright (> 2000 lux).

LIGHTING METHODS

Ambient accuracy (aa) – value is approximately equal the error from indirect illuminance interpolation. A value of zero implies no interpolation.

Ambient bounces (ab) – is the maximum number of diffuse bounces computed by the indirect calculation. A value of zero implies no indirect calculation.

Ambient division (ad) – The error in the Monte Carlo calculation of indirect illuminance will be inversely proportional to the square root of the number of ambient divisions. A value of zero implies no indirect illumination.

Ambient resolution (ar) – determine the maximum density of ambient values used in interpolation. Error will start to increase on surfaces spaced closer than the scene size divided by the ambient resolution. The maximum ambient value density is the scene size times the ambient accuracy divided by the ambient resolution.

Ambient sampling (as) – are applied only to the ambient divisions which show a significant change.

Backward raytracing – simulates individual rays from the points of interest to light source or other objects backwardly with respect to a given viewpoint (Figure A.1). It is possible to simulate different basic surfaces (e.g. 100% specular surfaces, lambertian surfaces, transparent surfaces and translucent surfaces) and a random mixture of these basic surfaces under raytracing.

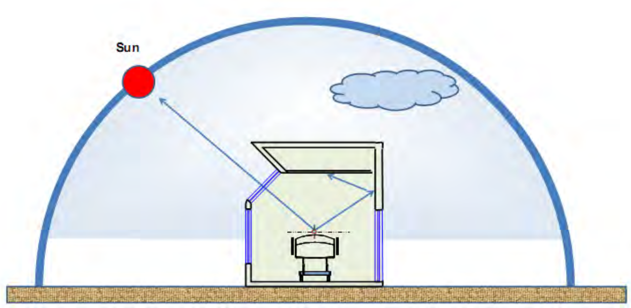


Figure C.1: Backward raytracing simulates individual rays from the points of interest to light source or other objects backwardly (after, Reinhart, 2006).

DAYSIM simulation – calculates the performance metrics considering the impact of local climate and generates a time series indoor annual illuminance profile at points of interest in a building. DAYSIM requires two steps to calculate the annual amount of daylight in a building. Daylight coefficients are calculated first considering the available daylight surrounding the building. After that, the daylight coefficients are combined with the specified climate data of building site. Based on generated illumination profile, DAYSIM derives several dynamic, climate-based daylight performance matrices, such as Daylight Autonomy (DA), Useful Daylight Index (UDI), Continuous Daylight Autonomy (DAcon) and Maximum Daylight Autonomy (DAmax). Figure A.2 shows the process of daylight simulation under DAYSIM. More details on the simulation algorithm used by DAYSIM can be found under Reinhart (2006).

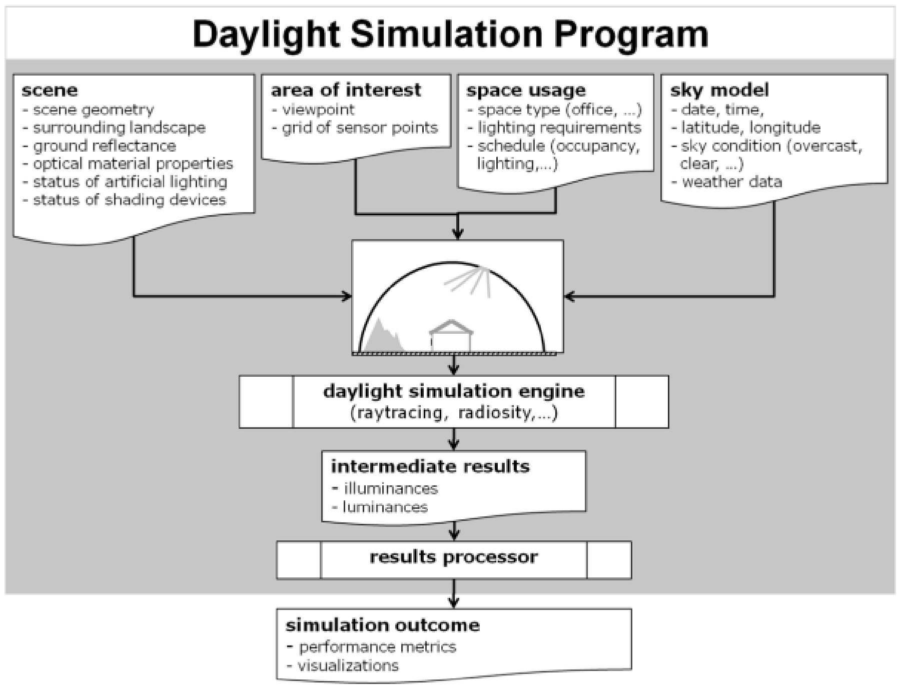


Figure C.2: The process of daylight simulation in DAYSIM (Reinhart, 2006).

DAYSIM uses Perez all weather sky luminance model. Perez sky model was developed in early nineties by Richard Perez et al. (1990; 1993). To investigate the performance of a building under all possible sky conditions that may occur in a year, DAYSIM first imports hourly direct and diffuse irradiances from a climate file and if required, a stochastic autocorrelation model is used to convert the time series down to five-minute time series of direct and diffuse irradiances from one hour. Then, these irradiances are converted into illuminance and a series of sky luminous distributions of the celestial hemisphere. The sky luminous distribution for a given sky condition varies with date, time, site and direct and diffuse irradiance values, and influence the relative intensity of light back-scattered from the earth surface, the width of the circumsolar region, the relative intensity of the circumsolar region, the luminance gradient near the horizon, and darkening or brightening of the horizon. Figure A.3 shows the background steps of using Perez sky model in DAYSIM.

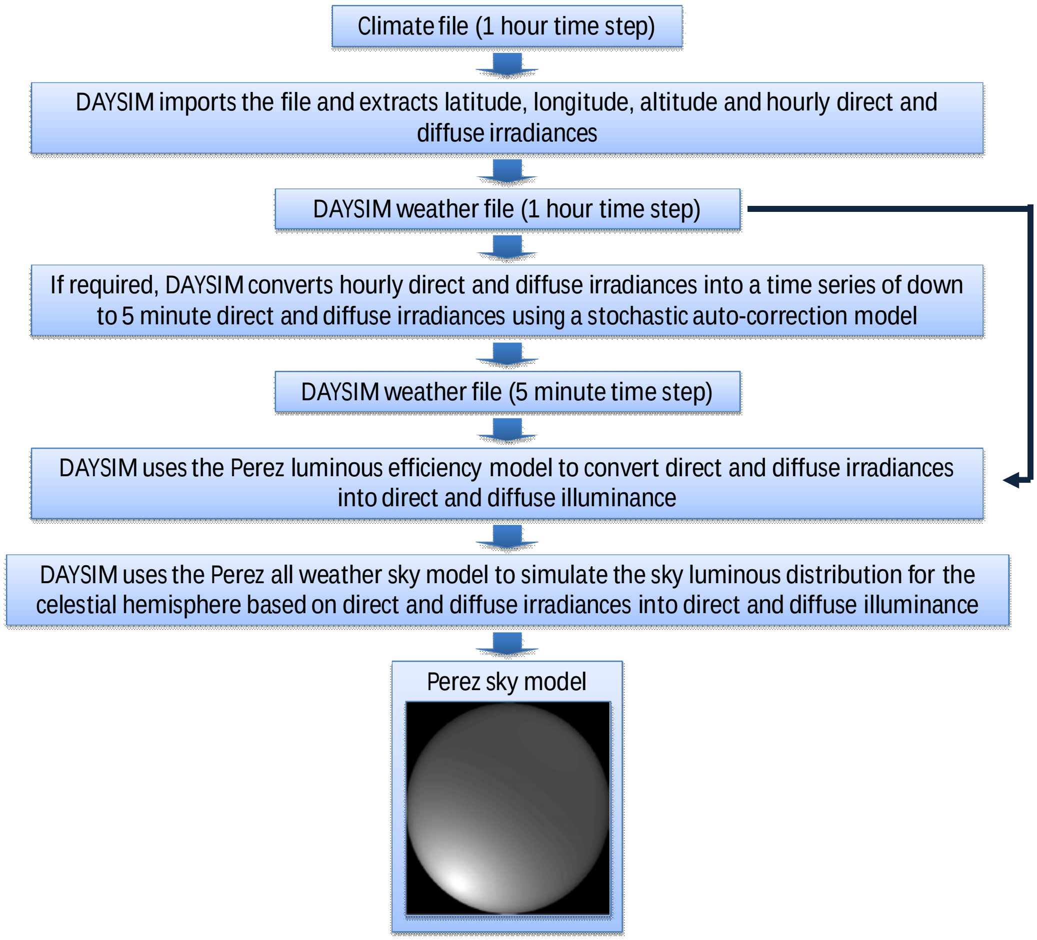


Figure C.3: The use of the Perez sky model in DAYSIM (Joarder, 2011).

Appendix D: Meteorological data of Dhaka

Table D1: Monthly average cloud cover in Dhaka (BMD, 2017)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1961	2	3	3	3	4	6	6	6	6	4	2	1
1962	1	2	1	3	5	7	6	6	5	4	1	1
1963	1	1	1	4	5	6	7	6	5	4	1	2
1964	1	2	2	5	4	6	7	6	6	5	2	1
1965	1	2	2	3	5	7	6	7	6	4	1	3
1966	*	0	0	3	3	7	6	6	5	3	2	2
1967	2	1	3	3	5	5	6	6	6	3	1	2
1968	1	2	2	4	5	6	6	6	5	4	3	1
1969	1	1	3	3	4	6	6	6	5	3	2	2
1970	2	2	3	3	4	6	6	6	6	4	2	0
1972	1	2	2	4	5	6	6	7	5	3	2	1
1973	0	2	2	4	6	6	*	7	7	4	3	1
1975	1	2	1	3	5	6	7	6	6	4	3	1
1976	1	1	2	4	5	6	7	6	5	3	3	1
1977	1	2	3	5	6	7	7	6	5	3	3	1
1978	1	2	2	3	6	6	6	6	6	4	2	1
1979	1	2	2	3	3	6	6	6	5	3	2	1
1980	1	2	3	4	4	6	6	5	5	4	2	1
1981	2	1	4	4	5	5	7	6	5	2	1	2
1982	0	2	2	4	3	6	6	6	5	2	2	1
1983	2	2	3	4	4	6	6	6	6	4	2	1
1984	1	2	2	3	5	7	6	6	5	4	1	1
1985	2	1	3	4	5	6	6	6	6	3	2	1
1986	1	2	1	5	4	6	7	6	6	3	2	2
1987	1	1	3	4	3	5	7	6	6	3	3	1
1988	1	2	3	4	6	6	6	7	6	4	2	1
1989	0	1	2	3	5	6	6	6	6	4	1	1
1990	0	3	4	4	5	6	7	6	6	4	3	2
1991	2	1	2	4	6	6	6	6	6	4	2	2
1992	1	2	1	3	4	5	7	6	5	3	3	1
1993	1	2	2	4	5	6	6	7	6	4	1	1
1994	1	1	3	3	4	6	6	6	5	3	3	1
1995	2	2	2	3	5	6	6	6	6	4	3	1
1996	1	1	2	3	5	5	6	6	5	3	1	1
1997	2	2	2	4	4	6	6	6	6	2	2	3
1998	3	2	3	4	5	5	7	6	5	4	3	0
1999	1	1	1	3	5	6	7	7	6	5	2	1
2000	1	3	3	4	5	6	6	6	6	4	1	1
2001	1	1	2	3	5	6	6	6	6	5	3	1
2002	2	1	3	5	6	7	7	7	6	4	3	1
2003	1	2	3	4	5	7	6	6	6	5	1	2
2004	2	1	3	5	5	6	7	6	6	3	1	1
2005	2	2	3	4	5	5	6	7	6	5	1	1
2006	1	1	2	4	5	7	7	6	6	4	3	0
2007	1	2	1	4	4	6	7	6	6	4	2	1
2008	2	2	4	3	5	6	7	6	6	4	1	2
2009	0	1	2	3	5	6	7	7	6	3	2	1
2010	1	1	3	5	5	6	6	6	6	4	1	2
2011	1	1	3	3	5	6	6	7	6	3	1	1
2012	2	1	2	4	4	6	7	6	6	4	2	1
2013	0	1	2	3	6	6	6	6	6	5	1	1
2014	1	1	2	2	5	6	6	6	5	3	1	2
2015	2	1	2	5	5	6	7	6	5	3	1	2
2016	1	2	3	4	5	6	7	6	6	4	2	1

Table D2: Monthly average sunshine hours in Dhaka (BMD, 2017)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1961	8.5	7.7	8.4	8.9	8.2	4.1	5.8	5.1	5.8	7.3	9.1	9.2	7.4
1962	9.4	9.2	10	8.5	8.5	4.1	6.7	4.1	6.3	7	9.9	9.3	7.8
1963	9.4	9.9	9.2	8.5	8.1	4.9	5.2	6.3	6.6	7.4	9.6	9.2	7.9
1964	8.7	8.9	8.5	*	8.3	5.6	4.6	6.5	5.9 *	*	8.9	9.4	7.6
1965	8	8.9	9.5	9.3	9.1	4.2	5.5	4.7	5.7	8.1	9.9	7.7	7.6
1966	8.1	9.6	8.5	9.2	8.8	3.8	5.9	5.5	5.7	7.8	8	8.3	7.5
1967	8	9	7.9	8.7	9.1	6.8	6	5.7	4.8	8	9.8	8.6	7.8
1968	8.3	8.4	7.9	8.1	8.1	4	5.7	5.5	6	6.7	8.3	8.5	7.2
1969	9.2	8.6	7.9	8.2	9.7	4.8	5.4	5.3	6.3	8.2	8.9	8.8	7.6
1970	9	9.8	8.9	8.8	8.9	5.6	4.5	6.4	5.8	7.2	9	10.2	7.9
1972	8.4	10	11	*	*	*	*	*	*	*	*	*	9.9
1973	*	*	*	*	*	*	*	*	*	*	7.8	9.9	8.9
1975	9.9	9.3	9	9.2	6.8	5.2	6.3	6.8	5.7	7.7	7.6	9.3	7.8
1976	9.8	10.7	9	10	8.2	5.7	2.6	5.7	6.1	7.6	8.5	9.8	7.8
1977	9.6	9.6	9.6	10.2	8.7	7.3	4.2	7.1	5.4	6.5	8.4	9.6	8.1
1978	9.5	9.5	10.1	10	8.4	4.6	5.8	5.7	8.5	9.2	7.8	8.9	8.2
1979	7.5	8.3	9.6	7.8	7.6	4.7	5.1	6.2	7.2	7.8	7.1	8.1	7.3
1980	8.9	9	7.5	7.9	5.7	4.1	4.2	6.3	5.1	7.5	8.4	8.6	7
1981	7.7	8.8	8.6	8.6	*	4.6	4.5	5.4	5.2	8.4	7	8.1	7
1982	8.1	8.4	8.2	8.8	7	4.4	4	5.8	5.7	6.7	9.2	7.6	7
1983	6.9	7.8	6.7	7.1	7.8	6.5	3	6.1	4.9	8.6	8.6	7.1	6.8
1984	7.6	7	7.1	7.3	8.2	4.2	5.2	5.7	5.8	8.1	7.8	7.5	6.8
1985	7.2	8	7.8	7.3	7.9	5.9	*	5.6	4.8	6.4	*	7.9	6.9
1986	7.6	7.9	8.6	8.7	6.2	3.5	4.2	4.3	5.3	6.2	9.5	8.3	6.8
1987	7.8	8.6	8.2	7.4	6.3	4.4	4.1	6.1	6	8.7	8.2	8	7
1988	7.5	8.9	9.1	8.5	8.5	10.3	*	5.8	4.4	7.3	7.6	8.1	7.9
1989	8.7	8.8	8.6	7.5	9	6.5	3.1	4.9	5.5	8.3	7.8	8.3	7.3
1990	8.1	8.1	8.2	7.6	6.7	4.5	4.6	3.9	6	8.3	7.7	7.4	6.8
1991	8.4	8.9	8.4	8.7	6.9	6	4.7	6.9	4.2	6.1	8.5	7.3	7.1
1992	*	*	*	*	7.1	6.1	4	4.9	5.7	6.4	7.2	7.5	6.2
1993	6.3	7.4	7.8	7.8	6.2	5.4	4.1	3.6	4.8	5.8	7.4	7.5	6.2
1994	6.9	7.6	7.3	7.4	7.2	4.6	5.4	5.4	6.2	7.1	6.1	7.3	6.6
1995	7.2	6.2	7.7	8.5	6.6	4.7	4.2	4.6	3.9	7.1	6.8	7.1	6.3
1996	7.5	8.9	9	7	7.7	4.5	3.9	3.8	5.4	7.8	8.6	6.6	6.8
1997	5.2	7.5	7.7	7.3	7.6	5.6	4.1	4.8	4.6	8.5	6.2	5.6	6.3
1998	4	6.1	8.1	7.3	5.8	6.8	2.8	3.7	4.3	5.8	7.4	7.8	5.9
1999	8.3	7.5	7.2	8.4	5.5	5	3.9	3.8	3.8	5.2	8.3	7.4	6.2
2000	6.1	5.8	8.5	8.5	5.2	4.6	5	4.8	4.6	5.8	8.3	8.2	6.3
2001	7.9	7.2	8.7	8.6	6.1	3.5	4.6	5.1	4.6	5.6	6.4	7.2	6.3
2002	7.4	8.8	7.8	8.2	5.6	2.5	1.8	4.3	5.5	6.7	6.6	6.3	6
2003	5.2	7.4	7.2	8	7.4	2.1	5	5.7	3.7	4.7	8.3	5.9	5.9
2004	5.3	7.6	7.6	6.5	7.8	2.9	3.8	5.6	2.7	6.6	7.8	6.7	6
2005	6.3	7.9	7	8.4	7.8	3.2	4.1	3.5	4.8	4.6	6.6	7	6
2006	5.3	6.1	7.3	7.8	6.5	2.2	4.8	6.2	5.1	5.1	6	5.5	5.7
2007	5.7	5.7	8.2	6.4	7.8	4.7	3.3	4.9	3	5.2	5.7	5.5	5.6
2008	4.7	6.6	5.9	8.5	7.7	4.2	3.1	4	4.4	5.8	7.9	3.9	5.6
2009	5.7	8.7	7.3	8.3	6.8	5.9	4.7	3.9	4.1	6.2	6.7	4.8	6.1
2010	5.7	6.7	8.3	7.3	6.7	3.7	4.9	4.4	3.8	5.8	6.2	6.2	5.9
2011	4.9	7.5	7	6.8	5.5	3.5	4.1	2.5	5.1	6.1	6	4.4	5.3
2012	4.6	7.1	7.6	7.1	6.2	2.9	3.9	3.8	4	6	5.6	3	5.2
2013	4.5	7	7.9	6.5	3.6	4.8	4.4	3.3	3.6	4.5	7	4.1	5.2
2014	4.2	6.3	8.6	8.6	6.7	3.3	3.9	3.2	4.8	5.8	5.2	2.8	5.3
2015	4.4	5.4	8.5	6.4	6.4	4.7	2.5	3.4	4.2	6.1	6.2	4.6	5.3
2016	5.1	6.2	7.1	7.4	5.8	5.5	3.4	4.8	4	5.9	6.7	4.3	5.5

Appendix F: Specification of daylighting measuring tools

Dr.Meter® DM-LX1330B

– Please Note: It is Dr.Meter® brand, not generic light meter.
– The Digital Light meters are used in the fields of cinematography and scenic design, in order to determine the optimum light level for a scene. They are used in the general field of lighting, where they can help to reduce the amount of waste light used in the home, light pollution outdoors, and plant growing to ensure proper light levels.

Specifications
– Display: 3-1/2 digit 18mm LCD
– Power: 9V battery
– Ranges: 0.1-200/2,000/20,000/200,000 Lux
– Accuracy: ±3% ±10 digits (0-20,000 lux) / ±5% ±10 digits (over 20,000 Lux)
– Repeatability: ±2%
– Temperature Characteristic: ±0.1%C
– Photo detector type: Silicon Photo Diode with Filter
– Operating temperature: 32-104 degrees F (0-40 degrees C)
– Sampling rate: 2-3 times per second
– Battery life: 200 hours (estimate)
– Dimensions: 149 x 71 x 41 mm
– Photo Detector Dimensions: 100 x 60 x 28 mm

Package Content
– 1 x Dr.Meter 1330B Light Meter
– 1 x Carrying case
– 1 x 9V battery
– 1 x User manual

Appendix F: Simulation Software

F1: About ECOTECT software

Dr. Andrew Marsh wrote the original 'Ecotect' software as a demonstration of some of the ideas presented in PhD thesis at the School of Architecture and Fine Arts at The University of Western Australia. Ecotect provides support at very early stages of a conceptual design as well as during the final stages of design. Designers can start generating vital performance-related design information before the building form has even been developed. One can start with a detailed climatic analysis to calculate the potential effectiveness of various passive design techniques or to optimize the use of available solar, light and wind resources. One can then move on to test these ideas on some simple sketch models before gradually developing the final design.

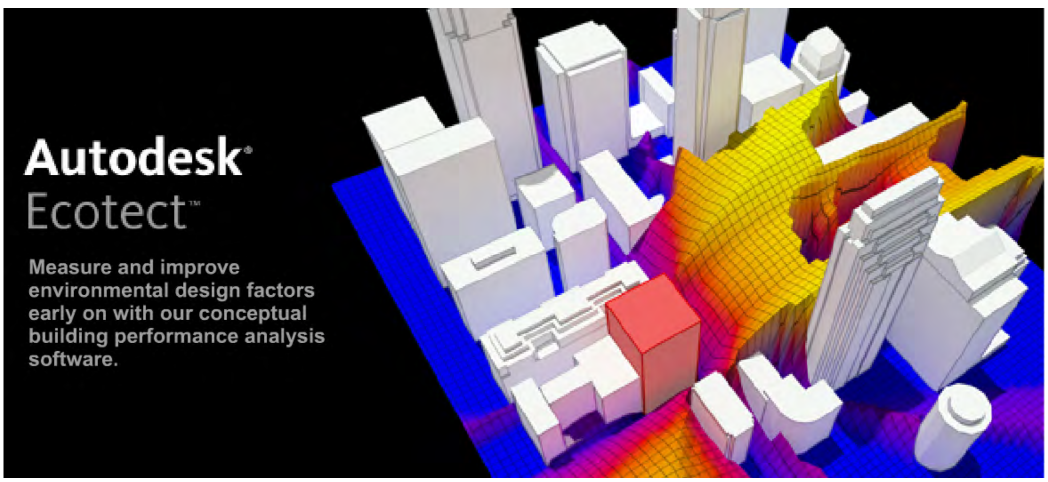


Figure F.1: Interface of ECOTECT v 5.5 simulation software.

ECOTECT has an innovative 3D interface. Traditional geometric CAD systems, requiring many technical inputs are not very appropriate for early design development, – forcing a designer to think mathematically at a time when they are only really thinking intuitively. The flexible and intuitive relational 3D construction system of Ecotect was designed to address this deficiency.

ECOTECT offers a range of lighting analysis options, whilst its main focus is on natural lighting analysis, using an Anlysis Grid panel and Lighting Analysis dialog. Illumination level calculations of natural lighting are simply calculated by multiplying the daylight factor (%) by the current Design Sky value (Lux). Choices of sky model algorithms are currently limited to the CIE Overcast and CIE Uniform sky in Ecotect. As the daylight factor is meant to represent the worst-case design scenario, it is only really valid for the CIE Overcast Sky and is completely independent of time. The daylight factor in a space will not vary with orientation as there is no Sun visible in the sky, it is assumed to be all diffuse light.

In ECOTECT single room averaged IRC and the independent grid-point based calculation of the reflection coefficients is considered. In controlled tests this gives closer agreement with results obtained in Sky Dome and Radiance testing, however, the fact that the IRC calculation is based on the BRS formula, high internal reflectance will give high internal IRC components. (Mentioned in the license of the software). Relevant to the investigation of this work, Ecotect has been used to do the following:

- Work out daylight levels at specific points.
- Export to the Radiance Lighting Program for physically accurate lighting analysis.

The programme can also calculate the incident solar radiation on any surface and its percentage of shading, display and animate complex shadows and reflections, generate interactive sun-path diagrams for instant overshadowing analysis, calculate monthly heat loads and hourly temperature graphs for any zone etc. The program simulates daylight for a three dimensional model, generated within the environment and allows a qualitative evaluation of daylight levels. The latitudinal location of the model along with its orientation, time, month and the plane of interest are required to be specified for the simulation.

For physically accurate and comprehensive lighting analysis, Ecotect can output RADIANCE scene files data for direct input into RADIANCE software.

F2: About DAYSIM software

DAYSIM version 2.1

At the most fundamental level DAYSIM offers an efficient way to calculate the annual amount of daylight available in and around buildings. To do so DAYSIM combines a daylight coefficient approach with the Perez all weather sky model and the RADIANCE backward ray-tracer. The resulting time series of illuminance, radiances or irradiances at user defined sensors points can be used for a number of purposes:

- to derive climate-based daylighting metrics
- to calculate annual electric lighting use for different lighting controls based on available daylight

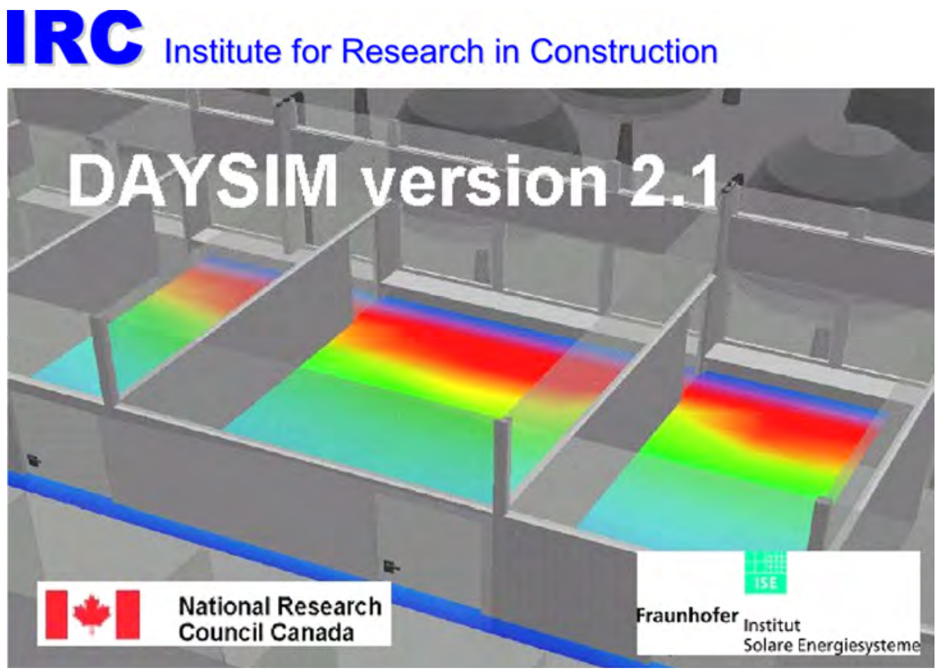


Figure F.2: Interface of DAYSIM simulation software

Climate-based Daylighting Metrics: Over the past decade a new family of daylighting metrics to describe and evaluate daylight in spaces has been developed. These metrics summarize the daylight availability over the year and throughout a space. Two prominent daylighting metrics which are calculated by DAYSIM are Daylight Autonomy and Useful Daylight Illuminance. Daylight Autonomy is now being a recommend metrics by the Illuminating Engineering Society of North America (IESNA).

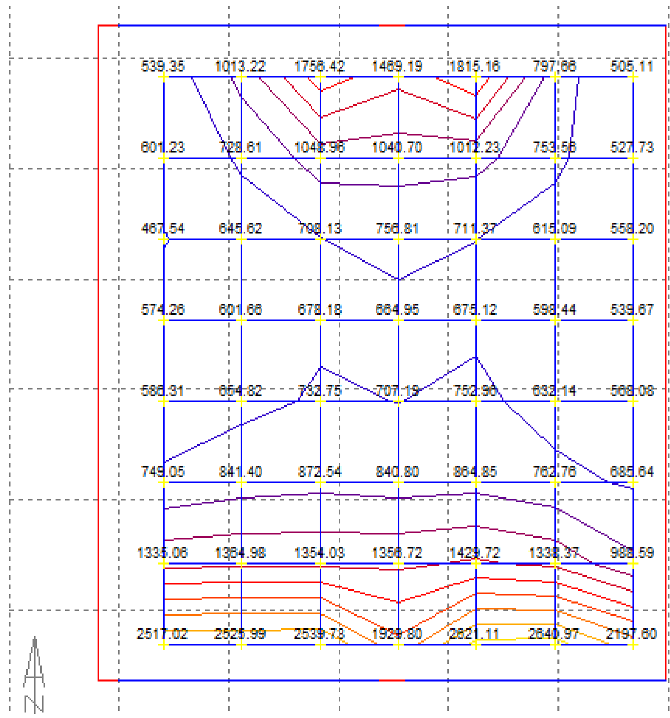
Electric Lighting Use: DAYSIM uses an occupant behaviour model called Lighswitch to model called Light switch to predict based on annual illuminance profiles and occupancy schedules how occupants in a spaces are going to manually operate electric lighting controls and shading systems (see below). The model thus predicts overall electric lighting energy use in a space. DAYSIM also outputs an Internal Gains schedule as can be used by energy simulation programs such as EnergyPlus^{TM} and eQuest to conduct an integrated thermal lighting analysis of a space.

Dynamic Shading: DAYSIM can also model spaces with multiple dynamic shading systems such as venetian blinds, roller shades and electro chromic glazings. In spaces with dynamic shading systems DAYSIM automatically generates multiple annual illuminance profiles each with the shading system(s) in a static position throughout the year. In a post-processing step it then uses the Light witch model to predict in which state the shading systems is going to be.

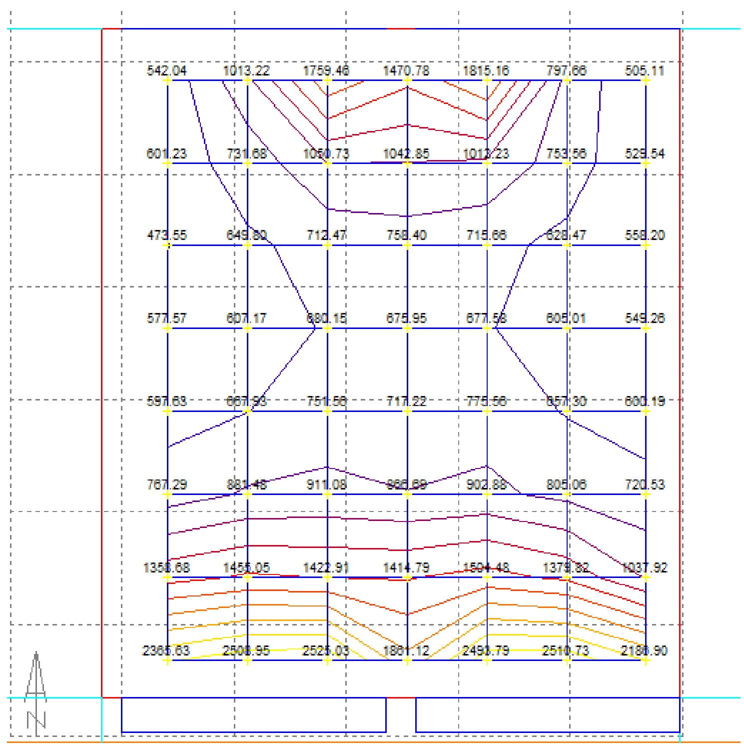
Glare Analysis: DAYSIM uses the daylight glare probability metric to predict discomfort glare from daylight for different viewpoint in a scene through the year. Similarly, as for the annual illuminance profiles DAYSIM generates annual daylight glare probability profiles for different shading device settings that in a post-process are then used to predict the setting of a dynamic shading system throughout the year.

Appendix G: Detail ECOTECT Simulation Results

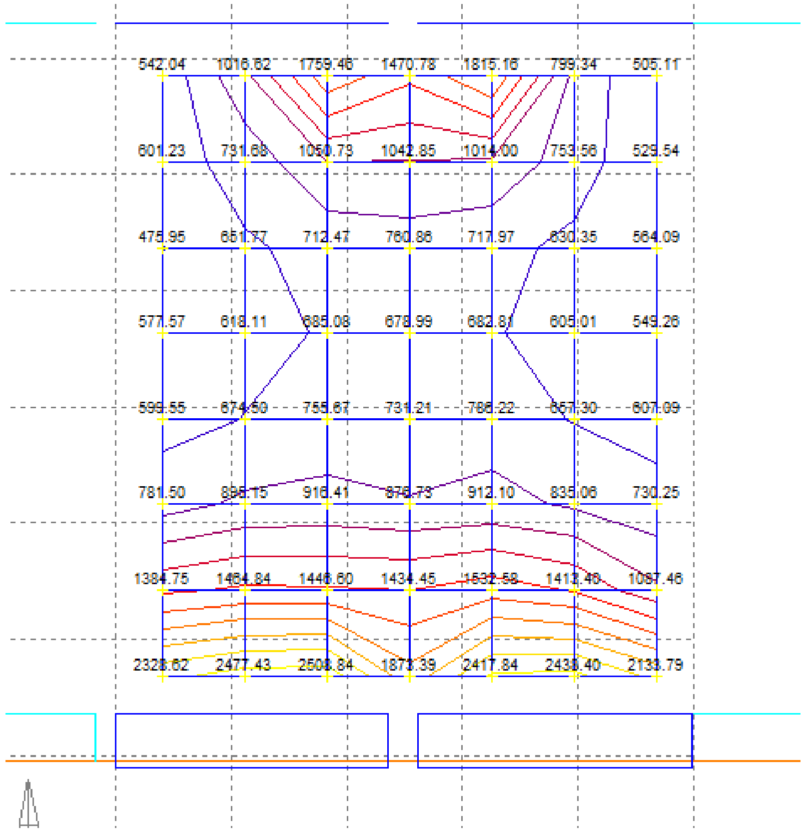
G1: Detail ECOTECT result of LSW 00



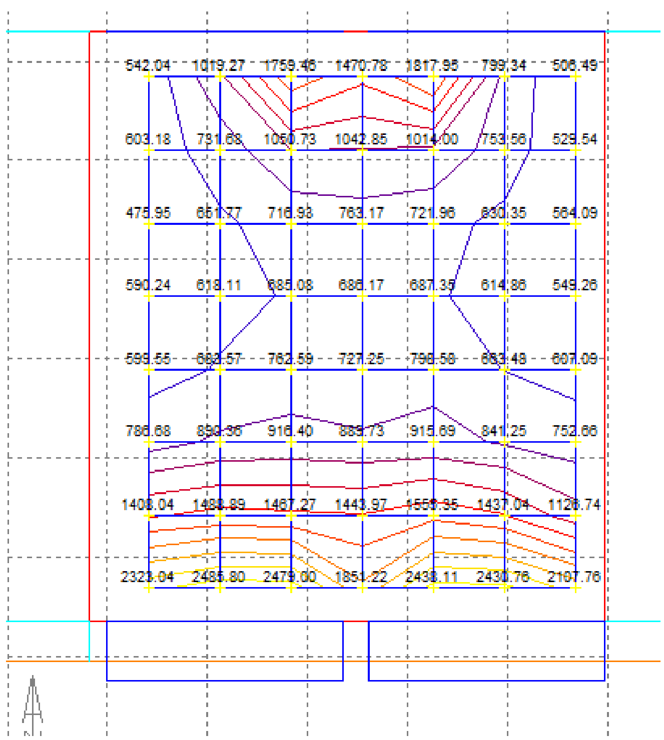
G2: Detail ECOTECT result of LSW 300



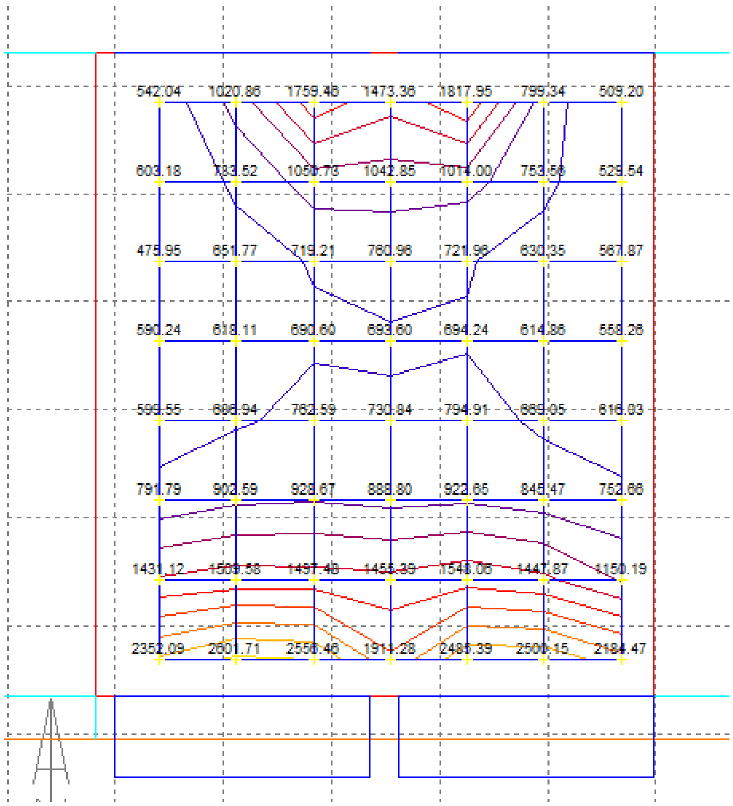
G3: Detail ECOTECT result of LSW 450



G4: Detail ECOTECT result of LSW 600



G5: Detail ECOTECT result of LSW 750



Appendix H: Detail DAYSIM Simulation Results

Table H1: Detail DAYSIM result of LSW 00

	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure
1A	16.3	95	97	73	3	18	79	0	53137508
1B	18.5	95	97	73	3	18	80	0	58860976
1C	18.8	95	97	71	3	19	78	0	57710760
1D	12.8	95	97	68	3	20	77	0	38602996
1E	19.4	95	97	71	3	19	78	0	59200960
1F	18.2	95	97	69	3	21	76	0	56898776
1G	14.9	95	96	66	3	25	72	0	44972936
2A	8.3	94	96	52	4	28	68	0	27797352
2B	9.5	94	96	60	4	27	70	0	29020012
2C	9.7	94	96	62	4	28	68	0	27349136
2D	9.5	94	96	61	4	28	68	0	27907332
2E	9.9	94	96	62	4	28	68	0	31091948
2F	9.7	94	96	60	4	29	67	0	25046884
2G	7.5	93	95	42	4	32	63	4	20917876
3A	3.4	89	94	12	5	65	30	90	6411624
3B	3.7	90	94	15	5	60	35	81	6913486
3C	3.5	89	94	13	5	61	33	88	6626998
3D	4.1	91	94	19	5	53	43	73	7514086
3E	4.1	91	94	17	5	53	42	73	7411749
3F	3.6	89	94	13	5	64	31	90	6519343
3G	2.7	83	91	7	6	76	18	99	5143277
4A	2.6	83	91	6	6	76	18	100	5033284
4B	2.7	84	92	8	6	74	20	100	5261360
4C	3	86	93	10	6	70	25	97	5763261
4D	3.1	86	93	11	6	68	26	96	5908730
4E	3	86	93	11	6	71	24	97	5736068
4F	2.8	84	92	7	6	76	18	100	5205961
4G	2.2	79	89	3	7	80	13	99	4254749
5A	2.2	81	90	1	7	81	13	100	4333664
5B	2.4	81	90	3	6	79	14	100	4594729
5C	2.6	83	91	6	6	76	17	100	5005355
5D	2.6	84	92	5	6	78	17	100	5013481
5E	2.6	83	92	5	6	79	15	100	4905195
5F	2.3	81	90	2	6	81	13	100	4417776
5G	2	77	88	0	7	83	10	99	3763521
6A	2	79	89	0	7	83	10	99	3831318
6B	2.3	81	90	1	7	82	12	100	4309546
6C	2.4	82	91	2	6	81	13	100	4527500
6D	2.5	83	92	2	6	80	14	100	4676991
6E	2.4	82	91	1	6	81	12	100	4429954
6F	2.2	80	90	0	7	83	10	100	4002032
6G	1.8	76	88	0	8	87	5	98	3337500
7A	1.9	79	89	0	7	89	4	99	3460140
7B	2.4	83	91	0	6	83	11	100	4258264
7C	2.8	85	92	1	6	81	13	100	4804103
7D	2.8	86	93	1	6	81	13	100	4823675
7E	2.6	83	92	0	6	82	11	100	4520967
7F	2.1	80	90	0	7	88	5	99	3659808
7G	1.6	75	86	0	8	91	1	95	2952154
8A	1.6	78	89	0	8	92	0	97	2943519
8B	2.7	86	93	0	6	83	11	100	4640759
8C	3.5	90	94	1	5	76	19	100	5675379
8D	3.2	88	93	1	5	78	17	100	5447489
8E	3.2	88	93	0	5	80	14	100	5179790
8F	1.8	77	88	0	7	92	1	98	3193781
8G	1.3	70	84	0	10	90	0	91	2395440

Table H2: Detail DAYSIM result of LSW 300

	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure
1A	0.9	54	73	0	22	78	0	67	1496683
1B	1	57	75	0	20	80	0	72	1642607
1C	1	56	73	0	22	78	0	69	1562819
1D	1	57	74	0	21	79	0	70	1600685
1E	1	57	74	0	21	79	0	70	1602038
1F	1	57	74	0	22	78	0	69	1566812
1G	0.9	53	71	0	25	75	0	58	1365606
2A	2.9	76	87	12	9	74	17	65	7285849
2B	3.8	81	90	17	7	67	26	48	9732359
2C	3.6	79	89	18	8	64	28	47	9736342
2D	3.3	76	88	18	9	66	25	47	9885082
2E	3.7	79	89	19	8	63	29	47	10325357
2F	3.3	76	87	14	9	70	21	55	8203064
2G	2.8	73	86	9	10	77	13	68	6541987
3A	3	79	89	14	8	75	18	60	7774307
3B	3	79	89	14	8	75	17	51	8985057
3C	3.4	81	90	18	8	68	24	47	8887140
3D	3.7	82	91	19	7	67	26	45	9306973
3E	3.4	80	90	18	8	68	24	45	10275286
3F	3	77	88	14	9	75	17	51	8768909
3G	2.5	72	85	11	10	77	13	57	6692597
4A	1.6	70	83	0	12	88	0	91	2278670
4B	1.7	70	83	0	11	89	0	91	2403148
4C	2	72	85	0	10	90	0	93	2714170
4D	2	72	85	0	10	90	0	93	2671622
4E	1.8	70	83	0	11	89	0	90	2405937
4F	1.7	69	82	0	12	88	0	88	2250206
4G	1.2	63	78	0	16	84	0	76	1684982
5A	1.3	64	79	0	14	86	0	79	1808939
5B	1.3	64	79	0	15	85	0	79	1837681
5C	1.6	68	82	0	13	87	0	86	2116844
5D	1.7	69	83	0	12	88	0	89	2277778
5E	1.6	69	82	0	12	88	0	88	2197413
5F	1.4	64	79	0	14	86	0	80	1836879
5G	1.1	60	77	0	17	83	0	71	1531272
6A	1.3	63	78	0	16	84	0	75	1637210
6B	1.6	68	82	0	12	88	0	86	2097445
6C	1.8	69	83	0	12	88	0	89	2306684
6D	1.7	69	82	0	12	88	0	86	2123598
6E	1.5	66	80	0	13	87	0	82	1911736
6F	1.3	64	79	0	15	85	0	77	1707325
6G	1.2	61	77	0	17	83	0	71	1526738
7A	1.3	64	79	0	14	86	0	78	1749595
7B	1.8	70	83	0	11	89	0	89	2304926
7C	2.1	73	85	0	10	90	0	92	2661953
6D	2.1	73	86	0	10	90	0	92	2673171
7E	1.8	69	83	0	11	89	0	88	2322855
7F	1.6	67	82	0	12	88	0	83	1944378
7G	1.1	57	76	0	19	81	0	65	1404901
8A	1.1	58	76	0	18	82	0	65	1366035
8B	2.1	73	85	0	10	90	0	91	2614833
8C	3.1	81	90	0	7	93	0	96	3794417
8D	2.7	78	88	0	8	92	0	95	3362457
8E	3	80	90	0	8	92	0	95	3563210
8F	1.4	64	79	0	14	86	0	77	1712762
8G	0.9	47	71	0	24	76	0	40	1100409

Table H3: Detail DAYSIM result of LSW 450

	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure
1A	0.8	52	71	0	23	77	0	58	1375003
1B	0.9	53	72	0	23	77	0	62	1404095
1C	0.9	53	72	0	23	77	0	63	1414762
1D	0.9	53	71	0	24	76	0	60	1378216
1E	0.9	55	72	0	23	77	0	65	1436570
1F	0.9	55	72	0	23	77	0	63	1437791
1G	0.8	52	71	0	25	75	0	54	1309262
2A	3.2	79	89	12	8	73	19	64	7669586
2B	3.3	78	89	16	8	69	22	50	9111559
2C	3.5	78	89	18	8	65	26	47	9589122
2D	3.3	76	88	18	9	67	25	48	9792752
2E	3.4	77	88	18	9	65	26	47	9929295
2F	3.3	76	87	14	9	71	20	55	8075399
2G	2.7	71	85	9	11	77	13	68	6402583
3A	2.8	77	88	14	8	75	17	60	7617878
3B	2.8	77	88	14	8	76	16	51	8727957
3C	3.2	80	89	18	8	70	22	47	8645309
3D	3.5	81	90	18	7	68	24	46	9007253
3E	3.3	79	89	18	8	69	23	45	10171904
3F	2.8	76	87	14	9	75	16	52	8465551
3G	2.3	70	84	11	11	77	12	57	6451041
4A	1.5	68	82	0	12	88	0	87	2108516
4B	1.6	68	82	0	12	88	0	88	2184423
4C	1.8	70	84	0	11	89	0	92	2476817
4D	1.9	70	84	0	11	89	0	92	2532473
4E	1.8	70	83	0	11	89	0	90	2377678
4F	1.5	65	80	0	14	86	0	82	1939895
4G	1.2	62	78	0	16	84	0	75	1644399
5A	1.3	64	79	0	14	86	0	78	1749387
5B	1.4	65	80	0	14	86	0	81	1908299
5C	1.6	68	82	0	12	88	0	88	2159693
5D	1.8	70	84	0	11	89	0	91	2345648
5E	1.6	68	82	0	12	88	0	86	2080762
5F	1.4	65	80	0	14	86	0	80	1848578
5G	1.1	60	77	0	17	83	0	70	1514596
6A	1.3	63	78	0	16	84	0	75	1642802
6B	1.4	65	80	0	15	85	0	80	1831911
6C	1.5	66	80	0	14	86	0	82	1916165
6D	1.7	69	83	0	11	89	0	89	2249159
6E	1.4	65	80	0	15	85	0	79	1803051
6F	1.4	64	79	0	14	86	0	78	1744145
6G	1.2	60	77	0	17	83	0	70	1503230
7A	1.2	62	78	0	16	84	0	73	1583955
7B	1.8	69	83	0	12	88	0	88	2200016
7C	2	71	85	0	11	89	0	91	2515524
6D	2.1	73	86	0	10	90	0	92	2625972
7E	1.9	71	84	0	11	89	0	90	2422240
7F	1.5	66	81	0	13	87	0	81	1844700
7G	1.2	59	76	0	18	82	0	68	1444300
8A	1.2	62	79	0	15	85	0	72	1494769
8B	2.1	72	85	0	10	90	0	90	2535682
8C	3	80	90	0	8	92	0	96	3591085
8D	2.7	78	88	0	8	92	0	94	3288344
8E	2.7	78	88	0	8	92	0	94	3233577
8F	1.4	64	79	0	15	85	0	75	1679701
8G	0.9	48	71	0	24	76	0	40	1099756

Table H4: Detail DAYSIM result of LSW 600

	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure
1A	0.9	54	73	0	22	78	0	66	1550049
1B	1	57	75	0	20	80	0	71	1680506
1C	1	56	74	0	22	78	0	69	1624154
1D	1	56	74	0	22	78	0	70	1626710
1E	1	56	74	0	21	79	0	70	1629284
1F	1	57	74	0	21	79	0	71	1649796
1G	0.9	55	72	0	23	77	0	64	1468732
2A	2.8	76	87	12	9	73	18	65	7277720
2B	3.5	80	90	16	8	68	25	49	9505107
2C	3.5	78	89	18	8	64	27	46	9736635
2D	3.4	79	89	19	8	64	27	46	10130839
2E	3.6	78	89	19	8	64	28	45	10282685
2F	3.4	76	88	15	9	69	22	54	8380592
2G	3.1	74	87	10	9	74	17	68	6963488
3A	3	79	89	14	8	73	19	60	7945728
3B	2.9	78	89	14	8	75	17	51	8928218
3C	3.1	79	89	18	8	69	23	47	8614386
3D	3.1	79	89	18	8	69	24	47	8637894
3E	3.4	79	89	18	8	68	24	45	10314520
3F	2.6	74	86	14	10	75	16	51	8284609
3G	2.5	73	86	11	10	77	13	57	6831274
4A	1.6	68	82	0	12	88	0	89	2240748
4B	1.6	68	82	0	12	88	0	88	2271261
4C	1.8	70	83	0	11	89	0	91	2473512
4D	2	72	85	0	10	90	0	93	2785875
4E	1.7	69	83	0	12	88	0	89	2392823
4F	1.7	69	82	0	12	88	0	88	2249563
4G	1.2	62	77	0	17	83	0	75	1673874
5A	1.4	66	81	0	13	87	0	83	1975225
5B	1.4	66	80	0	13	87	0	83	2002560
5C	1.7	69	83	0	12	88	0	89	2294587
5D	1.7	69	83	0	11	89	0	90	2364212
5E	1.6	68	82	0	12	88	0	86	2135287
5F	1.4	65	80	0	14	86	0	80	1869679
5G	1.2	63	78	0	16	84	0	75	1651326
6A	1.3	63	78	0	15	85	0	77	1706636
6B	1.6	67	81	0	13	87	0	84	2056548
6C	1.7	69	82	0	12	88	0	87	2208693
6D	1.8	70	84	0	11	89	0	89	2331013
6E	1.6	68	82	0	12	88	0	85	2093716
6F	1.4	65	80	0	14	86	0	80	1852586
6G	1.2	60	77	0	17	83	0	71	1537493
7A	1.3	63	79	0	15	85	0	77	1679642
7B	1.8	70	84	0	11	89	0	89	2335670
7C	2.1	72	85	0	10	90	0	91	2633218
6D	2.3	74	87	0	9	91	0	93	2803874
7E	2	71	84	0	11	89	0	90	2492470
7F	1.6	67	82	0	12	88	0	84	1973846
7G	1.2	60	77	0	17	83	0	70	1506907
8A	1.1	58	77	0	18	82	0	65	1374115
8B	2.1	73	86	0	10	90	0	91	2639890
8C	2.9	79	89	0	8	92	0	95	3437646
8D	2.7	78	88	0	8	92	0	95	3318102
8E	2.7	78	88	0	8	92	0	94	3246481
8F	1.4	64	79	0	15	85	0	76	1690733
8G	0.9	47	70	0	24	76	0	38	1081067

Table H5: Detail DAYSIM result of LSW 750

	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure
1A	0.9	54	73	0	21	79	0	67	1575962
1B	1	56	74	0	21	79	0	69	1652388
1C	1	56	73	0	22	78	0	69	1643351
1D	1	56	73	0	22	78	0	69	1626189
1E	1	57	74	0	21	79	0	71	1696161
1F	1	57	74	0	21	79	0	71	1686215
1G	0.9	54	72	0	23	77	0	64	1465634
2A	3.2	79	89	12	8	71	21	65	7765650
2B	3.9	82	90	17	7	65	28	47	9972318
2C	3.4	79	89	18	8	64	27	47	9669989
2D	3.6	79	89	19	8	63	29	46	10399751
2E	3.2	76	87	18	9	65	26	47	9856479
2F	3.4	76	88	14	9	69	22	54	8355654
2G	3.2	75	87	10	9	74	18	68	7141360
3A	3.1	80	90	15	8	73	19	60	8060692
3B	3.1	79	89	14	8	74	19	50	9137378
3C	3.4	80	90	18	8	67	25	46	9024228
3D	3.2	79	89	18	8	69	24	46	8724623
3E	3.4	80	90	18	8	67	25	45	10393623
3F	3.2	78	89	14	8	73	19	51	9091556
3G	2.3	71	85	11	10	77	13	58	6616370
4A	1.6	69	82	0	12	88	0	90	2251023
4B	1.7	70	83	0	12	88	0	91	2444646
4C	2	72	85	0	10	90	0	93	2826304
4D	1.9	71	85	0	11	89	0	93	2708880
4E	2	71	85	0	10	90	0	92	2735419
4F	1.5	67	81	0	13	87	0	85	2102868
4G	1.2	63	78	0	16	84	0	76	1714334
5A	1.4	65	80	0	14	86	0	82	1923367
5B	1.5	66	81	0	13	87	0	84	2054773
5C	1.6	69	82	0	12	88	0	89	2274118
5D	1.6	69	82	0	12	88	0	88	2267188
5E	1.5	66	81	0	13	87	0	83	2039634
5F	1.4	64	79	0	14	86	0	80	1870334
5G	1.2	61	77	0	18	82	0	72	1589335
6A	1.4	65	80	0	14	86	0	81	1878705
6B	1.6	68	82	0	12	88	0	86	2121313
6C	1.7	69	83	0	12	88	0	88	2271466
6D	1.9	72	85	0	10	90	0	92	2532362
6E	1.6	69	82	0	12	88	0	87	2173055
6F	1.4	65	80	0	14	86	0	81	1863931
6G	1.1	59	76	0	18	82	0	70	1505414
7A	1.4	64	79	0	15	85	0	78	1761655
7B	1.7	69	82	0	12	88	0	86	2148497
7C	2	72	85	0	11	89	0	91	2591662
6D	2.3	74	86	0	10	90	0	93	2836672
7E	1.8	70	83	0	11	89	0	88	2343984
7F	1.5	66	80	0	13	87	0	81	1837824
7G	1.1	58	76	0	19	81	0	66	1418222
8A	1.1	59	77	0	17	83	0	68	1422906
8B	2.2	74	86	0	10	90	0	93	2754155
8C	3.1	81	90	0	8	92	0	96	3721586
8D	2.7	78	89	0	8	92	0	95	3346387
8E	2.7	78	88	0	8	92	0	94	3217023
8F	1.3	63	78	0	15	85	0	74	1632441
8G	0.9	46	70	0	25	75	0	38	1076130