AN INVESTIGATION OF DUAL DUCTING SYSTEM FOR DAYLIGHTING OFFICE BUILDINGS IN DHAKA

By

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Dedicated to My Parents

Ranendra Chandra Paul

Monika Paul

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Abstract

With rapid development, commercial and economic activities increase parallel which accommodate lots of office spaces and buildings in Dhaka city. Deep plans are a common practice in middle and high-rise office building design, and large open plans have become the preferred office layout by modern businesses due to the flexibility of the space and economic benefits achieved from maximum plot to gross floor area ratios. Environmentally conscious assessments of building design are recognizing that daylight (along with natural fresh air) is an important commodity and should be exploited to the full. Generally, people when asked, always prefer to work in a daylit environment. There is a growing acknowledgement that daylight produces positive effects, both physiological and psychological. Consequently, the deep core areas of these buildings is difficult to be naturally illuminated by side windows, and depend entirely on electricity for illumination. Often major spaces of office buildings are running with artificial lighting.

Recent studies suggest the artificial lighting accounts for close to 50% of the total energy use in a building, through daylight is readily able to replace much of this energy use. Daylight is a major influence on building design. The light pipes are innovative devices able to transport and distribute daylight without heat transfer in dark rooms. Innovative daylighting strategies seek to break the conventional strategies barriers and 'guide' daylight beyond their limits to the remote zones and windowless spaces, whether in new or existing buildings. Daylight Guidance System (DGS) use lightpipes to distribute daylight, which occupy significant amounts of space. Most of the office building is also running with artificial heating, cooling and ventilation system which already occupy a lot of ceiling space of the buildings. The integration of light ducts with heating, ventilation and air conditioning (HVAC) ducts (dual ducting system) could be a practical solution that may ensure quality working environment, energy saving, reduction of costs and space management. The aim of the research is to study the installation of light pipe with HVAC ducting system and explore an integrated system (dual ducting system) for office buildings to increase the use of daylight in working space in the context of Dhaka. To explore the possibilities of installing lightpipe, computer simulation analysis were used by EnergyPlus software. Further simulation analysis was done to refine the design parameter, e.g. length and width, number and position of light pipe for the most effective use of daylight.

Results indicate that, there is a considerable potential for daylight inclusion into the deep office space by installing light pipe. Literature review, field observations, model experiments and simulation studies together provide the basis of design guidelines for consultants to design appropriate luminous environment. It is expected that the design strategies and recommendations from this research will improve the luminous environment of deep spaces of office buildings of Dhaka by installing duel ducting system.

Keywords

Dual Ducting System, Light Pipe, HVAC, Daylighting, Office Building.

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LIST OF ABBREVIATIONS

BUET	Bangladesh University of Engineering & Technology
CUET	Chittagong University of Engineering & Technology
DoA	Department of Architecture
DGS	Daylight Guidance System
AGS	Architectural Graphic Standards
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BMD	Bangladesh Meteorological Department
BNBC	Bangladesh National Building Code
CBDM	Climate-Based Daylight Modelling
CEC	California Energy Commission
CIE	International Commission on illumination
DA	Daylight Autonomy
DDS	Dynamic Daylight Simulation
DF	Daylight Factor
DGS	Daylight Guidance System
DLS	Day Lighting System
DMBCR	Dhaka Metropolitan Building Construction Rules
EC	European Commission
ERC	External Reflected Component
FAR	Floor Area Ratio
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IES	Illuminating Engineering Society
IESNA	Illuminating Engineering Society of North America
IRC	Internally Reflected Component
ISO	International Organization for Standardization
RAD	Return Air Ducts
SAD	Supply Air Ducts
TDD	Tubular Daylighting Device
UDI	Useful Daylight Illuminance

CHAPTER ONE: INTRODUCTION

Preamble

Problem Statement

Aim and Objectives

Overview of Research Methodology

Scope and Limitation of the Research

Structure of the Thesis

Conclusion

1.1 Preamble

Dhaka, the capital of Bangladesh, is growing rapidly with its economic and commercial activities, which increase the growth of commercial space as well as office buildings. Most of the office buildings are running with artificial lighting. The quality of luminous environment often affected by poor natural lighting system and high internal heat gains from artificial lighting (Hossain et al., 2013), which creates an intolerably hot and uncomfortable working environment for the users that fails to satisfy national and international standards (Sharmin, 2011). It is necessary to maintain an efficient working environment for maximizing productivity (PSL, 2007). Proper illumination condition of work space, is a major requirement of a suitable working environment since lighting directly affects visibility, light is critical to productivity, safety and healthy working conditions of workers (Zohir et al., 2008; Wilson et al., 2005). Recent studies suggest the artificial lighting accounts for close to 50% of the total energy use in a building, through daylight is readily able to replace much of this energy use (Jackson, 2006).

Daylight is a major element on building design. Daylight is one of the most important elements in individuals' regular life. The regular life style of human being is sleeping at night and working during daytimes. Human brain roles and responds to the motivation of daylight. In work space, daylighting is very crucial for the wellbeing, efficiency and safety for the occupants. It can also improve the internal environment of buildings significantly (NARM, 2009).

Daylight is also one of the most important natural resources available for architects to enhance the visual quality of interior spaces. It is an abundant resource in the tropics (e.g. Dhaka, Bangladesh), essential both as a primary source of illumination as well as an ingredient of drama, excitement and dynamism in the architecture and aesthetics of spaces (Ahmed et. al., 2007).

In case of buildings with large and wide plan, direct daylight can reach only double distance of side opening's height, but not into the remote parts of the building. The light pipes are innovative devices able to transport and distribute natural light without heat transfer in under lit (Malet-Damour et. al., 2013). Tubular Daylight guidance systems

(DGS) are linear structures that channel daylight by means of optical interactions into the core of a building, with minimal impacts on the building design (Mayhoub et. al., 2011, 2012, Carter et. al., 2008). Innovative daylighting strategies seek to break the conventional strategic barriers and 'guide' daylight to the remote zones and windowless spaces, whether in new or existing buildings (Mayhoub and Carter, 2012). DGS use light ducts to distribute daylight, which occupy significant amounts of space. Most of the office building is also running with artificial heating, cooling and ventilation system which already occupy a lot of ceiling space of the buildings. The integration of light ducts with heating, ventilation and air conditioning (HVAC) ducts (dual ducting system) could be a practical solution (Mayhoub, 2015) that may ensure quality working environment, energy saving, reduction of costs and space management.

1.2 Problem Statement

To meet the demand of huge economic activities and rapid urbanization, the majority of the office buildings of Dhaka are not properly planned (Khan, 2012). Existing office buildings in Dhaka were sometimes constructed disregarding the building codes and setback rules set by RAJUK and neglect their physical, environmental and socio-cultural effects on the overall condition of the city environment (Iqbal and Khan, 2005; Hafiz 2000; Rahman and Mowla, 2003). In commercial zones, as land prices are high, office buildings are of deep plans (Joarder, 2007). It is difficult to bring daylight into the central areas and different types of artificial lighting systems are used to illuminate office interiors during daytime.

The buildings which were designed and constructed in such a way that daylight may enter at the peripheral portion of the buildings, the users are often not interested to use daylight because of unwanted heat. Along with the high outdoor air temperature, solar radiation is a major source of heat gain for buildings in tropics (Koenigsberger et. at, 1973). These buildings are deprived of daylight driving the occupants to rely on the artificial lighting and increase the energy consumption. From the year 2005 to 2011, electricity consumption of Dhaka city has been doubled (Mondal and Denich, 2010).

Effective office space design is a challenging issue in case of building design as it embraces varieties of activities and users with different age groups. The size, shape, material and position of opening not only directly influences the availability of daylight

and sunlight but also indirectly influences the energy demand for heating, cooling and lighting due to heat production of the electric lighting (Bokel, 2007).

Limitation of energy resources, ever increasing energy price and the global warming, the necessity to reduce the energy consumption in the buildings can be an important issue in a developing country such as Bangladesh. In such a context the need to develop the use of daylight in deep spaces of office building and efficient design of lightpipes may address these issue significantly.

1.3 Aim and Objectives

The aim of the research is to develop architectural design strategies to incorporate daylight into office spaces through the light pipe by configuring HVAC ducting system in the context of Dhaka.

To achieve this aim, following objectives have been developed.

- **Objective 1:** To establish the potential of lightpipe in office building where direct sunlight cannot reach through openings.
- **Objective 2:** To observe the daylight inclusion pattern in different space of the office by side opening and by lightpipe where daylight cannot enter by window and roof.
- **Objective 3:** To identify effective configuration of lightpipe of the office space to ensure standard illumination levels of daylight at task plane in the context of Dhaka.
- **Objective 4:** To integrate lightpipe with HVAC system in office buildings to develop the dual ducting system in working spaces of office buildings.

1.4 Overview of the Research Methodology

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

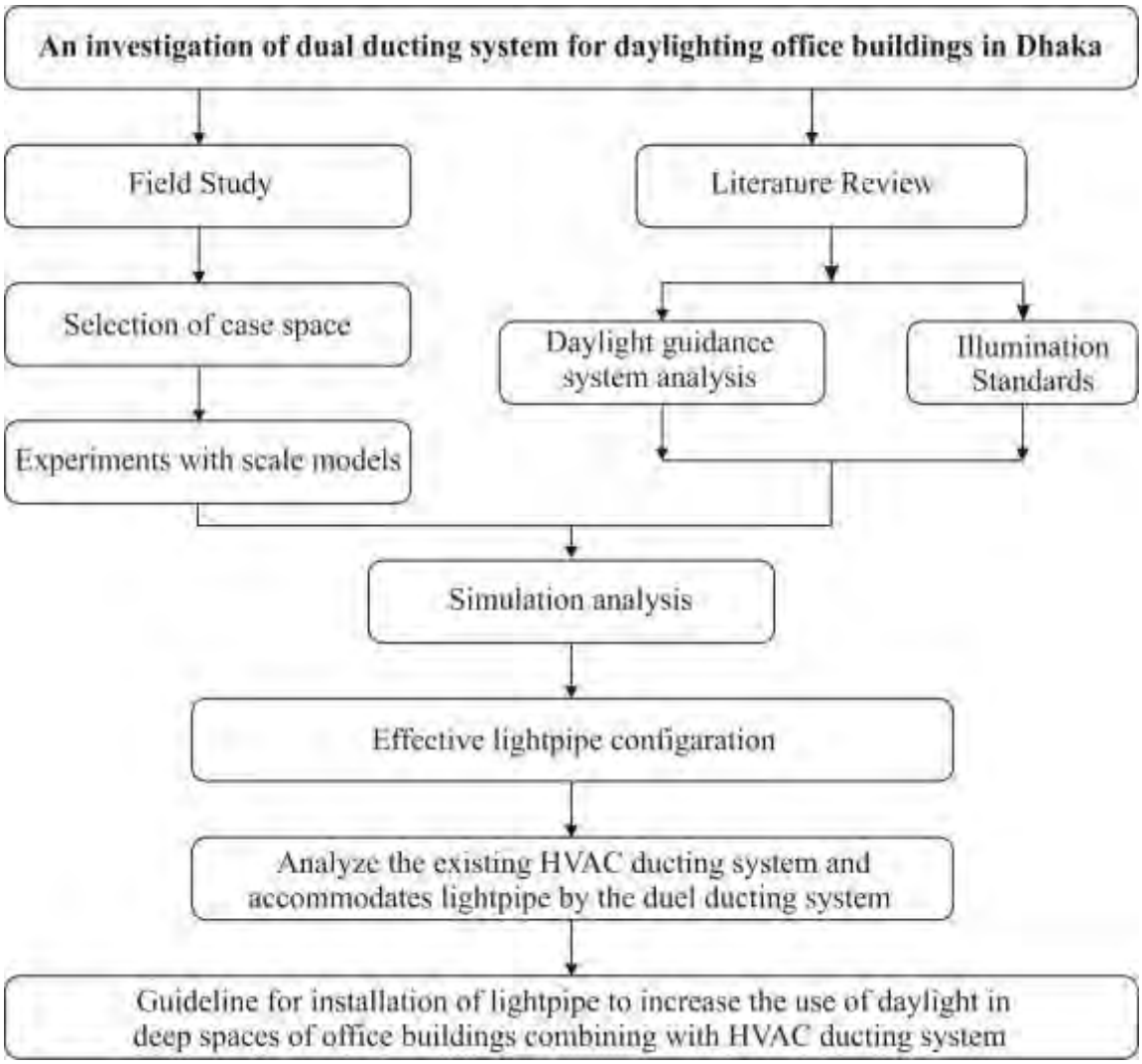


Figure 1.1: Flow diagram of the research process.

The research started with a literature survey to gather knowledge and information on Daylight guidance systems, layout pattern of the office spaces in Dhaka; national and international illumination standards and climatic context of Dhaka to understand the nature of expected luminous environment in office buildings.

A survey was conducted on 10 office buildings intermediate floor areas which were far away from the side window. Then case selection criteria were set (Section 4.5). From these 10 surveyed office buildings (Table 4.1), an office space which was operated by artificial light was selected as case area (Section 4.5) based on the selection criteria for simulation analysis. Then an experimental study with models of selected office space was conducted to observe the daylight inclusion pattern with different openings.

After that the simulation study were conducted with the model of selected office space under the climatic context of Dhaka. Several no. of simulations were done on the selected case by using EnergyPlus software by changing different parameter such as lightpipe diameter, length, numbers and presence or absent of side window. Then an analysis was done about the HVAC ducting system among the case studies and try to accommodate the lightpipe duct with the HVAC duct.

Finally, the experiences of the simulation study were compiled to recommend architectural design guidelines to improve the daylighting condition of office spaces through light pipe as well as dual ducting system in the context of Dhaka.

1.5 Scope and limitation of the research

The research work concentrates on strategies to use the daylight of office spaces under the context of Dhaka region. Recommendations and design guidelines of this research are made regarding the installation of lightpipe and combine it with the buildings HVAC ducting system for office buildings that can be applied in context of Dhaka.

In the tropics, with the daylight unwanted heat may enter and too much daylight may cause glare. This study concentrates on strategies for daylight inclusion into office's task spaces. Besides improving luminous environment, daylight inclusion is also related to aesthetics, energy consumption (electric lighting, mechanical heating and cooling), heat loss and gain, sound transmission, economics, glare control, ventilation, safety, security and subjective concerns of privacy and view.

Considering time and resource constraint for the research, the consequence of daylight inclusion on the previously mentioned concerns was however beyond the scope of this thesis. The present work focuses mainly on performance of lightpipe to improve the daylighting condition and find out a way to combine the pipes with the HVAC duct of the office building in the context of Dhaka.

1.6 Structure of the thesis

This Section provides an overview of each of the following six (6) chapters, which is shown graphically in Figure 1.2

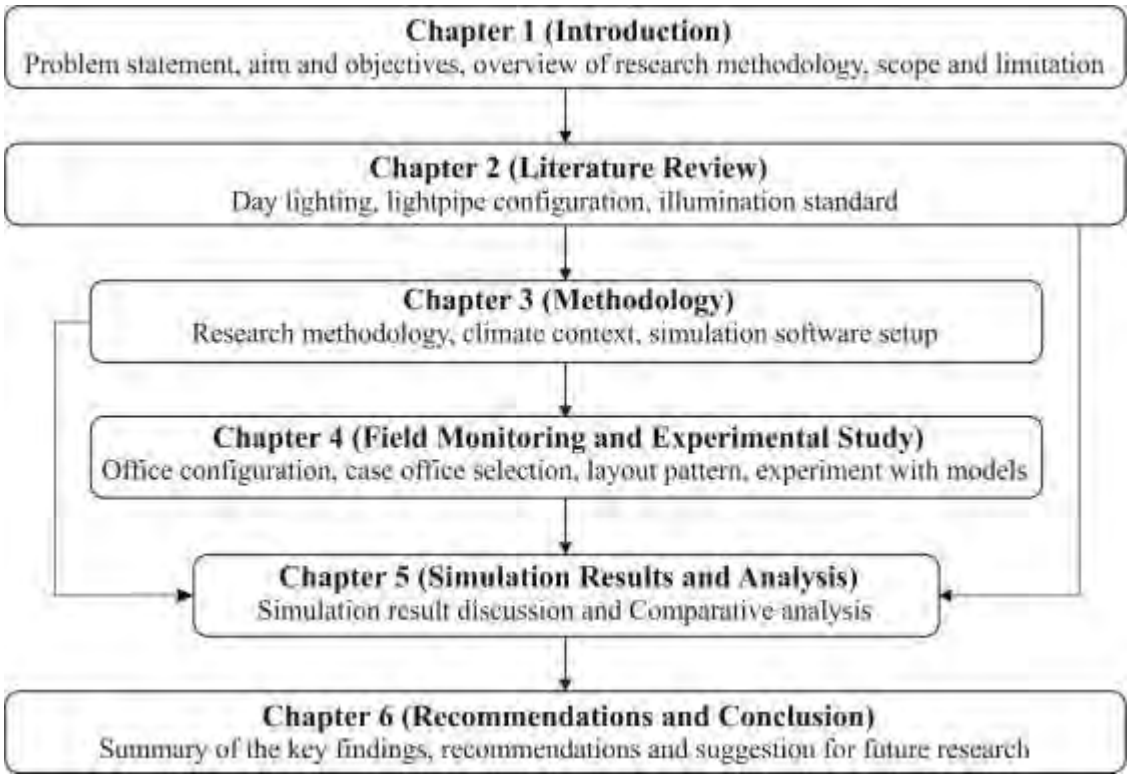


Figure 1.2: Organization of the chapters and structure of the thesis

Chapter 1 (Introduction) 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 (Literature Review) 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 (Methodology) describes the detail steps of the methodology for simulation study for this research. It also describes the criteria of the selection of the case space for simulation study. This chapter also setup perimeters for simulation, fix up the variables and determine the evolution process. This chapter also provides a general climatic overview of Bangladesh based on published data from different published thesis books and papers, mainly focused on the case area of this thesis, i.e. Dhaka. The purpose is to formulate an environmental database for simulation study.

Chapter 4 (Field Monitoring and Experimental Study) focuses the findings of present condition of different office spaces, layout pattern, use of natural and artificial daylight, material of external façade, to provide additional information which help to select the simulation area and determine the considerations. It also provides the description of experiments which was conducted by making physical scale model to observe the nature of light penetration by roof and window.

Chapter 5 (Simulation Results and Analysis) conduct EnergyPlus simulation of different lightpipes with the consideration of different variables. It also discussed the findings of the simulations, its different aspects and compare the findings to understand different parameters of lightpipes. It also discusses the dual ducting system and its technical aspects.

Chapter 6 (Recommendations and Conclusion) summarizes the findings of the whole research, 1st by fulfillment of aims and objectives described in this chapter and discusses the architecture design strategies to improve the daylighting condition of the office spaces in context of Dhaka. 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.

1.7 Conclusion

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 each stage 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.

CHAPTER TWO: LITERATURE REVIEW

Preamble

Office Buildings- Present Context

Daylight Source and Availability

Components of Daylight

The Daylight Factor

The Unique Qualities of Daylight

Space Geometry

Daylight Strategies for Office Buildings

Defining Deep Spaces of Office Buildings

Lighting Solutions for Deep Spaces

Daylight Guidance Systems

Dual Ducting System

Illumination Standards for Office Buildings

Critical Findings from Literature Review

Summery

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 investigation of dual ducting system for daylighting office buildings in Dhaka. This chapter mainly consists of five major parts. The first part of this chapter discusses the evolution of office building in Dhaka and analyses the function and different layouts of office spaces. The second part describes daylight as a potential source of lighting. The third part discusses about the Duel Ducting System as well as Tubular Daylight guidance system. This part also describes the daylighting strategies for deep space of office buildings. The forth part focuses on national, international and local illumination standards for office spaces. The methodology for experimental simulation studies and field investigation are discussed in the next chapters, developed with respect to the outcomes of this chapter.

2.2 Office Buildings-Present Context

A building may be intended for a particular use and may not necessarily be occupied continuously. An office is only in use during that part of the day known as 'office hours'(Joarder, 2007). Increased land value, limited urban accessibility, expanding urban population, globalization of national economy and locational preferences of business make the specified office building inevitable. In addition to accommodating different economic activity for the purpose of industrialization, multistoried high rise buildings are now extensively used as working space (Rahman, 2007).

Designs of office building, in general, are not responsive to the requirements of Dhaka's tropical climate. Office buildings are often designed without giving due importance to the parameters that are responsible for energy demand such as use of artificial lighting and cooling. Dependence on artificial lighting and ventilation is common in all offices. Furthermore, energy use in the office building sector is increasing dramatically due to the improvements of economic sector's standards. The increase in electricity use by the office building particularly in hot and humid periods has been caused by the growing demand for air conditioners to provide thermal comfort and use of artificial lighting rather than use of daylight for the occupiers (Wong and Li, 2007). Buildings use about 48% of all the

energy consumed, with 40% for the operation of buildings (Maleki 2011). Significant savings in operational costs would justify incorporation of climatically responsive design features, despite higher capital construction costs.

2.2.1 Office Layout Types

Internally, office buildings have been transformed in the past thirty years all over the world. Change continues as companies realize that the interior layout has a greater influence on productivity than ecological, showy statements to the outside world. New office designs are changing the way people view space. Hierarchical systems of top-down people management have been broken down and office plans now squeeze openness and transparency (Joarder, 2007).

In brief, an office is typically designed according to three planning options; closed, open, combination (Kim.G, 1998). Each option is distinguished by the proportion of partitioned or enclosed-to-open space that exists in the layout. The layouts structured by the independent workstations or clustered groupings organized in a variety of unit module of workstations. In the layout of partitioned open space, a common design is to place the unit workstation modules in rows (Joarder, 2007).

There is a growing tendency towards organizing office spaces according to an open plan, which encourages interpersonal contact and a homogenous workflow, rather than the stereotyped double-loaded corridor pattern (Islam, 2006), which is not appropriate in naturally ventilated offices. The open plan is a configuration of varying-height partitions or panels that are free-standing or integrated into furniture system. This is, perhaps, the most typical planning option in the perimeter spaces of an office building (Joarder, 2007).

Modular open-plan offices consist of an assembly of individual work stations which are in visual and acoustical contact with each other. The first open plan offices were designed by the brothers Schnelles in Germany in the 1960s and were called Burolandschaften (office landscapes). Burolandschaften were an architectural expression of the human relations movement of the 1950s which promoted 2-way communication between management and employees. Over time the original free-form floor concept disappeared and shifted to interlocking, modular furniture system that are arranged in tighter and highly predictable rectilinear groupings of work stations. Work stations have become

routinely equipped with phones and VDTs, i.e. they require enhanced acoustic separation and glare-free illumination (Reinhart, 2002).

However, open-plan offices reported problems range lack of privacy to distraction from other's noise and missing control over the thermal and visual conditions. Sometimes declining occupant satisfaction has negative significances for an organization's bottom line as the financial consequences of a dissatisfied workforce can far outweigh any savings associated with reduced office space (Joarder, 2007).

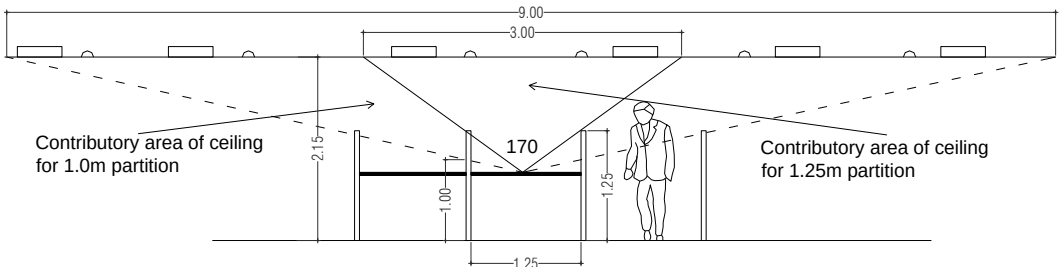


Figure 2.1: Light fixtures contributing over partitions (Source:Ahmed and Joarder 2007)

From the viewpoint of lighting, this environment presents unique opportunity for use of daylight-because there is no floor or ceiling partitions. Partition heights influence the distribution of light within large open spaces, as they are capable of cutting off light from overhead fixtures to workstations (Figure 2.1). In a space with partitions and furniture, illuminance distribution on the work plane is influenced by the inter-reflection and obstructions to which light emitting sources are subjected, creating light diminution and shadows. This study focus on that deep spaces of office where direct daylight haven't reach and the space running with open-plan arrangement with individual work area.

2.3 Daylight: Source and Availability

Daylight is desired because it accomplishes two very basic human needs such as to be able to see both a task and the space well, and to experience some psychological stimulation. Long-term working under artificial lighting is thought to be harmful to health; working with daylight is thought to result in less stress and discomfort. Daylight strategies depend on the availability of natural light, which is determined by the latitude of the building site and the conditions of immediate surroundings of the building, e.g., the presence of obstructions.

Daylighting strategies are also affected by climate. Daylight is the sum of sunlight and skylight (IEA, 2000, Sultana, 2017).

The sun is the source of natural light, energy and the path of the sun determines the available sunlight at a particular building location. The solar altitude and the solar azimuth are the two angles through which the sun's position can be defined at a reference point on earth's surface (Figure 2). The overcast sky, clear sky, and partly cloudy sky are three light conditions to be considered in daylighting design, according to the IESNA Lighting Handbook (IESNA, 2000).

The light may reach at a work space via a number of pathways (AGS, 2000). Direct sunlight is, no doubt, the brightest source. The other sources are the bright overcast sky, which is brighter than the clear blue sky (Ahmed, 1987). Daylight entering through windows under clear conditions illuminates an indoor point from five different sources as the day progresses. These are the sun, the circum-solar sky, the ground, opposite surfaces and the blue sky, with light entering downwards, upwards and horizontally (Evans, 1980). The available daylight that can replace artificial lighting is both direct sunlight and diffuse light from the sky.

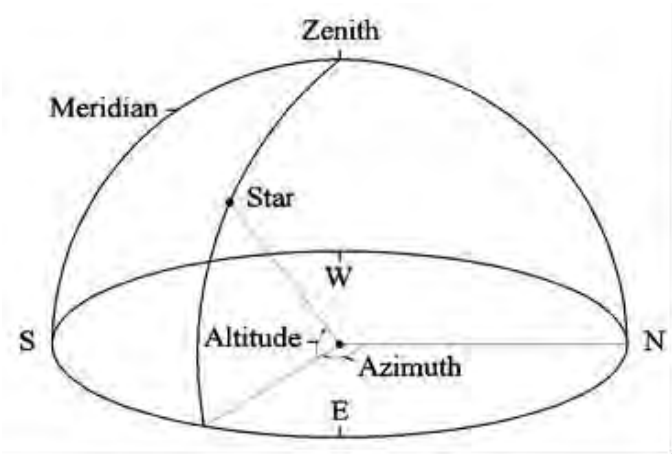


Figure 2.2: Solar altitude and the solar azimuth angle (Source:Sharmin, 2011)

The phrase “daylight availability” refers to the amount of light from the sun and the sky for a specific location, time, date and sky condition (Sharmin, 2011). The sun, sky, buildings and ground are the main sources of luminance distribution, latitude, climate and building orientation affect daylight availability, and hence need to be studied for daylight (IEA, 2000).

There are several sources of information on daylight availability. Daylight availability data has been mentioned every minute at more than 50 stations worldwide since 1991 and has also been monitored in the Meteosat satellite every half hour from 1996- 1997 (under beta testing) (Sharmin, 2011). In this research, daylight data from Bangladesh Meteorological Department has been used as input into the Energy Plus weather file for daylighting simulations (Sultana, 2017).

2.4 Components of Daylight

Light from the sky reaching a particular point in a room is composed of three distinct components as mentioned below (Figure 2.3).

a. Sky Component

b. Externally reflected component

c. Internally reflected component

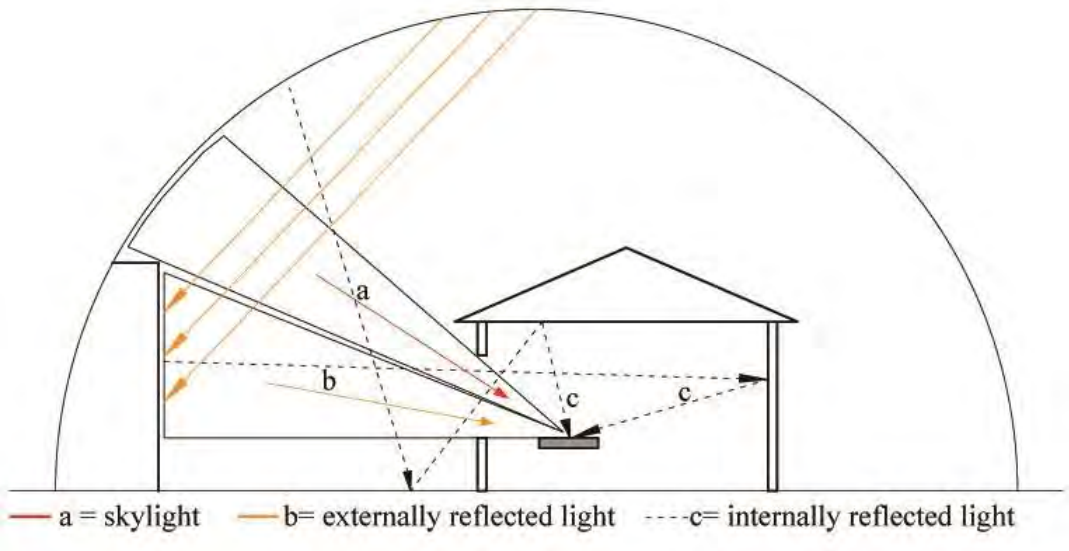


Figure 2.3: The components of daylight at a point in a room. (Source:Koenigsberger, 1975)

2.4.1 Sky Components

Sky component (SC) is the illuminance received at a point in the interior of a building, directly from the sky. The SC normally refers to the diffuse sky: i.e. it is not used to describe direct sunlight. This component depends upon there being a view of the sky from the point in the room being considered. It is the view of the sky that gets larger as the point considered approaches the window, and thus it is mainly the sky component that leads to the strong variation of light intensity in a side lit room (Joarder, 2007).

2.4.2 Externally Reflected Component

The externally reflected component (ERC) is the illuminance in the interior due to light reflected from external obstructions. The ERC is particularly relevant in dense urban situations, where, owing to the closeness of buildings, a view of the sky may be limited or even completely absent for all but positions very close to the window.

The ERC will tend to corner from a low angle, close to horizontal. Depending on reflectivity of the obstruction, this may penetrate deeper into the space than the sky component, but because of the absorption of light by the external obstruction it will generally, be much weaker (Joarder, 2007).

2.4.3 Internally Reflected Component

The internal reflected component (IRC) is the illuminance received at a point and is composed of light received indirectly from daylight that is inter-reflected around the internal surfaces of the space (Sharmin, 2011) (Figure 2.3). It is obvious from Figure 2.3 that any light that is reflected from below the horizontal must be reflected a second time on the ceiling or upper walls of the room, in order to illuminate the horizontal (upward-facing) plane, and will thus end up as the internally reflected component.

An important characteristic of the IRC is that it is fairly uniform all over the room. Figure 2.4 shows how the relative contributions of the components vary with the distance from the window. At the back of the room it is often the case that there is no SC and sometimes, in an L-shaped room for instance, no ERC. Clearly the IRC then becomes very important (Joarder 2007).

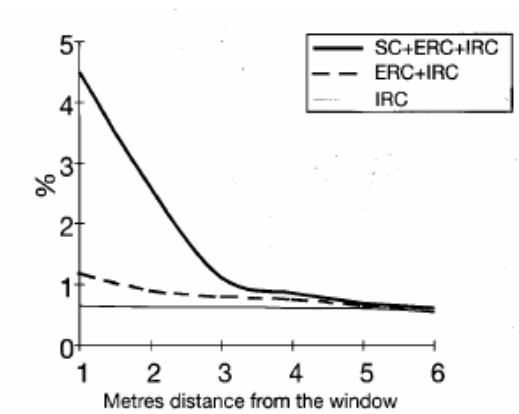


Figure 2.4: Relative contributions of sky component (SC), externally reflected component (ERC) and internally reflected component (IRC) for a typical room with an external obstruction. (Source: Baker, 2002)

2.5 The Daylight Factor

Under overcast conditions, the interior illuminance at a point in a building is proportional to the external horizontal illuminance. This means that these two quantities vary in parallel. The ratio of the daylight illuminance at an interior point to the simultaneous illuminance outside the building from an unobstructed hemisphere of sky is called Daylight Factor (DF) and can be expressed as a percentage: DF=Ei/Eo * 100% (Fig. 2.5).

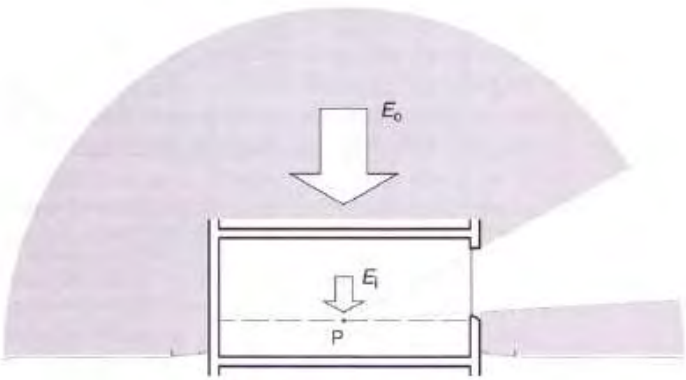


*Figure 2.5: Daylight factor as defined by DF=Ei/Eo * 100%. (Source: Baker, 2002)*

Thus the indoor distribution of Daylight can be carried out by the use of daylight factors (i.e. having as reference the overcast sky). Under clear sky conditions the above mentioned concept of daylight factor cannot be used as a design criterion since it varies significantly throughout the day (Joarder 2007). The ratio remains constant for wide variations in external illuminance and its effect on human vision also is considered steady.

Daylight inclusion as indicated by the Daylight Factor (DF) in buildings depends on three components mentioned before; the sky component (SC), internally reflected component (IRC) and externally reflected component (ERC), all of which contribute to the total daylight factor (Koenigsberger 1997). Thus: DF = SC + IRC + ERC

2.6 The Unique Qualities of Daylight

Physically, daylight is simply electromagnetic radiation in the wavelength range that is absorbed by the photo-receptors of the human eye. In this respect it is the same as all other light sources. The actual wavelengths present in daylight will vary over the day, with meteorological conditions, with latitude, and with season. It is this variability in

spectral content and the fact that, at all times, it is a continuous spectrum with elements in all parts of the visible wavelength range that separates daylight from several of the more widely used electric light sources, such as the fluorescent lamp used in nearly all commercial buildings and the high pressure sodium lamp used in many industrial buildings. Nonetheless, there are electric light sources available, such as the xenon lamp, the sulphur lamp and some filtered incandescent lamps, which have a spectral content similar to daylight conditions on some occasions. Thus, there is no unique physical characteristic of daylight which separates it from all other light sources (Boyce, 1998). The lights penetrates by lightpipe is the direct daylight which has all the qualities of daylight. However daylight and sunlight has unique qualities that separate it from other lighting sources as discussed below.

2.6.1 Change and variety

One of the most important aspects of daylighting is its capacity for change, leading to the infinite variety in appearance of the daylit interior. Daylight is a constantly changing source, varying from time of day, season of the year and the state of weather, whether sunny or cloudy. Changes in the weather can be observed, modifying the appearance of a room and helping to react to the external environment during the day. Change and variety are at the heart of daylighting (Bell et.al., 1995). The daylight penetrates by lightpipes has qualities that can make work easier, as well as create enjoyable interiors with variety in brightness and the refreshment and relaxation of a view outside.

2.6.2 Moving Direction

Daylight coming by lightpipes by its nature gives meaning and aids our understanding of a shape or space by its directional flow; a meaning which is emphasized even further by the addition of direct sunlight. Daylight has direction because of the movement of the sun from morning to evening, varying as it does from season to season and with higher brightness at different times of day. This direction adds both orientation and modelling to the appearance of a space; it provides clarity. We perceive and understand the spaces we inhabit by their three dimensional quality. Daylight provides changing modelling and increases our perception of time and space, with the added aspect of orientation, giving a person an awareness of where he is in relation to the exterior (Philips, 2000). The lights penetrates by lightpipes have the same characteristics.

2.6.3 Modelling

The appearance of the interior design is determined by the physical surfaces, edges and textures when acted upon by light falling on them. Interior spaces are judged to be pleasant, bright or gloomy as a result of modelling effects. The modelling on a dull overcast day is a different experience from that of a sunny day. This is a different experience again from the form of an object or space resulting from a room lit by artificial light, where the overall light may be received from a multitude of light sources. Light from windows on adjacent walls and lightpipes assists in modelling, with the main direction of light being supplemented by reflected light. Modelling from overhead daylight is of a different order; with greater vertical emphasis. Lightpipe provides directional light which gives good three dimensional modelling for tasks.

2.6.4 Sunlight effect

This effect is not measurable, and is therefore difficult to assess by engineering formulae. When sunlight is available, there is a human need for it to be taken into account, and a sense of disappointment when this is denied (Joarder, 2007). Sunlight is fundamentally good both therapeutically and visually, but it is always important to consider the obverse side in terms of heat gain and glare. Control may need to be exercised over the sunlight entering a building, depending upon geographical location and the purpose of the building. Lightpipe penetrated daylight is thought by most to be psychologically desirable, and there is growing evidence that it is biologically beneficial and can contribute to enhanced task performance.

2.6.5 Colour

The colour appearance of objects around us depends on the spectral composition of the light in which we see them, and daylight is the norm by which we judge the colour rendering properties of other light sources (Energy Research Group, 1994). Daylight is thought to be the true colour despite the fact that it varies in hue from morning to evening and is enhanced by sunlight (Philips, 2000). This is of particular importance in buildings where we have learned to adapt to the natural change which occurs and a white surface still appears white in evening light. Daylight penetrates by lightpipe is the colour we regard as natural. It is generally recognized that vision is enhanced by good contrast, and

that the natural colour of daylight increases contrast; it is argued that this permits lower illumination levels, whilst increasing visibility (Tregenza, 1998).

2.6.6 View

Daylight provides high illuminance and permits excellent colour discrimination and colour rendering. These two properties mean that daylight provides the condition for good vision (International Energy Agency, 2000). The variability of the intensity and colour of daylight over time stimulates the visual senses, and the view and visual connection with the outdoors that accompanies many daylighting designs is almost universally desired (A.G.S., 2000). The view out through a window, or how we perceive the world outside, is a dynamic experience associated with changes in daylight, sunlight and season. The adaptation of the eye to distance, an extension of view and an awareness of the environment beyond the building, all contribute to man's well-being. These unique qualities of daylight have been exploited throughout history and it is when these qualities are disregarded that buildings fail to provide satisfaction (Philips, 2000). The lights penetrates by lightpipes have the same characteristics as well.

2.7 Space Geometry

The geometry of a building plan plays a significant role on the usage of daylight, since directly related with the size of the perimeter zone (Figure 2.6). As internal reflected component (IRC) is highly dependent on surfaces near the task, therefore towards the center of large rooms, the ceiling becomes and important contributor to daylight, while in spaces near walls, the vertical surfaces gain in importance (Ahmed, 2014). If it is possible, the ratio of perimeter zone to total floor area should be increased. The higher the skin to volume ratio, the greater will be the percentage of floor space available for daylighting. Long and narrow footprints are preferable to square ones, up to a limit.

There are practical limits to room size beyond which conventional window systems are ineffective (AGS, 2000). The deeper the room, the poorer the uniformity of daylighting, and people furthest from the window wall will feel the need for supplementary electric lighting. For designs that use diffuse daylight from the sky, clouds and surrounding environment, it is difficult to provide adequate daylight when the depth of the space is more than 1.5 or 2 times the height of window head (Joarder, 2007).

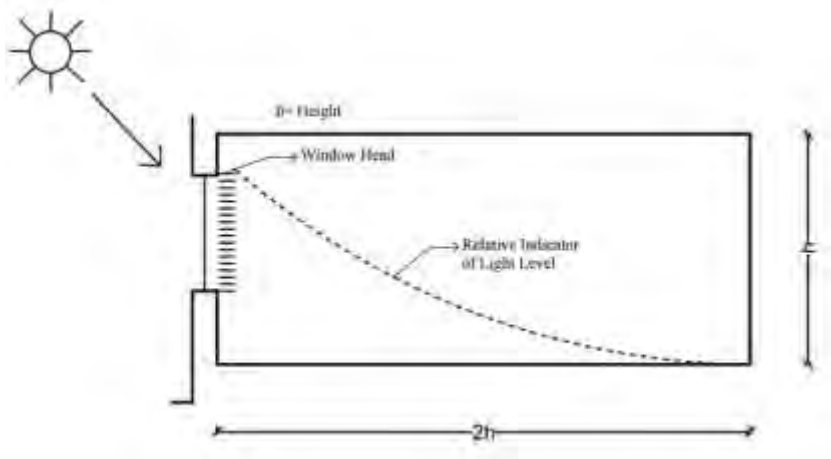


Figure 2.6: Diffuse daylight penetrations to space (Source: A.G.S., 2000)

2.8 Daylighting strategies for office buildings

Daylighting strategies and architectural design strategies are inseparable. Daylight not only replaces artificial lighting, reducing lighting energy use, but also influences both heating and cooling loads. Planning for daylight therefore involves integrating the perspectives and requirements of various specialties and professionals. Daylighting design starts with the selection of a building site and continues as long as the building is occupied. However, it is unusual for the architect to see daylighting design as a primary consideration for office building planning (Baker et.al, 2002). Usually the size of the site and the total built floor area requirements are governed, or at least limit, the range of options. Where site area is not so constrained, then other planning and organizational issues normally take precedence over considerations for daylighting (Joarder, 2007).

However, early design decisions can have a considerable impact on the potential use of daylight. And with increasing realization of the benefits of daylight from both energy and an environmental viewpoint, the daylight criterion should come to the upper priorities (Joarder, 2007). But the deep space where direct daylight cannot reach, need different daylighting strategies.

Daylighting planning has different objectives at each stage of office building design, which the International Energy Agency (2000) list as below:

- **Conceptual Design:** As the building scheme is being created, daylighting design influences and/or is influenced by basic decisions about the building's shape, proportions, and apertures, as well as about the integration and the role of building systems.

- **Design Phase:** As the building design evolves, daylighting strategies must be developed for different parts of the building. The design of facades and interior finishing, and the selection and integration of systems and services (including artificial lighting), are all related to the building's daylighting plan.
- **Final/Construction Planning:** The selection of materials and products is affected by the building's daylighting strategy; final details of the daylighting scheme must be worked out when construction plans are created.
- **Commissioning and Post-Occupancy:** Once the building is constructed, lighting controls must be calibrated and ongoing operation and maintenance of the system begins.

2.9 Defining Deep Spaces of Office Buildings

In any space, a light zone may consist of both direct sun light zone and diffuse light zone or only diffuse light zone. A direct sun light zone (area near the aperture) is lit directly by the sun's ray. Direct sun light helps to illuminate the nearest surroundings, and become diffuse with distance from aperture. In addition to this, sky light, internally and externally reflected light of daylight, act as prime components of the diffuse light zone (Haque, 2015). After a certain distance from the aperture, illumination level falls below the accepted level for specific works and can be called darkness or deep zone (Figure 2.7 and 2.8). It can also be called artificial light zone, due to the obvious need to use artificial light for vigorous deeds. The light zone and diffuse light zone uses less man-maid energy, than the dark zones/deep zones as it maintains effective illumination level.

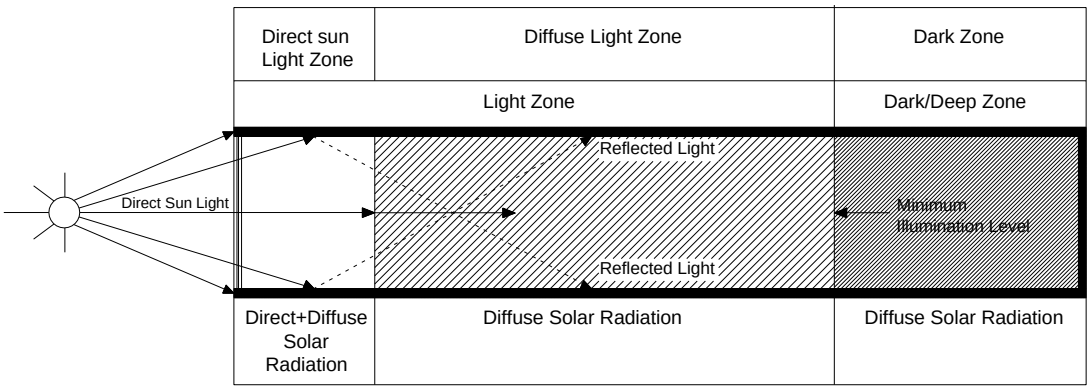


Figure 2.7: Distribution of light zone and dark zone in plan (Haque, 2015)

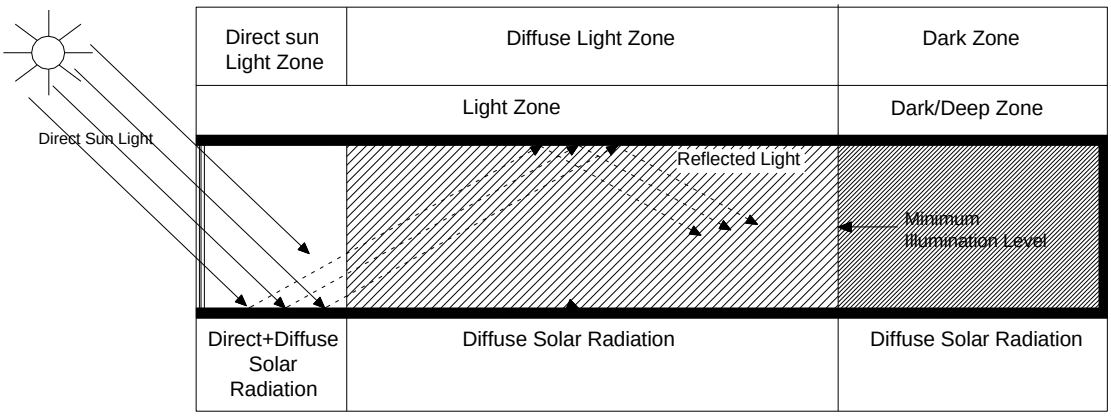


Figure 2.8: Distribution of light zone and dark zone in section (Haque, 2015)

2.10 Lighting Solutions for Deep Spaces

As direct daylight cannot reach at the deep spaces of office buildings, there are two alternative solutions for the employee of that spaces. Either they have to use artificial lights, or have to install Daylighting System to the deep spaces.

2.10.1 Artificial Lights

While considering artificial light, an extensive range of light sources and luminaires are available for visual task with technical progress. Sometimes, task lighting is provided to a local area to supply sufficient illumination for a specific task and this artificial light, such as a desk lamp, overhead lighting at shelves, or portable lamps for industrial tasks, is usually paired with ambient lighting, providing a lower level of general illumination.

Figure 2.9: Various types of light: Incandescent, Fluorescent, CFL, HID, LED lights, (Source: Global Warming Art 2009 and www.lixall.co.uk)

The artificial or technical lights are basically two types. They are: Thermal radiator (incandescent lamp, halogen lamps) and Discharge lamps (low pressure lamp or florescent lamp and high pressure lamp or Mercury lamps). These lights are available with different lumen output and colour. Among them, Incandescent lights, Fluorescent

tubelights, High Intensity Discharge (HID) Lamps, Compact Fluorescent Lamps (CFL), Light Emitting Diode (LED) lights are notable ones (Figure 2.7). In Bangladesh, incandescent and fluorescent lights are mostly used. Fluorescent lights are extensively used in factories especially garment industries (Khan 2010). Energy efficient lights are now available in the market but the cost is high (Khan 2010). The use of the remaining types, Compact Fluorescent Lamps (CFL), High Pressure Metal Halides lamps (PMHL), Halogen Lamps (HL), etc. are insignificant in numbers. A device named Ballast is used with a fluorescent or high intensity discharge (ID) lamp to obtain the necessary circuit conditions for starting and operating (Light Corp 2010)(Hossain, M. 2011).

Table 2.1: Comparative Analysis of Various Artificial lights and their characteristics (Source: Khan 2010)

Type	**Lumen Per watt**	**Life X 1000 Hours**	**Start-up-time (minute)**	**Lumen maintenance**	**Colour Rendition**	**Operating Cost**
Incandescent	15-25	0.75-12	Immediate	Fair to Excellent	Excellent	High
Florescent	55-85	7.5-24	Immediate	Fair to Excellent	Good to Excellent	Average
CFL	45-60	10	Immediate	Good	Good	Low
LED Lights	70- 120	50-100	Immediate	Very Good	Good	Very Low
Mercury Vapor	50-60	16-24	2-7	Very Good	Poor to Excellent	Average

2.10.2 Daylighting System

Two main approaches have been developed to allow daylight to effectively penetrate deeper within new buildings and to control and distribute direct sunlight. The first approach includes devices such as louvers or light shelves to improve the conventional technique's performance. The second approach intentions to deliver daylight into windowless and remote spaces within buildings via light wells, light pipes or fibre optics (Mayhoub, 2014). The systems which depend upon this approach are typically called Daylight Guidance Systems (DGS). The tubular daylight guidance system (TDGS) is believed to be the most commercially available. Figure 2.10 shows the different paths of Day Lighting System.

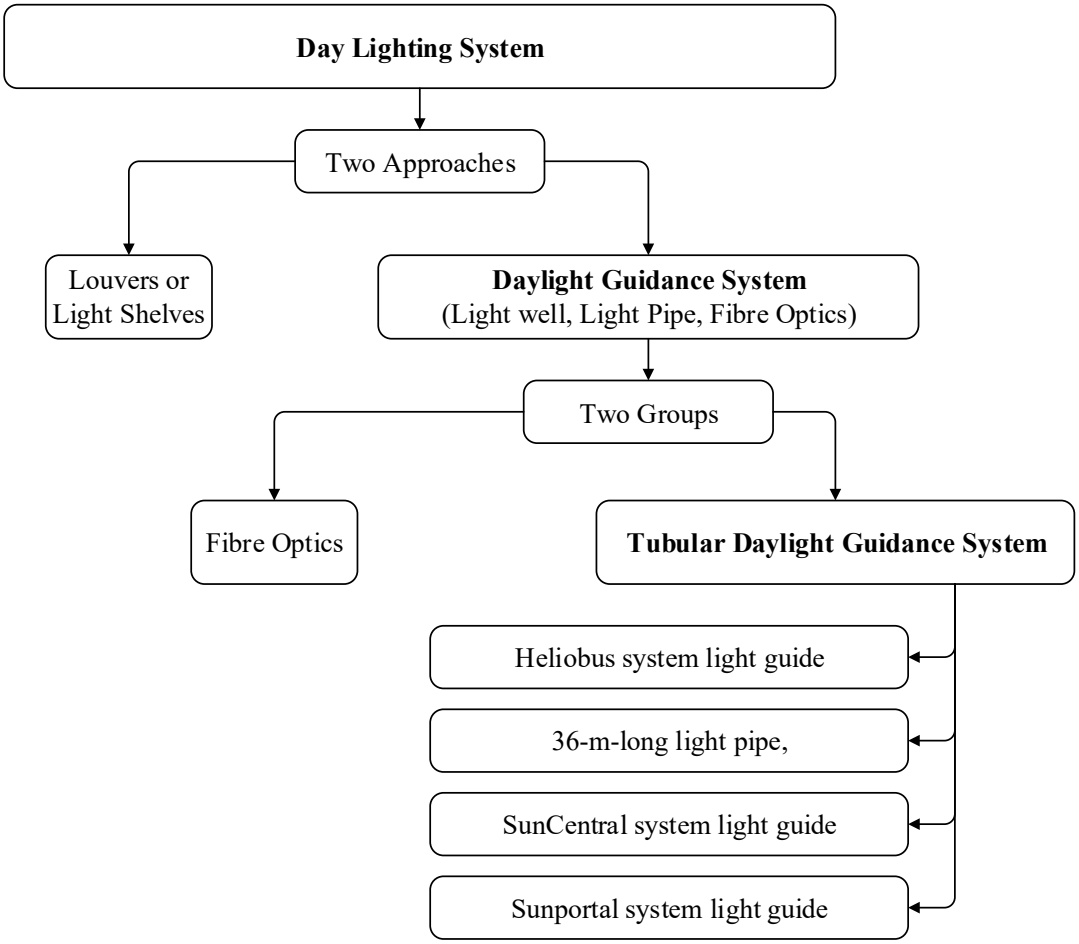


Figure 2.10: Day Lighting System Classifications.

2.11 Daylight Guidance Systems

Daylight Guidance Systems (DGS) delivers daylight into remote parts of buildings. DGS generally consist of three components: a light collector which harvests daylight, a light guide transport which coveys' daylight to where it is required and a diffuser which spreads daylight uniformly across the space (Mayhoub, 2014). The light collector technology determines under which sky conditions the DGS are most efficient and significantly influences the initial costs of the system. The light guide type considerably affects the ease with which the DGS can be integrated into the building. The light diffusers mainly depend on the illumination function. Reviewing the effects which the DGS components have upon the building reveals that the widespread use of the DGS is determined by the light guide, and more specifically, its ease of installation (Mayhoub, 2014).

DGS can be categorized into two groups based on light guide size, which determines the potential transportation distance, the capability to integrate into the building, the

possibility of fitting into new or existing buildings, the suitability for varying types of building and the applicability within diverse constructions.

The first group of DGS incorporates the use of light pipes. Light pipes are normally used with DGS that collect diffused daylight. These are not designed to concentrate direct sunlight. Light ducts have relatively large circular or rectangular cross-sections, typically in the range 0.20–0.50m diameter or around 0.25 x 0.60 m; depending on the distance the daylight has to be transported and the amount of light required. Larger ducts up to 1.75m diameter are used in some applications (Mayhoub, 2014).

The second uses fibre optics (or occasionally liquid guides). Fibre optics are usually used with DGS which highly concentrate direct sunlight. The Fibre optics are just a few centimetres in diameter and can thus be routed in buildings in similar way to electric cables (Mayhoub, 2014).

Among al DGS-"Lightpipe" is the most popular devices to penetrate daylight at the remote spaces of buildings where direct sunlight cannot reach.

2.11.1 Lightpipe

The lightpipes are innovative devices able to transport and distribute natural light without heat transfer in dark rooms. There are a lot of natural lighting applications able to predict the behaviour of light in a room through a traditional opening. Only few of them are able to model complex systems such as daylight guidance systems (Damour 2013) (Figure 2.11).

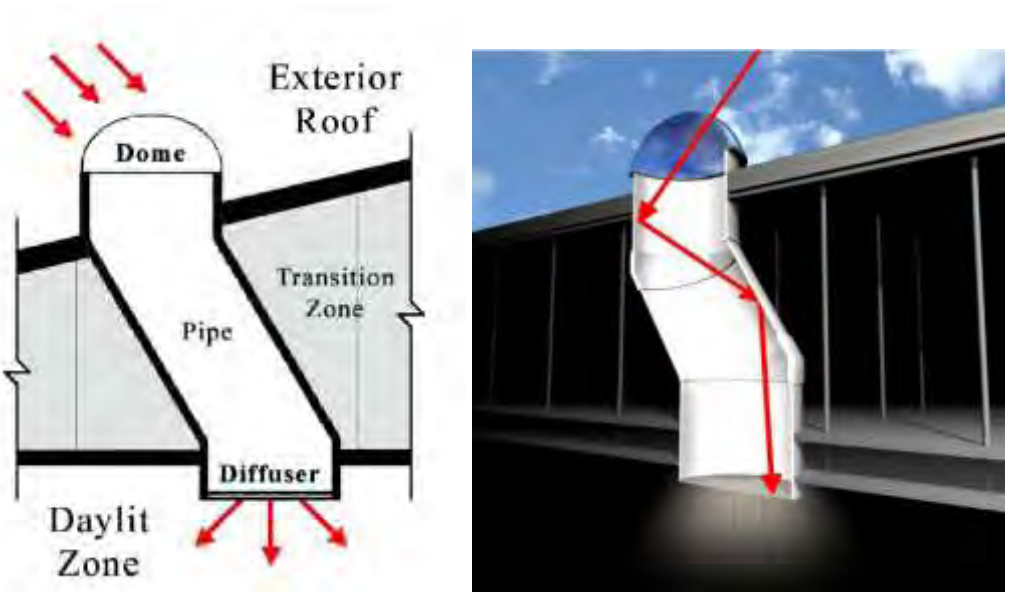


Figure 2.11:Light Pipe (Source:Ellis et.al.2016)

This system is made of a dome placed on the roof, a highly reflective tube walls (greater than 99%) and a diffuser. The dome should be shockproof and UV resistant. It protects the tube from dust and rain. The device can be coupled with an optical device to capture and redirect the sky radiation inside the tube. SOLATUBE® in Australia patented this concept in 1986. The light pipes are often called tubular skylight or lumiduc.

When entering through the vertical windows, natural light provides illumination whose values decrease as one moves away from windows. This decay is characterized by a very rapid decrease in the illuminance near the openings, and then progressively slower as it moves away from the facade. In the case of office building, without partition, light inputs are suitable for a distance of 6m from the front openings. Beyond this depth, light supplements should be considered, such as light pipes. The light pipes are generally required in this case. They permit to overcome problems related to direct illumination (glare, sunspot) by providing a diffused light (in the case of a Lambertian diffuser). Thus, depending on the configuration and requirements in lighting level, several processes of light pipe exist. The tube can be vertical or horizontal, with one or several diffusers. The pipe can be straight or have bends (Figure 2.12 and 2.13).

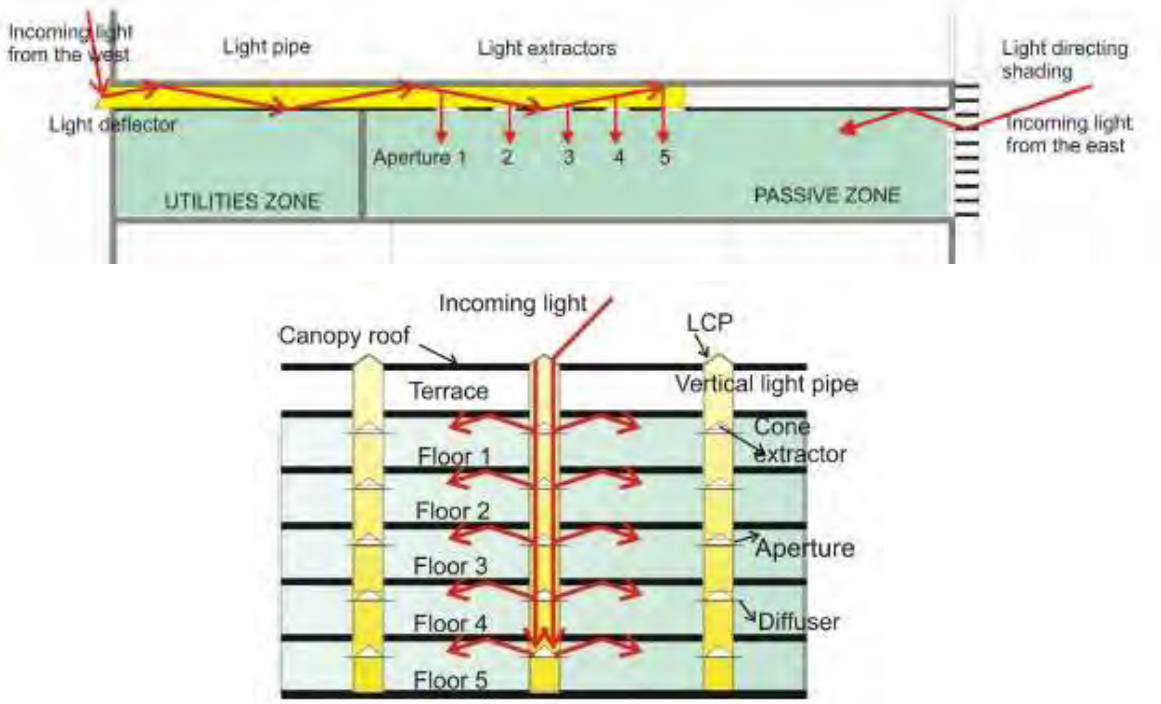


Figure 2.12: Lightpipes proposal (a) Horizontal and (b) Vertical (Hansen, 2003)

2.11.2 Paroncini's Experiments

In 2007, Paroncini conducted an experimental sequence of the light pipes, and the main objective was to highlight their efficiency. To do so, the study was set up near the campus of Monte Dago (Ancona, Italy), in an open area (without obstructions). A light pipe was installed in the center of the roof of the experimental cell, measuring 3.2 m by 2.6 m with a height of 3m (Paroncini, 2007). The walls are oriented North, East and West, and the ceiling panels are prefabricated with a reflection coefficient of 68%. The South wall has a reflectance of about 55%, while the floor is 45.6%.

The room was equipped with six sensors measuring the light levels. These sensors were positioned on tripods with a height of 0.80 m, corresponding to the height of a working plan. A plan was also provided in order to identify the names of these light meters. The sensors were indicated through alphabetic letters and through numerical codes (Figure 2.16). A sensor located outside is also used to measure the outside illuminance.

Figure 2.13: (a) The external dome with the optical device, (b) Diffuser device, (c) Diffuser device on working.

Figure 2.14: The Light Pipe.

Figure 2.15: Test Room.

The lightpipe has a diameter of 25 cm, with a 1m-length tube to achieve a ratio aspect of 4 (length / diameter). The tube is finished by an aluminium multi-layer film with high reflectance (over 99% as reported in the specifications of the producer). The surface of the diffuser has a convex shape enabling the light to spread in the room in an isotropic way (Figure 2.16).

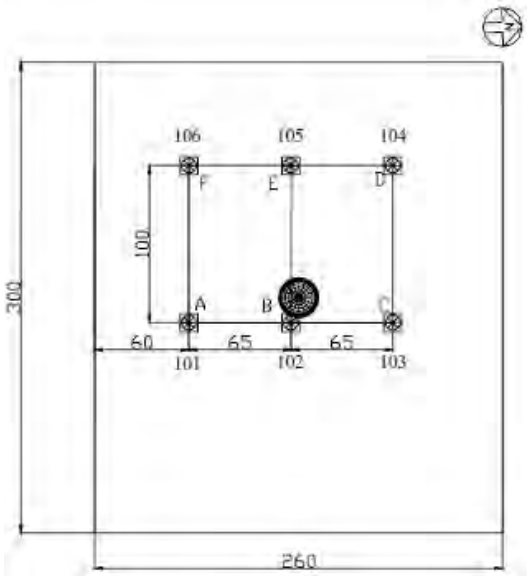


Figure 2.16: Sketch of the distribution of the sensors

2.11.3 Different Tubular Daylight Guidance Systems

Many DGS, using light ducts to deliver and/or distribute daylight, have been developed. Only the commercially available systems which generally named TDGS will be reviewed, since they are more likely to be efficiently cohesive.

The TDGSs are linear structures which channel daylight by means of optical interactions into the core of buildings. They are effective under both clear and overcast skies. The light pipe performance is affected by solar altitude, aspect ratio of the pipe, light pipe bends and cross-sectional shape. The reflective internal lining material can be silver-coated plastic film, polished and silvered aluminum or polymeric aluminum (MS Mayhoub, 2014).

The Heliobus DLS is a custom-produced system using a heliostat that tracks, collects and concentrates sunlight. A tracking mirror or Fresnel lens is usually located on the roof and uses light sensors, pulse motors and computers to track the sun. A second mirror or lens directs a concentrated beam of sunlight into a vertical prismatic light guide which

transfers light by total internal reflection into the building core (Figure 2.17). Reflective diffusing extractor foil distributes daylight over the entire surface of the guide which allows each floor along the guide path to receive similar quantities of light (Aizenberg, 1997).

Figure 2.17: The Heliobus DLS (https://www.heliobus.com/en/products/daylight-engineering)

A similar concept is used to build a **DGS with a 36-m-long light pipe** which has a doubleskin construction; an outer light-diffusing tube, which consists of tensioned translucent Lycra fibre, that reflects the sunlight horizontally into each floor, with a core consisting of prismatic glass panels with optical film. The glass pipe tapers from a diameter of 1.75m at the top to 0.50m at the bottom (Figure 2.18)(Carpenter, 2004).

Figure 2.18: a 36-m-long light pipe ((MS Mayhoub, 2012)

The SunCentral DLS is suitable for multistory buildings. It consists of a light collector of reflective louvres which pan and rotate redirecting sunlight as a stationary beam

throughout the day. The collector tracks the sun autonomously and projects a stationary collimated beam of sunlight along any side of the building or through an atrium or light well. The light is intercepted by optics integrated within an overhang which is positioned on every floor of the building. Sunlight is concentrated and directed into the façade integrated optical spandrel and is then channelled into luminaires which transport sunlight up to 15m into the building core. The luminaire has a dual function of transporting and transmitting sunlight. Its cross-section is approximately 0.1m_0.28m and is composed of aluminum tube lined with prismatic film and a semi-translucent emitter side (Figure 2.19).

Figure 2.19: The SunCentral DLS

The Sunportal DLS is suitable for large and small-scale architectural applications. It actively captures sunlight by a heliostat with an ultra-sunlight concentrator. The light travels through a series of compact optical relay lenses (0.20m diameter) over a distance of up to 200m or through mini optical relay lenses (0.10mm diameter) over a distance of up to 30m (Figure 2.20).

Figure 2.20: The Sunportal DLS (https://www.treehugger.com/sustainable-product-design/sunportal-pipes-sunlight-where-sun-dont-shine.html)

2.12 Dual ducting system

Bringing daylight into office building has significant benefits in lighting energy savings and increase workers' productivity (Heschong Mahone Group, 2003). By providing daylight, designers should consider the consequential cooling loads and also visual quality of building occupants. Daylight guidance systems use light ducts to distribute daylight, which occupy significant amounts of space. The majority of commercial buildings, and a high proportion of other building types, have heating, ventilation and air conditioning (HVAC) systems which use duct networks already integrated with the other building systems. The HVAC ducts are capable of reaching most spaces and are of comparable size to light ducts. Thus, they are a prime target for the development of dual ducts; a single duct to transport and distribute air and and another for light (Figure 2.21),(MS Mayhoub, 2014). This system known as Dual Ducting System.

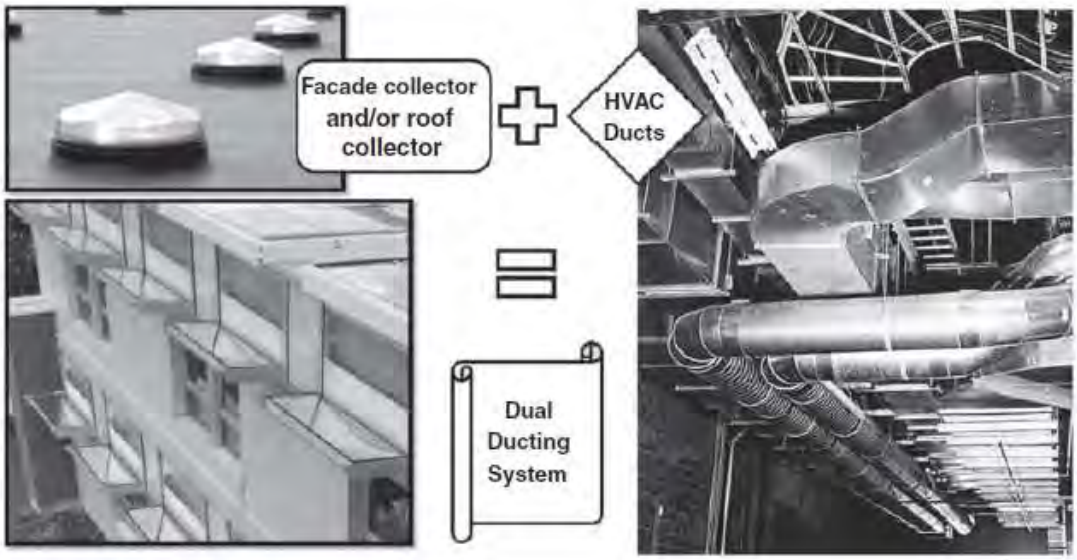


Figure 2.21 Facade light collectors (bottom left: Core SunCentral system collector) and/or roof collectors (top left: TDGS collector) are proposed to be connected to the HVAC ducts (right) after modification to produce a dual ducting system(Souece: Mayhoub, 2014)

2.12.1 Some considerations

The main criteria to be considered in order to successfully develop a dual ducting system are summarized as follows:

Ease of installation: This is the main objective of this proposal. However, route modifications of the HVAC duct network may be required for a uniform illuminance distribution, which in time would increase the air distribution efficiency. In addition, duct bends would require minimization in order to avoid excessive light attenuation. Furthermore, additional duct extensions are likely to be required in order to connect the network with the roof- or facade-mounted daylight collectors.

Economic viability: The proposed duct network is estimated to be more economical than the costs of the HVAC and DGS duct networks due to the reduction in the overall length of the duct. Although the highly reflective materials have recently became available at lower cost, it would not be economic to change the entire duct network, and thus this would only be required where there is a need to channel daylight.

Output devices: The existing HVAC output devices can be developed to be hybrid outputs and to diffuse both air and daylight; otherwise, separate illuminance output devices may be connected to the duct network.

Operation requirements: Great attention has to be paid to avoid the precipitation of air particulates and condensation on the duct and diffuser surfaces. Solid or liquid particulates such as dust, smoke and air vapour (if condensed) significantly reduce the duct's reflectance. Fire or smoke spread hazards throughout the ducts also have to be avoided. Thermal and acoustic insulation are also essential. Air pressure in the ducts has to be maintained in spite of the change of the duct sizes.

2.12.2 HVAC systems review

HVAC systems include cooling systems, heating systems and all-air systems, but they are frequently referred to as air conditioning (AC) systems. Many varieties of AC systems are used within buildings; however, only air duct systems, rather than ductless, are relevant to this study. This study will focus on the components and principles of a central AC system, as they are widely used and utilize a large-duct network across the whole building.

The central AC circulates cool air through a system of supply and return ducts. Supply ducts and registers (i.e. openings in the walls, floors or ceilings, covered by grills) carry cooled air from the air conditioner to the internal spaces of the building. This cooled air

becomes warmer, as it circulates through the space; then it flows back to the central air conditioner through return ducts and registers.

The system components and location within the building depends upon whether air, water or both are used for the cooling process. At most, the system consists of a water chiller/boiler, a cooling tower, an air handling unit and an air-duct distribution network for air supply, return and fresh air feed.

2.12.3 HVAC Duct Types

HVAC ducts and pipes must be thermally and acoustically insulated in order to achieve the desired levels of comfort and to reduce energy consumption in addition to contributing to fire safety. Thermal insulation materials such as glass wool, stone wool or mineral wool have an additional advantage of significantly reducing the operational and airflow noise. HVAC ducts are available in different types, such as metal ducts, glass wool ductboards, plastic ducts and flexible ducts as summarized in Table 2.2.

Table 2.2 HVAC duct type classification (Source: Mayhoub, 2014).

Type	Material	Shaping	Thermal insulation
Metal duct	Galvanized, stainless steel, copper or aluminum sheets	Cutting and shaping	Glass wool blanket faced with an aluminum foil
Glass wool duct	High-density glass wool board faced with an aluminum coating, a glass mat or a fabric layer on the internal side	Cutting and folding	Provide thermal insulation
Plastic duct	Plastic or foam boards faced with an aluminum coating on both internal and external sides	Cutting and folding	Provide thermal insulation
Flexible duct	Consists of two aluminum and polyester concentric tubes	--	Glass wool layer between the two tubes

2.12.4 Air Filters and Air Outlet

Air filters are typically located somewhere along the return ducts. They are available in a wide variety of media and budgets. Performance is determined by the size and density of the material used as well as the particle size and the volume (Mayhoub, 2014).

HVAC outlets have a wide variety of locations, shapes and materials, as they are the section of the system which is most visible. They may be installed within walls, floors or ceilings and covered by bars, grills, blades or louvres. They may be linear, rectangular or round in shape. They are usually made up of steel, aluminum or plastic; however, they may be even made up of wood or copper (Mayhoub, 2014).

2.13 Illumination Standards for Office Buildings

This section presents different international and Bangladeshi local illumination standards for different interior work spaces of office buildings.

Whether using daylight or artificial light separately or in conjunction with each other, lighting in offices in the developed world distinguishes between the ambient component and the task lighting. Ambient lighting gives the space its general operable illumination by which people can move around freely. The ambient lighting is usually relatively uniform, giving the space a well-lit appearance without patches that are overly bright or under-lit and gloomy (which create the illusion of low lighting even under functional/standard levels of average illumination). Here is the table that show the international standard Illumination level (AGS, 2000) of different spaces of office as well as National Standards determine by BNBC (1993). These latter values include ambient as well as task lighting.

Table 2.3: Standards Illumination levels for different activity zones (Lux) (Joarder, 2007)

Spaces	**AGS International Standards (Lux)**	**BNBC Standards (Lux)**
Lobbies & Hallways	100-200	150
Corridors	Not Specified	70
Typical Offices	400-600	300
Computer Works	200-400 (with task lighting)	450 (without task lighting)
Paper Task with Task Lighting	400-600	450
Specific Tasks	600-1200 (fine details)	450 (Drawing on Boards and Tracing)
Conference and Meeting	300-500	300

Although the International Building Code (IBC, 2012) states all habitable spaces to have natural or artificial light, in some jurisdictions, natural light is required for all space (even

bathrooms and kitchens) could be provided by lightpipe. Different international codes recommend minimum 2% daylight factor (DF) for interior space where common visual task are performed. Indian Green Building Council (IGBC) recommended 2% daylight factor for at least 50% of total floor area.

IESNA recommends 100 lux for working space, where simple visual task are performed. For performance of visual task of high contrast and large size, 300 lux is recommended, and for low contrast and small size 1000 lux is recommended. So, minimum value of common visual task, such as, tailoring ranges from 300 lux to maximum 1000 lux (IESNA 2000). According to IESNA codes, 3000-10000 lux is recommended for special visual task near threshold (Table 2.4)

Table 2.4: Determination of illuminance categories (IESNA 2000)

	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)

IES code recommends 600 lux for fairly severe task small detail work e.g. official task work, drawing etc. While it also recommends 900 lux for severe, prolonged task with very small detail (Table 2.5).

Table 2.5: Recommended illumination based on IES code, 1968 (Koenigsberger et al., 1997)

Visual task	**Illumination (lux)**
Casual seeing	100
Rough task with large detail	200
Ordinary task, medium task	400
Fairly sever task small detail (drawing)	600
Severe, prolonged task, very small detail	900
Very severe, prolonged task, very small detail	1300-2000
Exceptionally severe task, with minute detail	2000-3000

2.13.1 Uniformity Ratio

The uniformity Ratio is an important feature of the lighting in working environments. While it is important to achieve a relatively good uniformity at the task area (essentially the desk area), recent research has shown that a too uniformly lit environment will reduce alertness and cause people to get tired more quickly. It is particularly useful to create some contrasts on the walls since they form the centre of our field of view as soon as we look up from our task.

Uniformity Ratio is usually defined as ratio of the minimal illuminance over the area weighted average illuminance:

$u = E_{min} / E_{average}$

The minimum illuminance should correspond to the recommended illuminance as defined in the national codes of practice. The uniformity as created by a general lighting scheme should be better than 0.6 or 0.8 according to the German DIN norm and the UK CIBSE guidelines, respectively.

2.14. Critical Findings from Literature Review

(a) There is a growing tendency towards organizing office spaces according to an open plan, which encourages interpersonal contact and a homogenous workflow, rather than the stereotyped double-loaded corridor pattern (Islam, 2006), which is not appropriate in naturally ventilated offices.

(b) Daylight strategies depend on the availability of natural light, which is determined by the latitude of the building site and the conditions of immediate surroundings of the building, e.g., the presence of obstructions. Daylighting strategies are also affected by climate. Daylight is the sum of sunlight and skylight (IEA, 2000, Sultana, 2017).

(c) For designs that use diffuse daylight from the sky, clouds and surrounding environment, it is difficult to provide adequate daylight when the depth of the space is more than 1.5 or 2 times the height of window head (Joarder, 2007).

(d) The lightpipes are innovative devices able to transport and distribute natural light without heat transfer in dark rooms.

(e) The integration of light ducts and heating, ventilation and air conditioning ducts is a promising solution, which system known as Dual Ducting System (Mayhoub, 2014).

(f) The preferred illumination level at working plane for computer task/ paper task is 450 lux (Joarder, 2007) and the illumination level on work plane not exceed 2000 lux (Nabil, et.al, 2005)

(g) The distance that adequate daylighting will penetrate into a room depends upon window size and location on the wall (Robertson, 2002).

2.15 Summery

This chapter has described the potentiality of lightpipes as well as dual ducting system as strategy for daylighting in deep office spaces. Within the scope of this thesis, office buildings- present context, daylight source and availability, components of daylight, illumination standards for office buildings 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 simulation study has been developed in Chapter 5.

CHAPTER THREE: METHODOLOGY

Preamble

Methodology

Climatic Context of Dhaka

Observe Different Office Spaces

Selection of Case Spaces

Experiment with Scale Models

Selection of Simulation Tool

Parameters for EnergyPlus Simulation

Formation of 3D Model

Simulation Output Variables

Identifying the Evaluation Process

Summery

3.1 Preamble

Chapter 2 discusses the outcomes of the literature review to describe the basic information required to identify on which the simulation and experimental study could be conducted. This chapter contains the detailed steps of the methodology of simulation exercise done during this research. By using advance energy simulation tool, i.e. EnergyPlus, the amount of daylight can be identified. The performances of the different available lightpipe configurations with the same floor area was evaluated from the point of view of useful daylight inclusion.

This chapter includes the method of simulation tool selection, case office space selection and selection of different parameters for the case office building. The next chapter will describe the field investigations and experimental study, based on the recommended methodology developed in this chapter.

3.2 Methodology

In this research, the prospective simulation study was chosen to identify the design parameters of lightpipe configuration that can help inclusion of daylight and improve indoor luminous environment quality of office space. At first, field investigation was done to define the case office space and its microclimatic data was thoroughly studied. Then experiment with scale models was done by passing natural and artificial light to understand the physical condition of lightpipe as there is no example of lightpipe in Dhaka, Bangladesh. Simulation tool was selected for measuring the performance of the lightpipe configurations. The virtual 3D- case office building was formed based on the field investigation data of the case office building with the selected simulation software tools. Finally, the selection of the test points and core test points were done and a measuring criteria was developed for the performance evaluation process. Figure 3.1 shows the flow diagram of the methodology for the simulation process of this research.

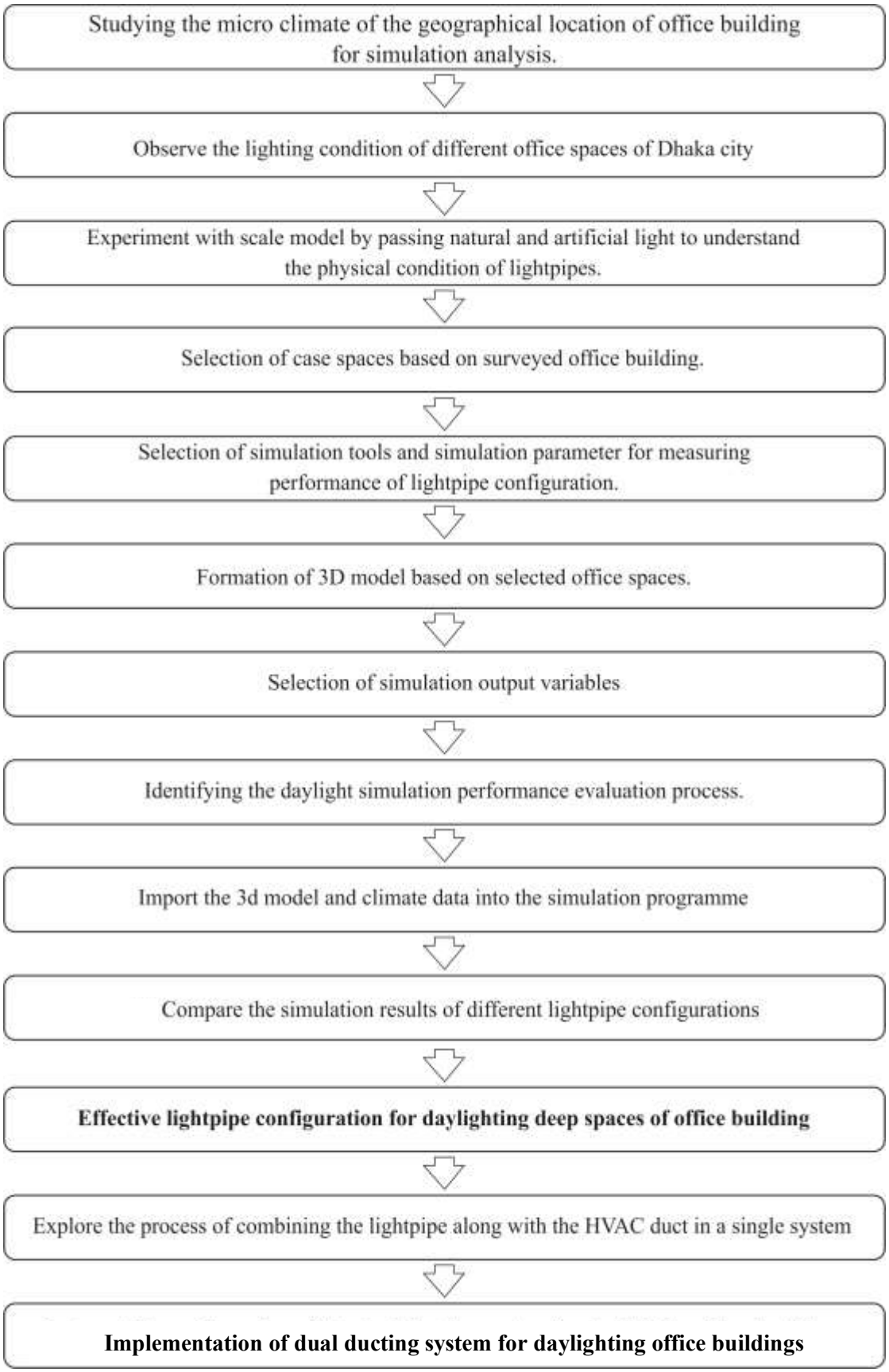


Figure 3.1: Flow diagram of the simulation process of this research.

3.3 Climatic Context of Dhaka

3.3.1 Climate of Bangladesh- General Overview

In terms of ecological region or biomes described by United Nations Educational, Scientific and Cultural Organization (UNESCO), Bangladesh, lying between 20º34′ N to 26º33′ N and 88º 01′E to 92º 41′E, is in the Indo-Malayan Realm (Lean,1990). Bangladesh has a humid, warm, tropical climate. Its climate is influenced primarily by monsoon and partly by pre-monsoon and post-monsoon circulations. The south-west monsoon originates over the Indian Ocean and carries warm, moist, and unstable air. The monsoon has its onset during the first week of June and ends in the first week of October, with some inter-annual variability in dates. Besides monsoon, the easterly trade winds are also active, providing warm and relatively drier circulation. There are four prominent seasons in Bangladesh, winter (December to February), Pre-monsoon (March to May), Monsoon (June to early-October), Post-monsoon (late-October to November) (Agrawala et.al, 2003). The general characteristics of the seasons are as follows:

Winter is relatively cooler and drier, with the average temperature ranging from a minimum of 7.2˚C to 12.8˚C to a maximum of 23.9˚C to 31.1˚C. The minimum occasionally falls below 5˚C in the north though frost is extremely rare. In winter, the general wind direction is from the northwest (Debnath, 2014).

Pre-monsoon is hot with an average maximum of 36.7˚C, predominantly in the west for up to 10 days, very high rate of evaporation, and erratic but occasional heavy rainfall from March to June (Agrawala et.al, 2003). The peak of the maximum temperatures are in April, the beginning of pre-monsoon season. During summer, winds are mainly from the southwest (Debnath, 2014).

Monsoon is both hot and humid, brings heavy torrential rainfall throughout the season. About four-fifths of the mean annual rainfall occurs during monsoon (Agrawala et.al, 2003). During the monsoon or rainy season, winds are from the southeast (Debnath, 2014).

Post-monsoon is a short-living season characterized by withdrawal of rainfall and gradual lowering of night-time minimum temperature (Agrawala et.al, 2003). In this period, the prevailing wind direction is from the northeast (Debnath, 2014).

The mean annual rainfall is about 2300mm and ranges from 1200mm in the extreme west to over 5000mm in the east and north-east (NWMP, 1991).

3.3.2 Microclimate of Dhaka City

Dhaka lies between longitude 90º20' E and 90º30' E and between latitudes 23º40' N and 23º55' N. According to the Koppen climate classification, climate of Dhaka is categorized as tropical savanna climate. It has mainly three distinct seasons – the hot dry (March-May), the hot humid (June-November) and the cool dry season (December-February) (Ahmed, 1995). 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.

Generally, the cool dry season is short while 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.

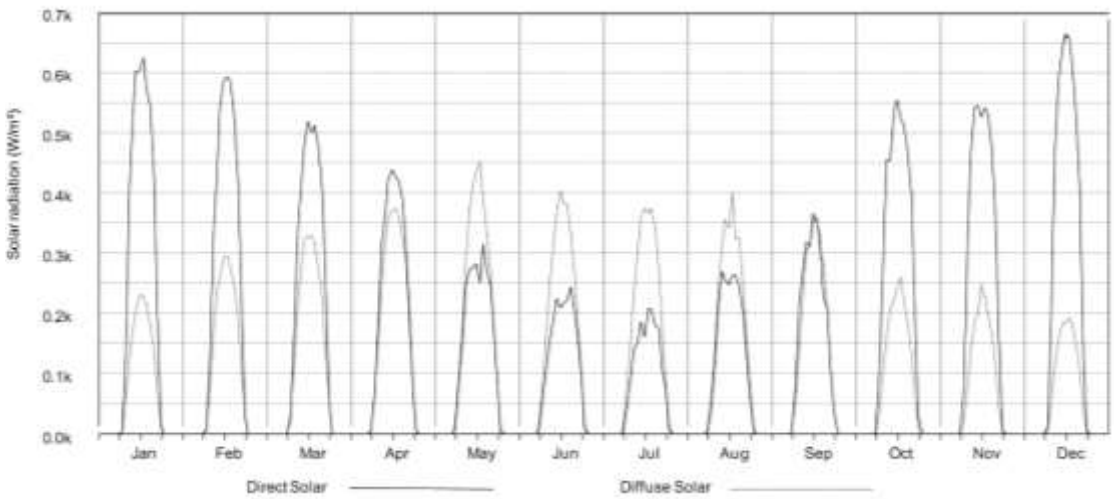


Figure 3.2 Hourly solar radiation averaged by month for TRYs, Dhaka (source: U.S. Department of Energy, 2008)

Although overheating is the major problem of Dhaka City, it is due to some associated factors. For example, it is observed that from March to May there is high air temperature associated with high solar radiation (Joarder, 2007) (Figure 3.2). From June to October, conditions with high humidity are associated with high air temperature. Therefore, 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 (Monsoon)	Oct-Nov (Post-Monsoon)	Dec-Feb (Winter)
Climatic Factors				
Air temperature (oc)				
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. In the cool period Dhaka has more than 8 hours of sunshine per day. But during monsoon months (warm-humid season) this comes down to 4 hours per day due to cloud cover.

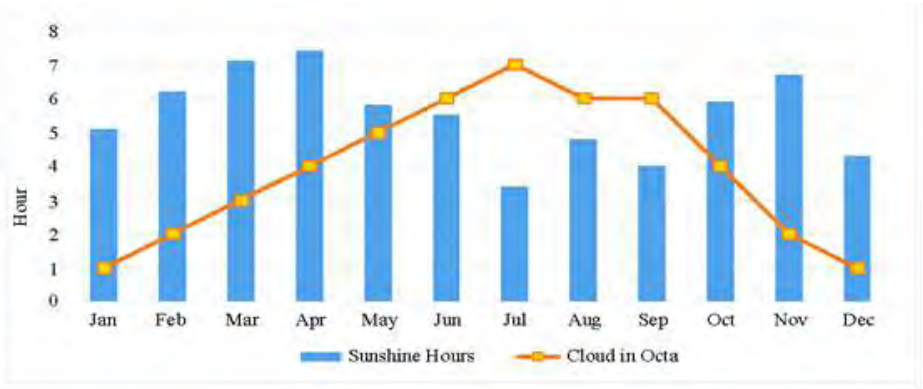


Figure 3.3:Monthly average cloud cover and Sun shine hours in Dhaka, year 2016 (Data source: Bangladesh Meteorological Department, Dhaka- 2017; cited from Aman, 2017)

It is after June and July that this once again increases steadily (Joarder, 2007). Figure 3.3 shows the monthly average cloud cover with respect to Monthly Average Sunshine Hours for Dhaka city for year 2016.

The atmospheric condition during the month of July to November period is cloudy. So, the diffused component of the daylight is considerably high. The variation in sunshine hours during July to November is wide. Figure 3.4 shows the sun path diagram of Dhaka, Bangladesh.

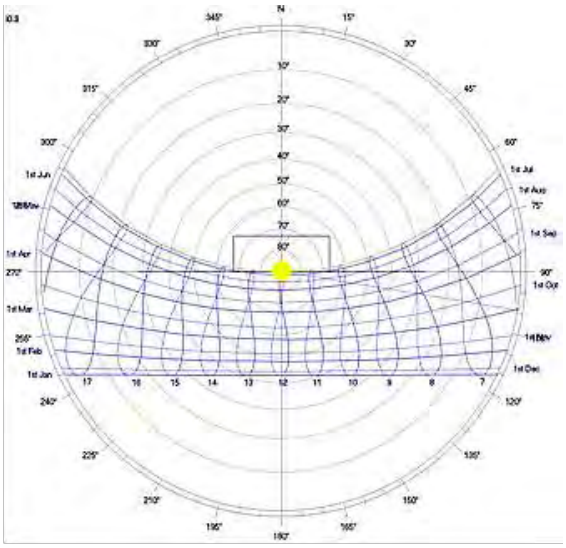


Figure 3.4: The sun path diagram of Dhaka, Bangladesh (Source: SUNTOOL - Solar Position Calculator, 1998; cited from Iqbal, 2015).

b. Sky condition

Dhaka has a composite climate, where both clear sky, overcast and partly overcast skies are observed round the year (Figure 3.5), and designers have to face difficulties while considering both sky conditions (Ahmed, 1987b).

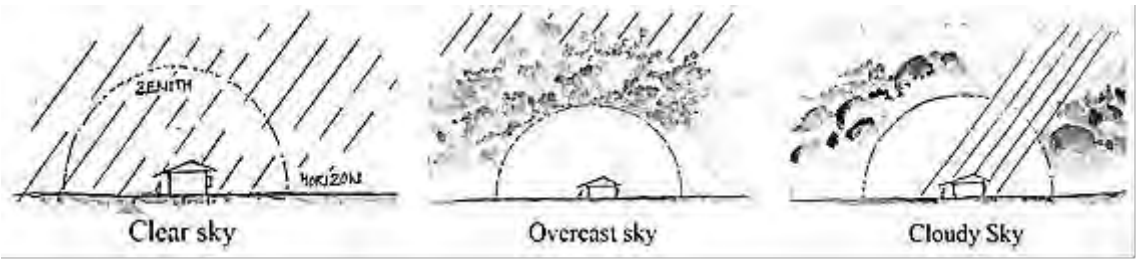


Figure 3.5: Various Sky Conditions (Source: Hossain, 2011)

Direct sunlight is intense and varies 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) (Joarder, 2007).

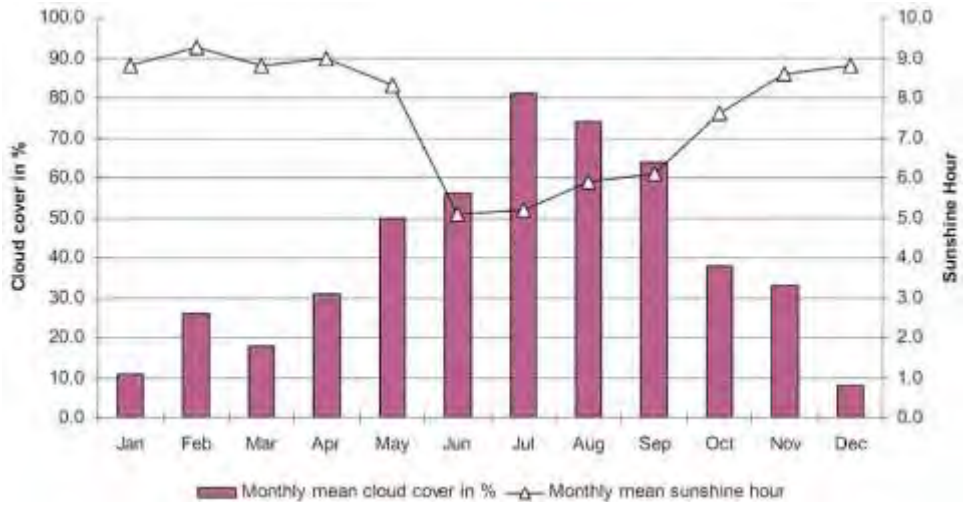


Figure 3.6: Monthly average cloud cover and monthly average sunshine hours in Dhaka (Source: Bangladesh Meteorological Department, Dhaka, 2005; cited from: Iqbal, 2015).

In context of Dhaka, the sky remains clear and overcast in different parts of various seasons (Figure 3.6). During 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 (December-February) the sky mostly remains clear. While during the rest of the year, both clear and overcast conditions are observed (Joarder *et al.*, 2009; Joarder, Price and Mourshed, 2009). Table shows sky condition of Dhaka city with respect to cloud cover for a year.

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

c. Design skies

Most of the researchers in temperate climates agree that design for daylight should be considered for a design sky; not the worst situation possible, as this would be unrealistic, but for a situation when illumination is exceeded for about 85% - 90% of the daylight hours. By statistical evaluation of long-term illumination records, a 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.

In lower latitudes the sky being much brighter than in the higher latitudes. Published data on outdoor design sky illuminance specifies a value of approximately 10,000 – 12,000 lux for Dhaka latitudes. This figure represents the outdoor illumination that is bettered 85% of total daylit hours in this location. In warm-humid climatic context with special reference to Dhaka, Bangladesh shows that for this reduced eight-hour time frame, an average of about 16,500 lux can be considered as outdoor design sky illuminance (Khan, 2005).

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

Suggested values for overcast sky	lux (lumen/m2)
Latitude 50-600	5,000
Latitude 40-500	5,000-6,000
Latitude 30-400	5,000- 8,000
Latitude 20-300	8,000-10,000
Latitude 10-200	10,000-15,000
Suggested values for overcast sky	
All latitude	5,000
Solar altitude 150	14,000
Solar altitude 300	36,000
Solar altitude 450	58,000
Solar altitude 600	75,000
Solar altitude 750	83,000
Solar altitude 900	94,000 to 110,000

3.4 Observe different office spaces

This research started with a study on offices located in different places of Dhaka to establish a picture of current lighting practice and to identify key issues where daylight could broadly enhance the luminous environment for offices. It is not possible in the given scope and objectives of this study, to take all the offices for case study. Ten offices have selected for detail luminous investigation to explore the different features of offices in Dhaka. In choosing these samples conventional typologies of offices, grouping them into single loaded or double loaded corridor offices or courtyard or atrium centric arrangements and other morphological categorization, could not be followed given the

local context. The groupings were principally made based on the surrounding context and on offices having elements that directly affect daylight inclusion into the office interiors and the overall luminous environment. The findings of luminous investigation helped to identify some specific problems and potentials of using daylight in deep spaces of offices on which the research then focuses. The ultimate goal of the total survey was to come up with one building that would be representative of the typical office of Dhaka city, which would then be used as the example building for daylight simulation during the preceding simulation exercises.

3.5 Selection of case spaces

One office space has been short listed on the basis of some selection criteria determine by field survey in order to explore the space-geometry and typologies of the office spaces in this region. Ten offices were surveyed to find out the existing lighting conditions of deep spaces of office buildings. One specific area with open floor office layout of typical floor of office building was selected for investigation. The investigation covered a broad area through a physical observation about the physical characteristics of the office spaces including conventional HVAC system and other relevant features. Items such as building surroundings, interior materials, finishes, office equipment and functions were excluded in the discussions, as these parameters were fixed in simulation study only for the selected case space.

3.6 Experiment with scale models

Daylight is one of the key elements of architecture projects. Architects have used scale models for centuries in order to evaluate their projects under a real sky. Moreover, the development of artificial skies has made the studies less dependent on different factors such as the weather, the time or the date for many years (Bodart et.al, 2006). Today, even if computer simulations can give very accurate results in a reasonable time, it is essential for architects to personally appreciate the luminous environment of a space and to compare several solutions qualitatively.

When properly constructed, scale models portray the distribution of daylight within the model as exactly as in a full-size room. Comparison works on simple models have shown that daylighting studies carried out under sky and sun simulators can give very accurate

results (Bodart et.al, 2006). However, the complexity of the models will generate errors if the models are not built accurately and with respect to several rules. In this research, experiments with scale models have done to observe the daylight inclusion pattern in different spaces of the office by side opening, roof and by light pipes where direct sunlight cannot enter at the deep spaces.

3.7 Selection of simulation tool

It is difficult to simulate light-dependent offices spaces accurately, with available knowledge and simulation program. There are numbers of lighting simulation tools available in the market. The Tools Directory of Building Energy Software (US-DOE, updated in August 12, 2014) listed 48 tools under the ―Lighting Systems category, among them 21 were advertising daylighting as a key feature (Reinhart et al., 2006). The listed computer-based tools have different level of prediction accuracy and modeling capacities. For example LUMEN MICRO (Baty 1996) and SUPERLITE (Modest 1982) can compute daylight under strict boundary limitations, whereas, some other software can compute complex model geometry and arbitrary environments, such as LIGHTSCAPE (Khodulev et al., 1996) and RADIANCE (Ward 1998), with photorealistic rendering capacity to evaluate quality of lighting in 3D space.

In this research, EnergyPlus was selected for daylight simulation analysis. Illumination on a specific point can be calculated by using EnergyPlus simulation program. Sketch Up for Modeling and EnergyPlus combined can provide more than 365 x 24 = 8760 hour's data for each sensor point. EnergyPlus have been validated comprehensively and successfully for daylighting analysis.

3.7.1 Energy Plus

Energy Plus is a modular, structured software tool based on the most popular features and capabilities of BLAST and DOE-2.1 E. It is a simulation engine with input and output of text files. Loads calculated (by a heat balance engine) at a user-specified time step (15-minute default) are passed to the building systems simulation module at the same time step.

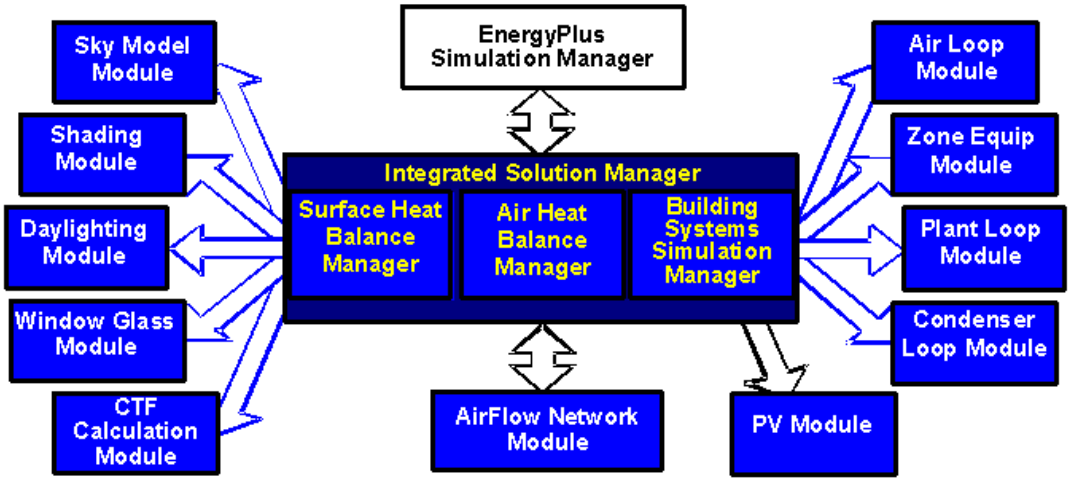


Figure 3.7. EnergyPlus -- Internal elements

The EnergyPlus building systems simulation module, with a variable time step, calculates heating and cooling system and plant and electrical system response. This integrated solution provides more accurate space temperature and daylight prediction - crucial for system and plant sizing, occupant comfort and occupant health calculations. Integrated simulation also allows users to evaluate realistic system controls, moisture adsorption in building elements, radiant heating and cooling systems, and interzone air flow.

3.7.2 EnergyPlus for Daylighting

Daylighting controls including interior illuminance calculations, glare simulation and control, luminaire controls etc. Daylighting can be invoked in EnergyPlus by the use of two objects: Daylighting:Controls and Daylighting:DELight:Controls.

Daylighting:Controls: In this method daylighting illuminance levels are calculated and then used to determine how much the electric lighting can be reduced. The daylight illuminance level in a zone depends on many factors, including sky condition; sun position; calculation point; location, size, and glass transmittance of windows; window shading devices; and reflectance of interior surfaces. Reduction of electric lighting depends on daylight illuminance level, illuminance set point, fraction of zone controlled and type of lighting control.

Daylighting: DELight:Controls: The first input object required for invoking the DElight method is the Daylighting:DELight:Controls object, which defines the parameters of each

daylighting zone within a building. This object must be associated with a specific thermal zone within the building for which the reduction in electric lighting due to daylight illuminance will be accounted.

3.7.3 Daylighting Device: Tubular

Tubular daylighting devices (TDDs), also known as tubular skylights or light pipes, are used to bring natural exterior daylight into the hard-to-reach, interior spaces of a building. TDDs consist of three components: a dome, a pipe, and a diffuser.

In EnergyPlus each of these components corresponds to an object in the input file. The dome and diffuser are defined in the same way as windows using the Fenestration Surface: Detailed object. The Surface Type field must be specified as Tubular Daylight Dome or Tubular Daylight Diffuser accordingly.

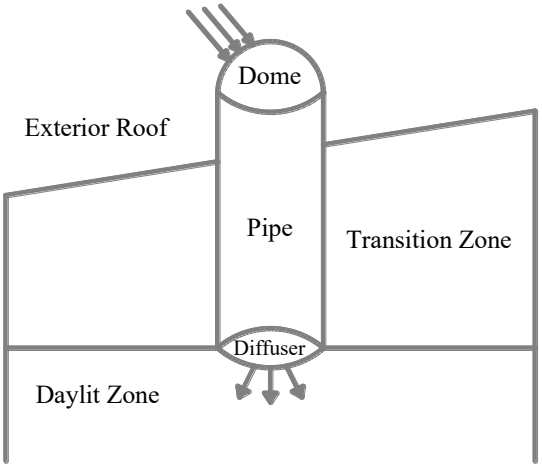


Figure 3.8. Tubular daylighting device diagram

The location and orientation of the dome surface affect the total amount of daylight collected. The Base Surface of the diffuser object determines to which zone the daylighting is delivered. The location and orientation of the diffuser surface affect the amount of daylight received at the Daylighting: Controls reference points.

Although the object definition is the same as for a window, there are several restrictions on Tubular Daylight Dome and Tubular Daylight Diffuser objects:

- Shading control devices are not allowed.

- Frames and dividers are not allowed.
- Multipliers must be 1.0.
- Dome, diffuser, and pipe areas (as given by diameter) must be approximately equal.
- Outside face environment objects are not allowed.
- Dome and diffuser constructions cannot be more than one layer.

Since commercial TDDs are assumed to be cylindrical in shape, it is recommended that the circular areas of the actual dome and diffuser be approximated with a square of equivalent area for the Tubular Daylight Dome and Tubular Daylight Diffuser objects Although it is possible to use a triangular surface instead, a square is a much better geometric approximation of a circle. Note that the Tubular Daylight Dome surface is allowed to have a different position and tilt from the roof base surface. If the actual TDD projects some height above the roof surface, the Tubular Daylight Dome coordinates should be located accordingly (From EnergyPlus Software Documentations).

3.8 Parameters for EnergyPlus simulation

The following parameters were fixed for the quantitative and qualitative assessments of the design strategies which were collected in reference with the field and literature surveys (Table 3.4):

Table 3.4: Simulation parameters of test production zone for EnergyPlus simulation

Parameters	**Specifications**
Version	8.0
Location	Within greater Dhaka region, Bangladesh
Geographical Location:	i) Longitude : 90.25° (North)
	ii) Latitude : 23.95° (East)
Time Zone	+6 GMT
Month	6 (June)
Day of the Month	7
Day Type	Summer Design Day
Simulation period	12 Hours (6 am to 6 pm)
Max. Dry Bulb Temperature	36 ºC
Site Ground Temp. (Degree): Building Surface	January: 18, February: 20, March: 22, April, May, June, July: 24, August, September, October, November: 22, December: 20.

Table 3.4: Continued	
Parameters	**Specifications**
Sky Model	Clear sky
Calculation option	Standard
Units of Dimensions (Length, areas, etc.)	Metric (SI) (m, cm, etc.)
Units of Photometric Dimension	European (SI) (lux, cd/m^2, etc.)
Elevation	9m
Orientation	Front Elevation facing North
Plan Shape	Rectangular
Total number of floor	9
Simulated floor	5th (Intermediate Floor)
Solar Absorbance (for Exterior Surfaces)	0.55 for external walls (Light color) 0.35 for the roof (light color)
Occupancy Density	880 nos./floor ASHRAE 55-2004
Electric equipment	Lighting + Others = 205 W/Person, Personal Machine = 15 W/Person (min) Total = 220 W/Person
Glazing	Single panel of glass with aluminum frame (refl. 0.92)
Construction Type	ASHRAE 90.1 non Res.
Natural Ventilation	Simple (Operable simple window)(One Array)
Room Air Distribution Model	General cross ventilation and exhaust type
Ventilation Control Mode	Temperature
Design Flow Rate	0.25 ~ 0.5 (ms^{-1}) (min ~ max, variable) Fan/Off 4 air change/hour (min)
Leakage Component Name	Surface Object
Heat balance algorithm	Conduction transfer function
Numeric Type	Continuous/Discrete
Office Schedule Detail	Compact (According to Field Monitoring) Fraction (Including Summer and Winter Design Day) Efficiency limit (0-1; lower-upper), 1-24=Hours/Day (Appendix 2; Fig. 17)
i) Lights Schedule	Through: 1/31~12/31, For: Weekdays, Until: 07:00 =.2, Until: 08:00=.5, Until: 18:00=.8, Until: 20:00=.5, Until: 22:00=.3, Until: 24:00=.25
ii) Equipment Schedule	Through: 1/31~12/31, For: Weekdays, Until: 07:00 =.2, Until: 08:00=.25, Until: 12:00=.85, Until: 17:00=.80, Until: 18:00=.65, Until: 20:00=.5, Until: 22:00=.15, Until: 24:00=.05
iii) Occupancy Schedule	Through: 1/31~12/31, For: Weekdays, Until: 06:00 =.2, Until: 07:00=.25, Until: 08:00=.5, Until: 18:00=.9, Until: 22:00=.60, Until: 24:00=.2

Table 3.4: Continued	
Parameters	**Specifications**
iv) Infiltration Schedule	Through: 1/31~12/31, For: Weekdays, Until: 07:00 =.2, Until: 08:00=.35, Until: 13:00=.9, Until: 17:00=.80, Until: 18:00=.65, Until: 20:00=.25, Until: 24:00=.2
v) Operation Schedule	Through: 1/31~12/31, For: Weekdays, Until: 06:00 =.15, Until: 09:00=.65, Until: 18:00=.85, Until: 20:00=.45, Until: 22:00=.2, Until: 24:00=.05
vi) Clothing Schedule	Through: 1/31~12/31, For: Weekdays, Until: 06:00 =.25, Until: 18:00=.85, Until: 20:00=.35, Until: 24:00=.25
	[Here, each compact schedule contain the elements through (date), for (days), interpolate (optional), until (time of day) and value (0-1)].
Office construction	Exterior Roof: Plaster (1:5)+ RCC (1:2:4)+ Plaster (1:5)
	Exterior Floor: Plaster (1:5)+ RCC (1:2:4)+ Plaster (1:5)
	Exterior Wall: Plaster (1:5)+ 1st Class Brick+ Plaster (1:5)
	Interior Ceiling:19mm gypsum board
	Opening: Clear 6mm thickness glass (sliding)
	(Here, 1:5 = Cement : Sand and 1:2:4 = Cement : Sand : Aggregate)
Light Pipe construction	**Dome: Clear Acrylic**, Roughness: Very Smooth, Thickness: 3mm, Conductivity: 0.19W/m-K, Density: 1150 kg/m^3, Specific Heat: 1850 J/Kg-K, Thermal Absorptance: 0.9, Solar Absorptance: 0.7, Visible Absorptance: 0.7.
	Pipe: Reflective Aluminum, Roughness: Very Smooth, Thickness: 5mm, Conductivity: 235 W/m-K, Density: 2700 kg/m^3, Specific Heat: 900 J/Kg-K, Thermal Absorptance: 0.9, Solar Absorptance: 0.7
	Diffuser: Clear Acrylic/ prismatic material, Roughness: Very Smooth, Thickness: 3mm, Conductivity: 0.19W/m-K, Density: 1150 kg/m^3, Specific Heat: 1850 J/Kg-K, Thermal Absorptance: 0.9, Solar Absorptance: 0.7, Visible Absorptance: 0.7.
Material Specification	According to BNBC and ANSI/ASHRAE Standard (R, Cp, S, k),
Mechanical ventilation	None
Output variable	Illumination (Lux), AT (ºC), Radiation (W), RH (%)
Fraction Radiant	0.3~0.4
Heat Trans. Coef. Value	0.1 {W/m^2-K} Min.
Time steps per Hour	4
Output Schedule	Hourly
Output Option Type	Simple And Tabular

(Note: The whole simulations was conducted for the months of June.

3.8.1 Simulation Engine Parameters

Before starting the simulations, a set of parameters were set for EnergyPlus and Open studio plugin modeling which are shown in Table 3.5.

Table 3.5: Simulation engine detail parameters of test production zone for EnergyPlus simulation

Parameters	**Specifications**
Simulation Engine	Energy Plus
Version Identifier	8.0
Run Simulation for Weather File Run Periods	Yes
Run Simulation for Sizing Periods	Yes
Terrain	City
Loads Convergence Tolerance Value	0.04
Temperature Convergence Tolerance Value {deltaC}	0.4
Solar Distribution	Full Interior And Exterior
Calculation Method	Average Over Days In Frequency
Calculation Frequency	20
Sky Diffuse Modeling Algorithm	Detailed Sky Modeling
Algorithm	TARP & DOE-2
Number of Time steps per Hour	4

3.8.2 Simulation Run Period

Table 3.6: Simulation run period parameters of test production zone for EnergyPlus simulation

Name	**Weather File Days**
Begin Month	June
Begin Day of Month	7
End Month	June
End Day of Month	7
Day of Week for Start Day	Sunday
Start Year	2018
Use Weather File Daylight Saving Period	Yes
Use Weather File Rain and Snow Indicators	Yes
Period Selection	Tropical Hot

3.8.3 Simulation Schedule Load

Table 3.7: Simulation schedule parameters of test office space for EnergyPlus simulation

Name	**Office Occupancy Schedule**
Office Occupancy Schedule	Number of People Calculation Method
45	Number of People
Name	Office Lights Schedule
Lighting Level	Design Level Calculation Method
450	Lighting Level {W}(Table Task)
Name	Office Equipment Schedule
Watts/Person	Design Level Calculation Method
3600	Design Level {W}

3.8.4 Simulation Daylighting Specification

Table 3.8: Simulation daylighting parameters of test office space for EnergyPlus simulation

Name	**Office Occupancy Schedule**
Zone Name	Zone 1
Total Daylighting Reference Point	2
Daylighting Device	Tubular
Name	Pipe 1
Dome Name	Dome 1
Diffuser Name	Diffuser 1
Construction Name	Clear Acrylic Dome
Diameter	Variable
Total Length	Variable
Effective Thermal Resistance	0.28 m2-K/W
Transition Zone length	Variable
Output Illuminance Map Name	Illumination Map 1
Z Height	0.75m
No. of X Grid Point	10
No. of Y Grid Point	10

3.9 Formation of 3D model

In this study, two three-dimensional model were developed in Sketch-Up and Open Studio software for EnergyPlus engine to perform tubular daylight simulation for a typical office building which represents existing local condition in Bangladesh (Figure 3.9 and 3.10). Buildings daylighting condition has been analyzed for different aspects. In this study, simulation has been conducted for typical June month condition. Outdoor temperature consider for the study was average 27.83 °C. Obtained simulation results have been analyzed by mean of statistical distribution. Basically for this study-three types of variables were considered with Model 01: Lightpipe Diameter, Lightpipe Length, Lightpipe No. for a single space. Finally lightpipe performance was evaluated with or without consideration of side window with Model 02.

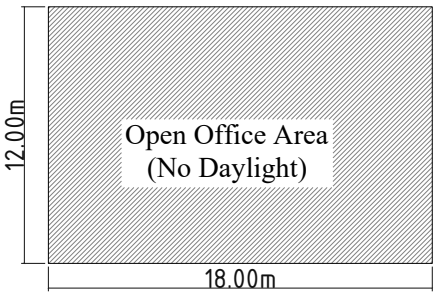


Figure 3.9: Model 01 Plan

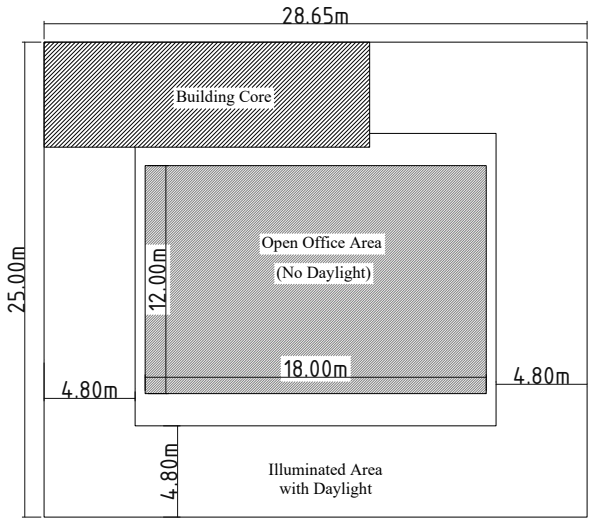


Figure 3.10: Model 02 Plan

Simulated result for each light pipe type was summarized in terms of statistical meaning. The regression and correlations models among the different lighting gradients have been established to understand the performance of different light pipes.

Table 3.9: Different study models for simulations.

Sl. No.	Simulation Model	Description
1.	**Model 01 with one Lightpipe** used in simulation Case 01, 02 and 03(a)	
		As this model was created only with the internal (open office area) space, there was no opening at the side wall of the model. It is considered that daylight entered from the side window can't reach at this area. There was one (1) light pipe at the center of the area with a transition space at the upper part of the model. The Dome of light pipe was set at the roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe.
2.	**Model 01 with two Lightpipes** used in simulation Case 03(b)	
		As this model was created only with the internal (open office area) space, there was no opening at the side wall of the model. It is considered that daylight entered from the side window can't reach at this area. There was two (2) light pipes at the central axis with a transition space at the upper part of the model. The Dome of light pipe was set at the roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe.
3.	**Model 01 with three Lightpipes** used in simulation Case 03(c)	
		As this model was created only with the internal (open office area) space, there was no opening at the side wall of the model. It is considered that daylight entered from the side window can't reach at this area. There was three (3) light pipes at the central axis with a transition space at the upper part of the model. The Dome of light pipe was set at the roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe.
4.	**Model 01 with six Lightpipes** used in simulation Case 03(d)	
		As this model was created only with the internal (open office area) space, there was no opening at the side wall of the model. It is considered that daylight entered from the side window can't reach at this area. There was three (6) light pipes at the central axis with a transition space at the upper part of the model. The Dome of light pipe was set at the roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe.

Table 3.9: Continued		
Sl. No.	**Simulation Model**	**Description**
5.	**Model 01 with nine Lightpipes** used in simulation Case 03(e)	
		As this model was created only with the internal (open office area) space, there was no opening at the side wall of the model. It is considered that daylight entered from the side window can't reach at this area. There was three (3) light pipes at the central axis with a transition space at the upper part of the model. The Dome of light pipe was set at the roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe.
6	**Model 02 with three Lightpipes without Window** used in simulation Case 04(a)	
		This model was created with the entire floor as surveyed floor area. There were no opening at the two side walls of the model. There was 3(three) light pipes at the center of the area with a transition space at the upper part of the model. The Dome of light pipe was set at the roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe. The daylighting performance of lightpipe, without side window was observed from the model.
7.	**Model 02 with three Lightpipes and Side Window** used in simulation Case 04(b)	
		This model was created with the entire floor as surveyed floor area. There were opening at the two side walls of the model and the opening height was 2.4m. It is considered that daylight entered from the side window and lighted the periphery area of the floor. There was 3(three) light pipes at the center of the area with a transition space at the upper part of the model. The Dome of light pipe was set at the roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe.
8.	**Model 02 with Side Window without Lightpipe** used in simulation Case 04(c)	
		This model was created with the entire floor as surveyed floor area. There were opening at the two side walls of the model and the opening height was 2.4m. It is considered that daylight entered from the side window and lighted the periphery area of the floor. In this case, no light pipe was considered.

3.10 Simulation Output Variables

For this simulation study the following output variables have been considered.

- Lighting distribution [lux](Hourly) at Work Plane (Illumination Plane Grid Point)
- Daylighting Reference Point 1 Illuminance [lux](Hourly)
- Daylighting Reference Point 2 Illuminance [lux](Hourly)
- Tubular Daylighting Device Pipe Absorbed Solar Radiation Rate [W](Hourly)
- Tubular Daylighting Device Transmitted Solar Radiation Rate [W](Hourly)
- Tubular Daylighting Device Diffuse Visible Transmittance (Hourly)
- Tubular Daylighting Device Diffuse Solar Transmittance (Hourly)

Besides these variables, there are other thermal variables such as Tubular Daylighting Device Beam Solar Transmittance (Hourly) and Tubular Daylighting Device Beam Visible Transmittance (Hourly) have been measured by Energy plus simulation engine in this research work for accuracy.

The data base of these variables has been given in the Appendix G and H.

3.11 Identifying the Evaluation Process

To model the building in Energy Plus, initially Google Sketch-Up with Open studio plug in software which is the most popular front end for Energy Plus was used. To visualize the file and edit the building geometry, Google Sketch Up with an Open Studio plug-in was used.

This free plug-in allows us to launch Energy Plus simulations, assign some attributes and view the results without leaving the Google Sketch Up 3D drawing program.

Open Studio allows us to import the .IDF file and edit surfaces and zones in the file. Using open studio one can match inter zone surface boundary conditions, add internal gains and simple outdoor air for load calculations and can set and change default constructions and assign day lighting controls. Figure 3.11 presents the whole simulation and evaluation process for this research work.

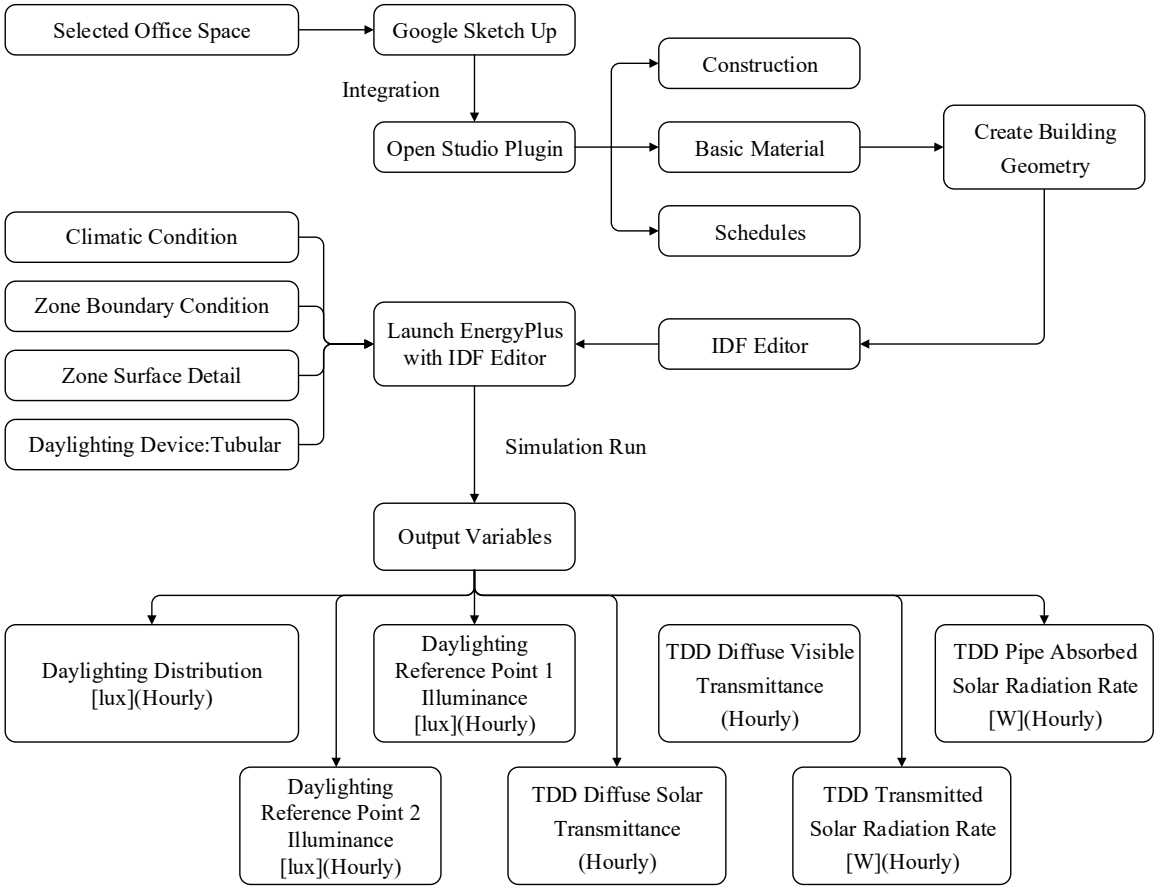


Figure 3.11: Simulation and evaluation process of EnergyPlus parametric studies

Since Open Studio is not yet developed to the level of being a full-fledged front end for Energy Plus, some of the text file editing was required to do using an IDF Editor. EnergyPlus comes with several utilities to help create input files and run simulations. IDF Editor is one such utility in which any EnergyPlus object may be viewed and edited using a spreadsheet i.e. grid. The simulated lighting levels at the calculation points of the office space were collected and plotted onto the chart. This result will help to obtain the total luminous condition more accurately with more reference or distributed points and to get output in spreadsheet, text file and ESO graph or contour lines in chapter five. Details of the above mentioned simulation program is provided in Appendix G and H.

3.12 Summary

This Chapter describes the methodology for simulation study and selection criteria of case office space. Present condition of different office spaces, layout pattern, use of natural and artificial daylight and experiment with scale models have been presented in the next Chapter 4.

CHAPTER FOUR:

FIELD MONITORING AND EXPERIMENTAL STUDY

Preamble

Field Survey

Findings of Field Survey

Critical Observations from Field Survey

Selection of Example Building and Office Space

Simulation Model Preparation

Experimental Study

Observations from Experiments

Conclusion

CHAPTER FOUR: FIELD MONITORING AND EXPERIMENTAL STUDY

4.1 Preamble

Chapter 3 discusses methodology to describe the basic information required to identify on which the simulation could be conducted. This chapter contains the details of the surveyed offices for the selection of that specific space which will be simulated. Experimental studies with scale models have done to understand daylight inclusion pattern by side windows, roof openings and lightpipes. The findings from field monitoring and results of the experiments were used in the simulation study which was described in the next chapters.

4.2 Field Survey

As Dhaka is the capital of Bangladesh, most of the Government organizations, NGOs, multinational and private companies establish their corporate/ head offices in Dhaka (Joarder, 2007). A total number of ten (10) offices were surveyed from different locations of Dhaka. Table 4.1 lists offices included in the field survey. The survey covered a broad area through a questionnaire (see Appendix D) about the physical characteristics of the offices of Dhaka. Discussions of this section are restricted to only that extent, based on which the daylight simulation would be done later to come up with design suggestions. Items such as building surroundings, orientation, interior materials and finishes are excluded in the discussions as these parameters were fixed in simulation study for example space. The items covered in the field survey are:

1. Total story of the office and surveyed floors
2. Dimension (length and width) of the office.
3. Area lighted with daylight and lighted with artificial light.
4. Height of openings (type, sill, lintel).
5. Height of different objects in office interior (work plane, partition, ceiling height).
6. Health symptoms of the employee of the offices.

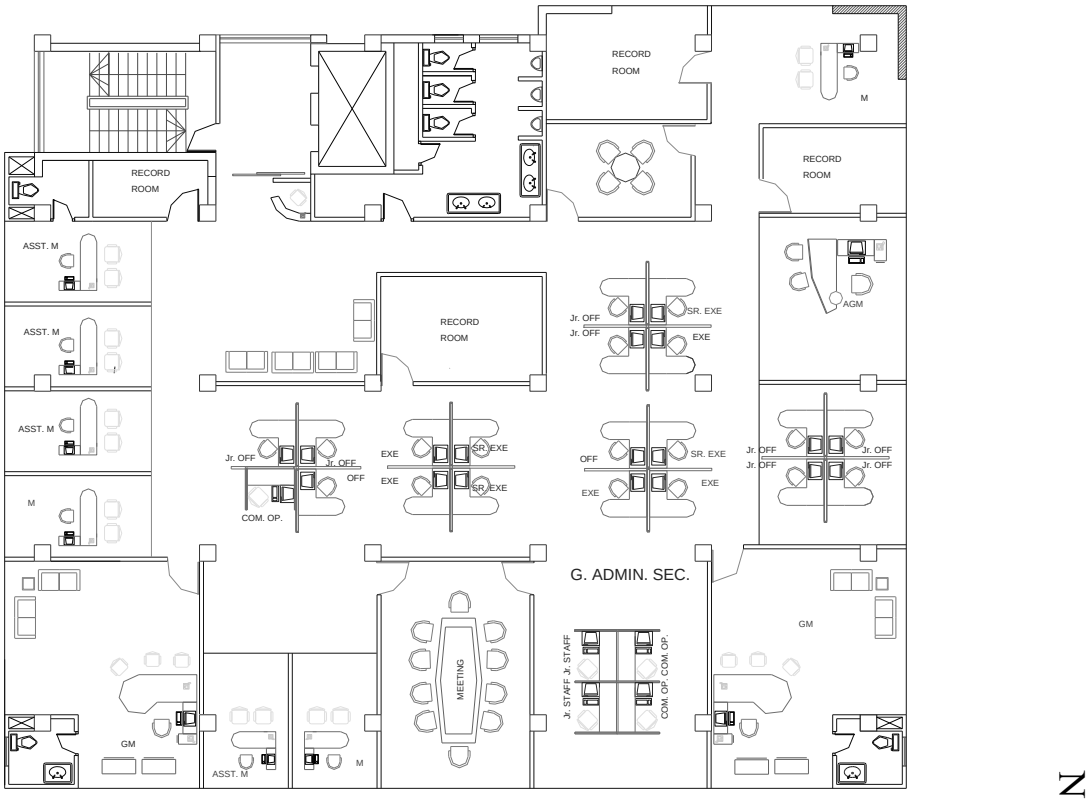
Table 4.1: Offices for field survey

Sl. No.	Name of the Office	Location	Story	Surveyed Floor
A.	Opsonin Chemical Industries Ltd.	New Eskaton Road, Dhaka.	09	5th
B.	Akiz House, Cement Division	198 Bir Uttam,Mir Shawkat Sarak. Gulshan Link Road, Tejgaon, Dhaka-1208	14	4th
C.	Pubali Bank Ltd. Credit Division	7th Floor, Motijheel, Dhaka.	15	7th
D.	Markentile Bank Ltd. International Division	Eunoos Centre, Dilkusha, Dhaka	22	12th
E.	Renata Ltd. International Business Division	Plot No. 1, Milk Vita Road, Section-7, Mirpur, Dhaka-1216,	02	1st
F.	Bangladesh Bank, Head Office	Motijheel, Dhaka.	31	24h
G.	BASF Bangladesh Ltd.	SAM Tower, (Level 7), House #4, Road #22, Gulshan 1, Dhaka 1212	11	7th
H.	I-Pay Office	Silver Tower, Gulshan -1, Dhaka	19	13th
I.	IFIC Bank Ltd., Progoti Saroni Branch	AJ Heights Building, Cha-72/1/D, Progoti Saroni, Badda, Dhaka.	15	1st
J.	Robi Head Office, Nafi Tower	Plot No. 53, Gulshan Avenue, Dhaka 1212	20	5th

Detail layout plan and other information are given below:

Table 4.2: Field survey data of Opsonin Chemical Industries Ltd.

Office Name (A)	**No. of Story**	**Survey Floor Location**	**Core Location**	**Opening**	**Length**	**Width**	**Floor Area**
Opsonin Chemical Industries Ltd.	09	5th	West	North, East, South	28.65 m	25 m	7460 sft= 693 sqm



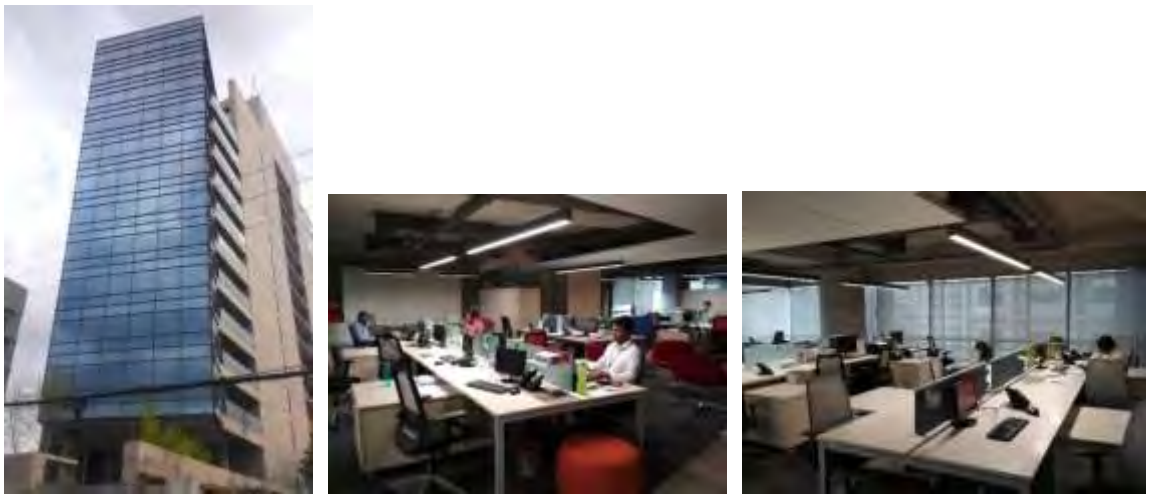
5th Floor plan

Building Exterior and Interior Image

Table 4.3: Field survey data of Akiz House

Office Name (B)	**No. of Story**	**Survey Floor Location**	**Core Location/ Block**	**Opening**	**Length**	**Width**	**Floor Area**
Akiz House	14	4th	West	North, East, South	43 m	18 m	6683 sft= 621 sqm

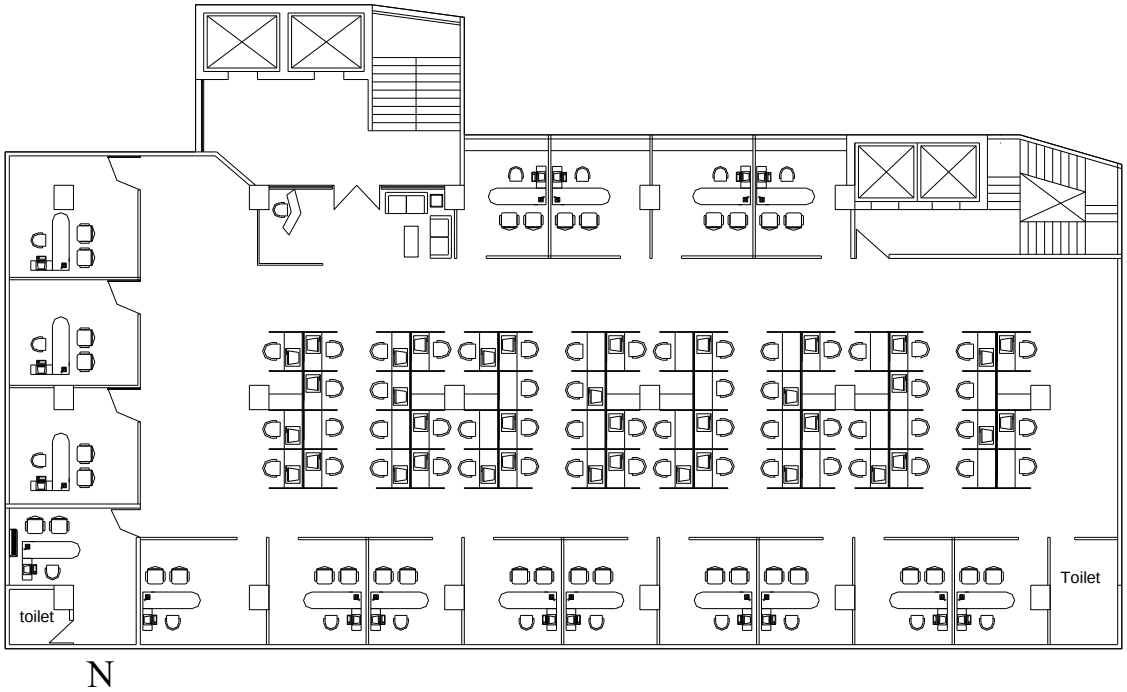
4th Floor plan



Building Exterior and Interior Image

Table 4.4: Field survey data of Pubali Bank Ltd.

Office Name (C)	**No. of Story**	**Survey Floor Location**	**Core Location/ Block**	**Opening**	**Length**	**Width**	**Floor Area**
Pubali Bank Ltd. Credit Divition	15	7th	North/ South	North, East, West	35 m	16.15 m	6330 sft= 590 sqm

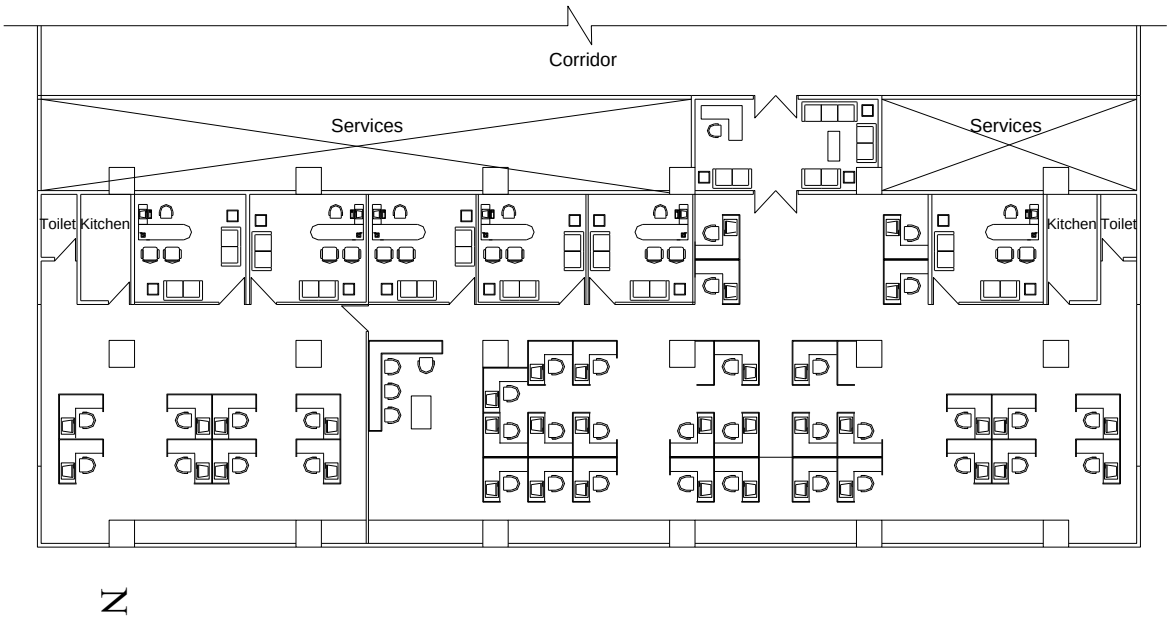


7th Floor plan

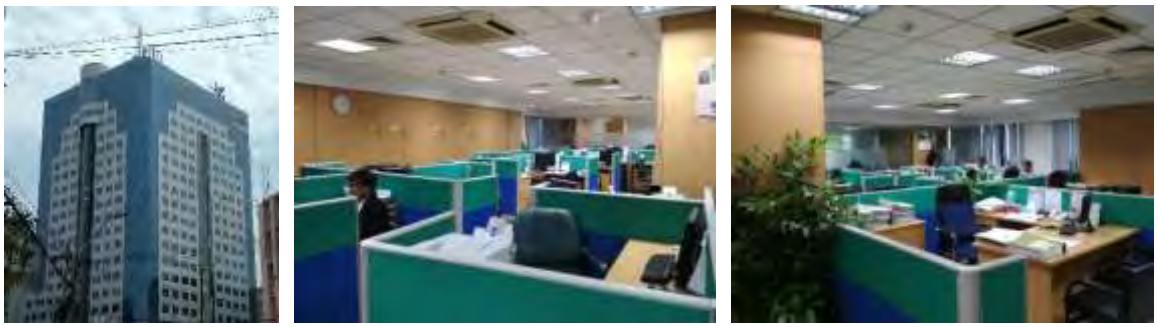
Building Exterior and Interior Image

Table 4.5: Field survey data of Markentile Bank Ltd.

Office Name (D)	**No. of Story**	**Survey Floor Location**	**Core Location/ Block**	**Opening**	**Length**	**Width**	**Floor Area**
Markentile Bank Ltd.	22	12th	Center/ East, West	North, South	38 m	15.24 m	7135 sft= 663 sqm



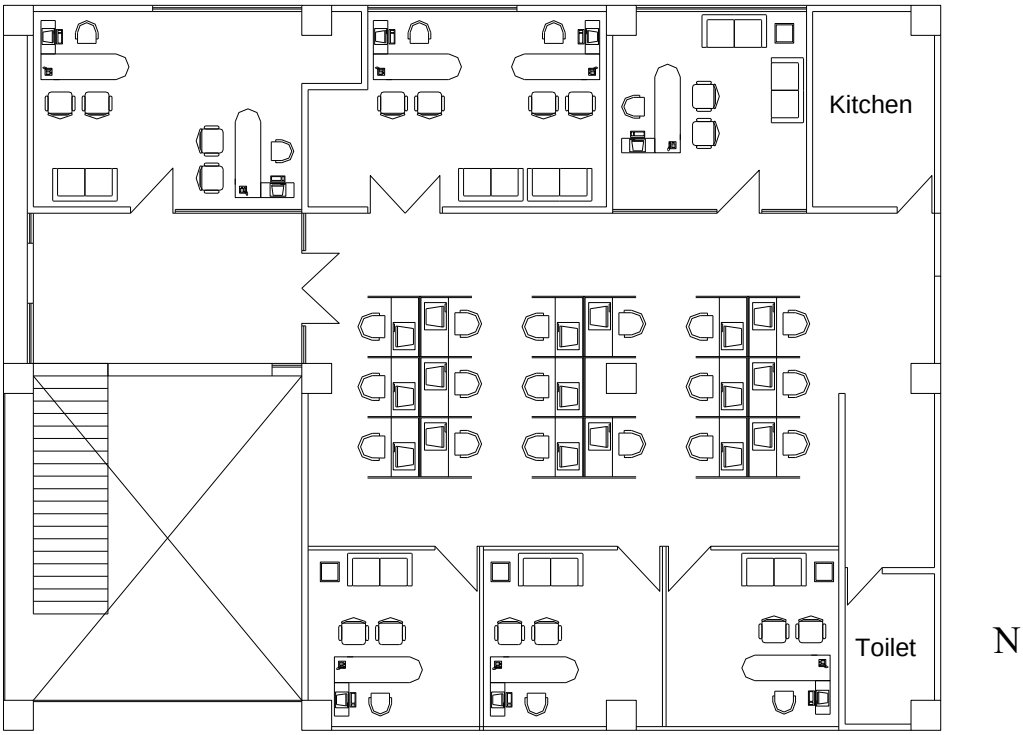
12th Floor plan



Building Exterior and Interior Image

Table 4.6: Field survey data of Renata Ltd.

Office Name (E)	**No. of Story**	**Survey Floor Location**	**Core Location/ Block**	**Opening**	**Length**	**Width**	**Floor Area**
Renata Ltd.	03	1st	West/ East	North, South	19.2 m	16 m	3050 sft= 285 sqm

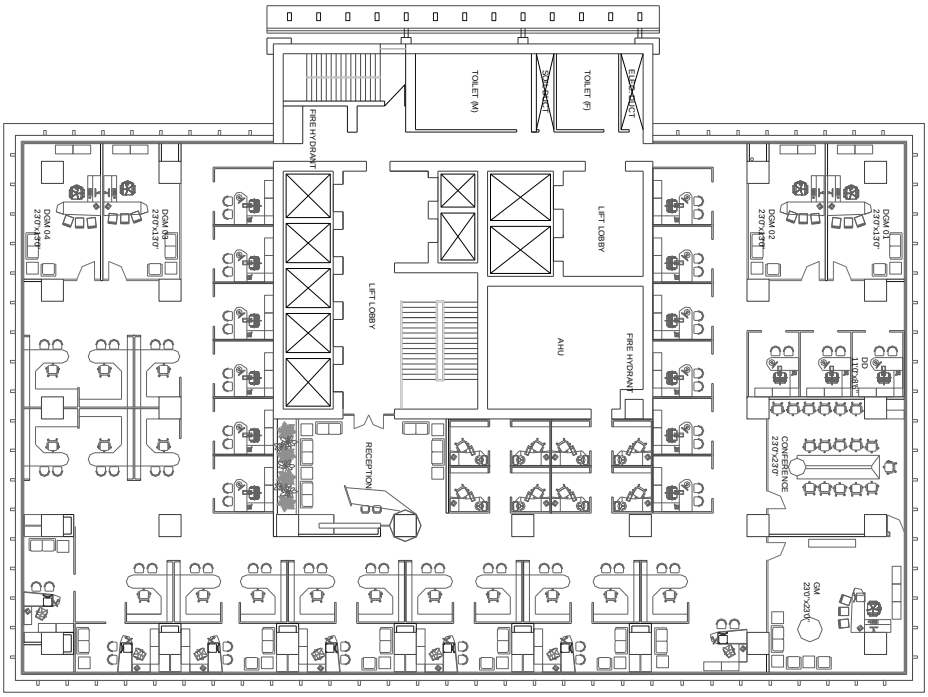


2nd Floor plan

Building Exterior and Interior Image

Table 4.7: Field survey data of Bangladesh Bank

Office Name (F)	**No. of Story**	**Survey Floor Location**	**Core Location/ Block**	**Opening**	**Length**	**Width**	**Floor Area**
Bangladesh Bank, Head Office	31	24th	West/ East	North, South	45.72 m	28 m	15100 sft =1400 sqm



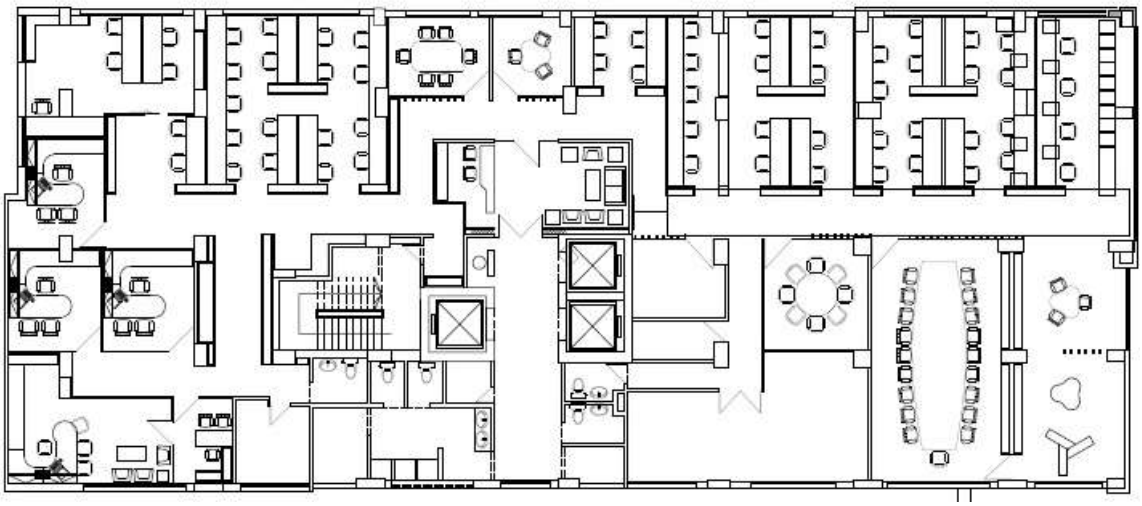
N

24th Floor plan

Building Exterior and Interior Image

Table 4.8: Field survey data of BASF Bangladesh Ltd.

Office Name (G)	No. of Story	Survey Floor Location	Core Location/ Block	Opening	Length	Width	Floor Area
BASF Bangladesh Ltd.	11	7th	Middle	North, East, South, West	46.25 m	19.80 m	10100 sft = 945 sqm



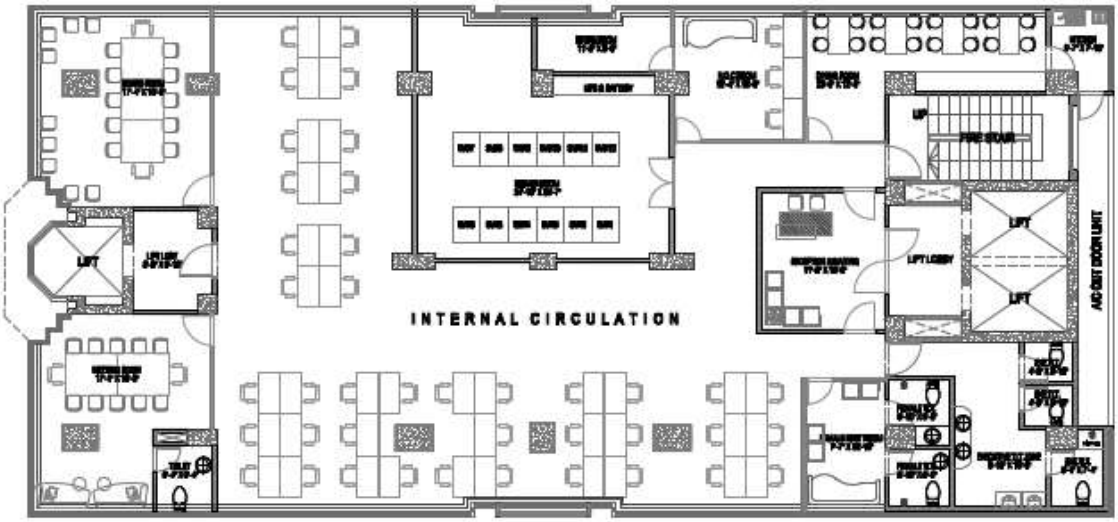
N

7th Floor plan

Building Exterior and Interior Image

Table 4.9: Field survey data of I-Pay *Office*

Office Name (H)	**No. of Story**	**Survey Floor Location**	**Core Location/ Block**	**Opening**	**Length**	**Width**	**Floor Area**
"I-Pay"	19	13th	East	West, North, South	40 m x 18.29 m	7800 sft= 725 sqm	



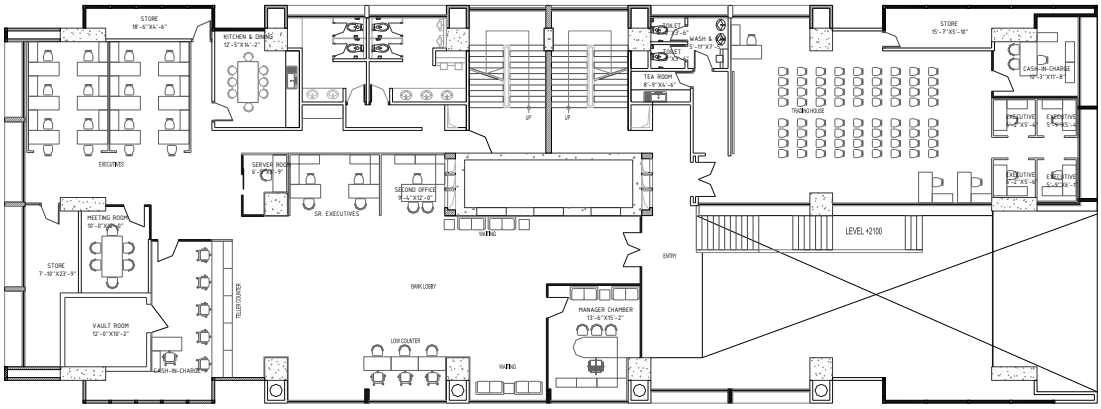
N

13th Floor plan

Building Exterior and Interior Image

Table 4.10: Field survey data of IFIC Bank Ltd.

Office Name (I)	**No. of Story**	**Survey Floor Location**	**Core Location/ Block**	**Opening**	**Length**	**Width**	**Floor Area**
IFIC Bank Ltd., Progoti Saroni Branch	15	1st	West	East, North, South	48.76 m	17 m	8800 sft= 818 sqm



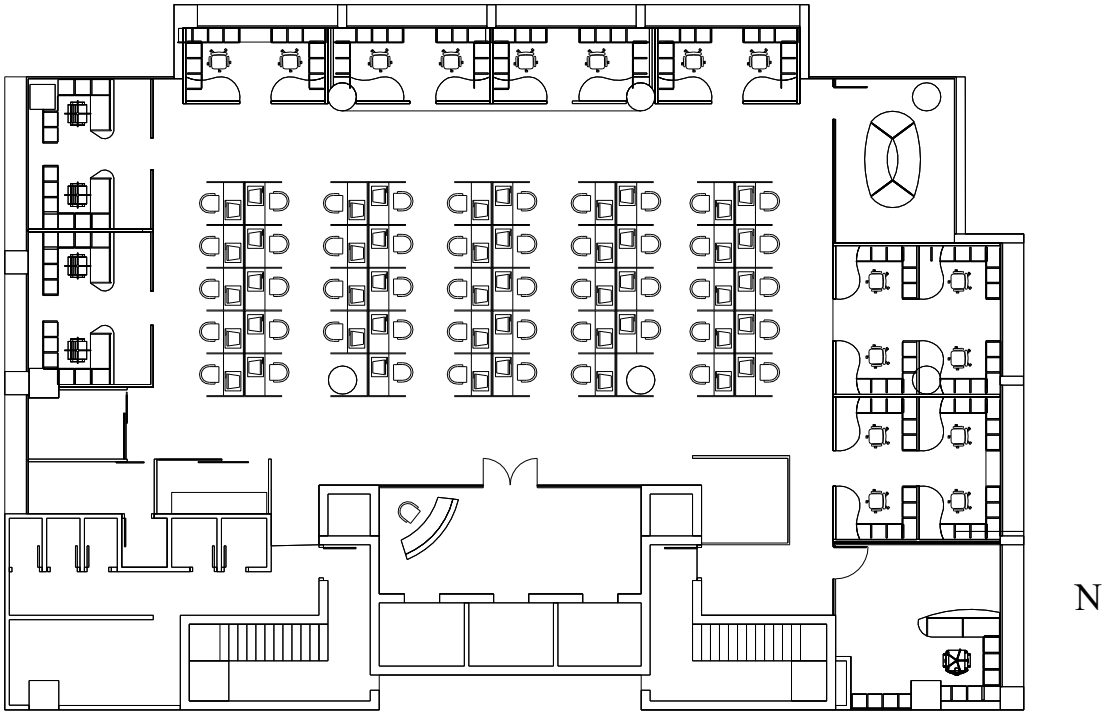
N

1st Floor plan

Building Exterior and Interior Image

Table 4.11: Field survey data of Robi Head Office, Nafi Tower

Office Name (J)	**No. of Story**	**Survey Floor Location**	**Core Location/ Block**	**Opening**	**Length**	**Width**	**Floor Area**
Robi Head Office, Nafi Tower	20	5th	South	East, North, West	29 m	20m	5800 sft = 539 sqm



5th Floor plan

Building Exterior and Interior Image

4.3 Findings of the Field Survey

As Dhaka city possesses almost similar climatic, geographical, technical and other aspects in its different parts, the characteristics features are also quite similar for office in different areas. Some variations in features were however identified during the survey.

6.3.1 Building Floor Number and Surveyed Floor

After selection it was found that different height offices were surveyed. There was one building which was three (3) storied and on the opposite side, the highest no. of story of surveyed building was 31. At the same time surveyed floor situated in different intermediate floors of these buildings. At two (2) cases, it were 1st floor, but most of the cases, it were 5th floor and above. These findings are presented in Fig.4.1.

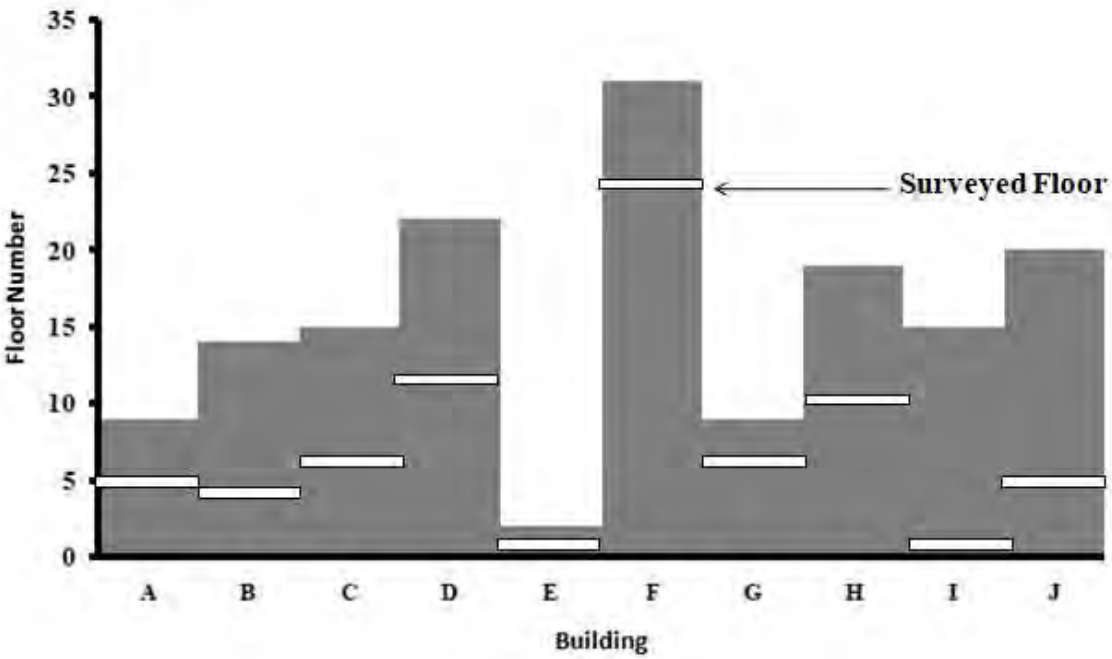


Figure 4.1: Floor Number and Surveyed Floor

6.3.2 Ceiling, sill and work plane height with relation to floor height

In the surveyed cases the floor height of the buildings varies from 3m to 3.66m. Among them most of the floor (6 cases) have a height of 3.66 m. The lintel height varies from 2.1m to 2.75m, but in most cases it was 2.1m. Most of the offices were covered by curtain glass. So the sill level of most cases were 0m but there were 2.1m wall in four cases. So for that buildings, the seal level were 2.1m. That's why the height of the opening varies

from 1.35m to 2.75m. The average opening height was 2.4m. But there were uniformity in work plane height. In all cases, it were 0.75m. These findings are presented in Fig.4.2.

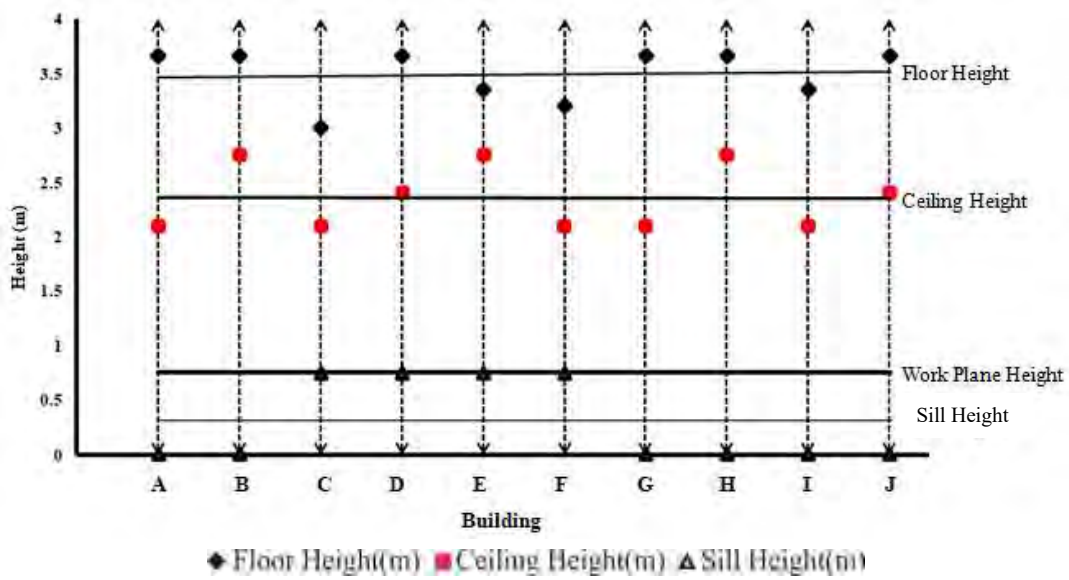


Figure 4.2: Ceiling, sill and work plane height with relation to floor height

6.3.3 Partition height and work plane height

In the surveyed office spaces 90% of the offices use low partitions to demarcate individual workstations. Most of the offices (7 cases) have 1.2m high partitions around workstations. The partition height were less than 1.2m (1.06m) in two (2) cases. But previously found that the work plane height were 0.75m in all cases. So these partitions become a barrier for using daylight (weather available). Only one office didnot use any partition. These findings are presented in Fig.4.3.

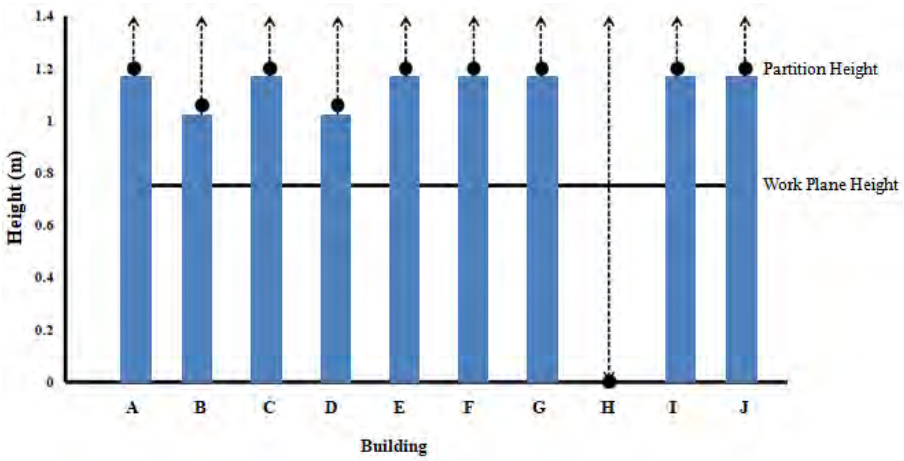


Figure 4.3: Partition height with relation to work plane height

6.3.4 Illumination Level

Illumination level were measured at the open office areas of the ten offices. As the targeted area were far away from openings, the employees have to use artificial light. In every cases illumination level were measured with the artificial lights switched on and also when the artificial lights were off, to test the daylight penetration and its contribution to the illumination of the space during the day. In the absence of task lighting, only ambient lighting data could be obtained.

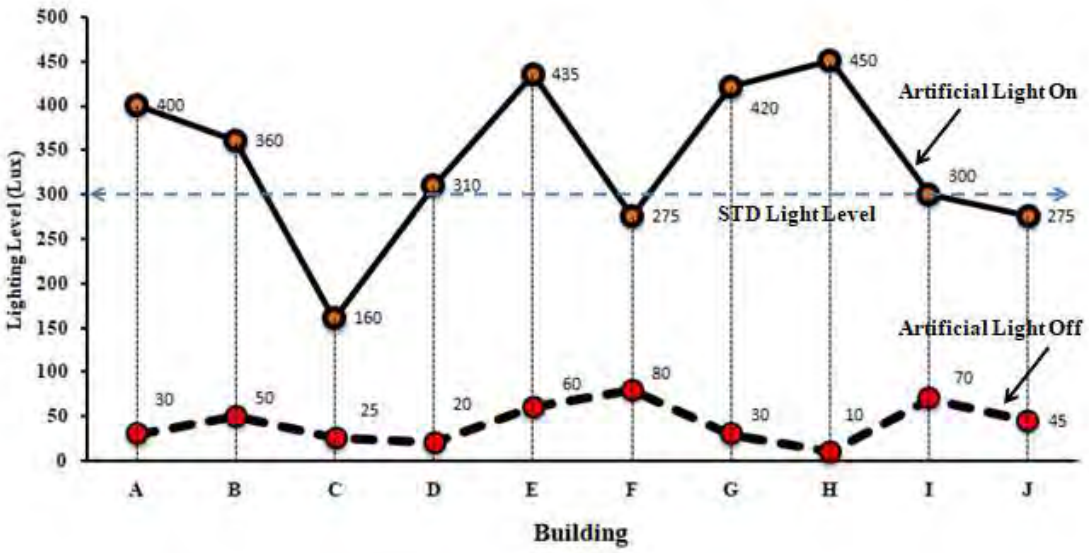


Figure 4.4: Illumination level comparison

Fig.4.4 shows that the illumination level were very poor without artificial light as the open area of office spaces with low partition generally situated at the center of the office where there were no scope of inclusion of daylight. But when the employee use artificial light, most of the cases, the illumination level were up to the standard (BNBC) task lighting level (300-450 lux). However there were also some examples which did not reach the standard of illumination even with artificial lights switched on.

6.3.5 Building's Floor Width

Length and width of the office building is a major factor because it determine the area where penetrated daylight reach. As it found that average ceiling height was 2.4m, so daylight can reach max 4.8m on an average (2 times of opening height). In the surveyed cases, half of the minimum width was 7.62m. So the surveyed spaces were far away from the range of reaching daylight by side opening (Figure 4.5).

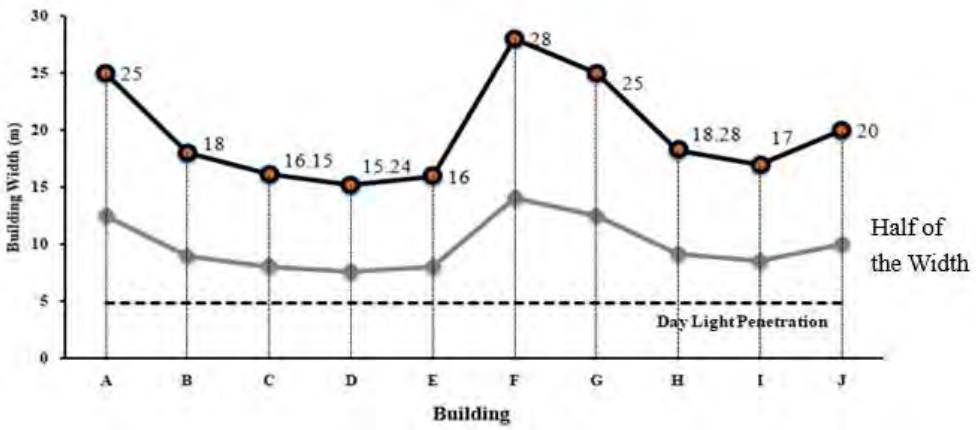


Figure 4.5: Comparison of different surveyed building's floor width

6.3.6 Health Symptoms

By the questionnaire survey (see Appendix D) about the physical characteristics of the office spaces, 220 employee gave there feedback about their health issues which were affected by the lighting condition of work space. It was found that 95 no. of people who had the opportunity to work in natural daylight, 48% of them have no problem with health issue. But 11% of them suffering from headache, 18% had eye irritation and 23% were suffering from fatigue (Figure 4.6).

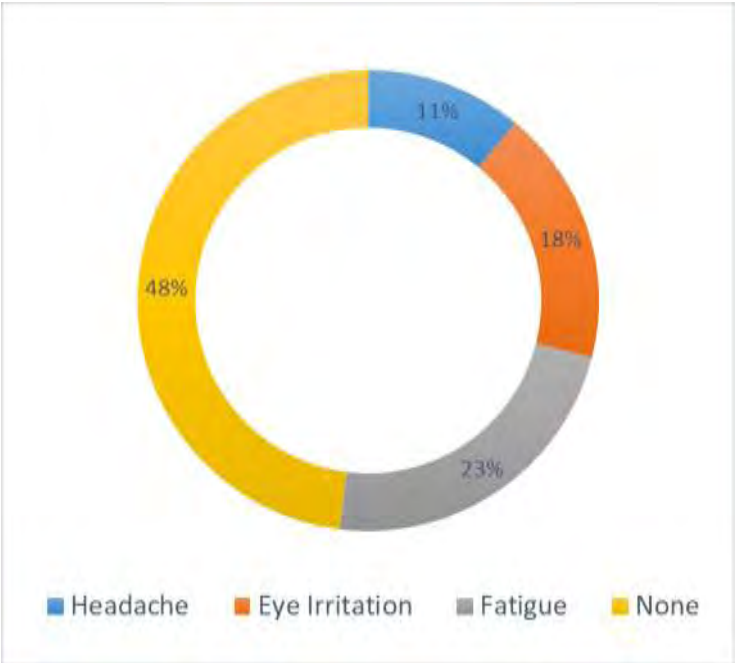


Figure 4.6: Health Symptoms of the employees who work beside openings

On the other hand, the 125 no. of employee, who worked in the open office area, only 13% of them had no health issue. But 25% of them suffering from headache, 26% had eye irritation and 26% were suffering from fatigue (Figure 4.7).

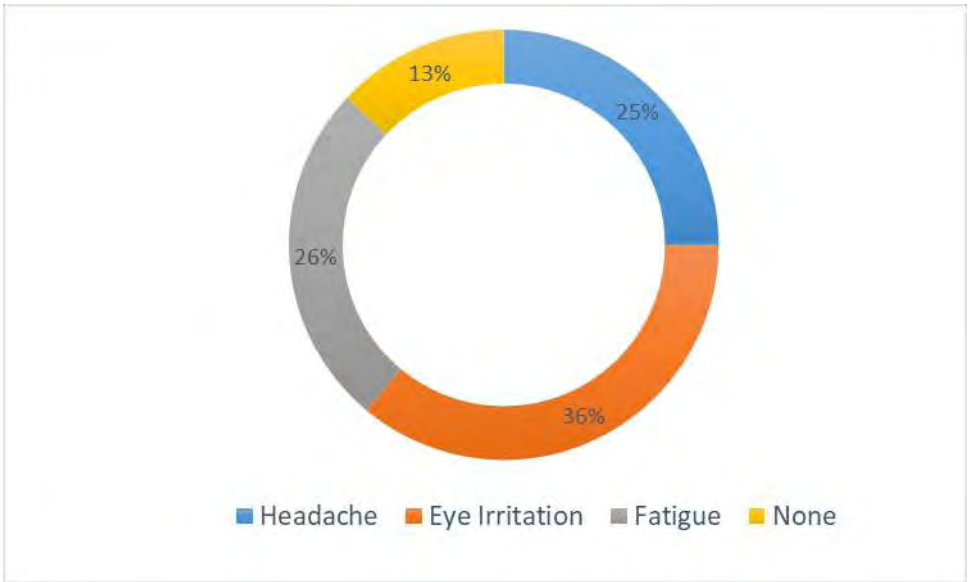


Figure 4.7: Health Symptoms of the employees who work without daylight

4.4 Critical Observations from Field Survey

The findings of field survey can be summarized as below to establish the potential of lightpipe.

a) 25% to 40% of office space are fully and 15% to 20% of the space are partly lack of direct daylight. Most of them are at the middle position of the floor plan.

b) The height of floor, ceiling, opening (lintel to seal height) are directly related for inclusion of daylight in surveyed office buildings. But full height windows are not enough to reach daylight at the deep space of the offices

c) Introduction of false ceiling in all of the surveyed office interiors terminates the option of positioning windows height on the walls, allowing only low level windows for daylight penetration.

d) From the measured illumination levels of the limited surveyed offices, it is apparent that lighting levels are well below acceptable national and international standards.

e) Near the window it is natural light that is the dominant lighting source and but at the deep spaces it observe that there is a sharp drop from measured artificial lighting level to daylight level. This is when the effect of daylight is extremely low or no daylight, due to distance or lack of opening, but often it was not up to the standard.

f) The employees who work at the deep space of the office, are affected by different health problems i.e. headache, eye irritation and fatigue, mostly rather than the employees who work besides the opening. So it is very clear that work without daylight as well as with artificial light for a long time had an inverse health impact to the employees.

4.5 Selection of Case Building and Office Space

The main target of the entire investigation was to identify one office as example space for computer simulation. This case office would match the target goal of the research (inclusion of daylight in deep space) along with common typology of office in Dhaka city.

The criteria for site and building selection to determine the case office space were based on the following factors (Joarder et.al, 2009).

a) The site should be in urban context and should have characteristics typical of the general urban fabric of the Dhaka city.

b) The case office building should represent the trend of typical office design in Dhaka.

c) The case office building should be architect-designed and built in accordance with the Building Construction Regulations of the City Authority.

d) The case office space should have minimum complexity in design and detailing for easy of simulation with different daylight strategic options.

e) Internal layout of the case office space should be such that, there should be provision for daylight inclusion near opening along with deep spaces where direct sunlight can't reach by opening.

f) The scale and volume of the building be convenient to handle within the time limit of this study.

Figure 4.8: Site and Surroundings of nine (9) Storied Opsonin Building (Joarder, 2007)

According to the above criteria the nine storied Opsonin Building (Corporate office of Opsonin Chemical Industries Ltd.) was selected for detailed examination and simulation study. The 5th floor of the building was chosen as example space to take for detail experiment. This floor is one of the typical floors, the plan of which is repeated in other floors. The building has a 7m wide road on the west, some single storied semi-pacca establishments on the east, another nine storied building 2.5 m from the northern edge and 2.5 m from the south is a three storied building. There is a four storied building and some greenery just opposite the road in front of the office building (Figure 4.9)

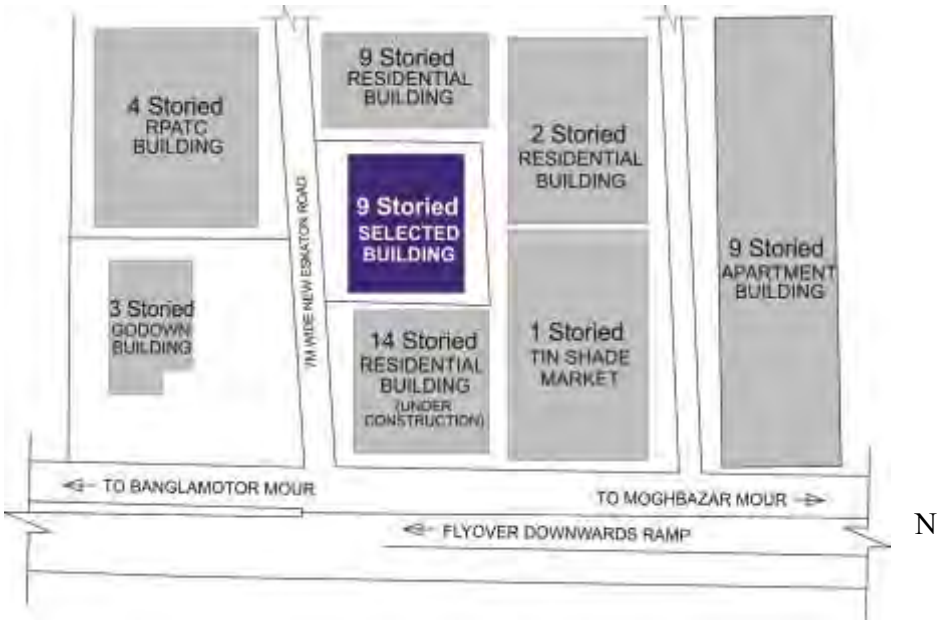


Figure 4.9: Location Map (With Site and Surroundings)

After selection of the building a check has been done (Table 4.12) to see that the example building in fact suitable for detail observation and simulation.

Table 4.12: Different aspects for case building

Characteristics	**Opsonin Building**
Type	High Rise Intermediate Foor Designed as Office Building 3 Side open
Date of Establishment	2001-2007
Starting Time	9.00 AM
Closing Time	6.00 PM
Window Type	Sliding(3 Sides) and Fixed(Front)
Window Material	Glass
Type of the Glass	Coloured
Glass Specification	Thickness: 10mm, Conductivity: 0.9 W/m-K, Visible Transmittance: 0.55, Solar Transmittance: 0.775. Density: 160 lb/ft^3
Floor Height	3.0m
Window Height	2.1m
Sill Height	Below 0.75m
Lintel Height	2.1m
External Shading	No external shading
Internal Blinds	Vertical
Ceiling Height	2.1m
Partition Height	1.2 m
Work Plane Height	0.75 m

The fifth floor of the nine storied corporate office of Opsonin Chemical Industries Limited was taken as Example Space. Currently this 5th floor is being used as meeting and general office space (Fig. 4.10 and 4.11) for the office employee. Another reason to choose this floor for analysis was that this floor has a large open office area at the middle portion of the floor, i.e. uninterrupted by too many internal partitions and workstations (Fig. 4.12).

Figure 4.10: Axonometric view of 5th floor, Opsonin Building

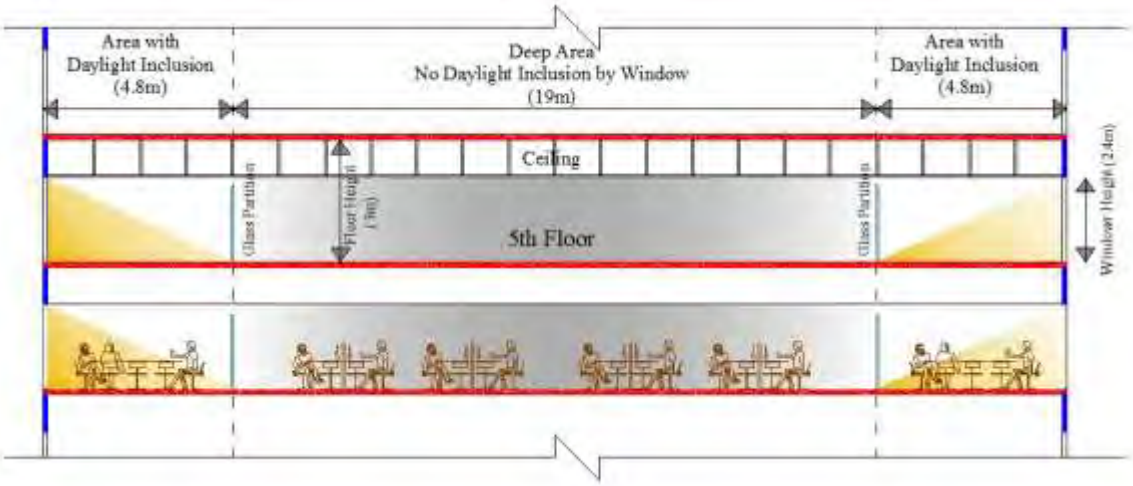


Figure 4.11: Typical section (Part) of nine storied Opsonin Building

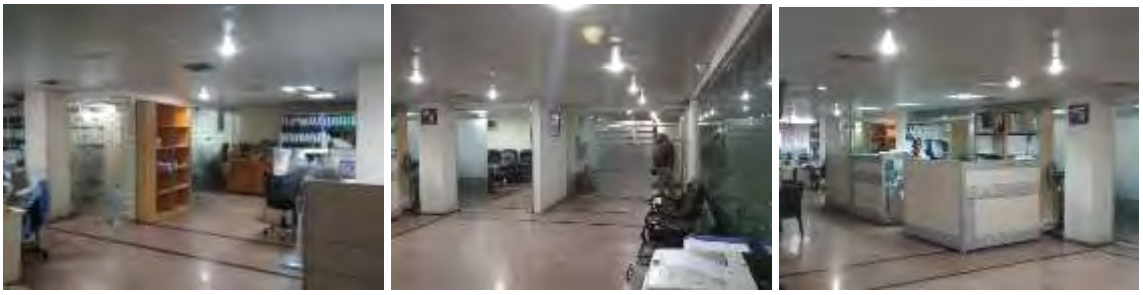


Figure 4.12: Interior view of 5th floor of Opsonin Building

4.6 Simulation Model Preparation

The model 01 was created only with the open office area of selected office where direct sunlight can't enter and with vacant interior space without any partitions or furniture, to avoid the effects of such surfaces, which both block and reflect daylight (Figure 4.13). The model 02 was created with the full area of surveyed office. (Figure 4.14). The other parameters of the model of example space are mentioned below.

General Parameters of the selected office floor and simulation models (incorporated from values found in a physical survey (Section 4.5 and Appendix C)

Selected Office Floor	
5th Floor Dimensions:	25m X 28.65m
Total Floor Area:	692 sqm
Open Office Dimension	12m X 18m
Open Office Area:	216 sqm
Clear Height of Office Space	3m (without false ceilings) 2.4m (with metal false ceilings)
Work Plane Height:	0.75 m above floor level
Glass Specification:	Thickness: 10mm, Conductivity: 0.9 W/m-K, Visible Transmittance: 0.55, Solar Transmittance: 0.775. Density: 160 lb/ft^3
Simulation Model 01	
Simulation Area Dimension:	12m X 18m (open office area)
Simulation Area:	216 sqm
Simulation Model Height	3.65m
Transition Floor Height	3.65m
Work Plane Height:	0.75 m above floor level
Simulation Model 02	
Simulation Area Dimension:	25m X 28.65m (Total Floor)
Simulation Area:	692 sqm
Simulation Model Height	3.65m
Transition Floor Height	3.65m
Work Plane Height:	0.75 m above floor level

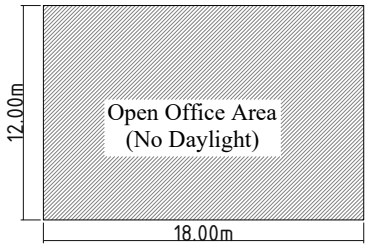


Figure 4.13: Model 01 Plan

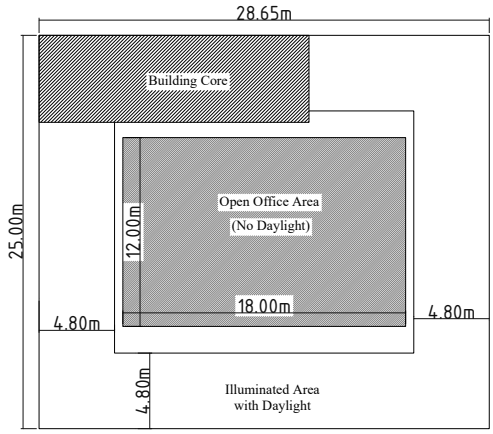


Figure 4.14: Model 02 Plan

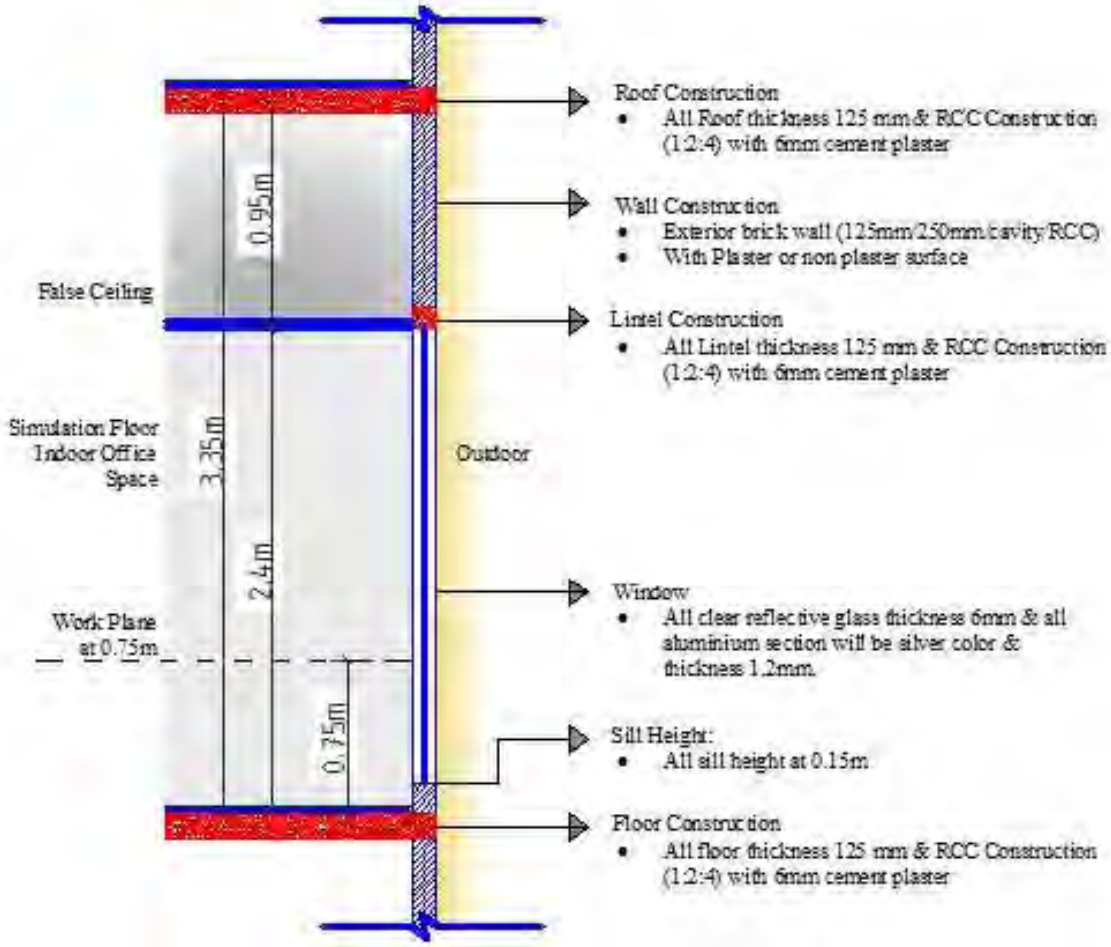


Figure 4.15: Detail section of office space for EnergyPlus simulation

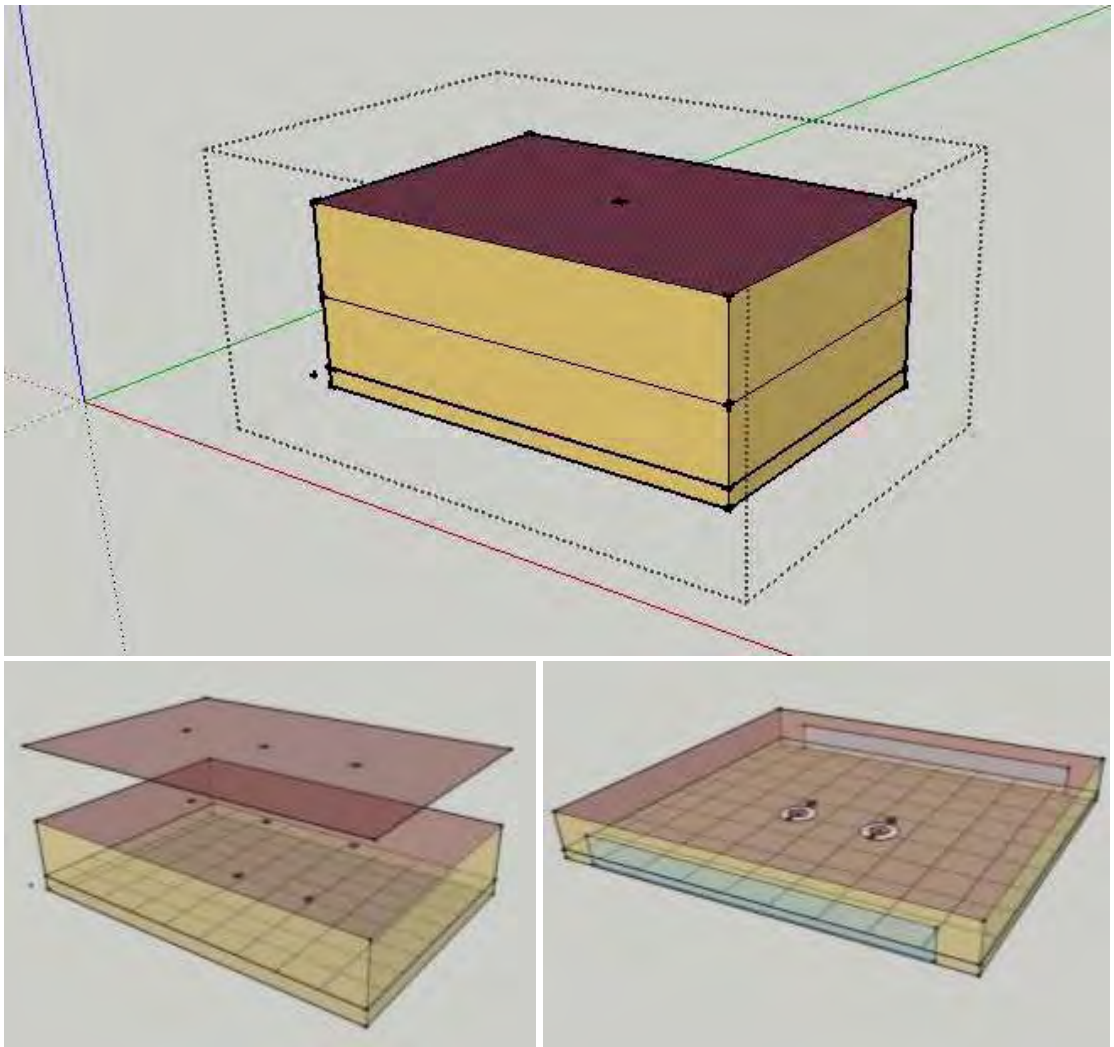


Figure 4.16: View of models used for the simulation. (Software: Open Studio/Sketch up)

4.7 Experimental Study

Scale models are frequently used to evaluate daylighting performances of buildings. (Cannon, 1997). In order to get accurate results, there are several rules to respect for building these scale models. Some of these rules are universal and others depend on the measurement and observation devices, the type of sky under which the study is carried out and the objectives of the study. This part discuss the experiments done by making scale models and observing the physical characteristics of daylight inclusion in the internal spaces of a building.

4.7.1 Experiment 01: Inclusion of Daylight by side Wall and Roof

This model was studied to observe the daylight inclusion pattern by side window and roof. For this study, a conceptual model was used by maintaining the scale and proportion. Firstly a single story building model has made with hard white paper. The model's length and width was 2m and 1m and height was 1m. Model scale was 1:60 (Figure 4.17). Then the model was placed in outdoor where the sunlight comes uniformly. Then some experiment/observation was done by modifying the model wall and roof and observe and measure the daylight by Luxmeter (Dr.Meter). Some images were taken by Thermal Imaging Camera to identify the presence of daylight.

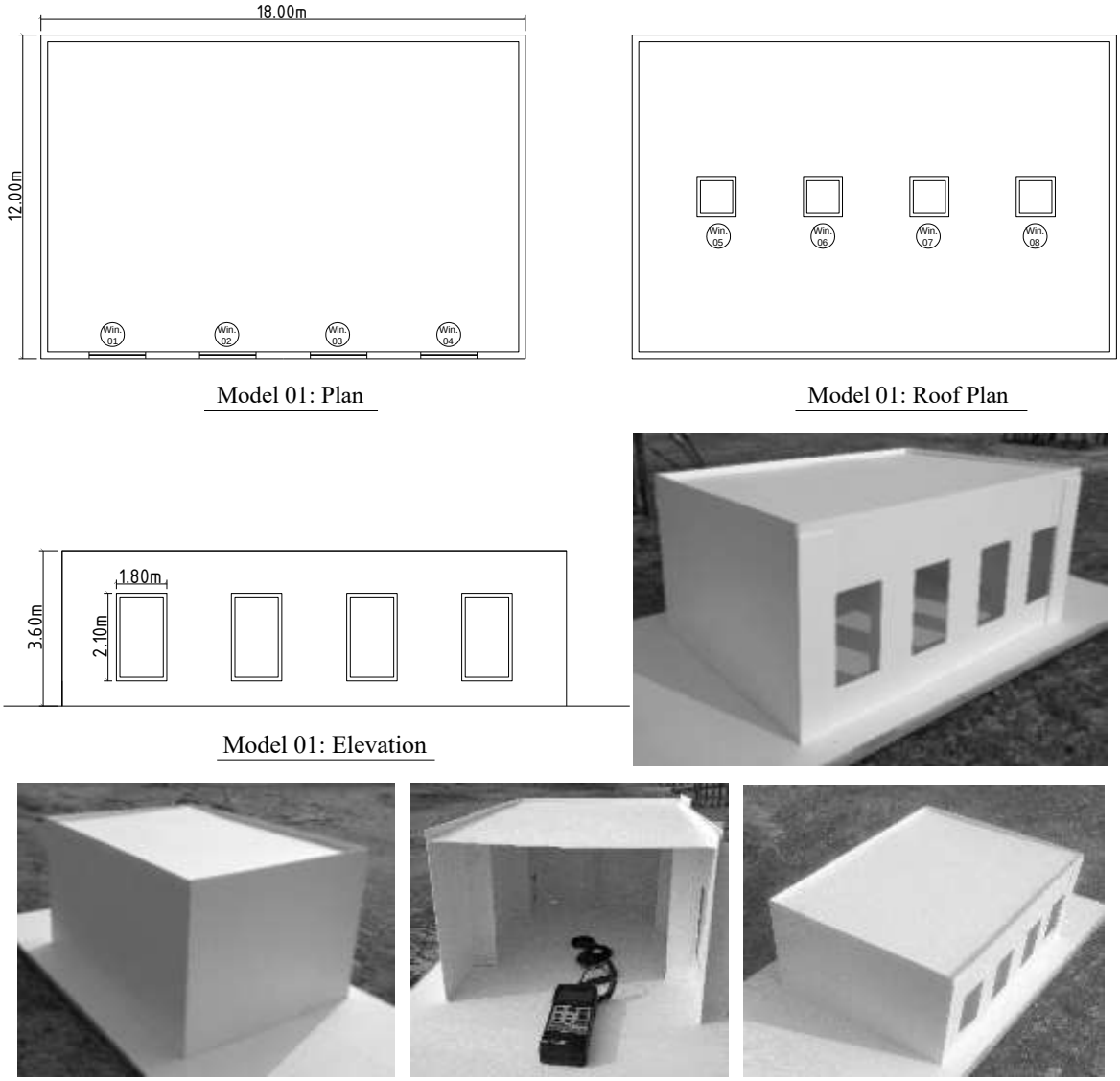


Figure 4.17: Model for experiment 01

In this experiment, the following steps have followed:

Step (a): At first there were no opening in wall and roof of the model. So there was no opportunity of inclusion of daylight in the interior space (Figure 4.18).

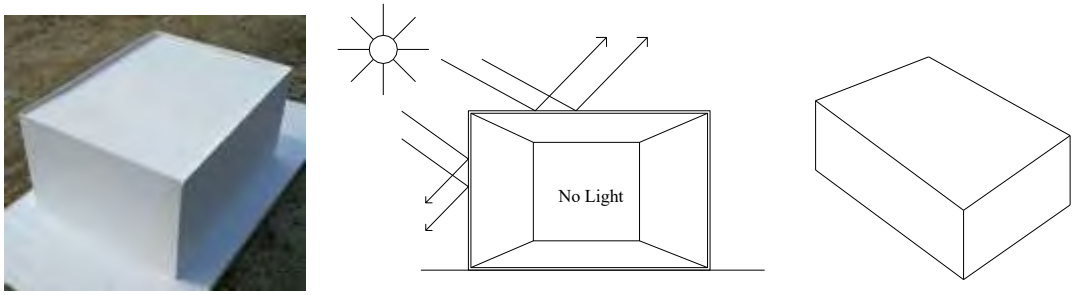


Figure 4.18: Model and sectional perspective of Step 1(a)

Step (b): There were four windows in one side of the model, but no opening at roof. So direct daylight entered to the model interior by side window (Figure 4.19).

Figure 4.19: Model and sectional perspective of Step 1(b)

Step (c): There were four sky lights at the roof of the model, but no opening at side wall. So direct daylight entered to the model interior by sky/roof window (Figure 4.20).

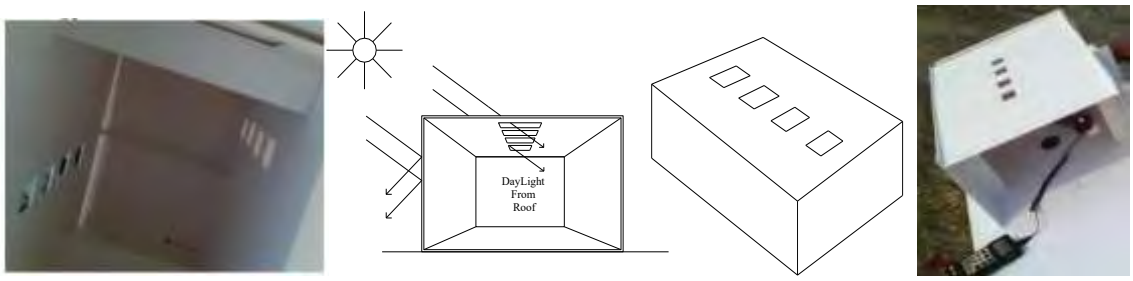


Figure 4.20: Model and sectional perspective of Step1(c)

Step (d): There were four windows in one side and four sky lights at the roof of the model. So a vast amount of direct daylight entered to the model interior through the windows (Figure 4.21).

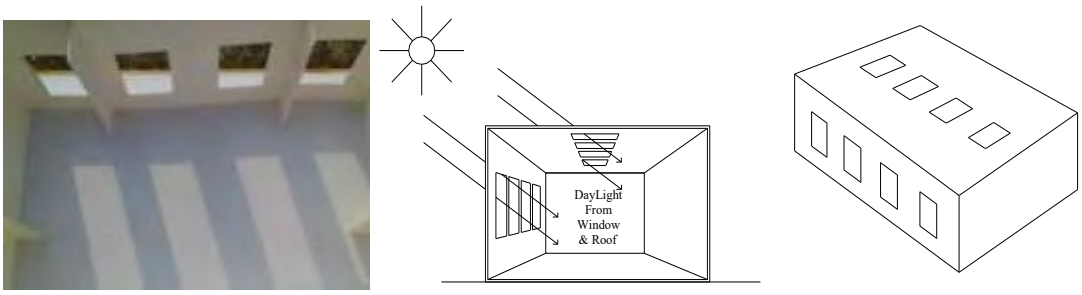


Figure 4.21: Model and sectional perspective of Step 1(d)

4.7.2 Experiment 02: Inclusion of Daylight by Light Pipe

This model was studied to observe the daylight inclusion pattern by light pipe. For the study, a multistoried building model has made with hard white paper. The model was built with half of the open office area (18m x 12m) which length was 9m and width was 6m. The height of the model of per floor was 3.6m and total height was 10.8m. The model was built considering surveyed floor and it was a part of the real space, maintaining the scale of the model as comparable as real scale floor (Figure.4.22 and 4.23). Model scale was 1:100. Reflective paper was used as the inner side material of light pipe and the cross-sectional area of the pipe was 6.25 cm^2 (2.5cm x 2.5cm).

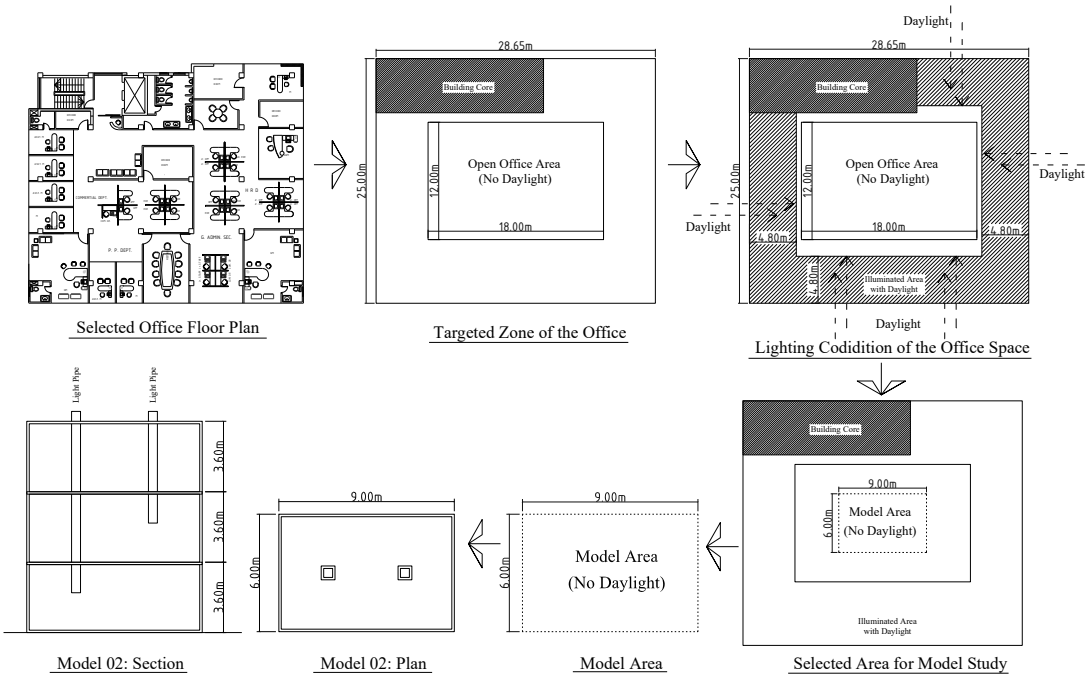


Figure 4.22: Selection of Model Area from Selected Office Space

Figure 4.23: Model for experiment 02

Then some experiment/observation was done by modifying the length and direction of light pipe and observe the daylight inclusion pattern by the light pipes.

Step (a): Inclusion of Daylight by Straight Light Pipe

Firstly two light pipes were built with paper which inner side was with reflected surface. The length of the pipes were different to observe the different situation. One pipe's length was roof to ground floor and another was roof to 1st floor. This experiment was done in indoor environment by artificial light. When artificial light was on, significant amount of light traveled through the light pipes and it reached to the respective floor by both pipes (Figure 4.24).

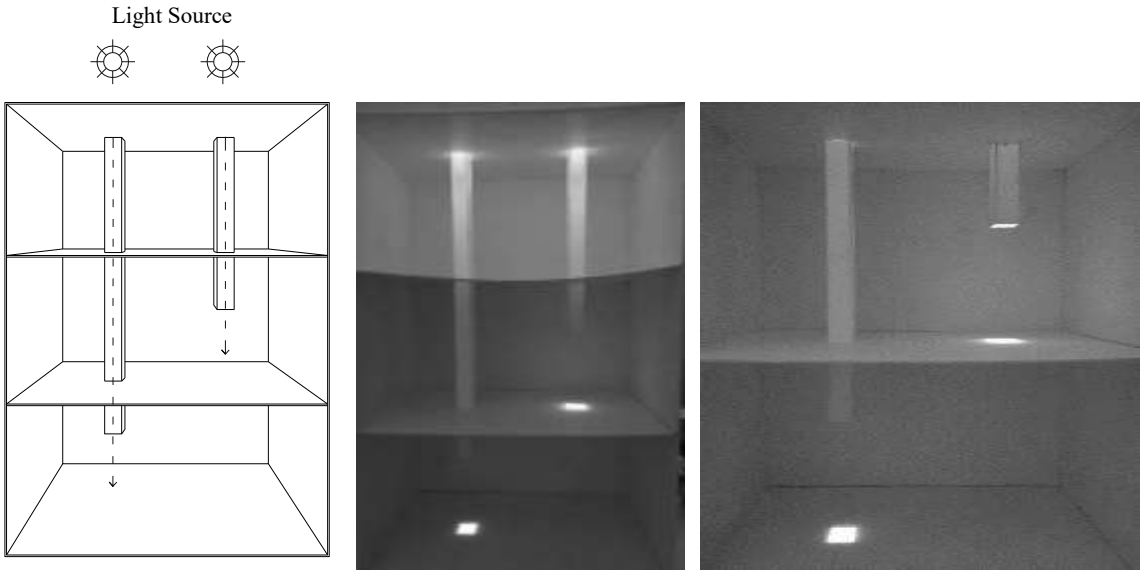


Figure 4.24: Model for Step 2(a)

Step (b): Inclusion of Daylight by Bent Light Pipe

At this stage, the light pipes were modified and changed the direction. One model light pipe was used, it started at roof, bend 90 degree at the 1st floor level and bend 90 degree again before entering at ground floor. This experiment was done in indoor environment by artificial light. When artificial light was on, light traveled through the light pipe and it reached to the ground floor by bended light pipe (Figure 4.25).

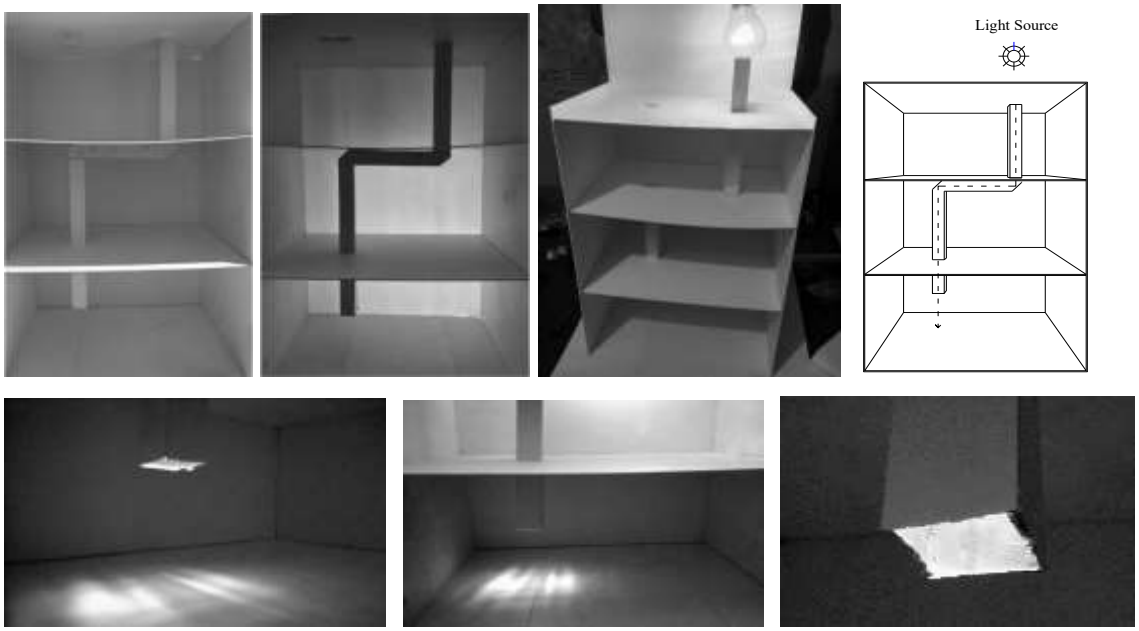
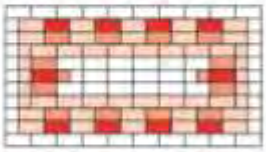
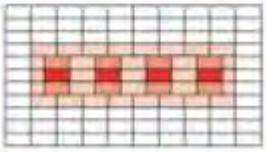
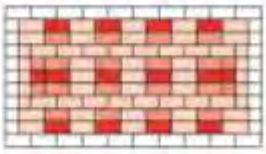
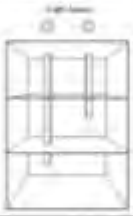
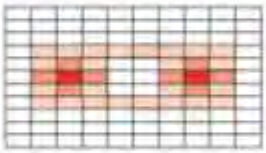
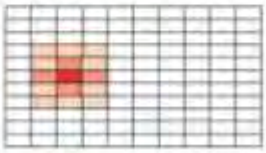


Figure 4.25: Model for Step 2(b)

Table 4.13: Observation from the Experiments

Experiment No./Steps	Catagory	Type/Name	Section	Location	Illumination
1(a)	Daylight	No Window/ Roof		Outdoor	
1(b)	Daylight	Window		Outdoor	
1(c)	Daylight	Roof		Outdoor	
1(d)	Daylight	Window & Roof		Outdoor	
2(a)	Artificial Light	Straight Light Pipe		Indoor	
2(b)	Artificial Light	Bending Light Pipe		Indoor	

4.8 Observation from the Experiments

The target of the experimental setup as well as scaled model study was to observe the daylight inclusion pattern in different space of the office by side opening and by light pipe where natural daylight cannot enter by window and roof. The findings of the experimental set up can be summarized in Table 4.13 from which it can be stated as following.

a) Light enters at the peripheral side of the office building by side window (if there is no obstructions) at any floor. If the window height is “h”, direct daylight reach at the distance of “2h”.

b) Light enters at the office building by roof opening at the top floor. But it is not possible for the intermediate floor.

c) At the center of the office of intermediate floor, where there is no provision of entering daylight by side window or roof, can be illuminated by installing light pipe.

d) Straight Light pipe should be used where there is no obstruction at the upper floor of the target space.

e) Light can be penetrate by bending of light pipe where there are some obstructions at the upper floor of the target space.

4.9 Conclusion

This chapter has discussed the first objective which was to establish the potential of lightpipe in office building by conducting field investigation and also second objective of the research which was to observe the daylight inclusion pattern in different spaces of the office by side opening and by lightpipe where daylight cannot enter by window and roof by model experiments. It discussed the field investigation to select the simulation models and experiments with scale models to observe the daylight inclusion pattern in different spaces of the office by side opening, roof and by lightpipes. The findings provide a practical knowledge about the office spaces and inclusion pattern of daylight into that spaces. This knowledge helped to understand the findings of simulation models for lightpipe studies (Chapter 5).

CHAPTER FIVE: SIMULATION RESULTS AND ANALYSIS

Preamble

Strategies of Simulation Result Analysis

Result Analysis of Daylighting Reference Points

Result Analysis of Daylighting by Straight Lightpipes

Amount of Light Penetration by day time (Hour)

CDF Actual Frequency distribution

Result Analysis of Daylighting by Lightpipes at Bending Position

Comparative Analysis of Straight and Bending Pipe

Implementation of Dual Ducting System

Critical Findings

Conclusion

5.1 Preamble

Chapter 2 describes the basic information required to identify on which simulation could be conducted. Chapter 3 reviewed the methodology of simulation study. Chapter 4 discussed the field investigations and experiments with scale models to select and identify the space for study and the simulation models. First part of this chapter has discussed the results from the simulation studies with different models and varying different variables and then analyze with comparative study. The next part of the chapter describe the possibilities of implementing duel ducting system with the best performed light pipes which identified in the first part. The strategies based on the activities of this chapter have been discussed in Chapter 3 and key findings have been presented in concluding Chapter 6.

5.2 Strategies of Simulation Result Analysis

The 1st model (Model 01) used for simulation was only with the internal (open office area) space, there was no opening at the side wall of the model. It is considered that daylight entered from the side window can't reach at this area (Figure 5.1). The 2nd model (Model 02) used for simulation was equivalent to the whole office space and both-lightpipe and side window were considered for different simulations (Figure 5.2).

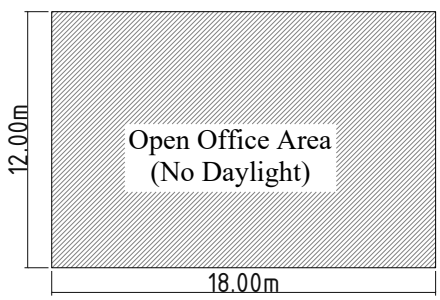


Figure 5.1: Model 01 Plan

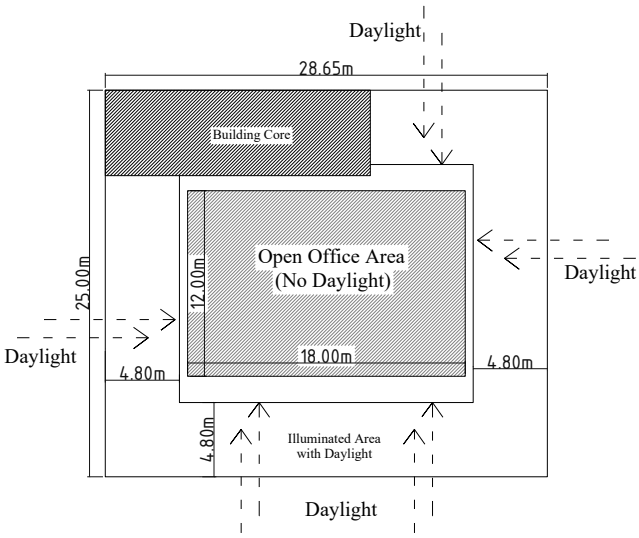


Figure 5.2: Model 02 Plan

In both model there were an illuminance plane with 100 illuminance point at the workplane height (Figure 5.3). Daylight entered into the interior space was measured at the illuminance point. The simulation time was set for 1.00 am to 12.00 am, but as the office hour starts generally at 9.00am and finished at 6.00pm, only the numeric data of these 10 hours have been considered. Commonly it was found that maximum light entered at the middle of the day-that is 12.00pm. For this reason, it has been considered the illuminance of the 100 points of 12.00pm for analysis of every case. There were also two (2) daylight reference point named "Daylighting Reference Point 1" and "Daylighting Reference Point 2" (Figure 5.4). Daylight was measured at both of these points also.

Figure 5.3: Illuminance points (plan)

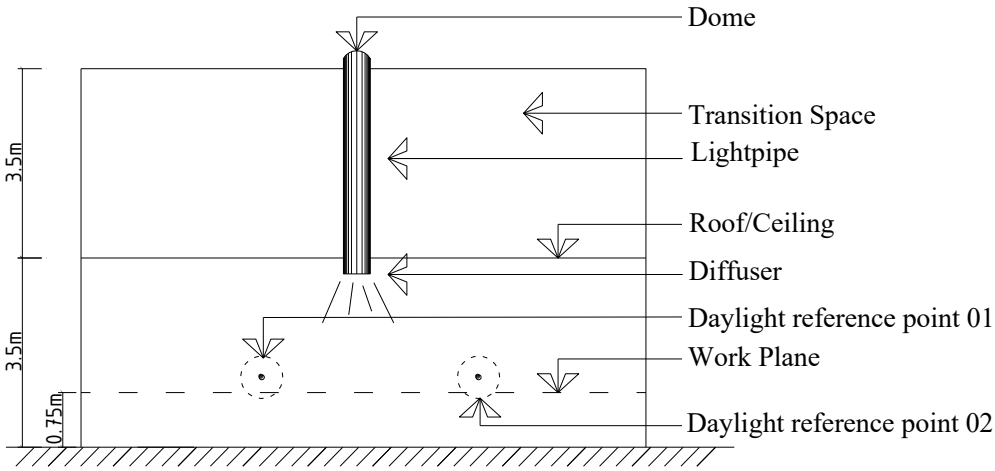


Figure 5.4: Lightpipe and daylight reference points (section)

The simulation results for straight lightpipes have presented in four segments by the variation of variables like 1. Light pipe diameter, 2. Light pipe length, 3. Light pipe number (Model 01) and 4. Lightpipes with the presence or absent of the side window (Model 02). The simulation results of bended lightpipes have presented in three segments

by the variation of variables like 5. Lightpipe length, 6. Lightpipe number (Model 01) and 7. Light pipe with the side window (Model 02). Diameter of Lightpipe starts from 0.25m and ends with 0.5m. Length of the lightpipe was varied according to floor height such as one floor height (3.5m), two floor height (7.0m), three floor height (10.5m) and four floor height (14.0m). Variation of diameter and length were determined from the available varities of lightpipes in market mentioned in the different published journal about lightpipes.

Before these, the other outputs like (i) Illuminance at Daylighting Reference Point 1 and 2, (ii) Tubular daylight Device (TDD) Diffuse Visible Transmittance (Hourly), (iii) TDD Diffuse Solar Transmittance (Hourly), (iv) TDD Pipe Absorbed Solar Radiation Rate [W](Hourly) & (v) TDD Transmitted Solar Radiation Rate [W](Hourly) are discussed separately because these remain almost same for the same light pipe properties (diameter and length).

5.3 Result Analysis of Daylighting Reference Points

(i) Illuminance at Daylighting Reference Point 1 and 2:

Table 5.1: Daylighting Distribution at Illumination Plane

Date/Time	Point 1 Illuminance [lux](Hourly)	Point 2 Illuminance [lux](Hourly)
9:00:00	0.28	0.25
10:00:00	0.41	0.36
11:00:00	5.76	5.00
12:00:00	125.93	109.16
13:00:00	90.21	78.20
14:00:00	2.72	2.36
15:00:00	0.37	0.32
16:00:00	0.26	0.23
17:00:00	0.19	0.16
18:00:00	0.11	0.0965

Daylighting reference point is used for determining the daylighting control sensor location. Table 5.1 show the Illuminance at daylighting reference point 1 and daylighting reference point 2 for one light pipe at different hours of the simulation day (Figure 5.4). From the Figure 5.5 it shows that very small amount of light enters at 9.00 am. It increases continuously till 12.00 pm. At 12.00 pm, it reaches its highest illumination-125.93 lux at point 1 and 109 lux at point 2. At 1.00 pm, it decreases at 90 lux at point 1

and 78 lux at point 2. This is the 2nd highest pick point. After 1.00 pm, it start to decrease and reach at minimum value at 6.00 pm.

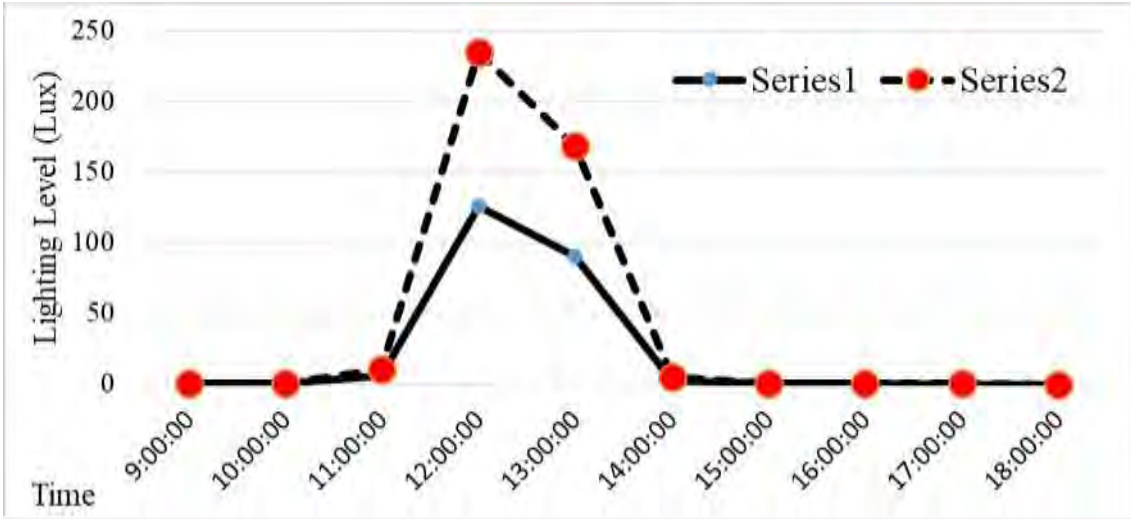


Figure 5.5: Daylighting distribution at illumination plane (Hourly)

(ii) TDD Diffuse Visible Transmittance (Hourly):

Table 5. 2: Different tubular daylighting properties at illumination Plane

Date/ Time	TDD Diffuse Visible Transmittance (Hourly)	TDD Diffuse Solar Transmittance (Hourly)	TDD Pipe Absorbed Solar Radiation Rate [W](Hourly)	TDD Transmitted Solar Radiation Rate [W](Hourly)
9:00:00	0.0061	0.0032	72.0308	0.0429
10:00:00	0.0089	0.0034	91.3874	0.0482
11:00:00	0.0141	0.0073	104.2848	0.1056
12:00:00	0.0204	0.1910	107.4998	2.7908
13:00:00	0.0189	0.0884	108.1807	1.2912
14:00:00	0.0124	0.0041	101.5148	0.0592
15:00:00	0.0080	0.0035	86.7931	0.0493
16:00:00	0.0056	0.0032	65.8732	0.0422
17:00:00	0.0043	0.0036	40.1981	0.0413
18:00:00	0.0038	0.0044	14.3196	0.0321

Table 5.2 show the TDD Diffuse Visible Transmittance for one light pipe at different hours of the simulation day. From the Figure 5.6 it shows that the value was 0.0061 at 9.00 am. It increases continuously till 12.00 pm. At 12.00 pm, it reaches its highest level (0.0204). At 1.00 pm, it decreases at the 2nd highest pick point. After 1.00 pm, it start to decrease and reach at minimum value at 6.00 pm.

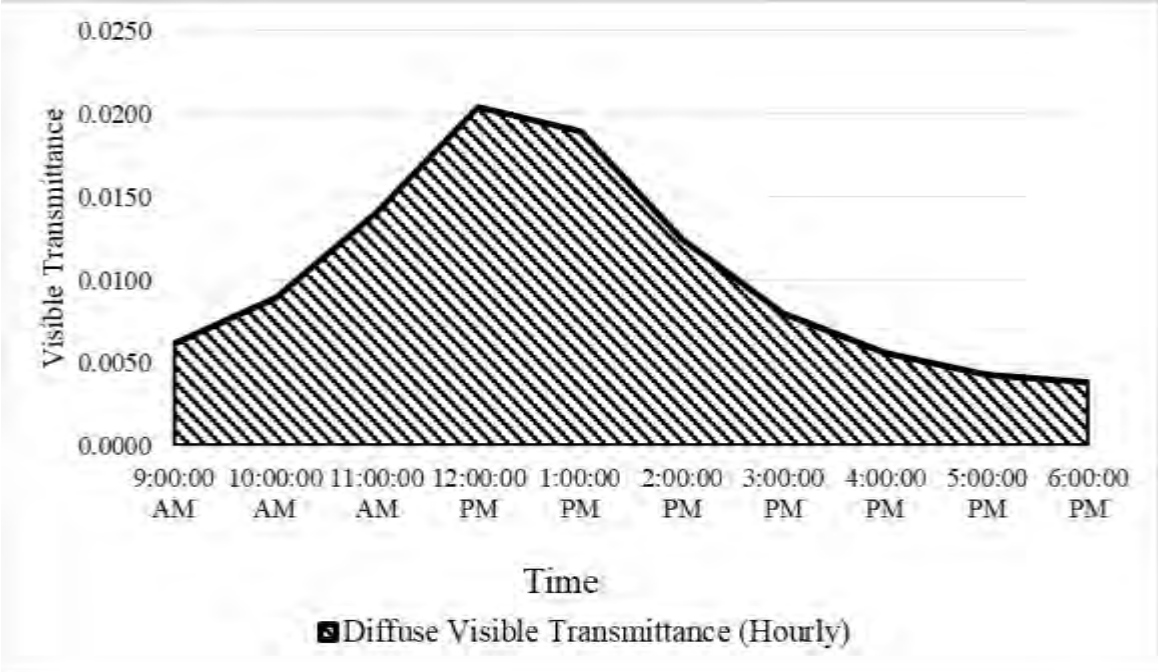


Figure 5.6: Diffuse visible transmittance (hourly)

(iii) TDD Diffuse Solar Transmittance (Hourly)

Table 5.2 show the TDD Diffuse Solar Transmittance for one light pipe at different hours of the simulation day. From the Figure 5.7 it shows that the value was minimum before 11.00 am and after 2.00 pm. It was 0.0032 at 9.00 am. At 12.00 pm, it reaches its highest level. At 1.00 pm, it decreases at the 2nd highest pick point. After 2.00 pm, it start to decrease and from 2.00 pm to 6.00 pm the value was minimum.

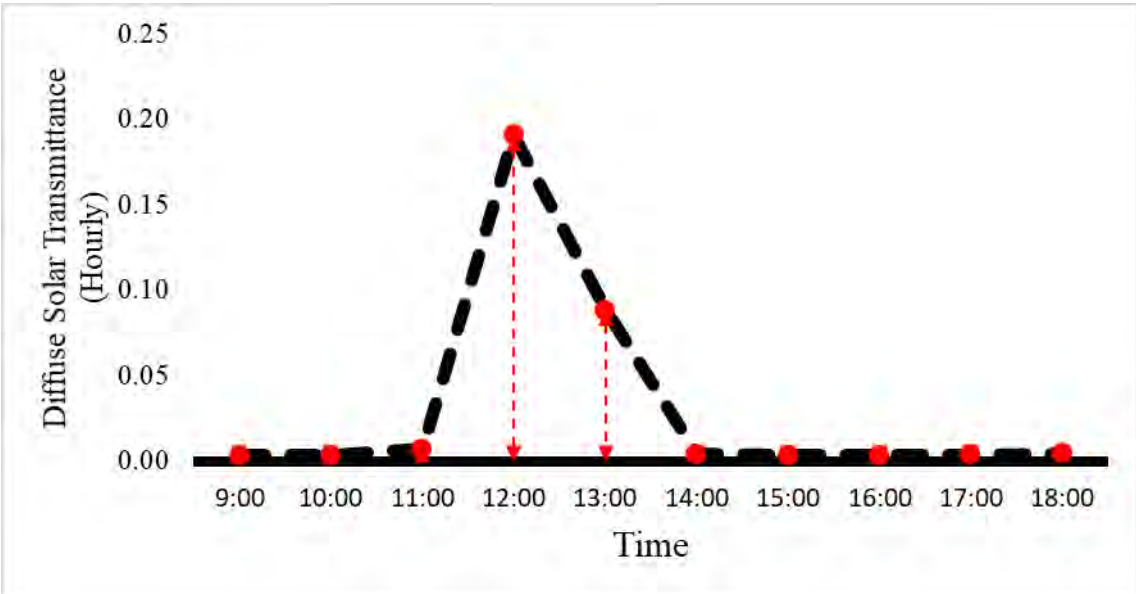


Figure 5.7: Diffuse solar transmittance (hourly)

(iv) TDD Pipe Absorbed Solar Radiation Rate [W] (Hourly)

Table 5.2 show the TDD Pipe Absorbed Solar Radiation Rate for one light pipe at different hours of the simulation day. From the Figure 5.8 it shows that the value was 72.03 W at 9.00 am. It increases continuously till 1.00 pm. At 1.00 pm, it reaches its highest level (108.18 W). At 1.00 pm, it decreases at the 2nd highest pick point. After 1.00 pm, it start to decrease and reach at minimum value at 6.00 pm (14.32 W).

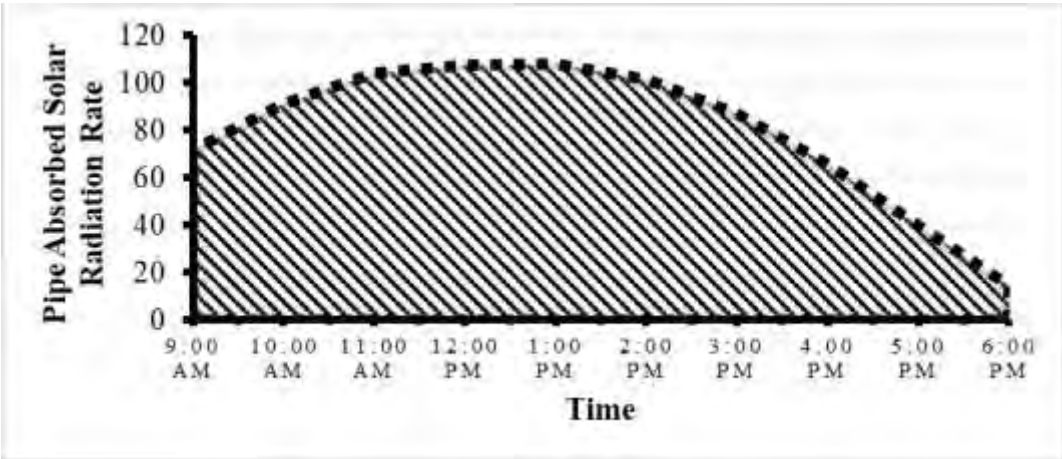


Figure 5.8: Pipe absorbed solar radiation rate [W](hourly)

(v) TDD Transmitted Solar Radiation Rate [W](Hourly)

Table 5.2 show the TDD Transmitted Solar Radiation Rate for one light pipe at different hours of the simulation day. From the Figure 5.9 it shows that the value was minimum before 11.00 am and after 2.00 pm. It was 0.0429 W at 9.00 am. At 12.00 pm, it reaches its highest level (2.79W). At 1.00 pm, it decreases at the 2nd highest pick point (1.29W). After 2.00 pm, it start to decrease and from 2.00 pm to 6.00 pm the value was minimum.

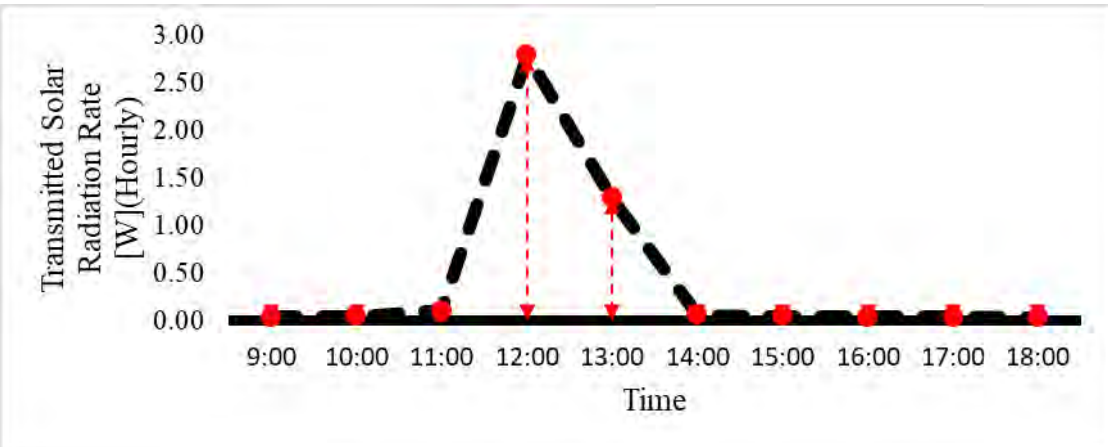


Figure 5.9: Transmitted solar radiation rate [W](hourly)

5.4 Result Analysis of Daylighting by Straight Lightpipes

Index:

5.4.1 Lighting Simulation with Different Diameter of Lightpipe				
Case No.	**Pipe Diameter**	**Pipe Length**	**Number of Pipe**	**Presence of Window**
01(a)	0.25m	3.5m	01	No.
01(b)	0.30m			
01(c)	0.35m			
01(d)	0.40m			
01(e)	0.45m			
01(f)	0.50m			
5.4.2 Lighting Simulation with Different Length of Lightpipe				
Case No.	**Pipe Diameter**	**Pipe Length**	**Number of Pipe**	**Presence of Window**
02(a)	0.50m	3.5m	01	No.
02(b)		7.0m		
02(c)		10.5m		
02(d)		14.0m		
5.4.3 Lighting Simulation with Different No. of Lightpipe				
Case No.	**Pipe Diameter**	**Pipe Length**	**Number of Pipe**	**Presence of Window**
03(a)	0.50m	3.5m	01	No.
03(b)			02	
03(c)			03	
03(d)			06	
03(e)			09	
5.4.4 Lighting Simulation with Lightpipe and Window				
Case No.	**Pipe Diameter**	**Pipe Length**	**Number of Pipe**	**Presence of Window**
04(a)	0.50m	3.5m	03	No.
04(b)	0.50m	3.5m	03	Yes
04(c)	No Pipe			Yes

5.4.1 Lighting Simulation with Different Diameter of Lightpipes

I. Case 01(a): Pipe Diameter 0.25m

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model (Table 5.3). There was one (1) light pipe which diameter was 0.25m at the center of the area with a transition space (height 3.5m-one floor) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.10).

Table 5.3: Simulation model parameters for case 01(a)

Case	**Pipe Diameter**	Pipe Length	Number of Pipe	Presence of Window
01(a)	**0.25m**	3.5m	01	No.

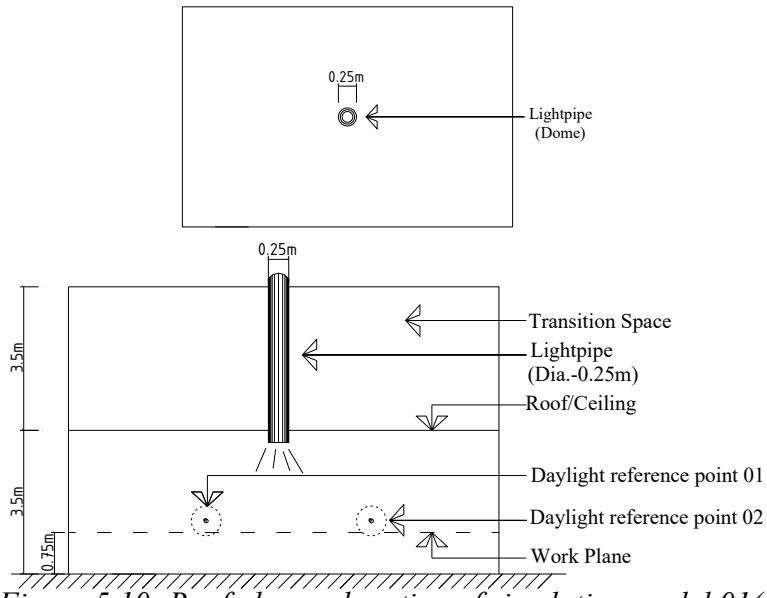


Figure 5.10: Roof plan and section of simulation model 01(a)

Table 5.4: Daylighting distribution at illumination plane for case 01(a)

Point	A	B	C	D	E	F	G	H	I	J
a	3	3	3	3	3	3	3	3	3	3
b	4	4	6	10	15	15	11	7	5	4
c	4	5	8	17	30	32	19	9	5	4
d	4	6	11	28	68	75	33	13	6	4
e	4	6	13	40	130	149	49	15	7	4
f	4	6	13	42	142	165	52	16	7	4
g	4	6	12	31	83	93	38	14	6	4
h	4	5	9	19	38	40	22	10	6	4
i	4	5	7	12	18	18	13	8	5	4
j	3	4	5	7	10	10	8	6	4	3

Note. Color bar indicates the different intensity of illuminance of workplane

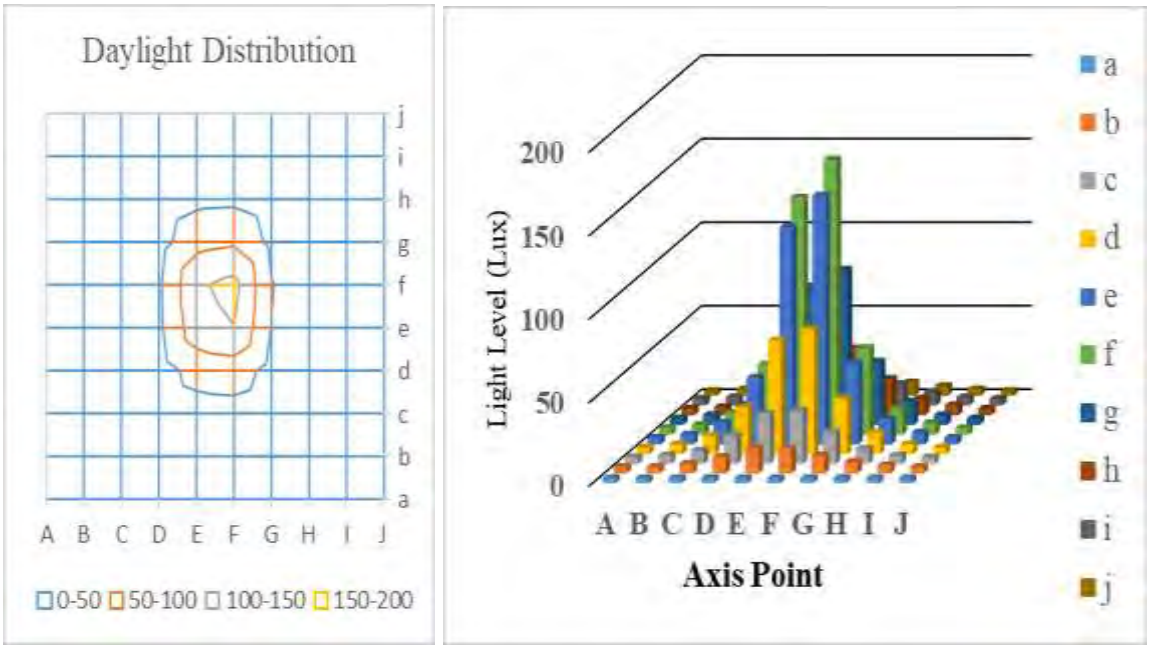


Figure 5.11: Daylighting distribution at illumination plane for case 01(a)

Table 5.4 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm for the lightpipe of 0.25m diameter. This light was penetrate by the light pipe installed at the ceiling level. Figure 5.11 show that this daylight only illuminate the center of the space and constantly decrease at the periphery area. The brightest level of light 165 lux was found at the center of the space and the light found at the periphery area was very low (less than 50 lux). The average light was only 19.6 lux and the standard deviation was 31.4 lux (Figure 5.12). The median was 7 lux. The uniformity ratio below the light at workplane was 0.37.

LIGHT Level	Value (Lux)
Min	3
Max	165
Avg	19.6
Median	7
SD	31.4

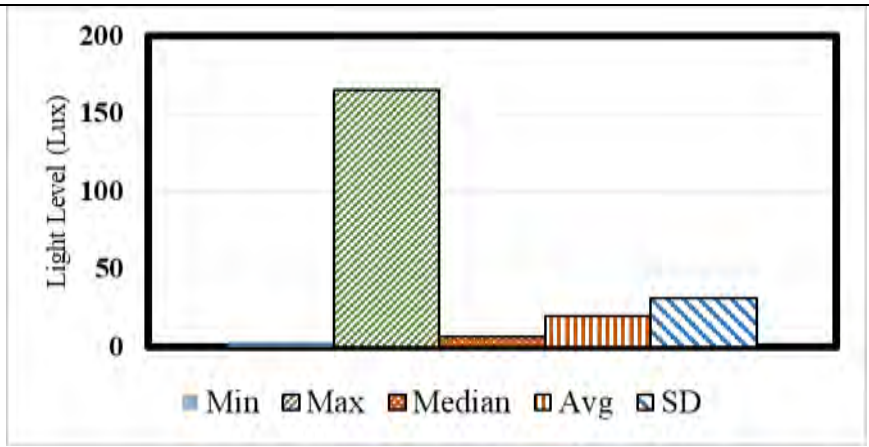


Figure 5.12: Daylighting distribution data analysis for case 01(a)

While considering only the illuminance level at the central part-f (Table 5.4), it has generated a curve line which indicate that the highest light found at the center of the space

(Figure 5.13) and the lighting was very poor near the edge of the simulated area as installed lightpipe with 0.25m diameter can't penetrate more light away from the center.

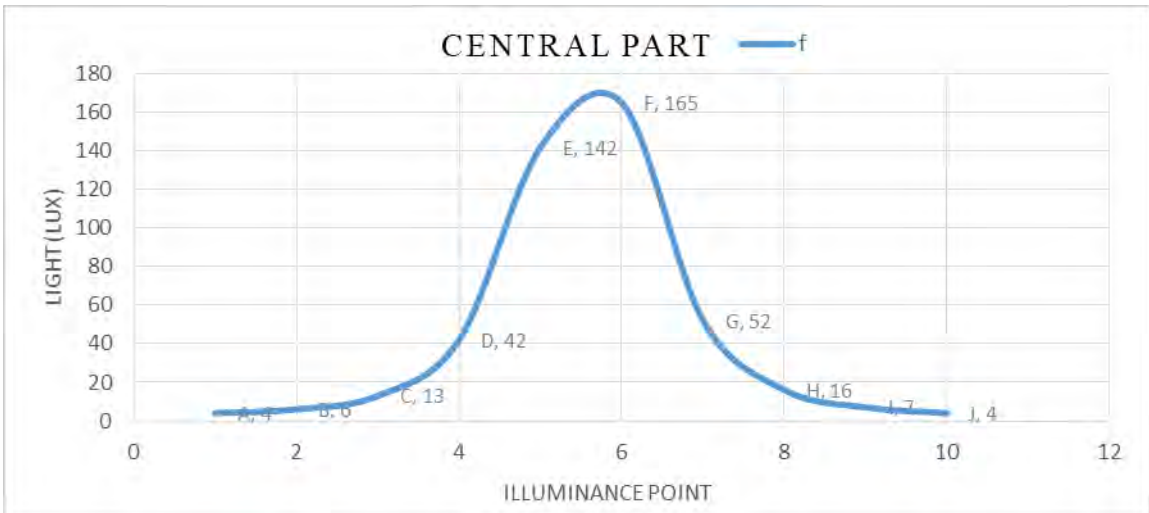


Figure 5.13: Daylighting distribution at central part (f) for case 01(a)

II. Case 01(b): Pipe Diameter 0.30m

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model (Table 5.5). There was one (1) light pipe which diameter was 0.30m at the center of the area with a transition space (height 3.5m-one floor) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.14).

Table 5.5: Simulation model parameters for case 01(b)

Case	**Pipe Diameter**	Pipe Length	Number of Pipe	Presence of Window
01(b)	**0.30m**	3.5m	01	No.

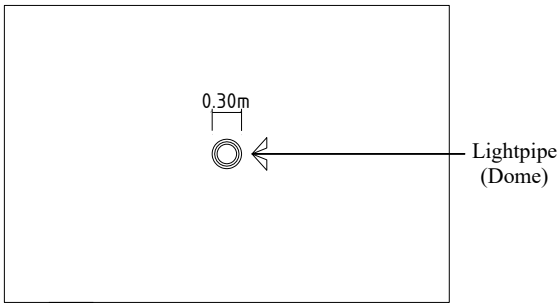


Figure 5.14(a): Roof plan of simulation model 01(b)

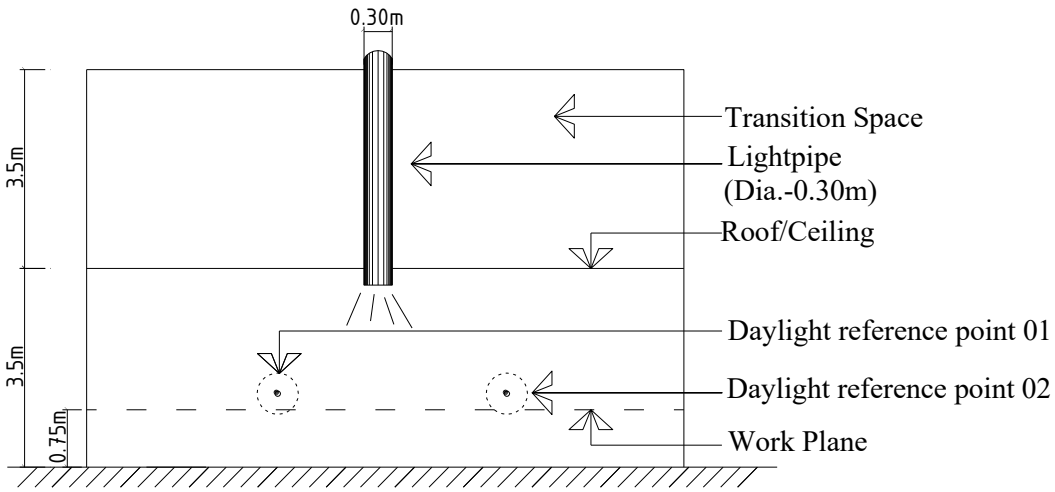


Figure 5.14(b): Section of simulation model 01(b)

Table 5.6: Daylighting distribution at illumination plane for case 01(b)

Point	A	B	C	D	E	F	G	H	I	J
a	3	3	3	3	3	3	3	3	3	3
b	4	5	7	10	15	16	11	7	5	4
c	4	5	9	17	31	33	19	10	6	4
d	4	6	11	28	69	76	34	13	6	4
e	4	6	13	40	132	151	50	16	7	4
f	4	6	13	42	144	167	53	16	7	4
g	4	6	12	32	84	94	38	14	7	4
h	4	5	9	20	38	41	22	10	6	4
i	4	5	7	12	18	19	13	8	5	4
j	3	4	5	8	10	10	8	6	4	4

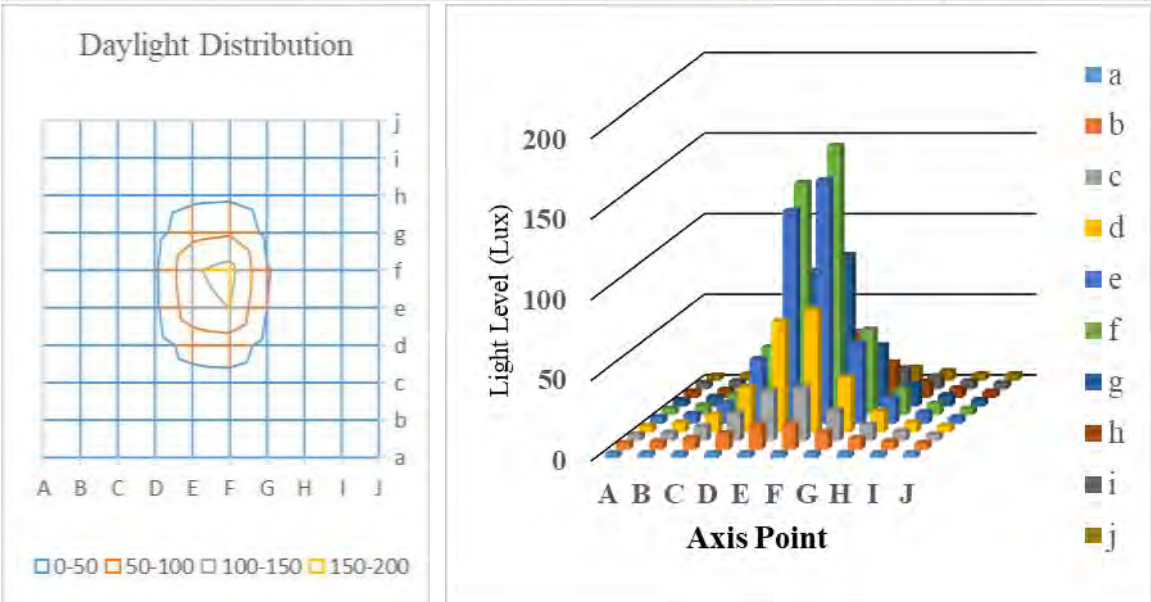


Figure 5.15: Daylighting distribution at illumination plane for case 01(b)

Table 5.6 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the light pipe installed at the ceiling level. Figure

5.15 show that this daylight only illuminate the center of the space and constantly decrease at the periphery area. The brightest level of light 167 lux found at the center of the space and the light found at the periphery area was very low (less than 50 Lux). The average light was only 19.9 and the standard deviation was 31.9 lux (Figure 5.16). The median was 7 Lux. The median was 7 lux. The uniformity ratio below the light at workplane was 0.36.

LIGHT Level(Lux)	Value
Min	3
Max	167
Avg	19.9
Median	7
SD	31.9

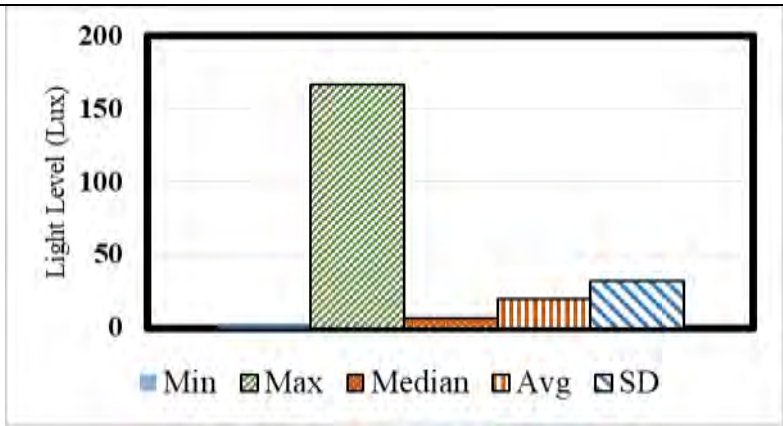


Figure 5.16: Daylighting distribution data analysis for case 01(b)

While considering only the illuminance level at the central part-f (Table 5.6), it has generated a curve line which indicate that the highest light found at the center of the space (Figure 5.17) and the lighting was very poor near the edge of the simulated area as installed lightpipe with 0.30m diameter can't penetrate more light away from the center.

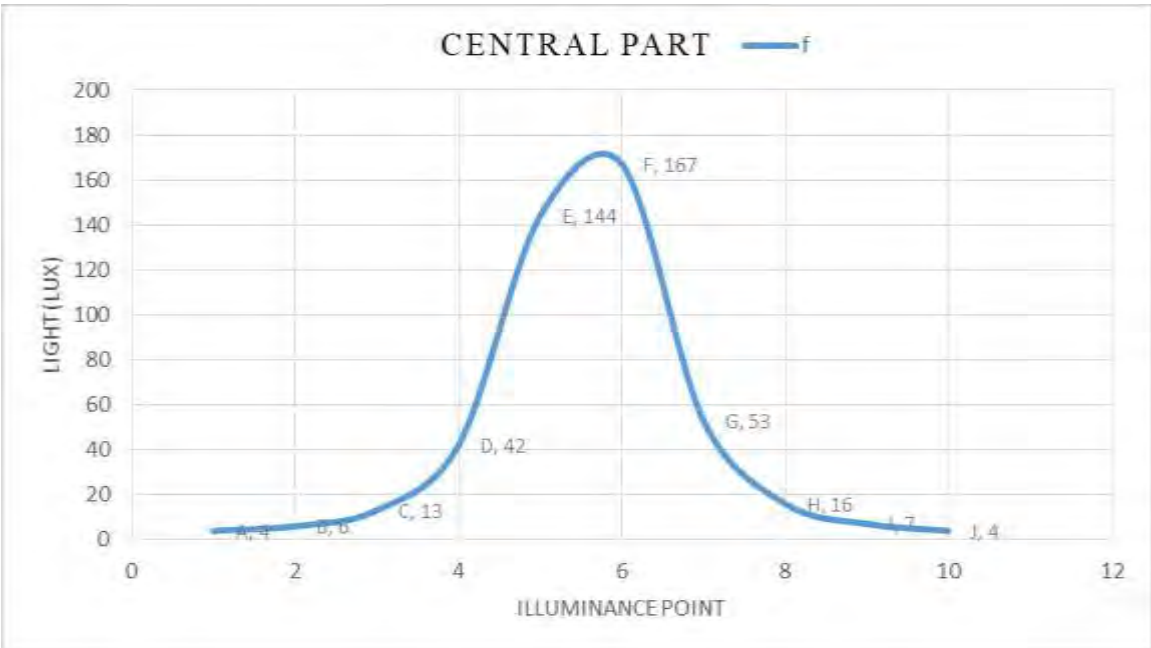


Figure 5.17: Daylighting distribution at central part (f) for case 01(b)

III. Case 01(c): Pipe Diameter 0.35m

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model (Table 5.7). There was one (1) light pipe which diameter was 0.35m at the center of the area with a transition space (height 3.5m-one floor) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.18).

Table 5.7: Simulation model parameters for case 01(c)

Case	**Pipe Diameter**	Pipe Length	Number of Pipe	Presence of Window
01(c)	**0.35m**	3.5m	01	No.

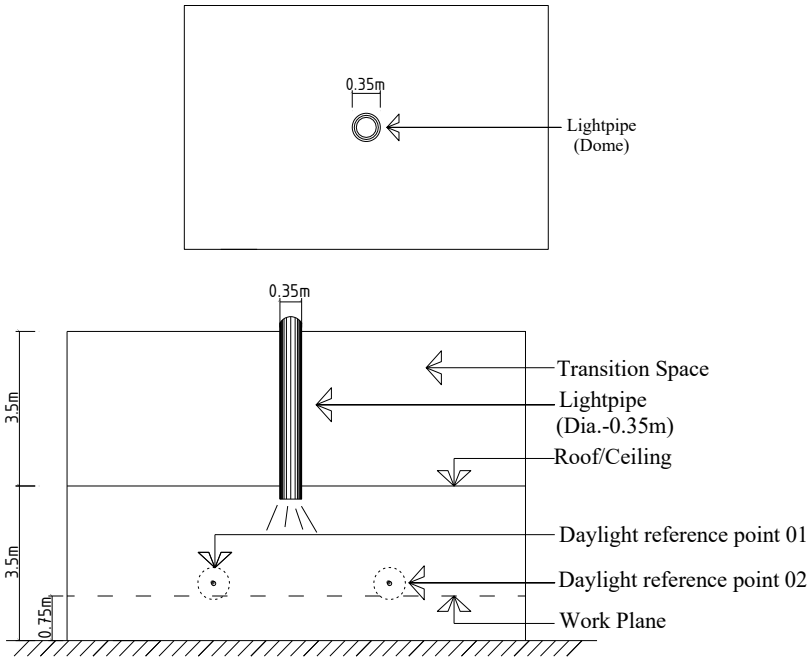


Figure 5.18: Roof plan and section of simulation 01(c)

Table 5.8: Daylighting distribution at illumination plane for case 01(c)

Point	A	B	C	D	E	F	G	H	I	J
a	3	3	3	3	3	3	3	3	3	3
b	4	5	7	10	15	16	11	7	5	4
c	4	5	9	17	31	33	20	10	6	4
d	4	6	11	29	70	77	34	13	6	4
e	4	6	13	41	133	153	51	16	7	4
f	4	6	14	43	146	169	54	16	7	4
g	4	6	12	32	85	95	39	14	7	4
h	4	5	9	20	39	41	23	11	6	4
i	4	5	7	12	18	19	13	8	5	4
j	3	4	5	8	10	10	8	6	4	4

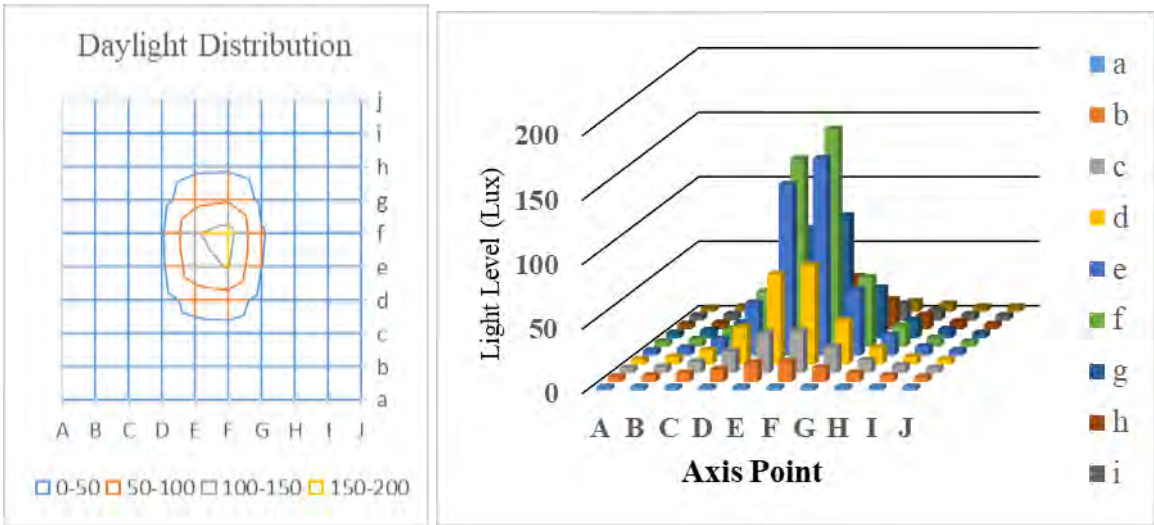


Figure 5.19: Daylighting distribution at illumination plane for case 01(c)

Table 5.8 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the light pipe installed at the ceiling level. Figure 5.19 show that this daylight only illuminate the center of the space and constantly decrease at the periphery area. The brightest level of light 169 lux found at the center of the space and the light found at the periphery area was very low (less than 50 lux). The minimum light was only 3 lux. The average light was 20.2 lux and the standard deviation was 32.3 lux (Figure 5.20). The median was 7 lux. The uniformity ratio below the light at workplane was 0.37.

LIGHT Level(Lux)	Value
Min	3
Max	169
Avg	20.2
Median	7
SD	32.3

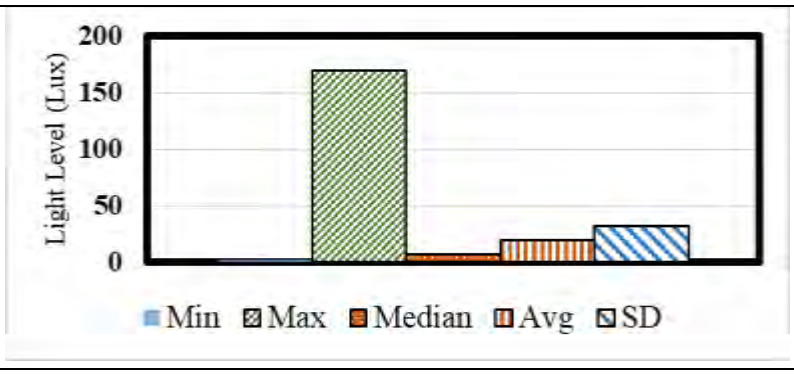


Figure 5.20: Daylighting distribution data analysis for case 01(c)

While considering only the illuminance level at the central part-f (Table 5.8), it has generated a curve line which indicate that the highest light found at the center of the space (Figure 5.21) and the lighting was very poor near the edge of the simulated area as installed lightpipe with 0.35m diameter can't penetrate more light away from the center.

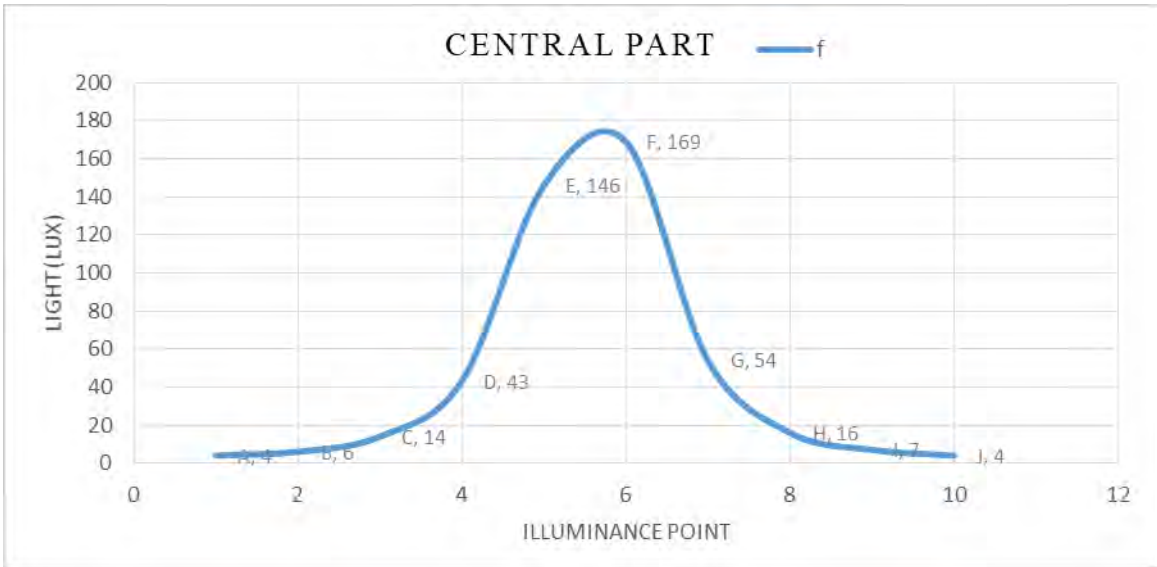


Figure 5.21: Daylighting distribution at central part (f) for case 01(c)

IV. Case 01(d): Pipe Diameter 0.40m

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model (Table 5.9). There was one (1) light pipe which diameter was 0.40m at the center of the area with a transition space (height 3.5m-one floor) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.22).

Table 5.9: Simulation model parameters for case 01(d)

Case	**Pipe Diameter**	Pipe Length	Number of Pipe	Presence of Window
01(d)	**0.40m**	3.5m	01	No.

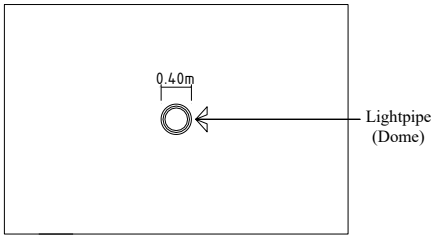


Figure 5.22(a): Roof plan of simulation model 01(d)

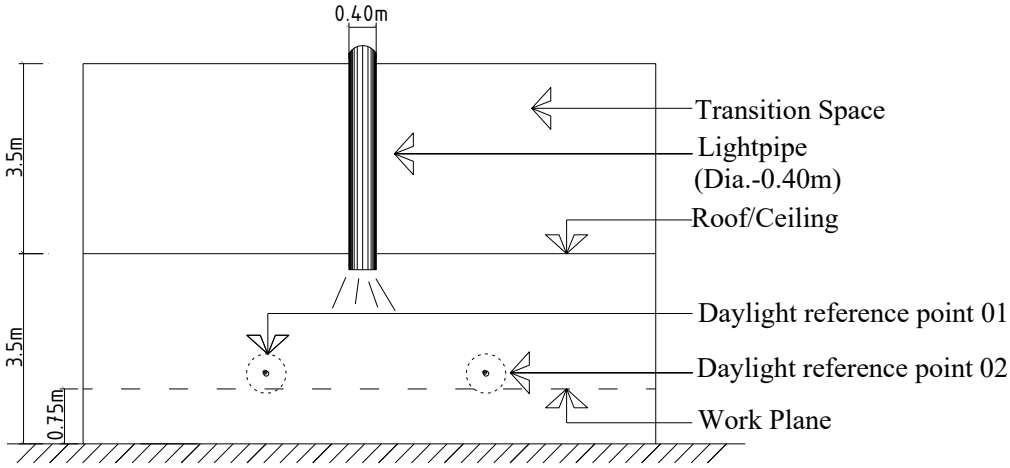


Figure 5.22(b): Section of simulation model 01(d)

Table 5.10: Daylighting distribution at illumination plane for case 01(d)

Point	A	B	C	D	E	F	G	H	I	J
a	3	3	3	3	3	3	3	3	3	3
b	4	5	7	11	15	16	12	7	5	4
c	4	5	9	18	32	34	20	10	6	4
d	4	6	12	29	71	79	35	13	7	4
e	4	6	14	42	136	156	52	16	7	5
f	4	7	14	44	149	173	55	17	7	5
g	4	6	12	33	87	97	39	14	7	4
h	4	6	10	20	39	42	23	11	6	4
i	4	5	7	12	18	19	13	8	5	4
j	4	4	6	8	10	10	8	6	4	4

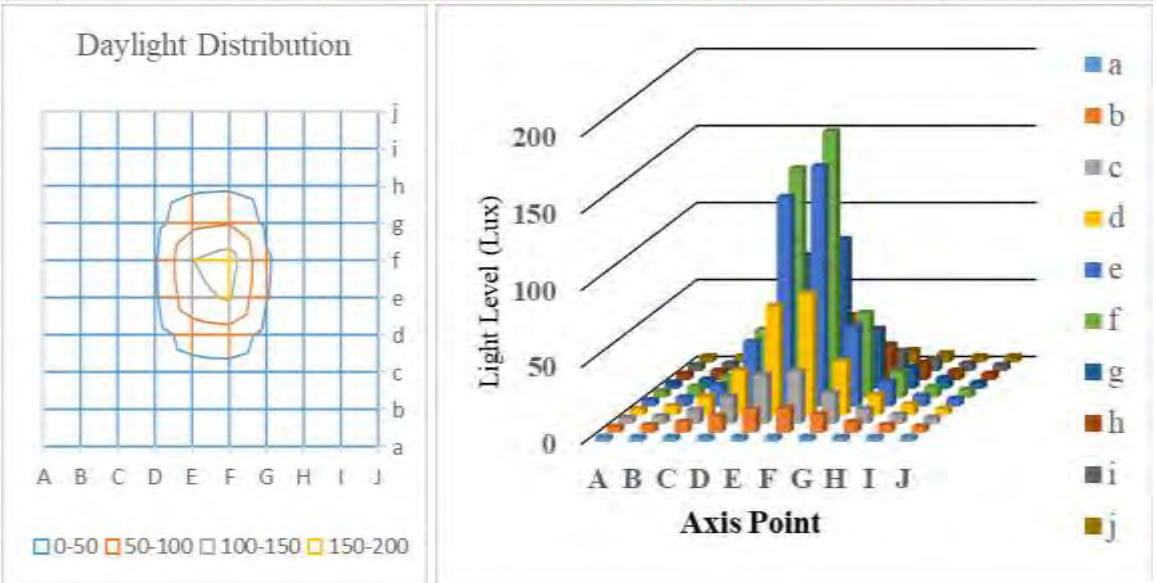


Figure 5.23: Daylighting distribution at illumination plane for case 01(d)

Table 5.10 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the light pipe installed at the ceiling level. Figure

5.23 show that this daylight only illuminate the center of the space and constantly decrease at the periphery area. The brightest level of light 173 lux found at the center of the space and the light found at the periphery area was very low (less than 50 lux). The minimum light was only 3 lux. The average light was 20.6 lux and the standard deviation was 32.9 lux (Figure 5.24). The median was 7 lux. The uniformity ratio below the light at workplane was 0.36.

LIGHT Level (Lux)	Value
Min	3
Max	173
Avg	20.6
Median	7
SD	32.9

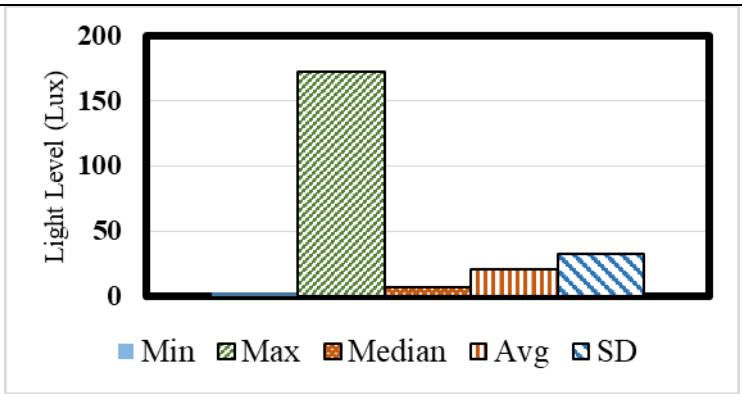


Figure 5.24: Daylighting distribution data analysis for case 01(d)

While considering only the illuminance level at the central part-f (Table 5.10), it has generated a curve line which indicate that the highest light found at the center of the space (Figure 5.25) and the lighting was very poor near the edge of the simulated area as installed lightpipe with 0.40m diameter can't penetrate more light away from the center.

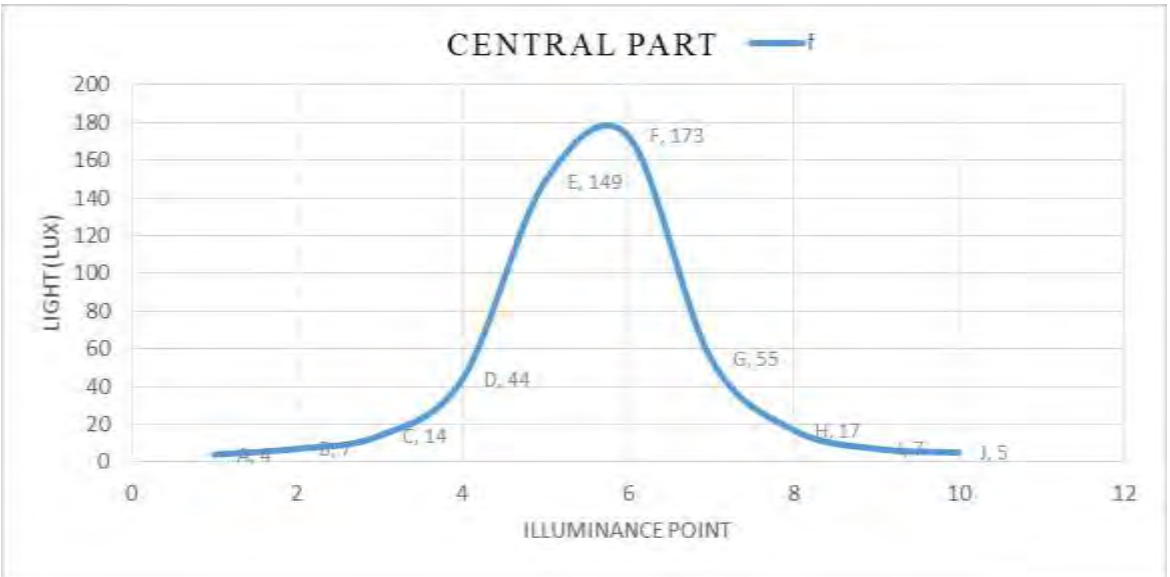


Figure 5.25: Daylighting distribution at central part (f) for case 01(d)

V. Case 01(e): Pipe Diameter 0.45m

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model (Table 5.11). There was one (1) light pipe which diameter was 0.45m at the center of the area with a transition space (height 3.5m-one floor) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.26).

Table 5.11: Simulation model parameters for case 01(e)

Case	**Pipe Diameter**	Pipe Length	Number of Pipe	Presence of Window
01(e)	**0.45m**	3.5m	01	No.

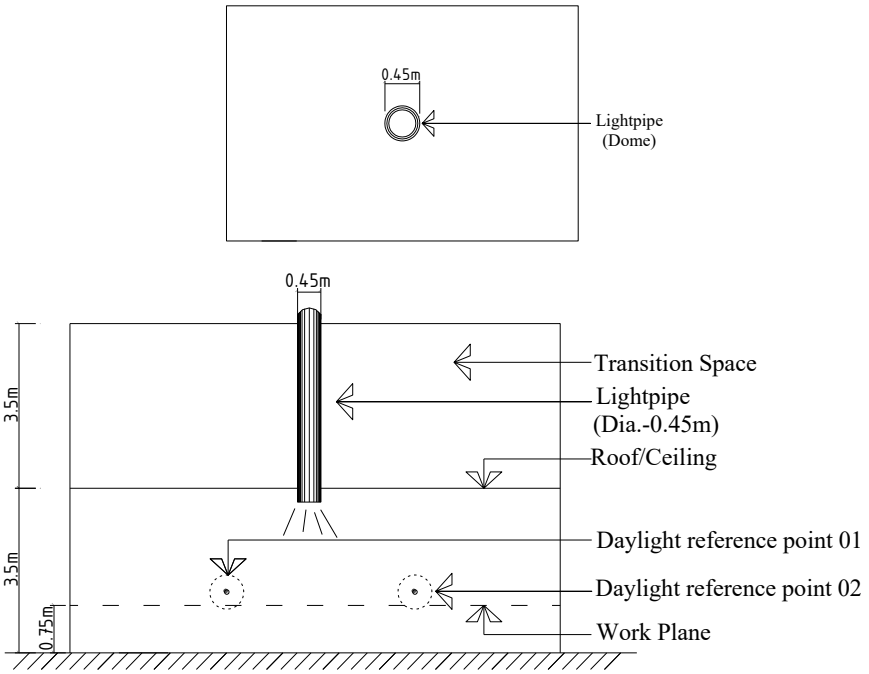


Figure 5.26: Roof plan and section of simulation model for case 01(e)

Table 5.12: Daylighting distribution at illumination plane for case 01(e)

Point	A	B	C	D	E	F	G	H	I	J
a	3	3	3	3	3	3	3	3	3	3
b	4	5	7	11	16	16	12	7	5	4
c	4	5	9	18	33	35	20	10	6	4
d	4	6	12	30	73	80	35	14	7	4
e	4	7	14	42	139	159	53	16	7	5
f	4	7	14	44	152	176	56	17	7	5
g	4	6	12	33	89	99	40	14	7	4
h	4	6	10	21	40	43	24	11	6	4
i	4	5	7	12	19	20	13	8	5	4
j	4	4	6	8	10	10	8	6	5	4

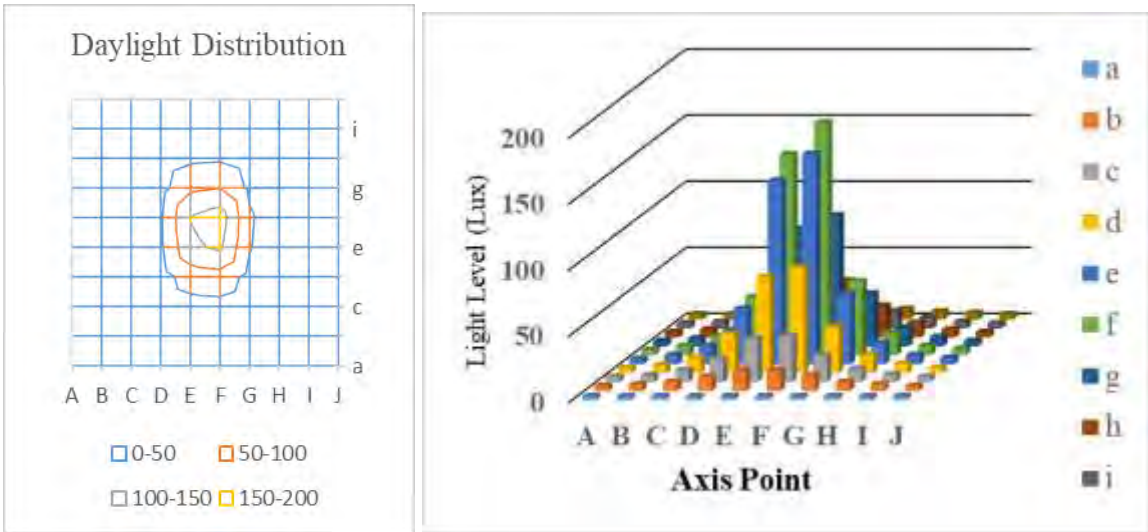


Figure 5.27: Daylighting distribution at illumination plane for case 01(e)

Table 5.12 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the light pipe installed at the ceiling level. Figure 5.27 show that this daylight only illuminate the center of the space and constantly decrease at the periphery area. The brightest level of light 176 lux found at the center of the space and the light found at the periphery area was very low (less than 50 lux). The minimum light was only 3 lux. The average light was 20.9 lux and the standard deviation was 33.6 lux (Figure 5.28). The median was 7 lux. The uniformity ratio below the light at workplane was 0.37.

LIGHT Level(Lux)	**Value**
Min	3
Max	176
Avg	20.9
Median	7
SD	33.6

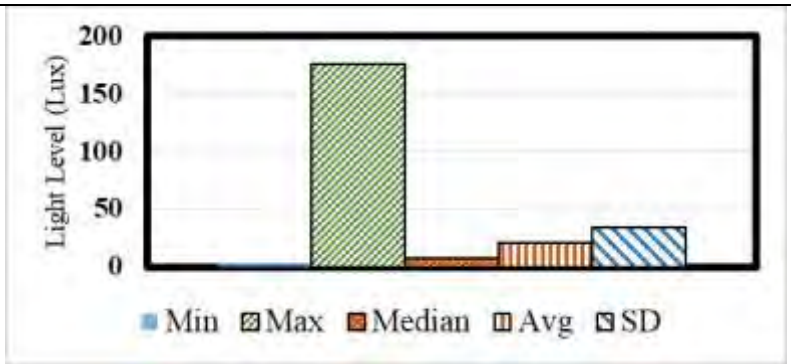


Figure 5.28: Daylighting distribution data analysis for case 01(e)

While considering only the illuminance level at the central part-f (Table 5.12), it has generated a curve line which indicate that the highest light found at the center of the space (Figure 5.29) and the lighting was very poor near the edge of the simulated area as installed lightpipe with 0.45m diameter can't penetrate more light away from the center.

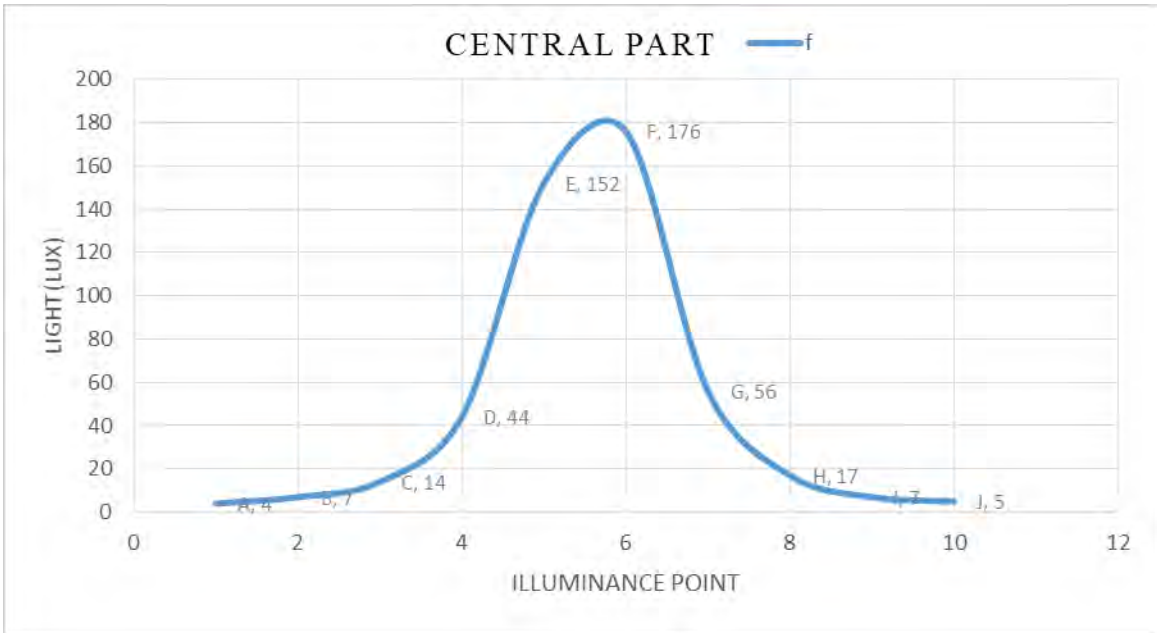


Figure 5.29: Daylighting distribution at central part (f) for case 01(e)

VI. Case 01(f): Pipe Diameter 0.50m

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model (Table 5.13). There was one (1) light pipe which diameter was 0.50m at the center of the area with a transition space (height 3.5m-one floor) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.30).

Table 5.13: Simulation model parameters for case 01(e)

Case	**Pipe Diameter**	Pipe Length	Number of Pipe	Presence of Window
01(f)	**0.50m**	3.5m	01	No.

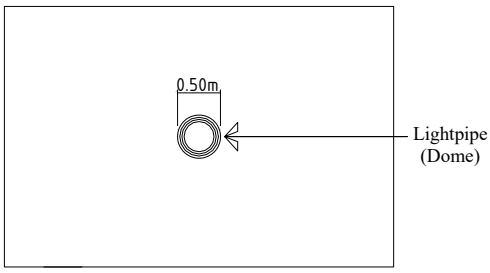


Figure 5.30: Roof plan of simulation model 01(f)

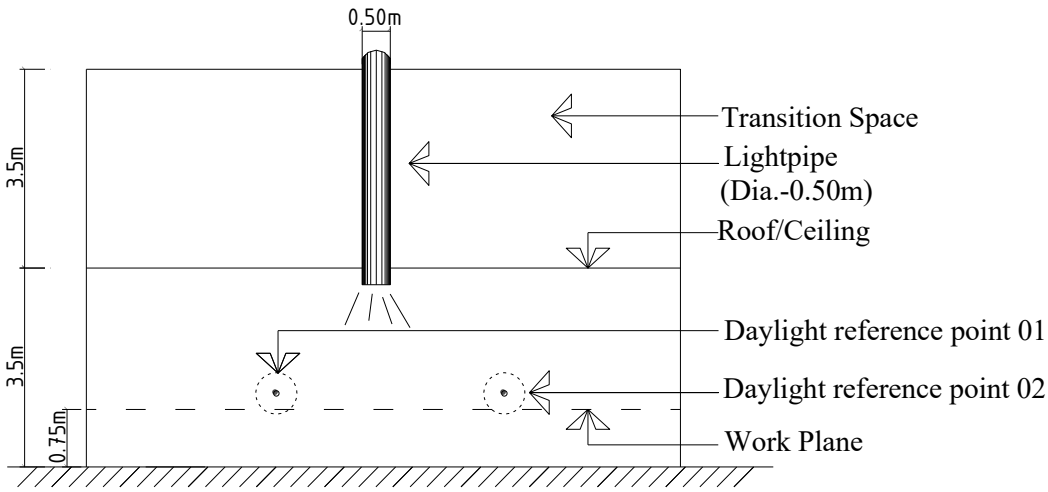


Figure 5.30: Section of simulation model 01(f)

Table 5.14: Daylighting distribution at illumination plane for case 01(f)

Point	A	B	C	D	E	F	G	H	I	J
a	3	3	3	3	3	3	3	3	3	3
b	4	5	7	11	16	17	12	8	5	4
c	4	6	9	18	33	35	21	10	6	4
d	4	6	12	30	74	81	36	14	7	5
e	4	7	14	43	141	162	54	17	7	5
f	4	7	14	45	155	179	57	17	8	5
g	4	6	13	34	90	101	41	15	7	5
h	4	6	10	21	41	44	24	11	6	4
i	4	5	8	13	19	20	14	8	5	4
j	4	4	6	8	10	11	9	6	5	4

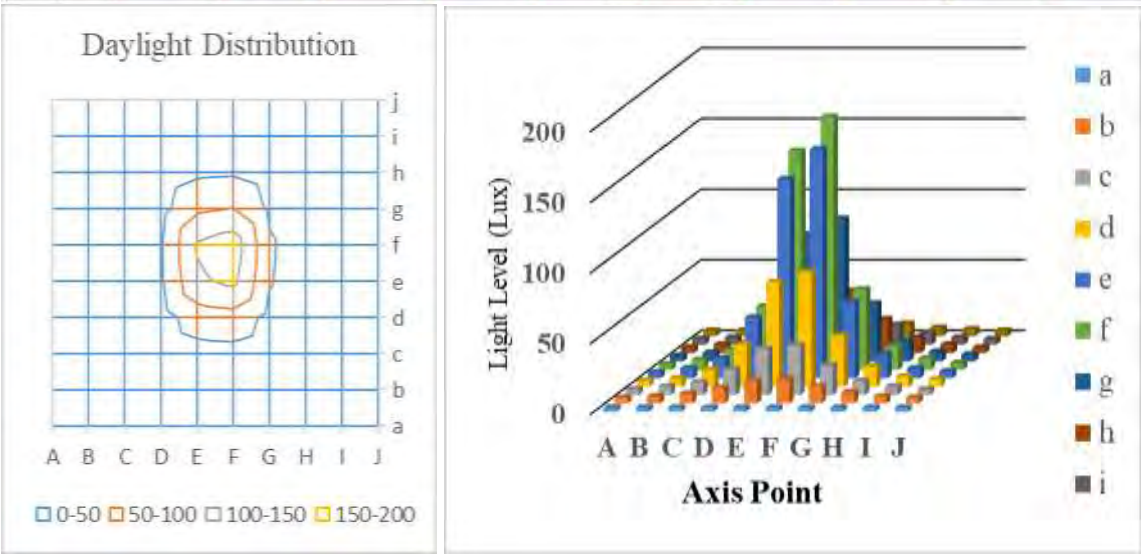


Figure 5.31: Daylighting distribution at illumination plane for case 01(f)

Table 5.14 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the light pipe installed at the ceiling level. Figure

5.31 show that this daylight only illuminate the center of the space and constantly decrease at the periphery area. The brightest level of light 179 lux found at the center of the space and the light found at the periphery area was very low (less than 50 lux). The minimum light was only 3 lux. The average light was 21.3 lux and the standard deviation was 34.2 lux (Figure 5.32). The median was 8 lux. The uniformity ratio below the light at workplane was 0.36.

LIGHT Level(Lux)	Value
Min	3
Max	179
Avg	21.3
Median	8
SD	34.2

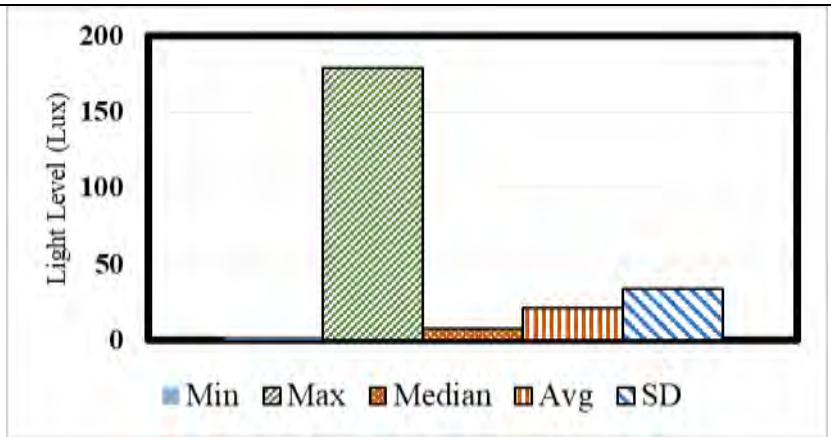


Figure 5.32: Daylighting distribution data analysis for case 01(f)

While considering only the illuminance level at the central part-f (Table 5.14), it has generated a curve line which indicate that the highest light found at the center of the space (Figure 5.33) and the lighting was very poor near the edge of the simulated area as installed lightpipe with 0.50m diameter can't penetrate more light away from the center.

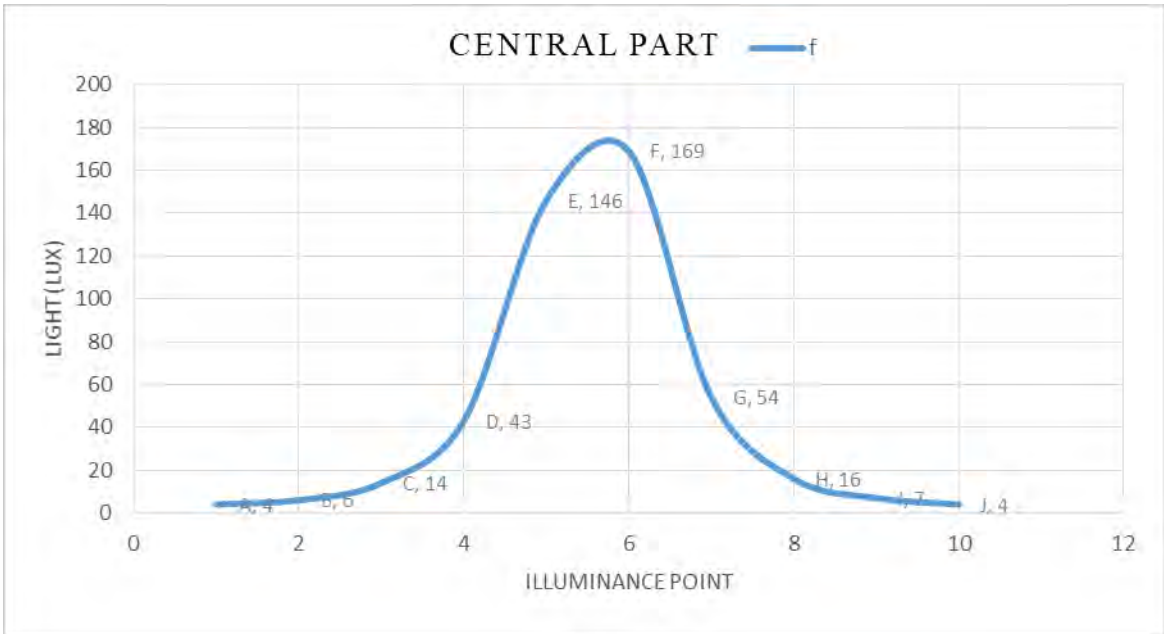


Figure 5.33: Daylighting distribution at central part (f) for case 01(f)

VII. Comparative Analysis

Table 5.15 show the lighting level at the central part (f) of the illuminance plane for every variation for **different diameter** of light pipes with **Model 01**(The deep part of the office floor). From these data, it is observed that the difference of amount of daylight entered by lightpipe of different diameters are very minimum. Daylight entered into the office space at the same ratio by the time (hour) and reach at the maximum level at 12.00 PM. After 01.00 PM, it start to decrease and reach at the minimum level at the end of the office time (06.00 PM) (Figure 5.34). It is also observed that penetration of light increases with the increasing diameters of lightpipe. The maximum light found with the lightpipe of 0.50m diameter as well as minimum light found with the lightpipe of 0.25m diameter. The **uniformity ratio** below the light at workplane varied from 0.36 to 0.37.

Table 5.15: Daylighting distribution at central part (f) of illumination plane for lightpipe of different diameter

Diameter	A	B	C	D	E	F	G	H	I	J
0.25 m	4	6	13	42	142	165	52	16	7	4
0.30 m	4	6	13	42	144	167	53	16	7	4
0.35 m	4	6	14	43	146	169	54	16	7	4
0.40 m	4	7	14	44	149	173	55	17	7	5
0.45 m	4	7	14	44	152	176	56	17	7	5
0.50 m	4	7	14	45	155	179	57	17	8	5

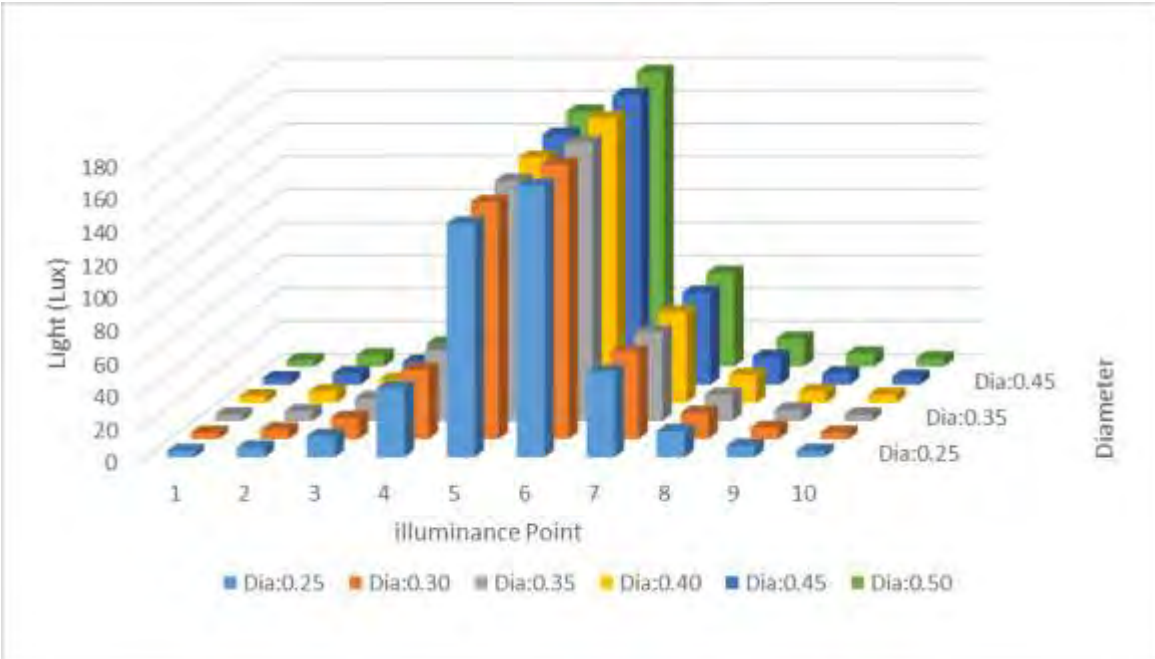


Figure 5.34: Daylighting variation for different diameter of lightpipes

5.4.2 Lighting Simulation with Different Length of Lightpipes

I. Case 02(a): Pipe Length 3.5m

This model simulation criteria and results were similar to the case 01(f) –Page 113.

II. Case 02(b): Pipe Length 7.0m

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model (Table 5.16). There was one (1) light pipe which diameter was 0.50m at the center of the area with a transition space (height of two floor-7.0m) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.35).

Table 5.16: Simulation model parameters for case 02(b)

Case	Pipe Diameter	**Pipe Length**	Number of Pipe	Presence of Window
02(b)	0.50m	**7.0m**	01	No

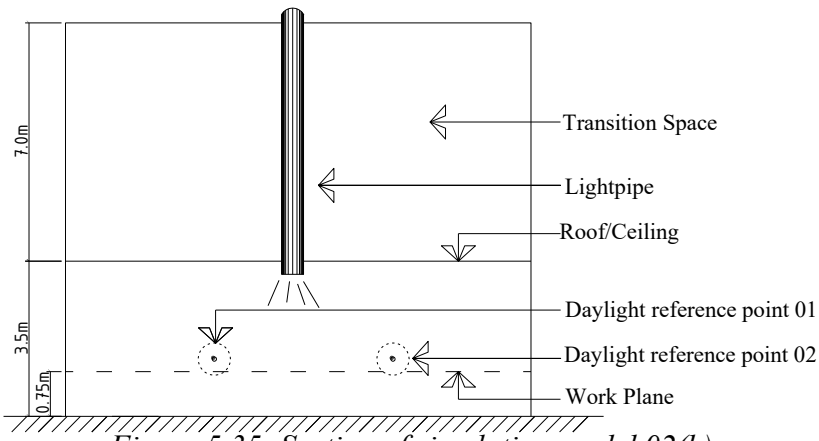


Figure 5.35: Section of simulation model 02(b)

Table 5.17: Daylighting distribution at illumination plane for case 02(b)

Point	A	B	C	D	E	F	G	H	I	J
a	3	3	3	3	3	3	3	3	3	3
b	3	4	6	10	15	15	11	7	5	4
c	4	5	8	17	30	32	19	9	5	4
d	4	6	11	27	67	74	33	13	6	4
e	4	6	13	39	128	147	49	15	7	4
f	4	6	13	41	140	162	51	16	7	4
g	4	6	11	31	82	91	37	13	6	4
h	4	5	9	19	37	40	22	10	6	4
i	4	5	7	11	17	18	12	7	5	4
j	3	4	5	7	9	10	8	6	4	3

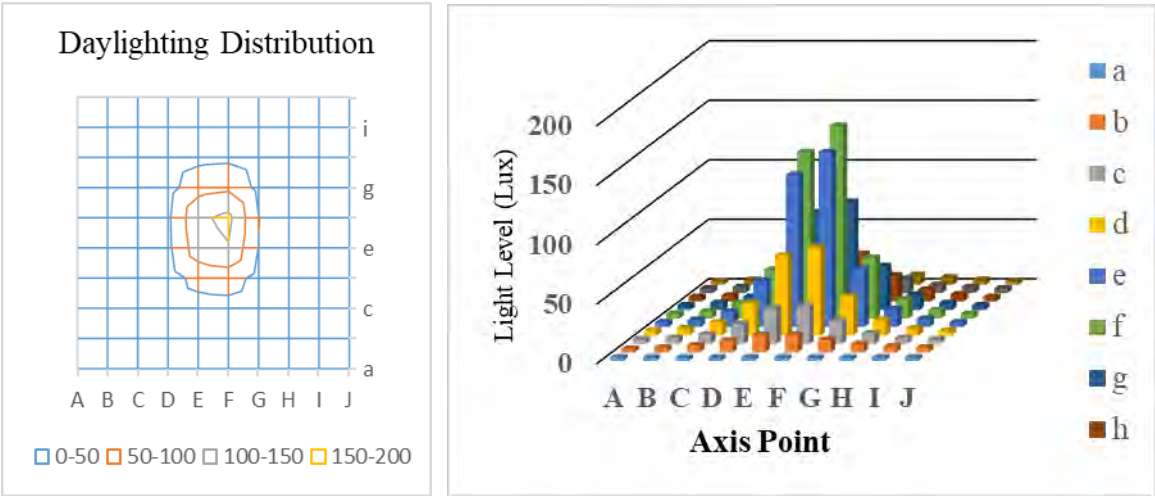


Figure 5.36: Daylighting distribution at illumination plane for case 02(b)

Table 5.17 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light penetrate by the light pipe installed at the ceiling level. Figure 5.36 show that this daylight only illuminate the center of the space and constantly decrease at the periphery area. The brightest level of light 162 lux found at the center of the space and the light found at the periphery area was very low (less than 50 lux). The minimum light was only 3 lux. The average light was 19.3 lux and the standard deviation was 31 lux (Figure 5.37). The median was 7 lux. The uniformity ratio below the light at workplane was 0.36.

LIGHT Level(Lux)	Value
Min	3
Max	162
Avg	19.3
Median	7
SD	31

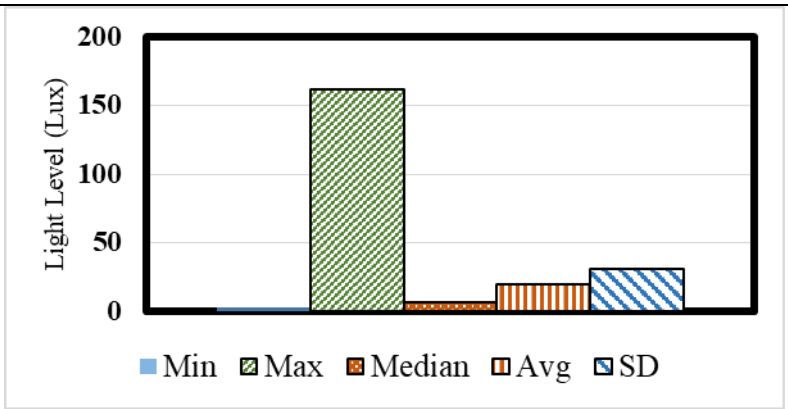


Figure 5.37: Daylighting distribution data analysis for case 02(b)

While considering only the illuminance level at the central part-f (Table 5.17), it has generated a curve line which indicate that the highest light found at the center of the space (Figure 5.38) and the lighting was very poor near the edge of the simulated area as installed lightpipe with 7.30m length can't penetrate more light away from the center.

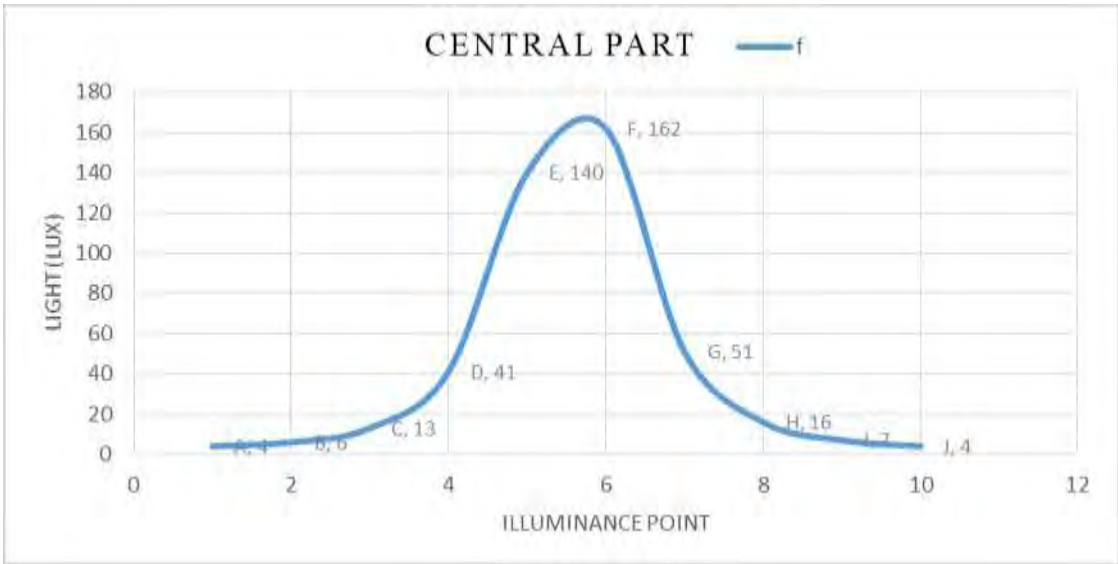


Figure 5.38: Daylighting distribution at central part (f) for case 02(b)

III. Case 02(c): Pipe Length 10.5m

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model (Table 5.18). There was one (1) light pipe which diameter was 0.50m at the center of the area with a transition space (height of three floor-10.5m) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.39).

Table 5.18: Simulation model parameters for case 02(c)

Case	Pipe Diameter	**Pipe Length**	Number of Pipe	Presence of Window
02(c)	0.50m	**10.5m**	01	No

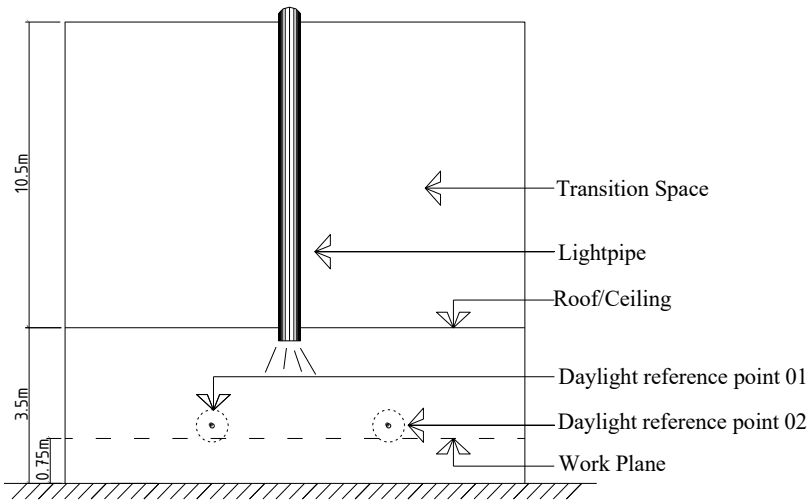


Figure 5.39: Simulation model section for case 02(c)

Table 5.19: Daylighting distribution at illumination plane for case 02(c)

Point	A	B	C	D	E	F	G	H	I	J
a	2	2	2	2	2	2	2	2	2	2
b	3	4	6	10	14	15	11	7	5	4
c	4	5	8	16	30	32	19	9	5	4
d	4	6	11	27	67	73	32	12	6	4
e	4	6	13	39	127	146	48	15	7	4
f	4	6	13	41	139	161	51	15	7	4
g	4	6	11	31	81	91	37	13	6	4
h	4	5	9	19	37	39	22	10	6	4
i	4	5	7	11	17	18	12	7	5	4
j	3	4	5	7	9	10	8	6	4	3

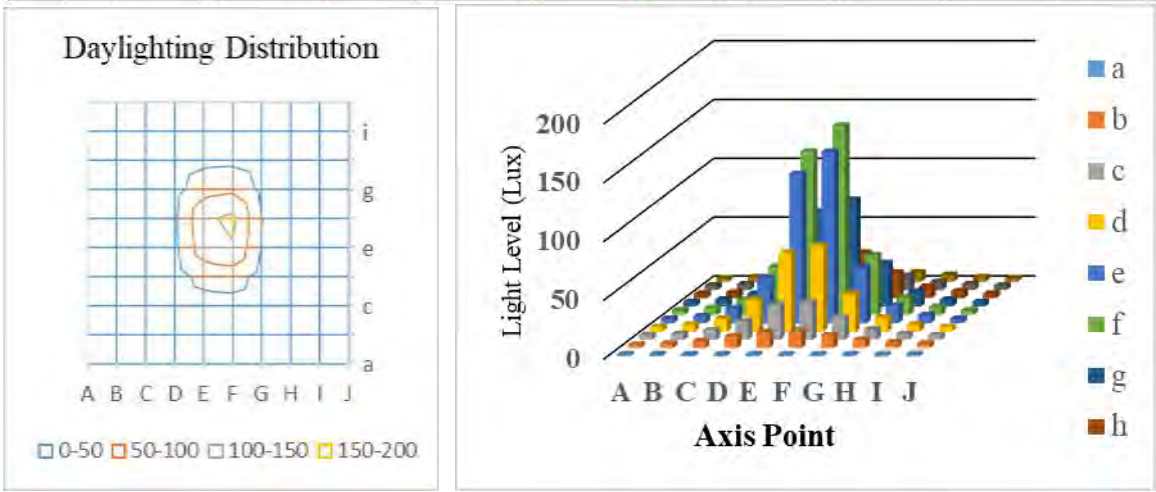


Figure 5.40: Daylighting distribution at illumination plane for case 02(c)

Table 5.19 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the light pipe installed at the ceiling level. Figure 5.40 show that this daylight only illuminate the center of the space and constantly decrease at the periphery area. The brightest level of light 161 lux found at the center of the space and the light found at the periphery area was very low (less than 50 lux). The minimum light was only 2 lux.

LIGHT Level(Lux)	**Value**
Min	2
Max	161
Avg	19.1
Median	7
SD	30.8

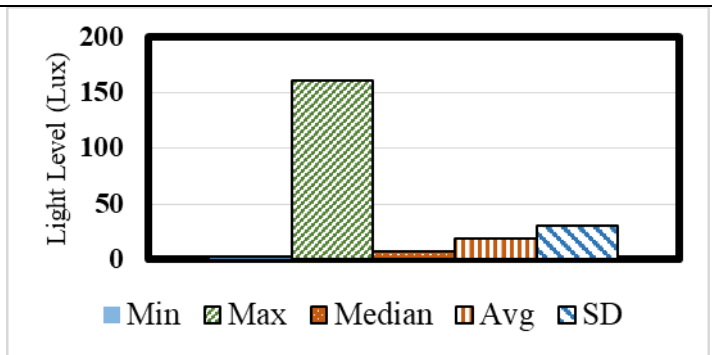


Figure 5.41: Daylighting distribution data analysis for case 02(c)

The average light was 19.1 lux and the standard deviation was 30.8 lux (Figure 5.41). The median was 7 lux. The uniformity ratio below the light at workplane was 0.36.

While considering only the illuminance level at the central part-f (Table 5.19), it has generated a curve line which indicate that the highest light found at the center of the space (Figure 5.42) and the lighting was very poor near the edge of the simulated area as installed lightpipe with 10.95m length can't penetrate more light away from the center.

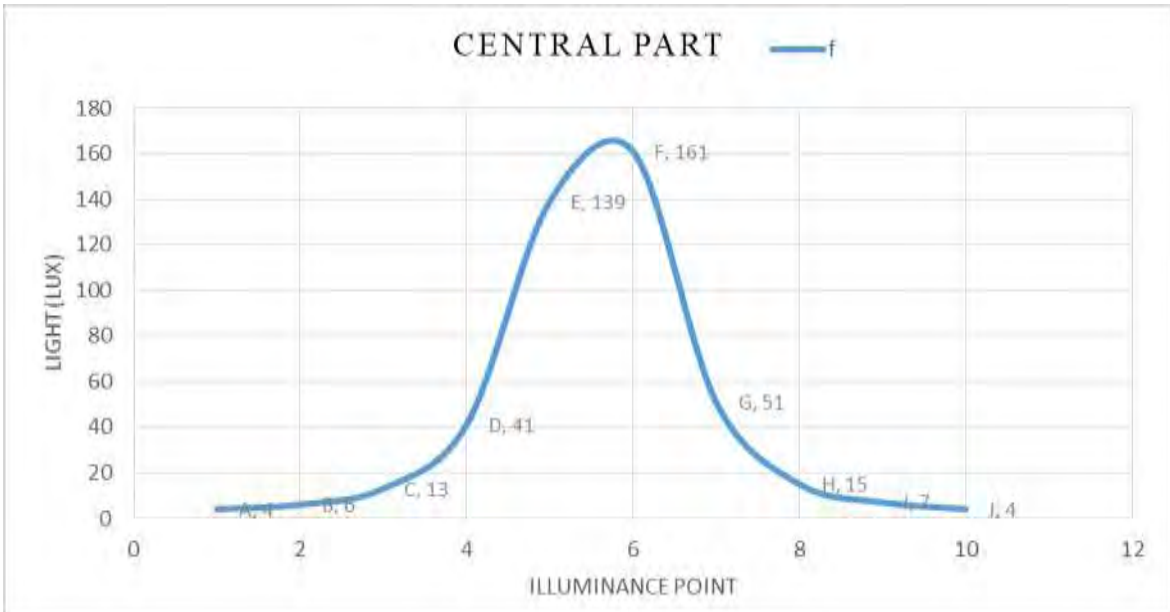


Figure 5.42: Daylighting distribution at central part (f) for case 02(c)

IV. Case 02(d): Pipe Length 14.0m

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model (Table 5.20). There was one (1) light pipe which diameter was 0.50m at the center of the area with a transition space (height of four floor-14.0m) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.43).

Table 5.20: Simulation model parameters for case 02(d)

Case	Pipe Diameter	**Pipe Length**	Number of Pipe	Presence of Window
02(d)	0.50m	**14.0m**	01	No

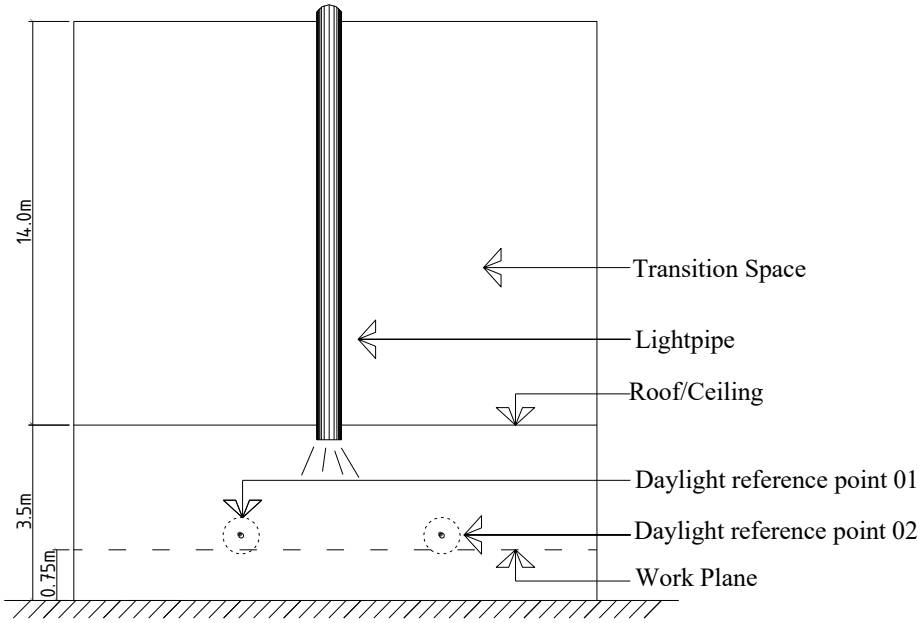


Figure 5.43: Section of simulation model 02(d)

Table 5.21: Daylighting distribution at illumination plane for case 02(d)

Point	A	B	C	D	E	F	G	H	I	J
a	2	2	2	2	2	2	2	2	2	2
b	3	4	6	10	14	15	11	7	5	4
c	4	5	8	16	30	32	19	9	5	4
d	4	6	11	27	67	73	32	12	6	4
e	4	6	13	39	127	146	48	15	7	4
f	4	6	13	41	139	161	51	15	7	4
g	4	6	11	30	81	91	37	13	6	4
h	4	5	9	19	37	39	22	10	6	4
i	4	5	7	11	17	18	12	7	5	4
j	3	4	5	7	9	10	8	6	4	3

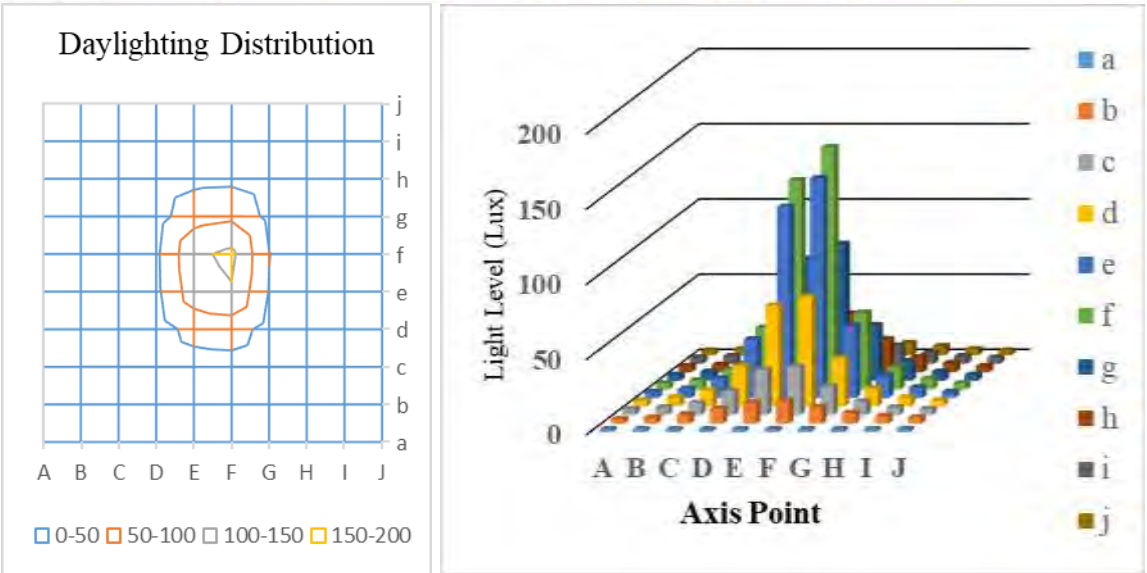


Figure 5.44: Daylighting distribution at illumination plane for case 02(d)

Table 5.21 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the light pipe installed at the ceiling level. Figure 5.44 show that this daylight only illuminate the center of the space and constantly decrease at the periphery area. The brightest level of light 161 lux found at the center of the space and the light found at the periphery area was very low (less than 50 lux). The minimum light was only 2 lux. The average light was 19.1 lux and the standard deviation was 30.8 lux (Figure 5.45). The median was 7 lux. The median was 7 lux. The uniformity ratio below the light at workplane was 0.36.

Light Level(Lux)	Value
Min	2
Max	161
Avg	19.1
Median	7
SD	30.8

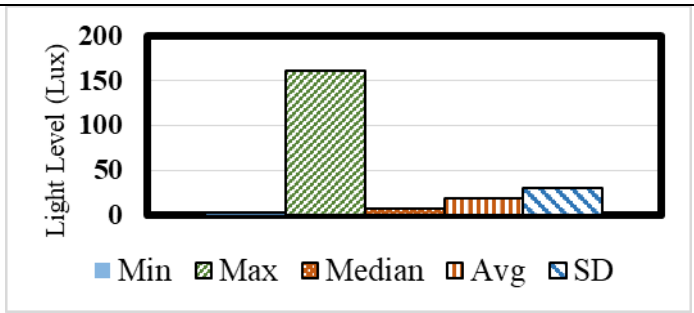


Figure 5.45: Daylighting distribution data analysis for case 02(d)

While considering only the illuminance level at the central part-f (Table 5.21), it has generated a curve line which indicate that the highest light found at the center of the space (Figure 5.46) and the lighting was very poor near the edge of the simulated area as installed lightpipe with 14.6m length can't penetrate more light away from the center.

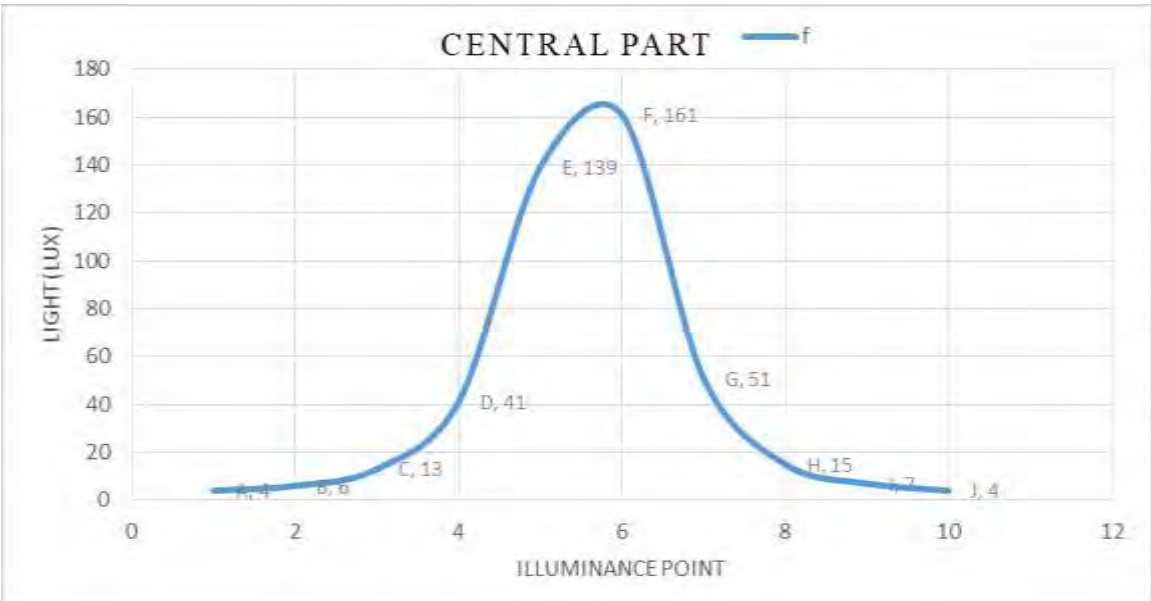


Figure 5.46: Daylighting distribution at central part (f) for case 02(d)

V. Comparative Analysis

Table 5.22 show the lighting level at the central part (f) of the illuminance plane for every variation for different length of light pipes with **Model 01** (The deep part of the office floor). From these data, it is observed that the difference of amount of daylight entered by lightpipe of different length are very minimum. Daylight entered into the office space at the same ratio by the time (hour) and reach at the maximum level at 12.00 PM. After 01.00 PM, it start to decrease and reach at the minimum level at 06.00 PM (end of the office time) (Figure 5.47). Maximum daylight entered by the lightpipe of 3.65m length and minimum light found by the lightpipe of 14.60 m length. The **uniformity ratio** below the light at workplane was found 0.36.

Table 5.22: Daylighting distribution at central part (f) of illumination plane for lightpipe of different length

Length	A	B	C	D	E	F	G	H	I	J
3.65m	4	6	14	43	146	169	54	16	7	4
7.30m	4	6	13	41	140	162	51	15	7	4
10.95m	4	6	13	39	139	156	49	13	7	4
14.60m	4	6	12	36	137	153	48	12	7	4

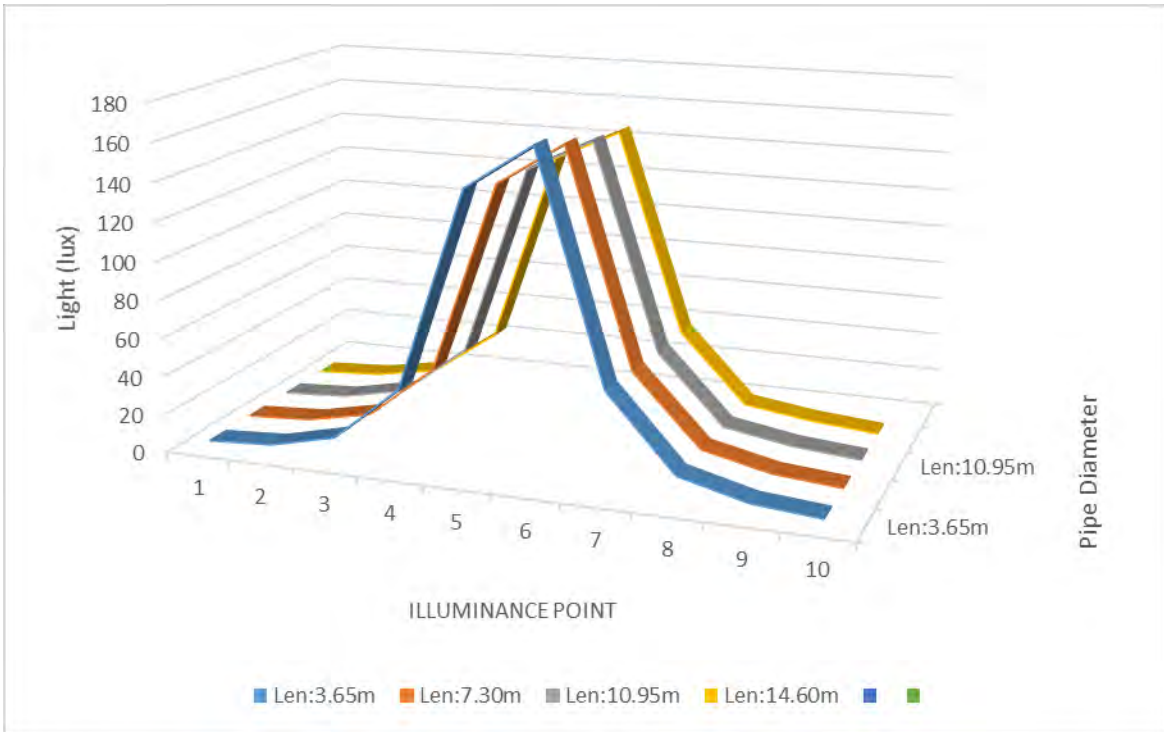


Figure 5.47: Daylighting variation for different length of lightpipes

5.4.3 Lighting Simulation with Different No. of Lightpipes

I. Case 3(a): One(1) Pipe

This model simulation criteria and results were similar to the case 01(f) –Page 113.

II. Case 3(b): Two(2) Pipes

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model (Table 5.23). There were two (2) lightpipes which diameter was 0.50m at the center of the area with a transition space (height 3.5m-one floor) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.48).

Table 5.23: Simulation model parameters for case 03(b)

Case	Pipe Diameter	Length	**Number of Pipe**	Presence of Window
03(b)	0.50m	3.5m	**02**	No

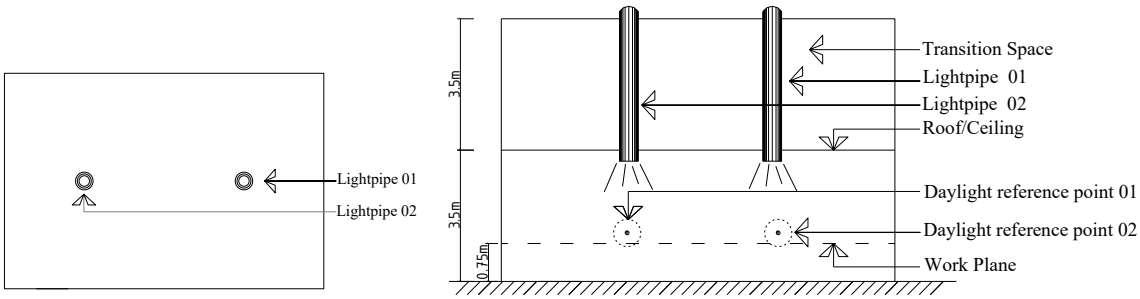


Figure 5.48: Roof Plan and section of simulation model 03(b)

Table 5.24: Daylighting distribution at illumination plane for case 03(b)

Point	A	B	C	D	E	F	G	H	I	J
a	5	5	5	5	5	5	5	5	5	5
b	11	16	20	18	15	15	18	20	17	12
c	14	26	38	32	21	20	30	39	29	16
d	19	47	87	63	30	28	55	89	54	22
e	24	73	177	108	39	35	90	181	90	28
f	24	78	196	117	41	36	96	201	96	29
g	21	54	108	75	33	30	64	110	64	24
h	16	30	47	38	23	22	35	48	34	17
i	12	18	23	21	16	16	20	23	19	13
j	9	12	14	13	12	12	13	14	12	10

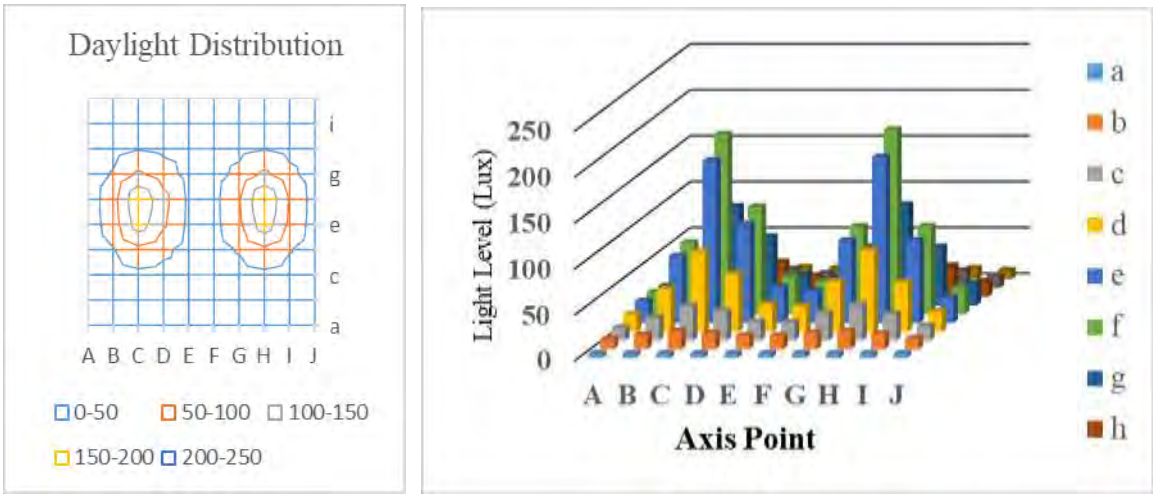


Figure 5.49: Daylighting distribution at illumination plane for case 03(b)

Table 5.24 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the light pipe installed at the ceiling level. Figure 5.49 show that this daylight only illuminate the center of the space and constantly decrease at the periphery area. The brightest level of light 201 lux found at the center of the space and the light found at the periphery area was very low (less than 50 lux). The minimum light was only 5 lux. The average light was 39.3 lux and the standard deviation was 41.3 lux (Figure 5.50). The median was 23 lux. The uniformity ratio below the light at workplane was 0.48.

LIGHT Level(Lux)	**Value**
Min	5
Max	201
Avg	39.3
Median	23
SD	41.3

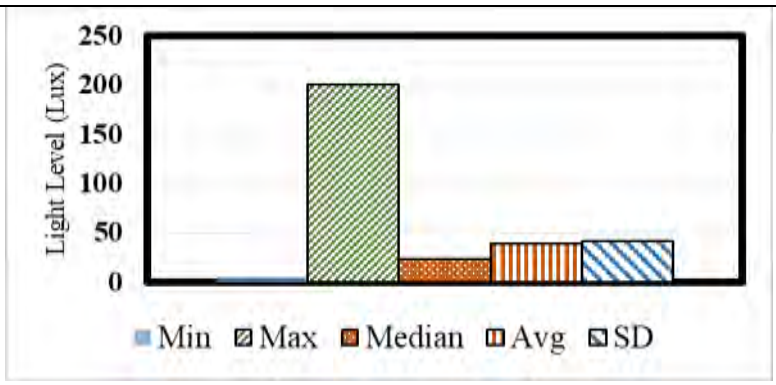


Figure 5.50: Daylighting distribution data analysis for case 03(b)

While considering only the illuminance level at the central part-f (Table 5.24), it has generated a curve line with two peak points which indicate that the highest light found at the center of the space under two lightpipes (Figure 5.51). The lighting was very poor away from the pipe near the edge of the simulated area as the installed lightpipes penetrate little amount of light away from the center.

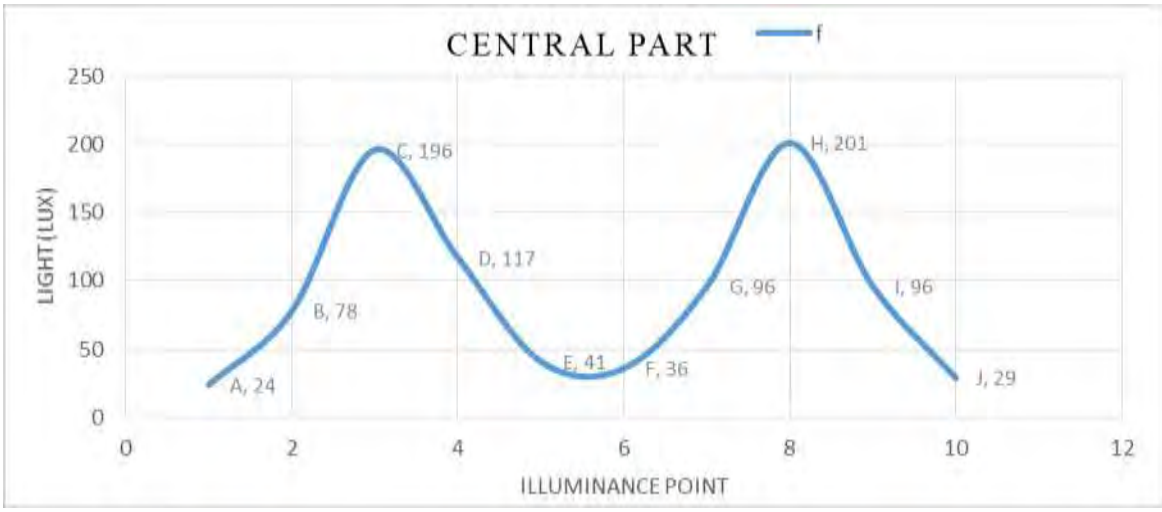


Figure 5.51: Daylighting distribution at central part (f) for case 03(b)

III. Case 3(c): Three(3) Pipes

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model (Table 5.29). There were three (3) lightpipes which diameter was 0.50m at the center of the area with a transition space (height 3.5m-one floor) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.52).

Table 5.25: Simulation model parameters for case 03(c)

Case	Pipe Diameter	Length	**Number of Pipe**	Presence of Window
03(c)	0.50m	3.5m	**03**	No

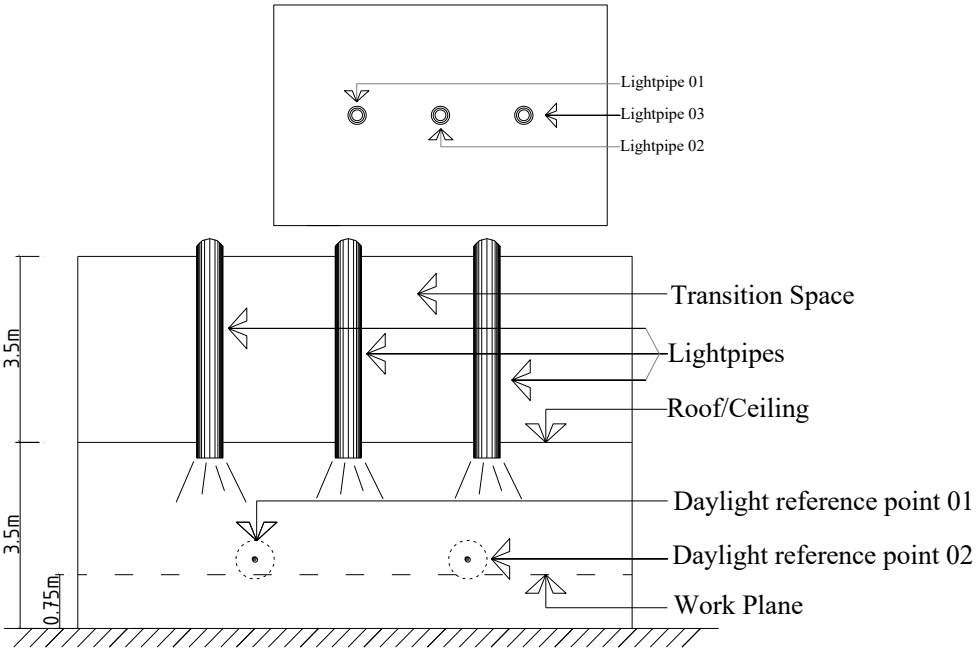


Figure 5.52: Roof plan and section of simulation model 03(c)

Table 5.26: Daylighting distribution at illumination plane for case 03(c)

Point	A	B	C	D	E	F	G	H	I	J
a	6	6	6	6	6	6	6	6	6	6
b	13	19	25	27	29	29	27	25	20	14
c	17	30	46	48	51	52	48	47	33	18
d	22	51	97	90	99	104	88	100	59	25
e	26	78	189	148	171	187	139	196	95	31
f	27	83	208	158	185	204	148	216	102	32
g	23	58	119	105	117	124	101	123	69	27
h	18	34	55	57	60	62	56	57	38	20
i	14	21	28	31	33	33	31	29	22	15
j	11	14	17	19	20	20	19	18	15	12

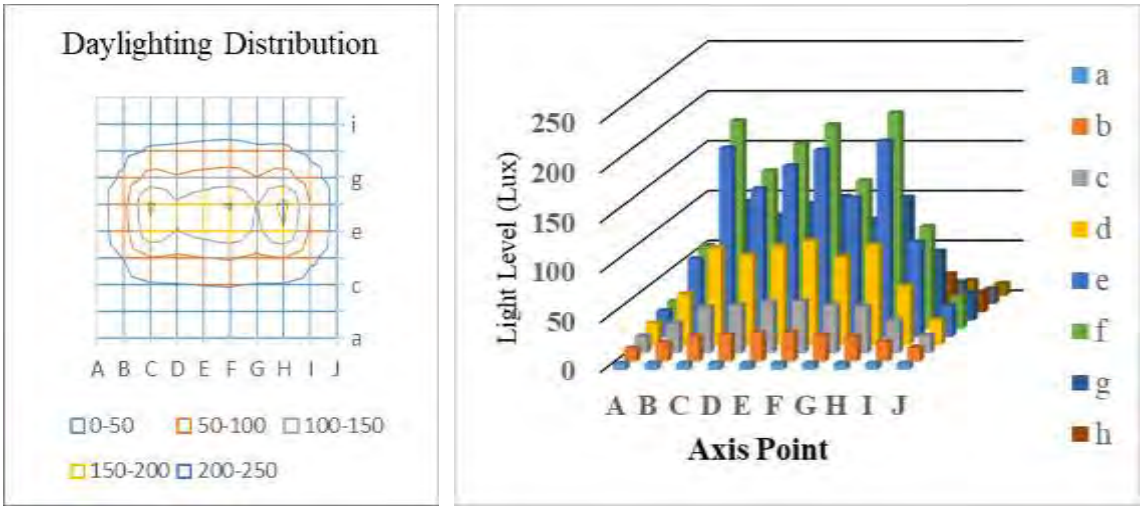


Figure 5.53: Daylighting distribution at illumination plane for case 03(c)

Table 5.26 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the light pipe installed at the ceiling level. Figure 5.53 show that this daylight illuminate the center part of the space and was minimim at the periphery area.

LIGHT Level(Lux)	Value
Min	6
Max	216
Avg	57.8
Median	31.5
SD	55.2

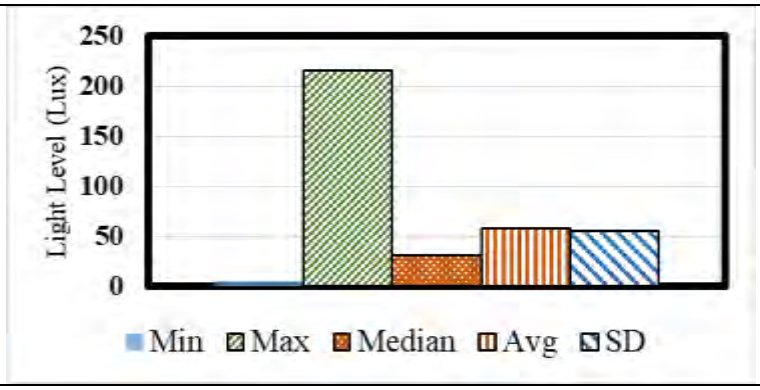


Figure 5.54: Daylighting distribution data analysis for case 03(c)

The brightest level of light 216 lux found at the center of the space and the light found at the periphery area was very low (less than 50 lux). The minimum light was only 6 lux. The average light was 57.8 lux and the standard deviation was 55.2 lux (Figure 5.54) were very close to each other. The median was 31.5 lux. The uniformity ratio below the light at workplane was 0.65 which met the standards (≥0.60).

While considering only the illuminance level at the central part-f (Table 5.26), it has generated a curve line with three peak points which indicate that the highest light found at the center of the space under three lightpipes (Figure 5.55) and the lighting was low at the edge of the simulated area. But Maximum area of central part was lighted with these three lightpipes.

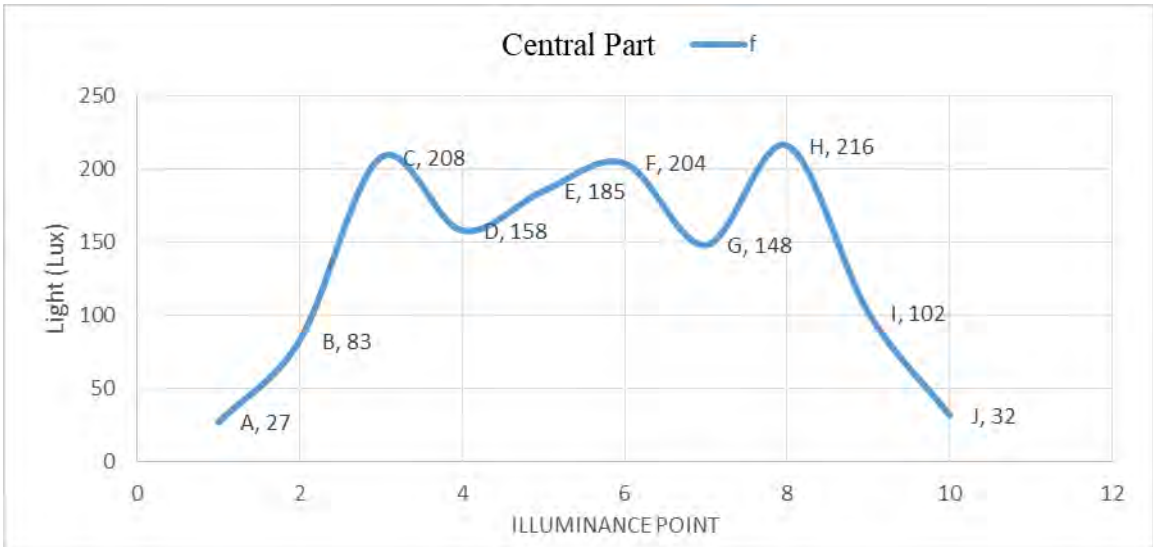


Figure 5.55: Daylighting distribution at central part (f) for case 03(c)

IV.Case 3(d): Six(6) Pipes

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model (Table 5.27). There was six (6) light pipes which diameter was 0.50m at the center of the area with a transition space (height 3.5m-one floor) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.56).

Table 5.27: Simulation model parameters for case 03(d)

Case	Pipe Diameter	Length	**Number of Pipe**	Presence of Window
03(d)	0.50m	3.5m	**06**	No

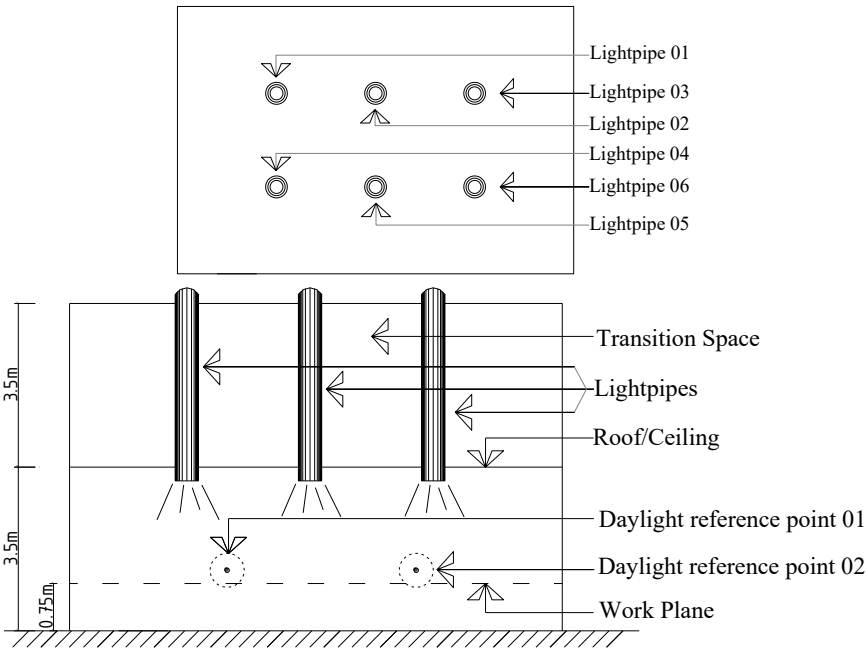


Figure 5.56: Roof plan and section of simulation model 03(d)

Table 5.28: Daylighting distribution at illumination plane for case 03(d)

Point	A	B	C	D	E	F	G	H	I	J
a	16	16	16	16	16	16	16	16	16	16
b	35	71	132	119	131	138	116	136	82	39
c	40	98	225	177	204	223	167	233	118	45
d	42	98	215	175	200	216	167	222	117	47
e	41	81	140	135	146	152	133	144	92	45
f	40	78	129	129	138	142	127	133	87	45
g	41	94	193	165	185	198	158	200	110	47
h	41	101	238	184	214	234	173	246	122	46
i	36	79	157	136	152	161	131	162	92	41
j	30	51	79	80	85	87	79	82	57	33

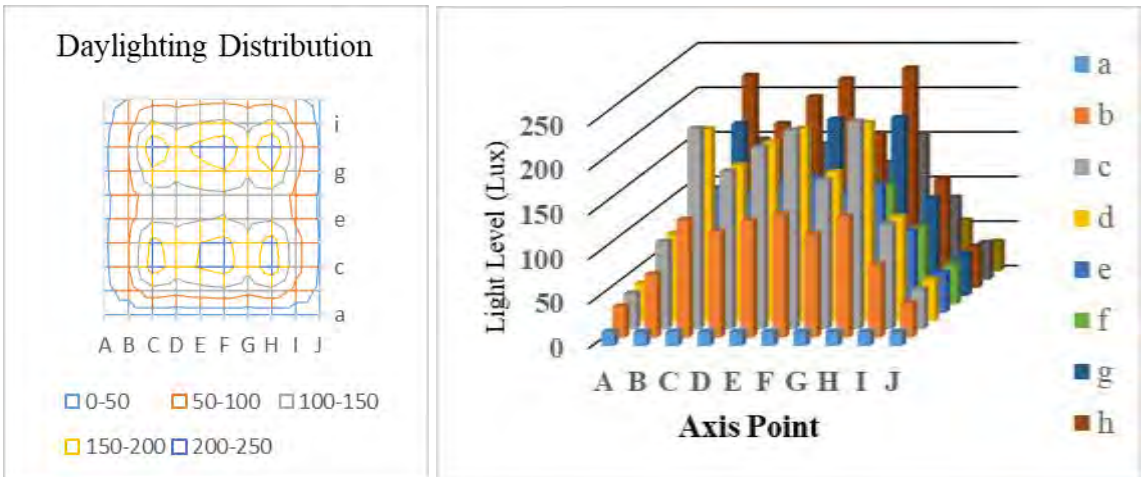


Figure 5.57: Daylighting distribution at iIllumination plane for case 03(d)

Table 5.28 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the light pipe installed at the ceiling level. Figure 5.57 show that this daylight illuminate the center part of the space and was minimum at the periphery area. The brightest level of light 246 lux found at the center of the space and the light found at the periphery area was very low (less than 50 lux). The minimum light was 16 lux. The average light was 111 lux and the standard deviation was 65.7 lux (Figure 5.58). The median was 117 lux. . The uniformity ratio below the light at workplane was 0.68 which meet the standard (≥ 0.60).

LIGHT Level(Lux)	Value
Min	16
Max	246
Avg	111
Median	117
SD	65.7

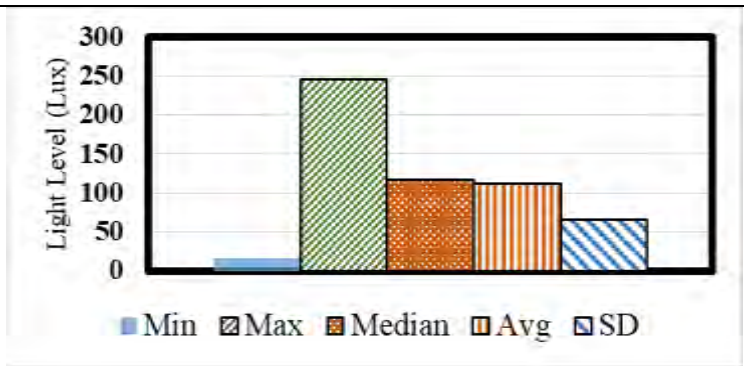


Figure 5.58: Daylighting distribution data analysis for case 03(d)

While considering only the illuminance level at the central part-f (Table 5.28), it has generated a curve line with three peak points which indicate that the highest light found at the center of the space under six lightpipes (Figure 5.59) and the lighting was low at the edge of the simulated area. But Maximum area of central part was lighted with these six lightpipes.

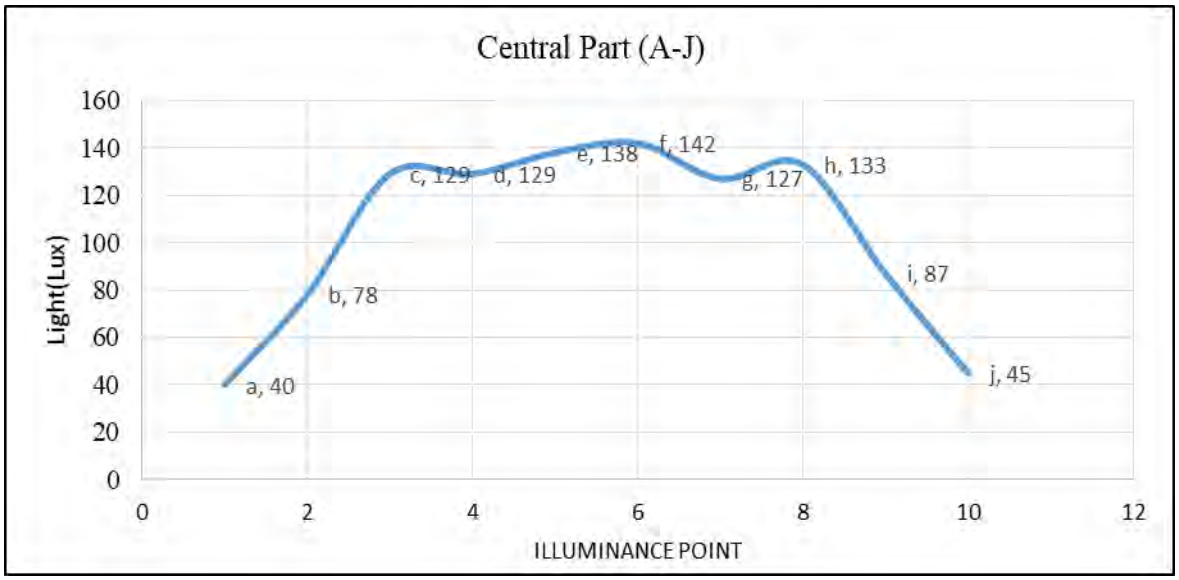


Figure 5.59: Daylighting distribution at central part (f) for case 03(d)

V. Case 3(e): Nine(9) Pipes

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model (Table 5.29). There were nine (9) lightpipes which diameter was 0.50m at the center of the area with a transition space (height 3.5m) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.60).

Table 5.29: Simulation model parameters for case 03(e)

Case	Pipe Diameter	Length	**Number of Pipe**	Presence of Window
03(e)	0.50m	3.5m	**09**	No

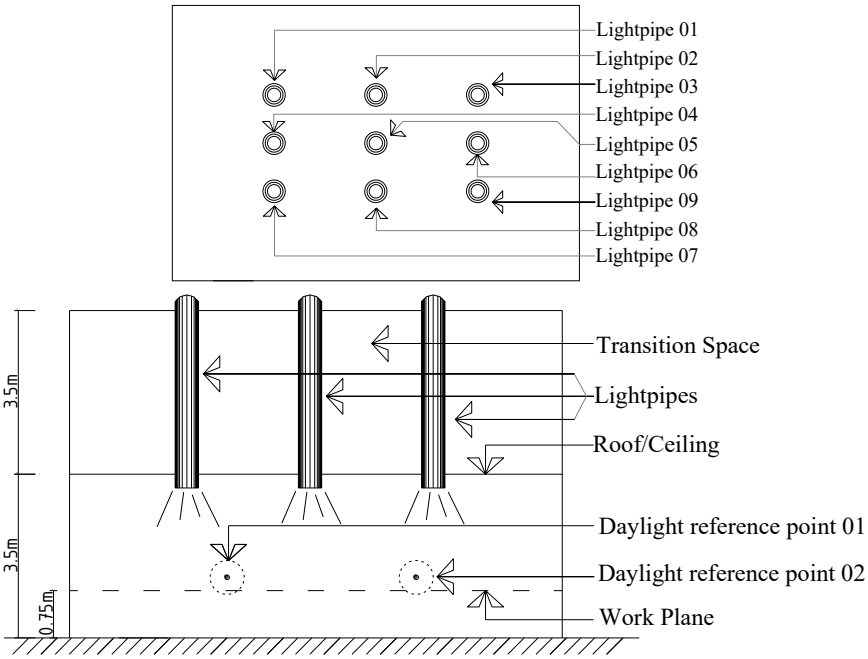


Figure 5.60: Roof plan and section of simulation model 03(e)

Table 5.30: Daylighting distribution at illumination plane for case 03(e)

Point	A	B	C	D	E	F	G	H	I	J
a	24	24	24	24	24	24	24	24	24	24
b	24	110	191	169	199	177	165	180	95	50
c	24	151	297	238	302	255	236	280	126	57
d	24	165	306	263	318	276	257	288	139	62
e	24	174	329	279	340	294	273	310	146	64
f	24	175	334	280	344	297	275	314	147	65
g	24	165	305	264	317	277	258	288	140	62
h	24	154	304	243	308	261	241	286	129	58
i	24	115	204	178	212	187	174	193	99	50
j	24	74	107	108	117	110	104	102	67	43

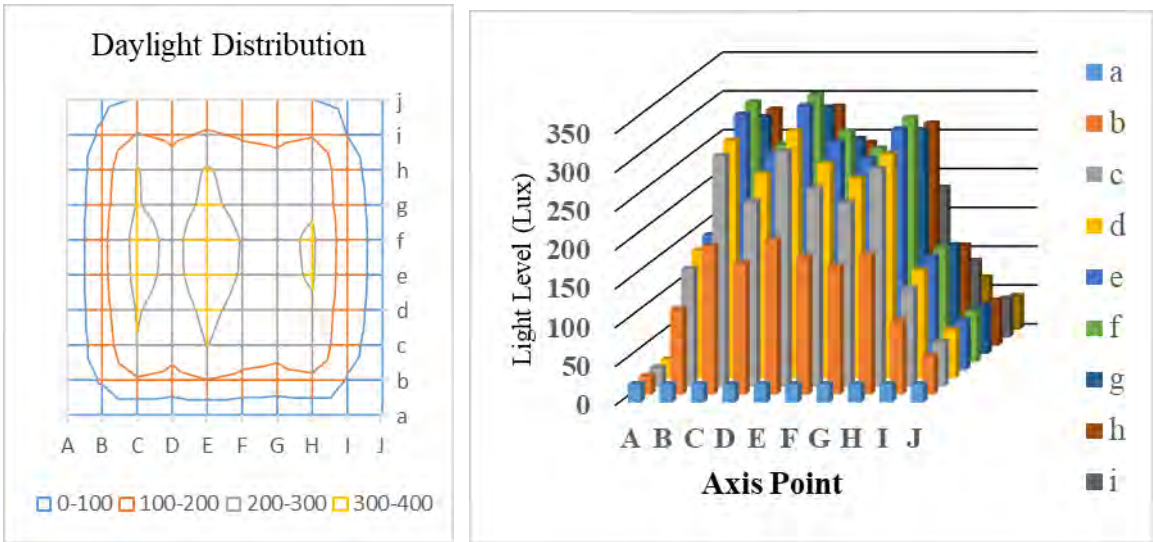


Figure 5.61: Daylighting distribution at illumination plane for case 03(e)

Table 5.30 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the light pipe installed at the ceiling level. Figure 5.61 show that this daylight illuminate the entire space along with the periphery area. The brightest level of light 344 lux found at the center of the space and the light found at the periphery area was 24 lux. The average light was 166 lux and the standard deviation was 106 lux (Figure 5.62). The median was 165 lux. The uniformity ratio below the light at workplane was 0.91 which was over the standard (≥ 0.60) very much.

LIGHT Level(Lux)	**Value**
Min	24
Max	344
Avg	166
Median	165
SD	106

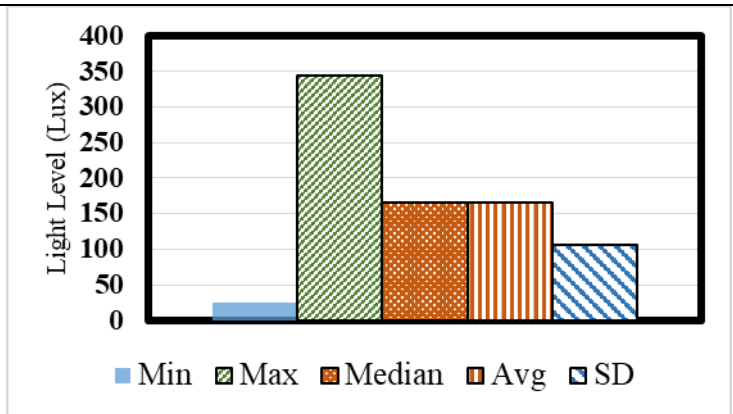


Figure 5.62: Daylighting distribution data analysis for case 03(e)

While considering only the illuminance level at the central part-f (Table 5.30), it has generated a curve line with three peak points which indicate that the highest light found at the center of the space under nine lightpipes (Figure 5.63) and the lighting was low at the edge of the simulated area. But Maximum area of central part was lighted with these nine lightpipes.

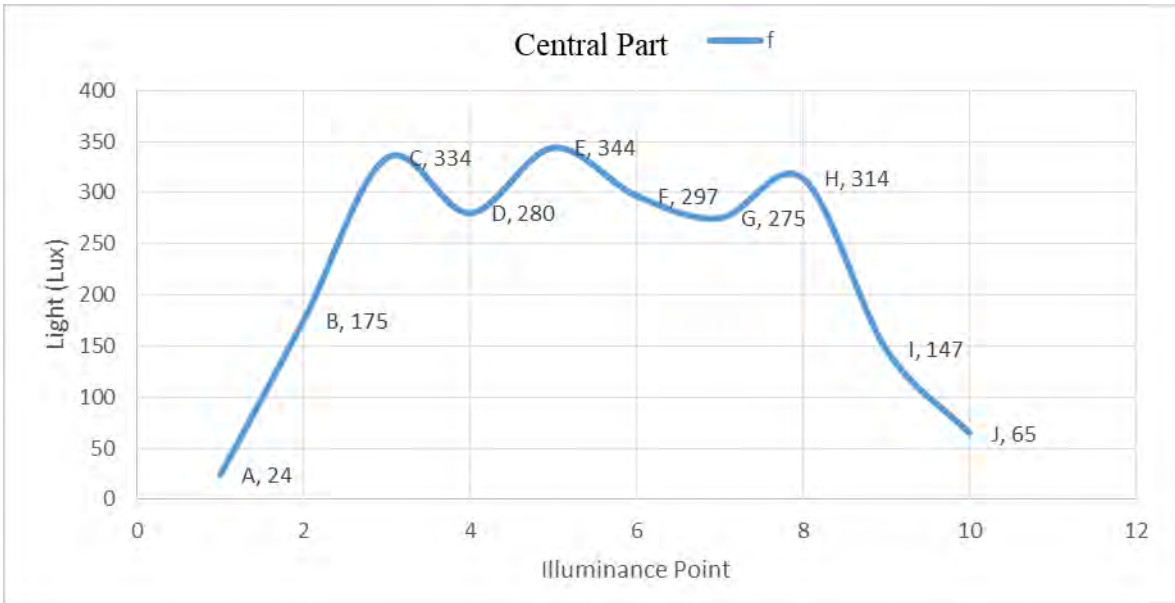


Figure 5.63: Daylighting distribution at central part (f) for case 03(e)

VI. Comparative Analysis

Table 5.31: Daylighting distribution at illumination plane for lightpipe of different nos (Model 01)

Point	A	B	C	D	E	F	G	H	I	J
1 Pipe	4	6	13	42	142	165	52	16	7	4
2 Pipes	24	78	196	117	41	36	96	201	96	29
3 Pipes	27	83	208	158	185	204	148	216	102	32
6 Pipes	41	101	238	184	214	234	173	246	122	46
9 Pipes	24	175	334	280	344	297	275	314	147	65

Table 5.31 show the lighting level at the central part (f) of the illuminance plane for every variation for different light pipe numbers with **Model 01**(The deep part of the office floor). From these data, it can be calculate the maximum, minimum and average value (Table 5.32). From the table it is observed that amount of daylight increase significantly with the increasing number of light pipes (Figure 5.64).

Table 5.32: Daylighting distribution data analysis (model 01)

Option	Max	Min	Avg
1 Pipe	159	4	43.5
2 Pipes	201	24	91.4
3 Pipes	216	27	136.3
6 Pipes	246	41	159.9
9 Pipes	344	24	225.5

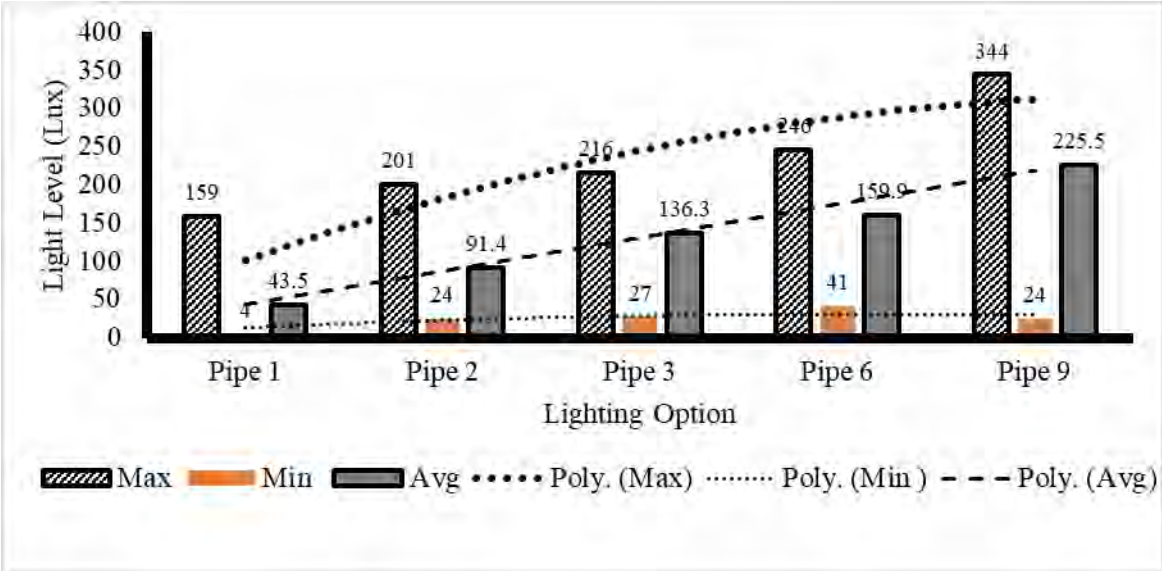


Figure 5.64: Daylighting distribution data analysis (model 01)

Maximum light was found with nine (9) lightpipes in maximum illumination point of the illuminance plane. The standard light level (>300 lux) was found in 2 points under the lightpipe and the average light level was 225 lux (below standard level). So it can be stated that only lightpipe is not enough to create a standard luminous environment. It can be achieve by installing more lightpipe or artificial light.

VII. Lighting Performance Comparison of Central Part

From the Table 5.32 it is also observed that the highest amount of daylight penetrates by Nine (9) lightpipes. The illuminance were higher under the lightpipes (Figure5.65) and light degrease at the edge of the space. The pattern of light comes by 6 lightpipes and 3 lightpipes was similar. It was observed that the amount of light increase with the higher number of lightpipe installation.

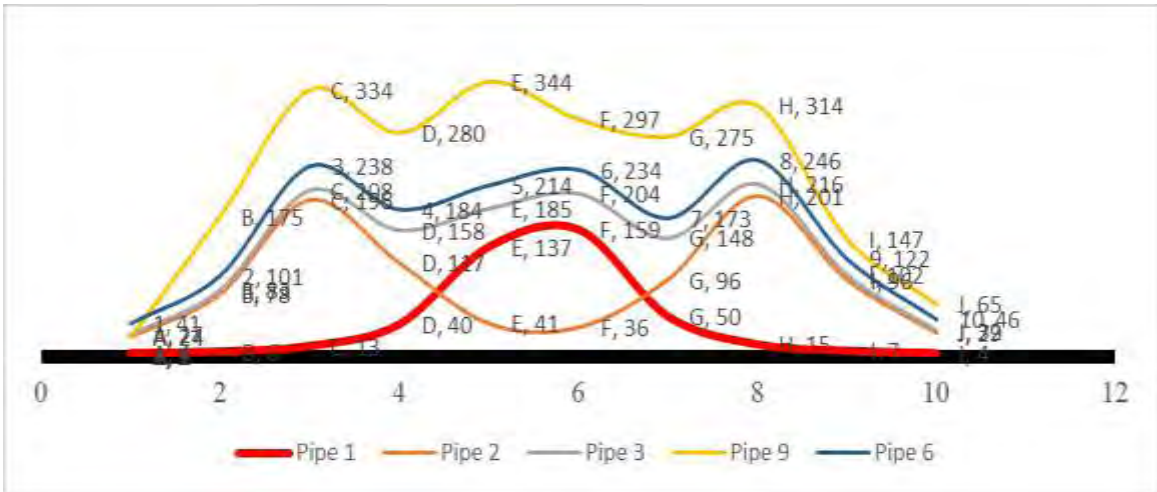


Figure 5.65: Daylighting distribution comparison at central part (model 01)

VIII. Uniformity Ratio

The uniformity ratio found for different nos of lightpipes has stated at the Table 5.33. Here we found that the ratio has increased with the increasing nos of lightpipes simulations. But the uniformity ratio of 3 pipes and 6 pipes have met the standards of the ratio most accurately which is ≥0.60%.

Table 5.33: Uniformity ratio for model 01

Pipe No.	1 Pipe	2 Pipes	3 Pipes	6 Pipes	9 Pipes
Uniformity Ratio	0.36	0.48	0.65	0.68	0.91

5.4.4 Lighting Simulation with Lightpipes and Windows

I. Case 4(a): Three (3) Pipes with no Window

This model was created with the entire floor as surveyed floor area. There were no opening at the side walls of the model (Table 5.34). There were 3(three) lightpipes (0.50m diameter) at the center of the area with a transition space (height 3.5m-one floor) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.66). The daylighting performance of lightpipe, without side window was observed from the model.

Table 5.34: Simulation model parameters for case 04(a)

Case	Pipe Diameter	Length	**Number of Pipe**	**Presence of Window**
04(a)	0.50m	3.5m	**03**	**No**

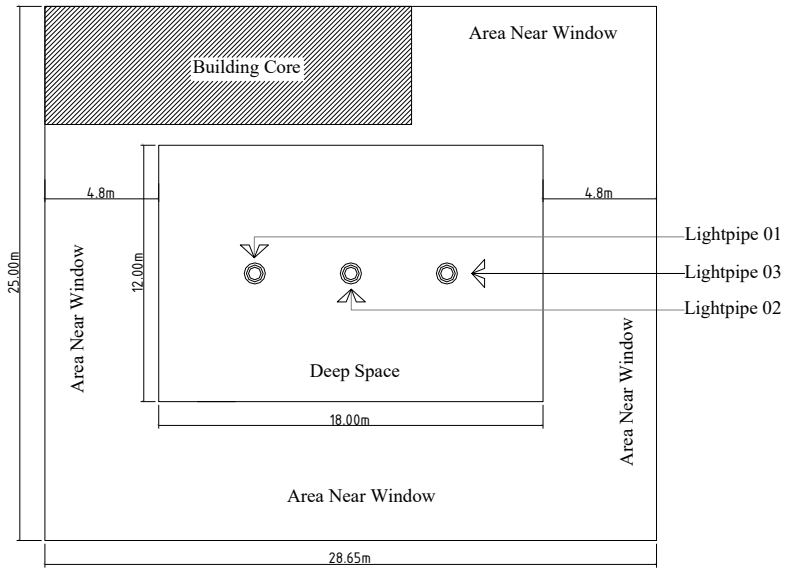


Figure 5.66(a): Plan of simulation model of 04(a)

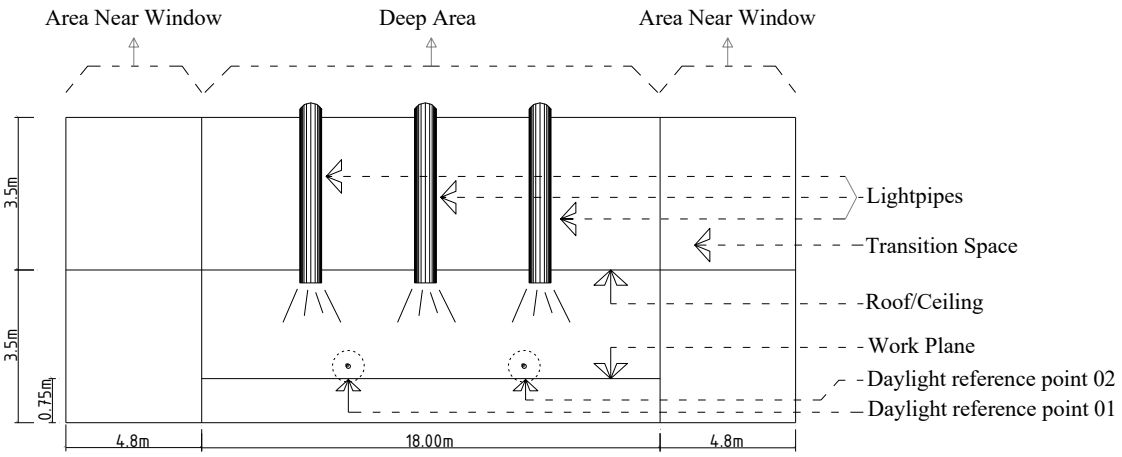


Figure 5.66(b): Section of simulation model of 04(a)

Table 5.35: Daylighting distribution at illumination plane for case 04(a)

Point	A	B	C	D	E	F	G	H	I	J
a	3	3	4	4	4	4	4	4	3	3
b	3	4	5	5	6	6	6	5	4	3
c	4	5	7	10	12	12	10	8	5	3
d	4	7	15	30	33	34	31	17	7	3
e	4	9	37	141	117	125	142	45	10	3
f	5	9	40	168	132	143	169	49	10	3
g	4	7	17	36	39	40	37	19	8	3
h	4	5	8	11	13	13	12	8	5	3
i	3	4	5	6	6	6	6	5	4	3
j	3	3	3	3	3	3	3	3	3	3

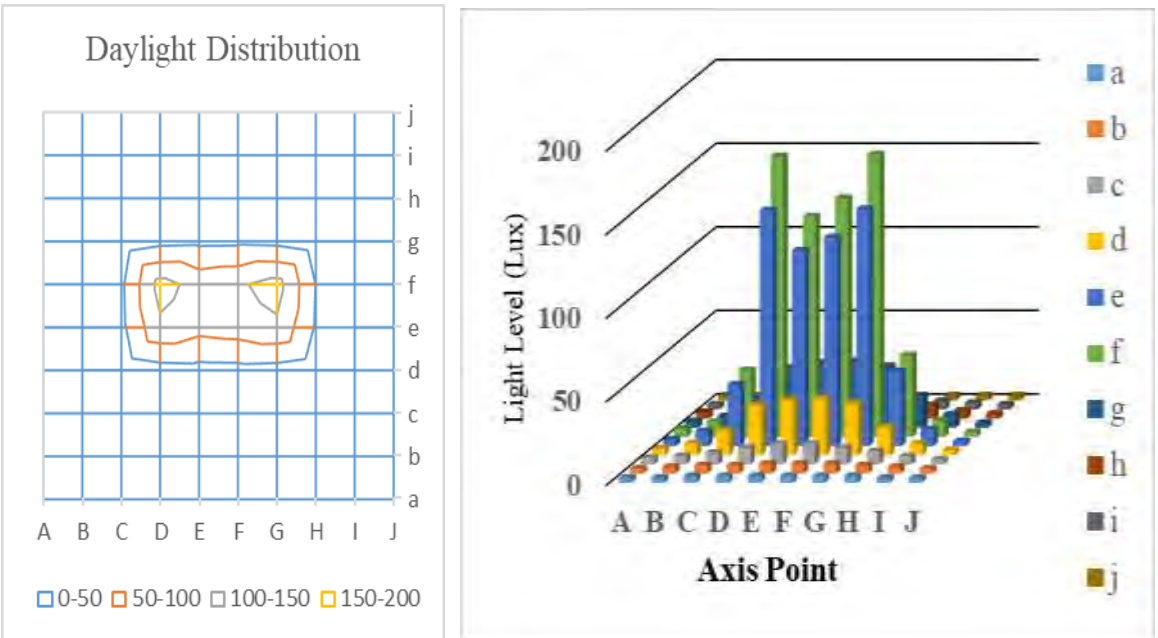


Figure 5.67: Daylighting distribution at illumination plane for case 04(a)

Table 5.35 shows the light level at the 100 point of the illuminance plane of Model 02 (whole office area) at 12.00pm. This light was penetrate by the light pipe installed at the

ceiling level. Figure 5.67 show that this daylight only illuminate the center of the space and constantly decrease at the periphery area. The brightest level of light 169 lux found at the center of the space and the light found at the periphery area was very low (less than 50 lux). The minimum light was only 3 lux. The average light was 20.7 lux and the standard deviation was 37.9 lux (Figure 5.68). The median was 6 lux. The uniformity ratio below the light at workplane was 0.34 which was very poor comparing with the standard (≥ 0.60).

LIGHT Level (Lux)	Value
Min	3
Max	169
Avg	20.7
Median	6
SD	37.9

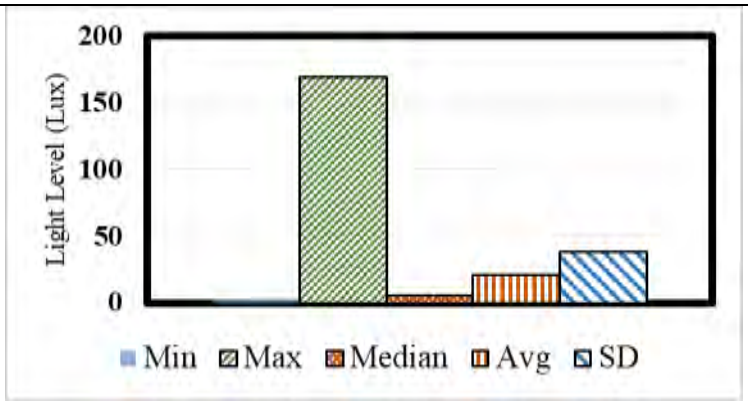


Figure 5.68: Daylighting distribution data analysis for case 04(a)

While considering only the illuminance level at the central part-f (Table 5.35), it has generated a curve line which indicate that the highest light found at the center of the space (Figure 5.69) and the lighting was very poor near the edge of the simulated area as there was no window and the of the installed lightpipe can't penetrate more light away from the center.

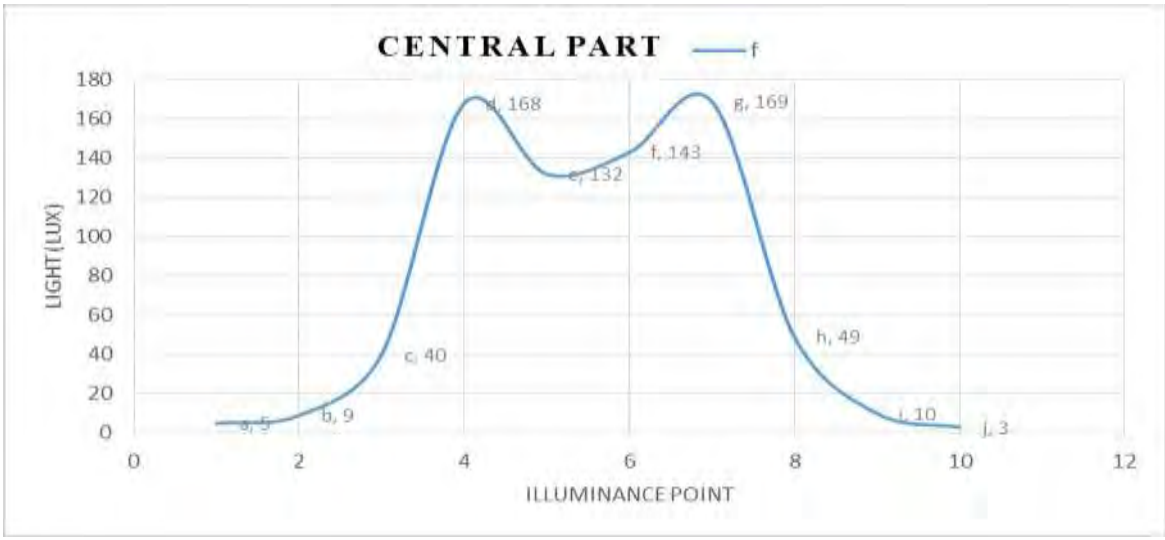


Figure 5.69: Daylighting distribution at central part (f) for case 04(a)

II. Case 4(b): Three (3) Pipes with Windows

This model was created with the entire floor as surveyed floor area (Table 5.36). There were opening at the three side walls of the model and the opening height was 2.4m. It is considered that daylight entered from the side window and lighted the periphery area of the floor. There were 3(three) lightpipes (0.50m diameter) at the center of the area with a transition space (height 3.5m) at the upper part of the model. The Dome of light pipe was set at the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe (Figure 5.70).

Table 5.36: Simulation model parameters for case 04(b)

Case	Pipe Diameter	Length	**Number of Pipe**	**Presence of Window**
04(b)	0.50m	3.5m	**03**	**Yes**

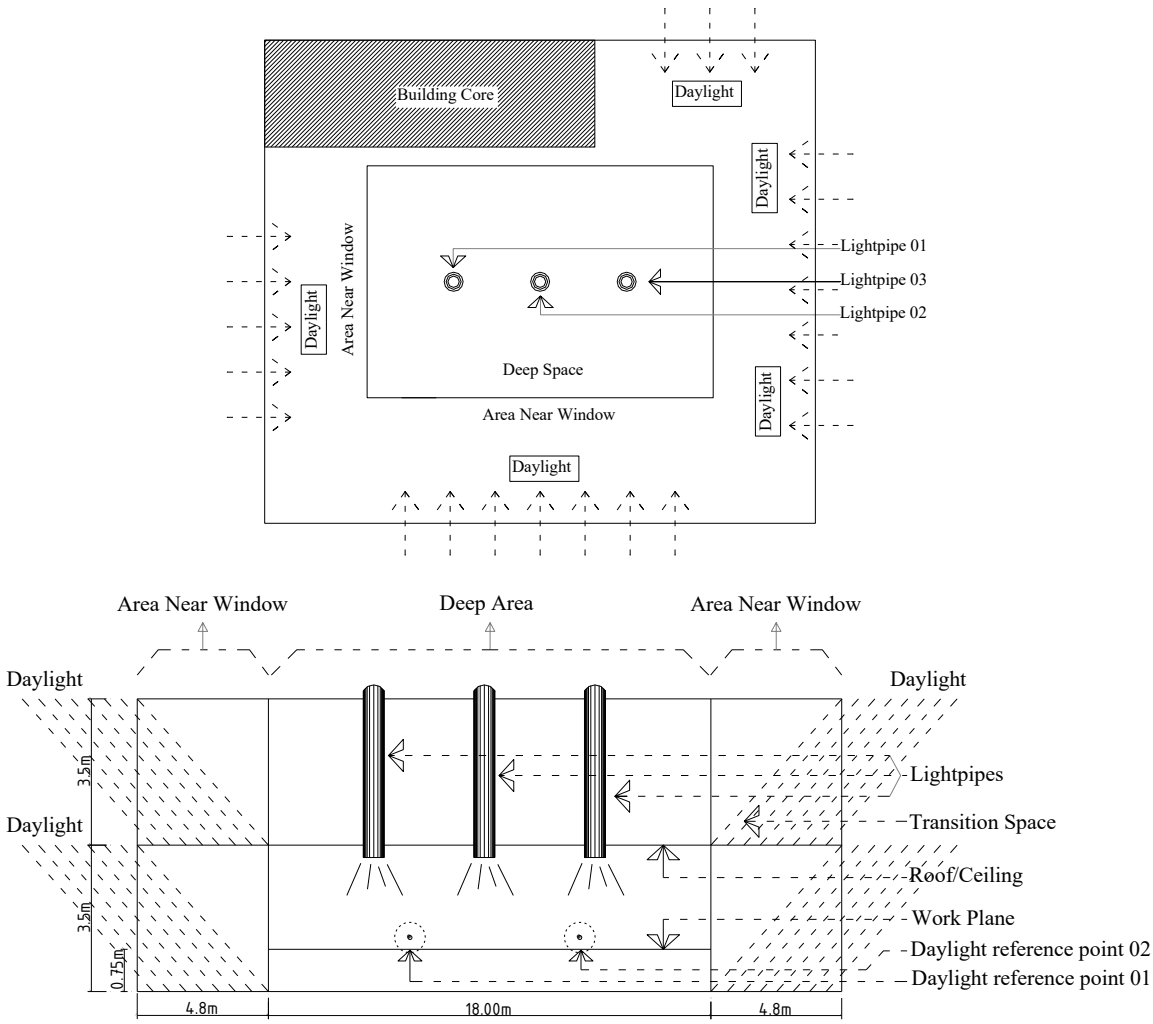


Figure 5.70: Plan and section of simulation model 04(b)

Table 5.37: Daylighting distribution at illumination plane for case 04(b)

Point	A	B	C	D	E	F	G	H	I	J
a	141	141	141	141	141	141	141	141	141	141
b	145	165	194	274	314	320	312	273	366	141
c	146	255	197	197	222	220	203	223	474	141
d	165	402	224	210	333	304	196	192	247	141
e	159	429	237	216	310	286	189	169	163	141
f	160	431	240	217	295	272	185	161	152	141
g	162	422	236	217	334	298	182	158	150	141
h	165	331	230	222	236	217	177	157	149	141
i	152	222	330	380	377	315	196	156	147	141
j	142	147	149	148	148	146	145	144	143	141

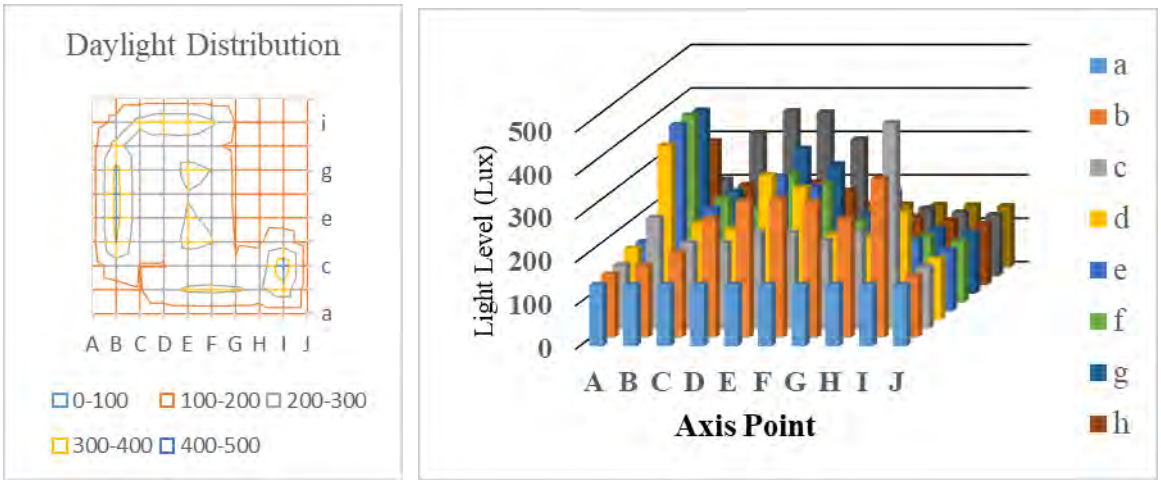


Figure 5.71: Daylighting distribution at illumination plane for case 04(b)

Table 5.37 shows the light level at the 100 point of the illuminance plane of Model 02 (whole office area) at 12.00pm. This daylight was penetrate by the light pipe installed at the ceiling level and by window at the periphery area. Figure 5.71 show that this daylight illuminate the overall area of the office. The brightest level of light-474 lux found at the center of the space and the minimum light was 141 lux. The average light was 214 lux and the standard deviation was 82.7 lux (Figure 5.72). The median was 187 lux. The uniformity ratio below the light at workplane was 0.65 which has met the standard (≥ 0.60).

LIGHT Level(Lux)	Value
Min	141
Max	474
Avg	214
Median	187
SD	82.7

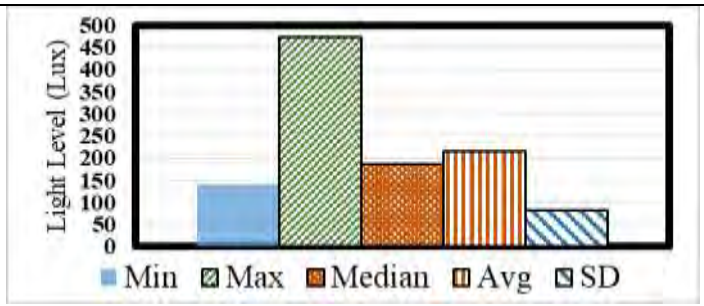


Figure 5.72: Daylighting distribution data analysis for case 04(b)

While considering only the illuminance level at the central part-f (Table 5.37), it has generated a curve line which indicate that the highest light found at the center of the space under lightpipes (Figure 5.73) and overall lighting condition of the simulated area was excellent as light has come from both side windows and lightpipes at the simulated space.

Figure 5.73: Daylighting distribution at central part (f) for case 04(b)

III. Case 4(c): With no Pipe

This model was created with the entire floor as surveyed floor area (Table 5.38). There were opening at the side walls of the model and the opening height was 2.4m. It is considered that daylight entered from the side window and lighted the periphery area of the floor. In this case, no lightpipe was considered (Figure 5.74).

Table 5.38: Simulation model parameters for case 04(c)

Case	Pipe Diameter	Length	**Number of Pipe**	**Presence of Window**
04(c)	-	-	**No Pipe**	**Yes**

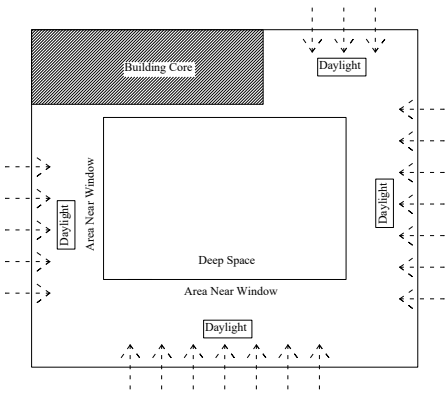


Figure 5.74(a): Plan of simulation model 4(c)

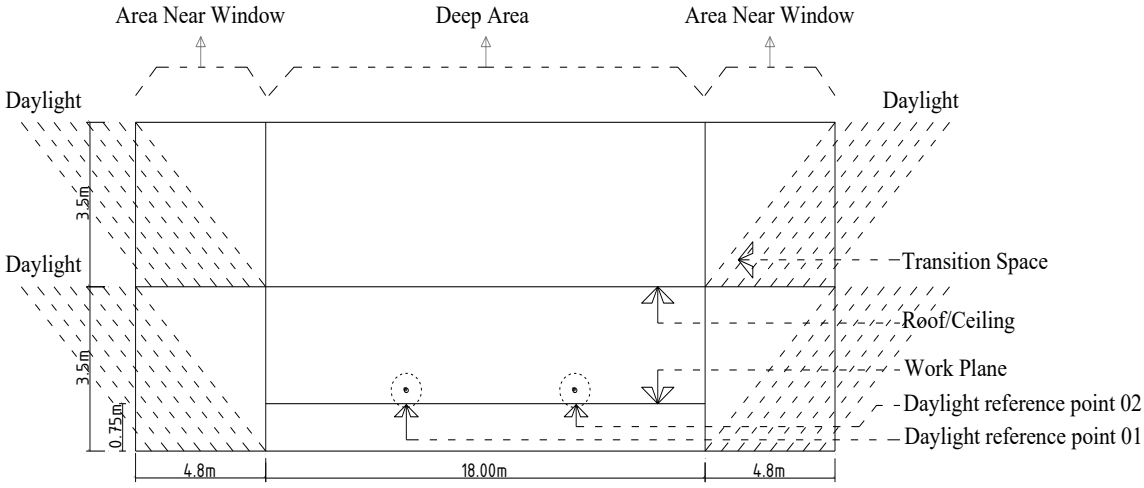


Figure 5.74(b): Section of simulation model 4(c)

Table 5.39: Daylighting distribution at illumination plane for case 04(c)

Point	A	B	C	D	E	F	G	H	I	J
a	138	138	138	138	138	138	138	138	138	138
b	141	162	189	268	305	311	306	268	362	138
c	142	250	190	180	181	183	188	217	469	138
d	164	297	85	70	65	72	88	92	242	138
e	159	323	80	40	16	17	30	50	157	138
f	160	326	89	35	17	18	36	61	147	138
g	162	317	110	78	66	95	90	90	145	138
h	165	274	223	206	196	181	163	150	145	138
i	149	218	325	373	368	306	190	151	143	138
j	139	143	145	144	143	142	141	140	140	138

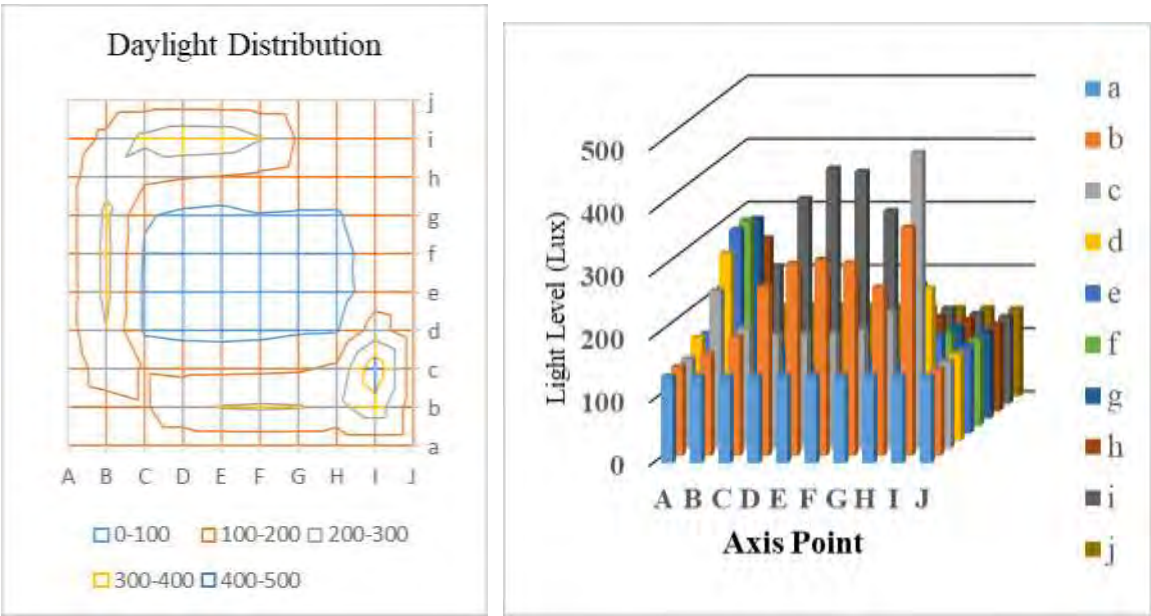


Figure 5.75: Daylighting distribution at illumination plane for case 04(c)

Table 5.39 shows the light level at the 100 point of the illuminance plane of **Model 02** (whole office area) at 12.00pm. This daylight was penetrate by window at the periphery area, but poor lighting at the central area as there was no light pipe installed at the ceiling level. Figure 5.75 show that the daylight coming from the windows illuminate the periphery area of the office. The brightest level of light 469 lux found at the edge of the space and the minimum light was 16 lux at the center of the space. The average light was 162 lux and the standard deviation was 88.2 lux (Figure 5.76). The median was 143 lux. The uniformity ratio below the light at workplane was 0.30 which was very poor comparing with the standard (≥ 0.60).

LIGHT Level(Lux)	**Value**
Min	16
Max	469
Avg	162
Median	143
SD	88.2

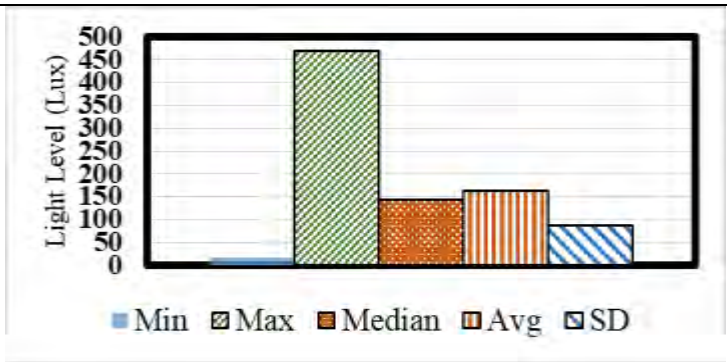


Figure 5.76: Daylighting distribution data analysis for case 04(c)

While considering only the illuminance level at the central part-f (Table 5.39), it has generated a curve line which indicate that the highest light found at the periphery area near the window of the space (Figure 5.77) and the lighting was very poor at the center of the simulated area as there was no lightpipe at the ceiling of the space.

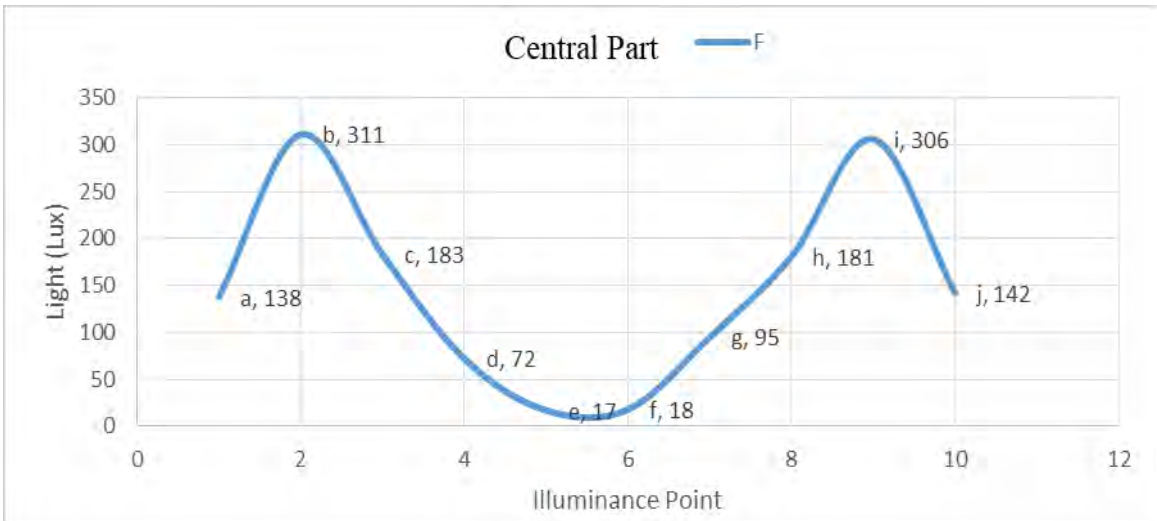


Figure 5.77: Daylighting distribution at central part (f) for case 04(c)

IV. Comparative Analysis

Table 5.40 show the lighting level at the central part (f) of the illuminance plane for every variation for different light pipe numbers with **Model 02** (Full area of office floor). From these data, it can be calculated the maximum, minimum and average value (Table 5.41).

Table 5.40: Daylighting distribution at illumination plane for lightpipe of different nos (model 02)

Point	A	B	C	D	E	F	G	H	I	J
3 Pipes +No Window	5	9	40	168	132	143	169	49	10	3
3 Pipes +Window	160	431	240	217	295	272	185	161	152	141
No Pipe +Window	160	326	89	35	17	18	36	61	147	138

Table 5.41: Daylighting distribution data analysis (model 02)

Option	Max	Min	Avg
3 Pipes +No Window	169	3	72.8
3 Pipes +Window	431	141	225.4
No Pipe +Window	326	17	102.7

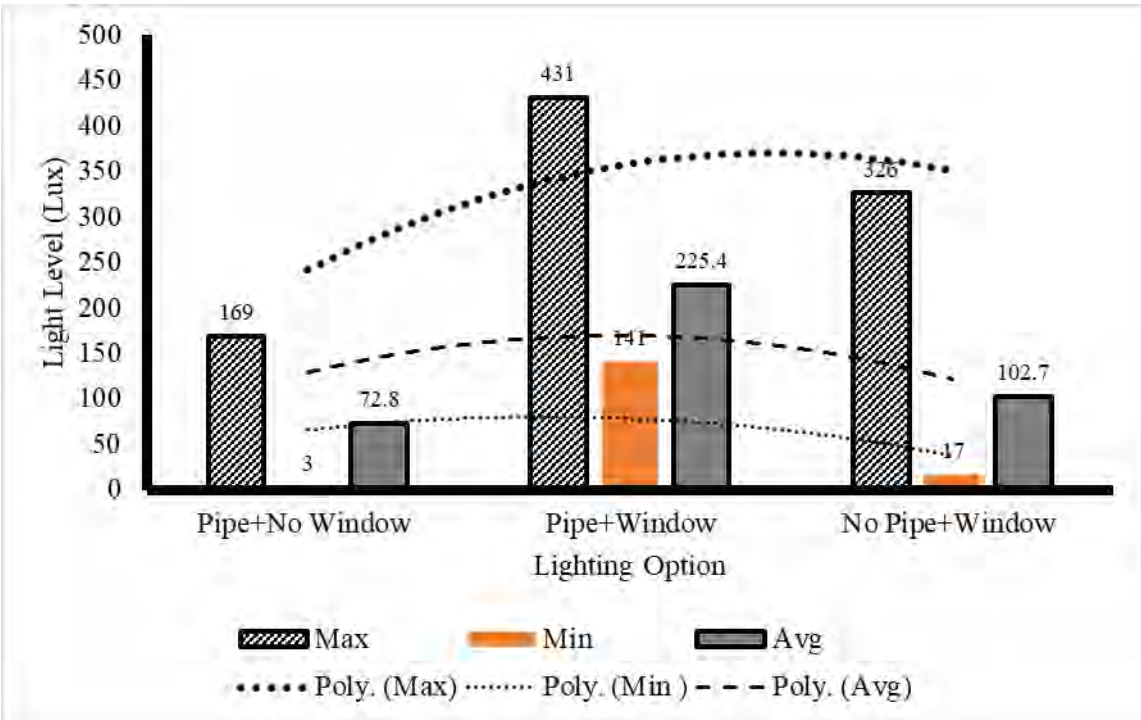


Figure 5.78: Daylighting distribution data analysis (model 02)

From the Figure 5.78 it is observed that the highest amount of daylight penetrate when window and lightpipe presents together. Only window without lightpipe brings much amount of light than only lightpipe without window. But the best result found by the combination of lightpipe and window.

V. Lighting Performance Comparison of Central Part

From the Table 5.41 it is also observed that the highest amount of daylight penetrates when window and lightpipe installed together (Figure 5.79). The illuminance was higher under the lightpipes when there was no window and light degrease at the edge of the space. Again there was no light at the central area but at the edge when there was no lightpipe but window at the side wall.

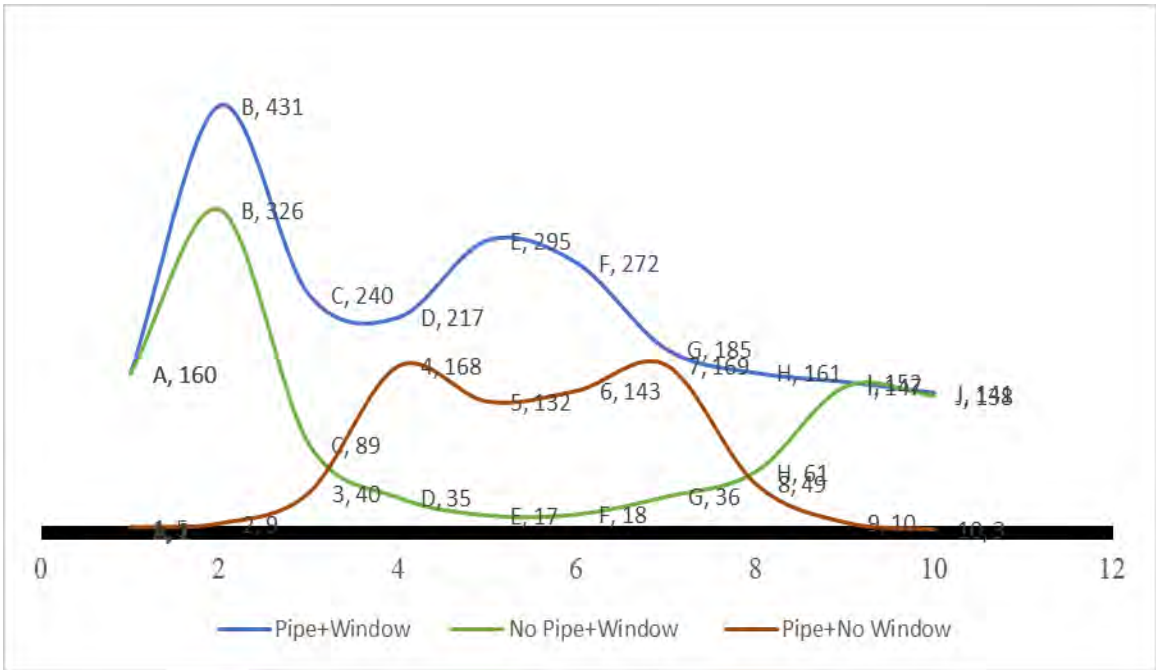


Figure 5.79: Daylighting distribution comparison at central part (model 02)

VI. Uniformity Ratio

The uniformity ratio found for different simulations of lightpipes with/without window below the pipes at the workplane have stated at the Table 5.42. The uniformity ratio of 03 pipes and windows was very close to the standards of the ratio most accurately which is ≥0.60%. Other results was far away from the standard value.

Table 5.42: Uniformity ratio of model 02

Pipe No.	3 Pipes, no window	3 Pipes and windows	No Pipe, only window
Uniformity Ratio	0.34	0.62	0.30

5.5 Amount of Light Penetration by day time (Hour)

The amount of light for an hour calculate by adding all light of 100 points of the illuminance plane for one lightpipe. Table 5.43 shows the amount of daylight enter by a

single lightpipe at different time (hour). At the starting of the office time, small amount of the daylight (88 Lux) enter by the lightpipe at the center of the office space. The maximum light enters at 12.00 am (2015 Lux) to 01.00 pm (1228 Lux). Then the amount of light again decreases by hours and no light enter at the end of the office time (Figure 5.88). Similar pattern of result was found in every simulation done by changing the variables. Figure 5.80 also shows that the standard error was 2.5%. From the standard error evolution it has been found that the calculated value may be deviated into (+/_) 2.5%. The trend line show that from 9.00am to 6.00pm-ovel shape distribution and from the overall calculation it was found that R^2=0.37.

Table 5.43: Hourly penetrated daylight (9am-6pm)

Time	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00
Lux	88	100	220	2015	1228	385	278	105	24	0

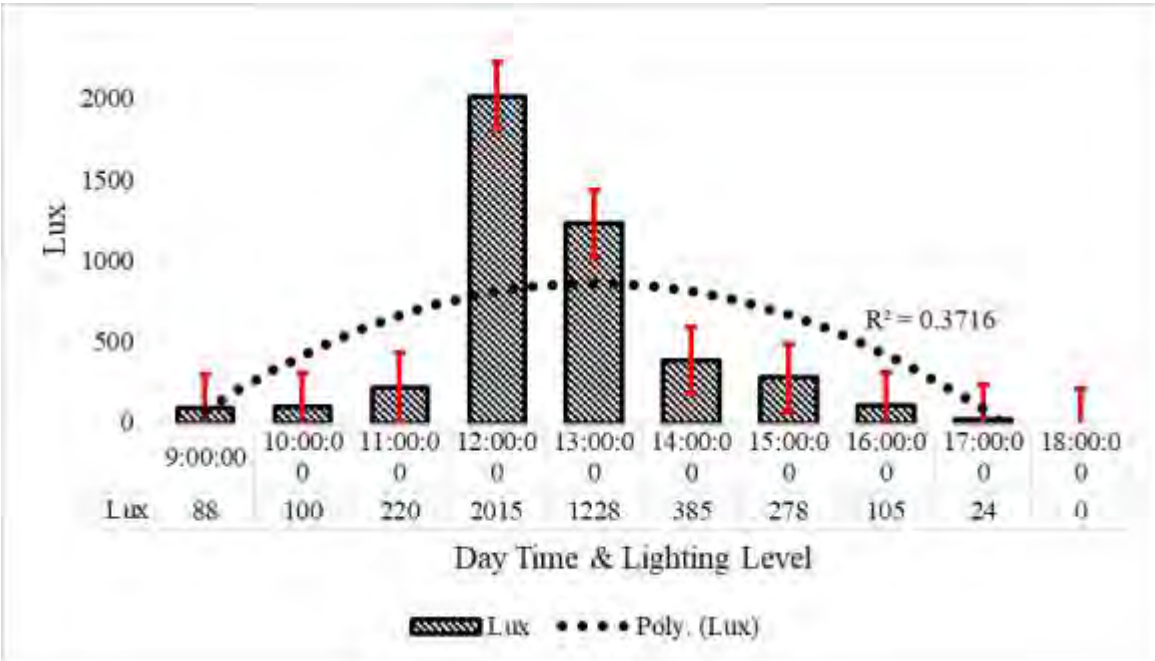


Figure 5.80: Hourly penetrated daylight (9am-6pm)

5.6 CDF Actual Frequency distribution

From the data of Appendix I, the Cumulative Distribution Function Actual Frequency Distribution graph (Figure 5.81) for Model 01 was generated. From the table it is observed that the highest value found for nine (9) lightpipes and the lowest value for one (1) lightpipe.

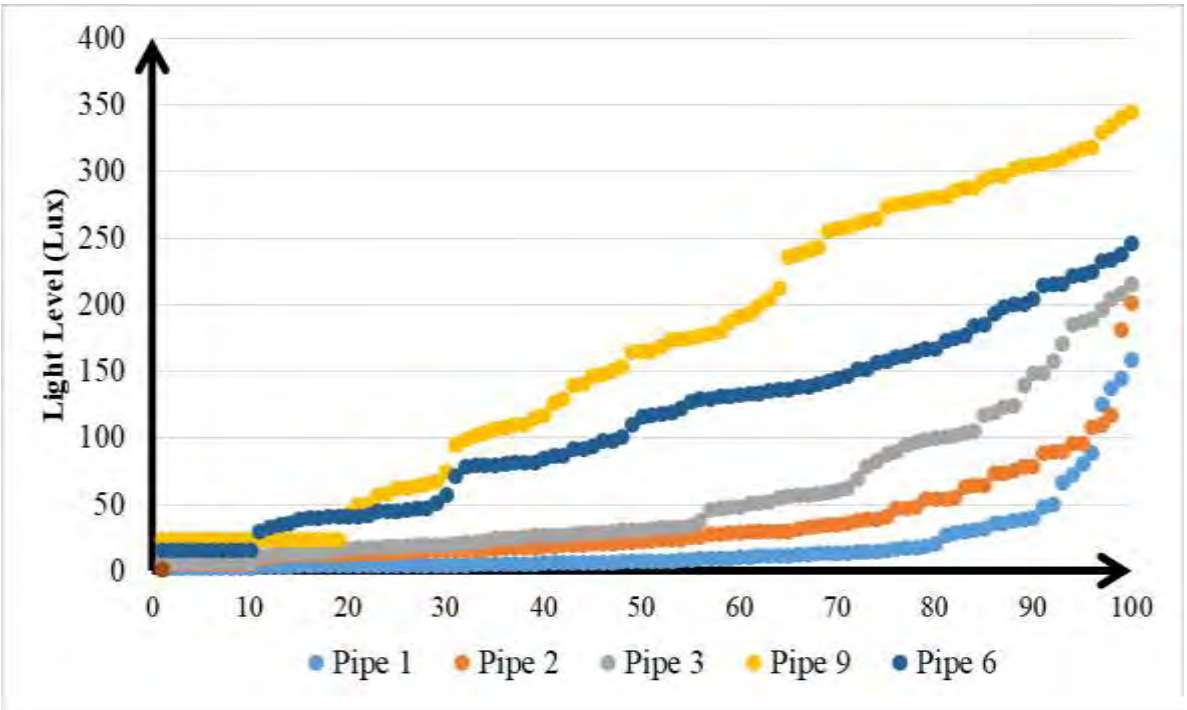


Figure 5.81: CDF actual frequency distribution for model 01

From the data of Appendix I, the Cumulative Distribution Function Actual Frequency Distribution graph (Figure 5.82) for Model 02 was generated. From the table it is observed that the highest value found when side window and lightpipes act together and the lowest value for lightpipes only.

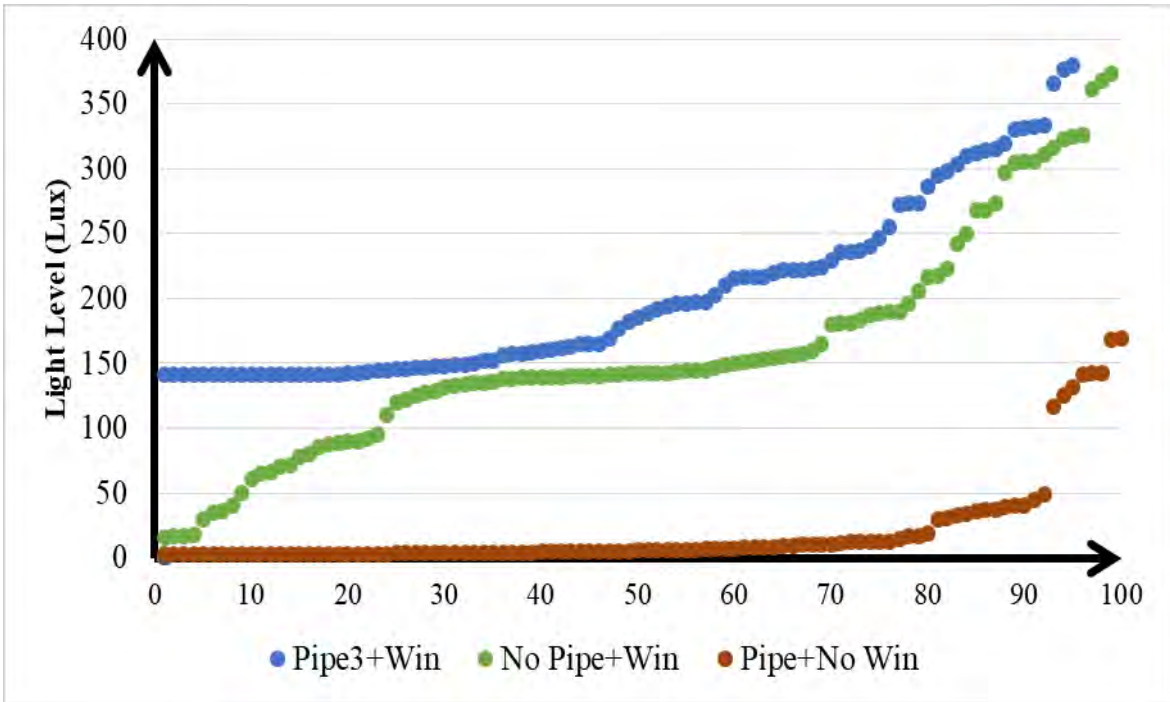


Figure 5.82: CDF actual frequency distribution for model 02

5.7 Result Analysis of Daylighting by Lightpipes at Bending Position

At this stage lightpipe at bending position were considered for simulation to find out illumination condition of example building (Opsonin Building) with lightpipes. For this simulation, Model 01 and Model 02 were used with all its properties remain same as discussed in 5.2 (Figure 5.1 and 5.2) (page 94). As it found the best illuminance with the lightpipe of 0.5m diameter, it remain fixed for every verities of simulations of Lightpipes at Bending Position (Figure 5.83). Bending angle was fixed at 90^0 for all cases.

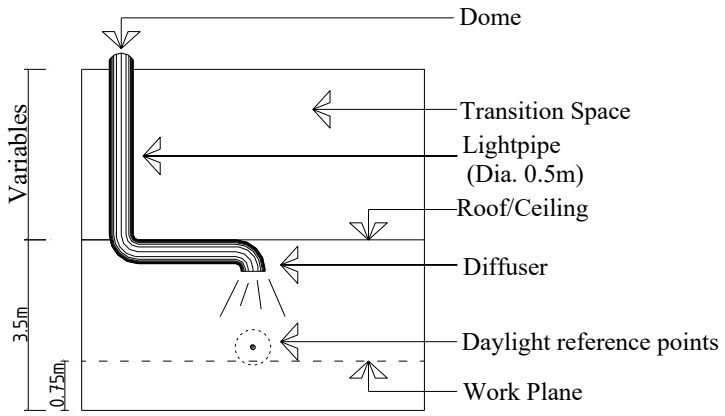


Figure 5.83: Typical section of lightpipe at bending positions

Index:

5.7.1 Lighting Simulation with Different Length of Bending Lightpipe				
Case No.	**Pipe Diameter**	**Pipe Length**	**Number of Pipe**	**Presence of Window**
05(a)	0.50m	3.5m	01	No.
05(b)		7.0m		
05(c)		10.5m		
05(d)		14.0m		
5.7.2 Lighting Simulation with Different No. of Bending Lightpipe				
Case No.	**Pipe Diameter**	**Pipe Length**	**Number of Pipe**	**Presence of Window**
06(a)	0.50m	3.5m	01	No.
06(b)			02	
06(c)			03	
06(d)			06	
06(e)			09	
5.7.3 Lighting Simulation with Bending Lightpipe and Window				
Case No.	**Pipe Diameter**	**Pipe Length**	**Number of Pipe**	**Presence of Window**
07(a)	0.50m	3.5m	03	Yes

5.7.1 Lighting Simulation with Different Length of Bending Lightpipes

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model. There was one (1) bended light pipe which diameter was 0.50m with a transition space (of variable heights) with one dome and diffuser. The Dome of light pipe was set at the edge of the area of roof (top of the transition space) and the ceiling (bottom of the transition space) contained the Diffuser of the light pipe at the center position (Figure 5.84). Horizontal distance was 5m between dome and diffuser. Length of the lightpipe was varied according to floor height such as one floor height (3.5m), two floor height (7.0m), three floor height (10.5m) and four floor height (14.0m).

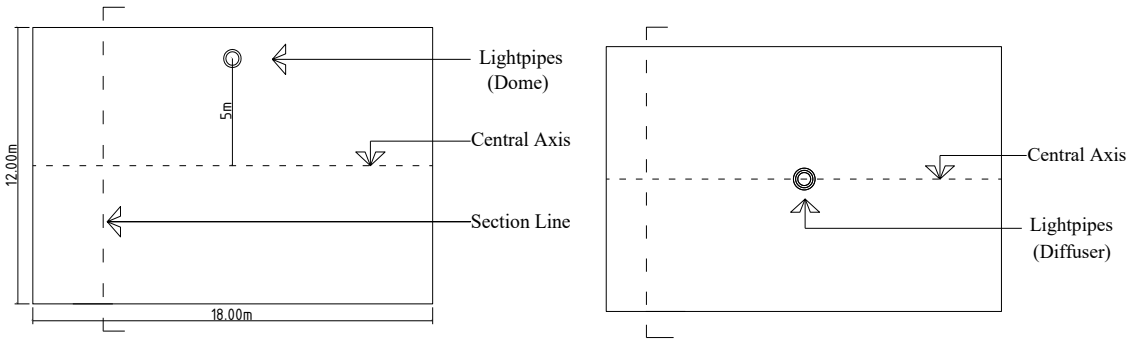


Figure 5.84: Typical plans showing position of dome and diffuser of lightpipes at bending positions

I. Case 5(a): Pipe Length 3.5m

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model. There was one (1) bended light pipe which diameter was 0.50m with a transition space (height 3.5m-one floor) with one dome and diffuser (Table 5.44). The dome of light pipe was set at one edge of the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the diffuser of the light pipe at the center position (Figure 5.84 and 5.85). Horizontal distance was 5m between dome and diffuser.

Table 5.44: Simulation model parameters for case 05(a)

Case	Pipe Diameter	**Pipe Length**	Number of Pipe	Presence of Window
05(a)	0.50m	**3.5m**	01	No

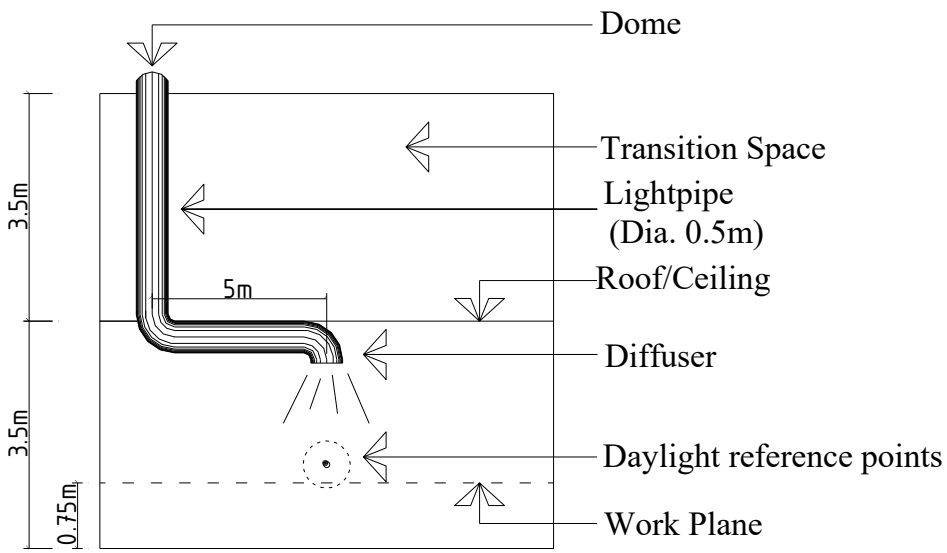


Figure 5.85: Section of simulation model 05(a)

Table 5.45: Daylighting distribution at illumination plane for case 05(a)

Point	A	B	C	D	E	F	G	H	I	J
a	3	3	3	3	3	3	3	3	3	3
b	3	5	7	11	16	17	12	7	5	4
c	3	5	9	18	34	36	20	10	6	4
d	3	6	11	29	75	83	35	13	6	4
e	3	6	13	41	137	158	51	16	7	4
f	3	6	13	41	137	158	51	16	7	4
g	3	6	11	29	75	83	35	13	6	4
h	3	5	9	18	34	36	20	10	6	4
i	3	5	7	11	16	17	12	7	5	4
j	3	4	5	7	9	9	7	5	4	3

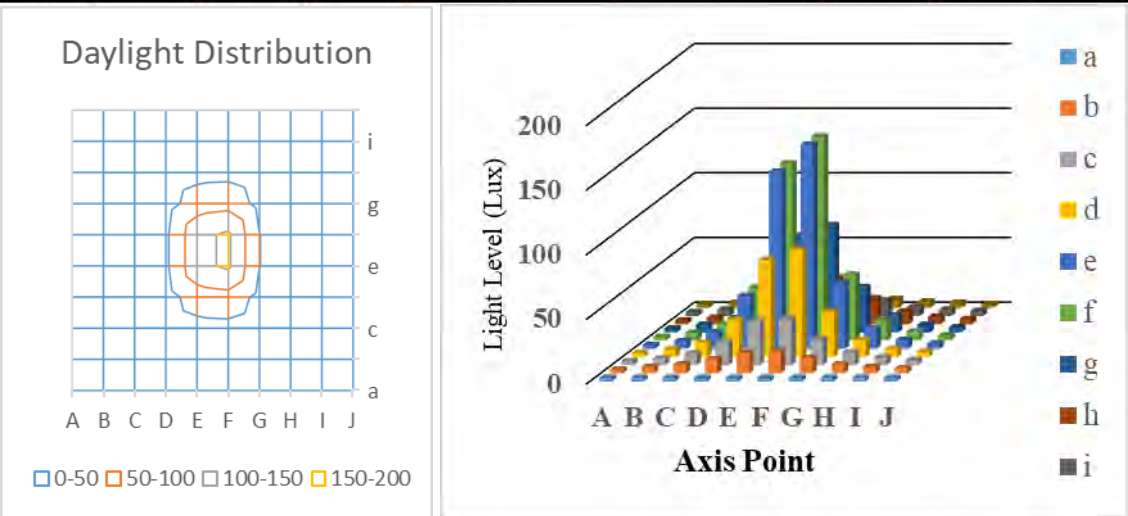


Figure 5.86: Daylighting distribution at illumination plane for case 05(a)

Table 5.45 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the installed light pipe. Figure 5.86 shows that daylight only illuminate the space under the diffuser and constantly decrease at the

periphery area. The brightest level of light 158 lux found at the space under the diffuser and the light found at the periphery area was very low (less than 50 lux). The minimum light was only 3 lux. The average light was 19.5 lux and the standard deviation was 31.5 lux (Figure 5.87). The median was 7 lux. The uniformity ratio below the light at workplane was 0.37 which was very poor comparing with the standard (≥ 0.60).

Light Level (Lux)	Value
Min	3
Max	158
Avg	19.5
Median	7
SD	31.5

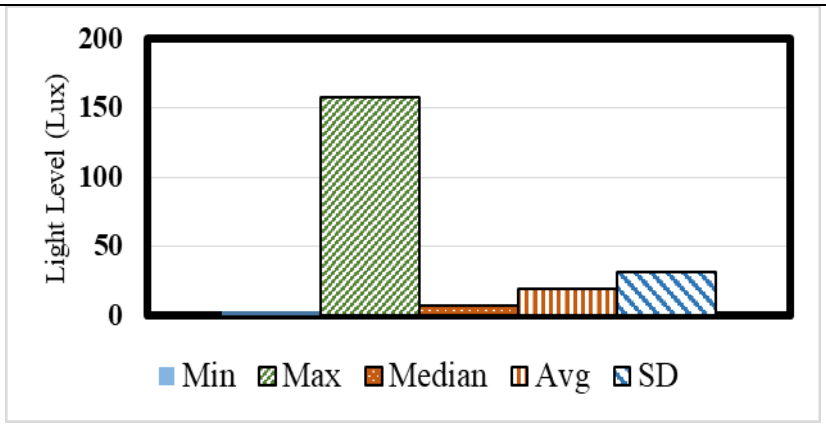


Figure 5.87: Daylighting distribution data analysis for case 05(a)

While considering only the illuminance level at the central part-f (Table 5.45), it has generated a curve line which indicate that the highest light found at 5m away from center of the space under the diffuser (Figure 5.88) and the amount of light decreases with the distance of the diffuser.

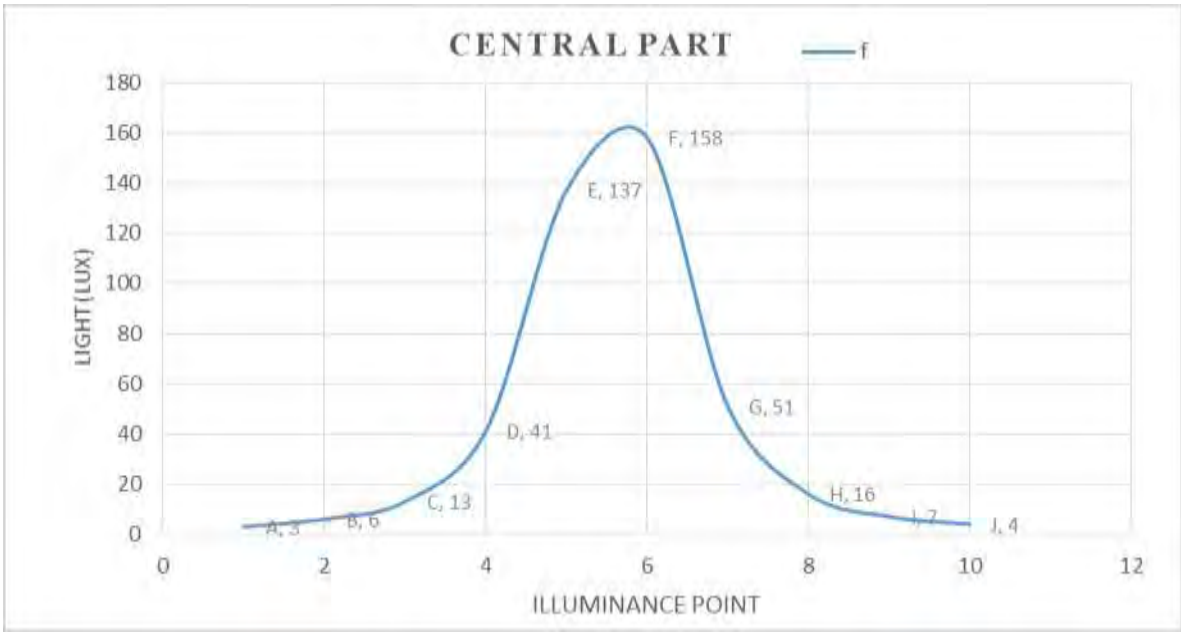


Figure 5.88: Daylighting distribution at central part (f) for case 05(a)

II. Case 5(b): Pipe Length 7.0m

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model. There was one (1) bended light pipe which diameter was 0.50m with a transition space (height 7.0m-two floor) with one dome and diffuser (Table 5.46). The dome of light pipe was set at one edge of the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the diffuser of the light pipe at the center position (Figure 5.84 and 5.89). Horizontal distance was 5m between dome and diffuser.

Table 5.46: Simulation model parameters for case 05(b)

Case	Pipe Diameter	**Pipe Length**	Number of Pipe	Presence of Window
05(b)	0.50m	**7.0m**	01	No

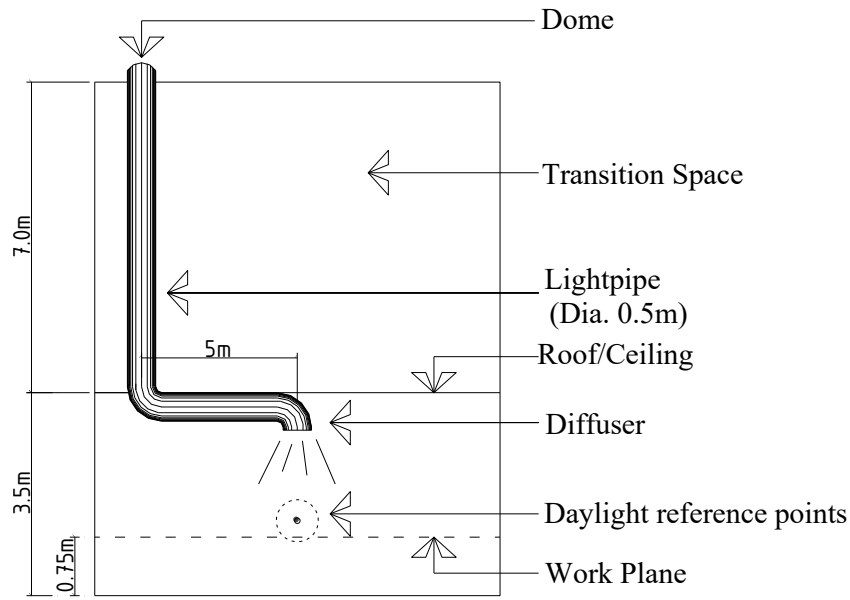


Figure 5.89: Section of simulation model 05(b)

Table 5.47: Daylighting distribution at illumination plane for case 05(b)

Point	A	B	C	D	E	F	G	H	I	J
a	2	2	2	2	2	2	2	2	2	2
b	2	4	7	11	16	16	12	7	5	4
c	2	5	9	18	33	35	20	10	5	4
d	2	6	11	29	74	82	35	13	6	4
e	2	6	13	40	134	155	50	15	7	4
f	2	6	13	40	134	155	50	15	7	4
g	2	6	11	29	74	82	35	13	6	4
h	2	5	9	18	33	35	20	10	5	4
i	2	4	7	11	16	16	12	7	5	4
j	2	4	5	7	9	9	7	5	4	3

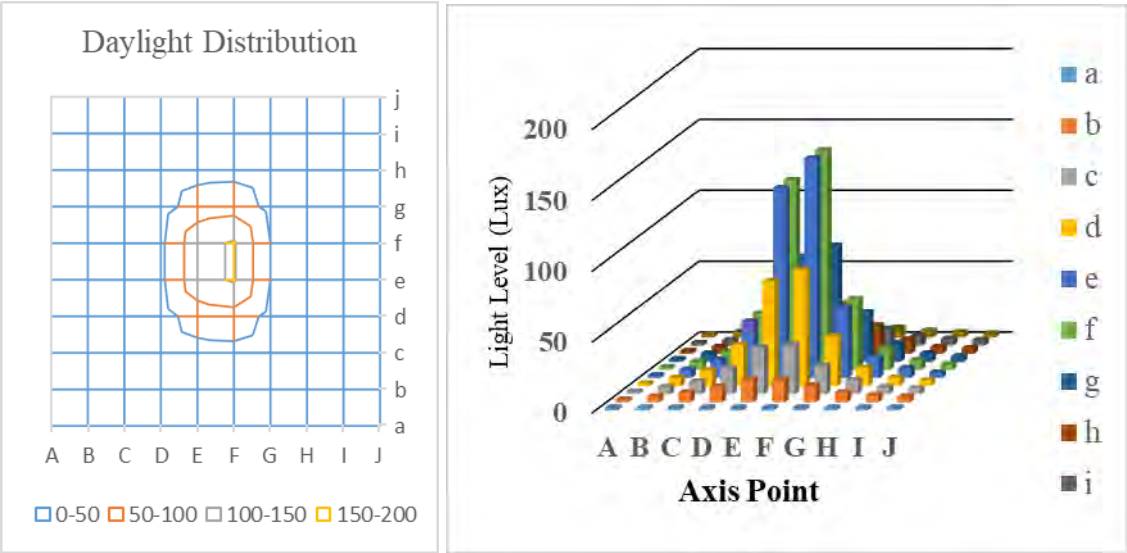


Figure 5.90: Daylighting distribution at illumination plane for case 05(b)

Table 5.47 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the installed light pipe. Figure 5.90 shows that daylight only illuminate the space under the diffuser and constantly decrease at the periphery area. The brightest level of light 155 lux found at the space under the diffuser and the light found at the periphery area was very low (less than 50 lux). The minimum light was only 2 lux. The average light was 19 lux and the standard deviation was 31 lux (Figure 5.91). The median was 7 lux. The uniformity ratio below the light at workplane was 0.37 which was very poor comparing with the standard (≥ 0.60).

Light Level (Lux)	Value
Min	2
Max	155
Avg	19
Median	7
SD	31

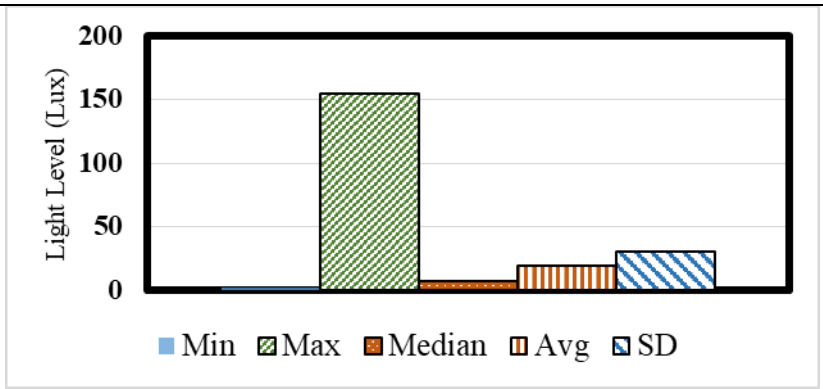


Figure 5.91: Daylighting distribution data analysis for case 05(b)

While considering only the illuminance level at the central part-f (Table 5.47), it has generated a curve line which indicate that the highest light found at 5m away from center of the space under the diffuser (Figure 5.92) and the amount of light decreases with the distance of the diffuser.

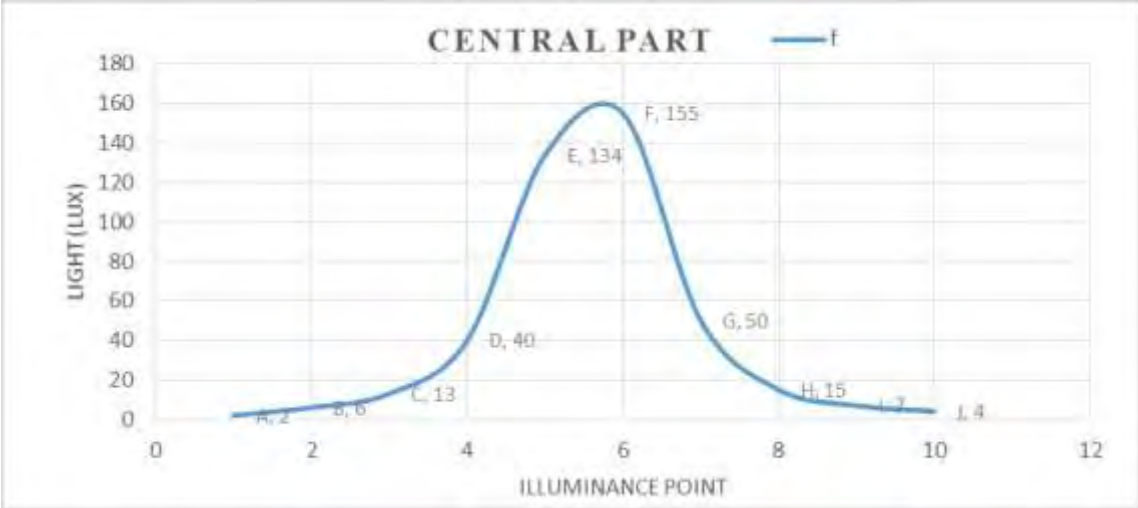


Figure 5.92: Daylighting distribution at central part (f) for case 05(b)

III. Case 5(c): Pipe Length 10.5m

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model. There was one (1) bended light pipe which diameter was 0.50m with a transition space (height 10.5m-three floor) with one dome and diffuser (Table 5.48. The dome of light pipe was set at one edge of the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the diffuser of the light pipe at the center position (Figure 5.84 and 5.93). Horizontal distance was 5m between dome and diffuser.

Table 5.48: Simulation model parameters for case 05(c)

Case	Pipe Diameter	**Pipe Length**	Number of Pipe	Presence of Window
05(c)	0.50m	**10.5m**	01	No

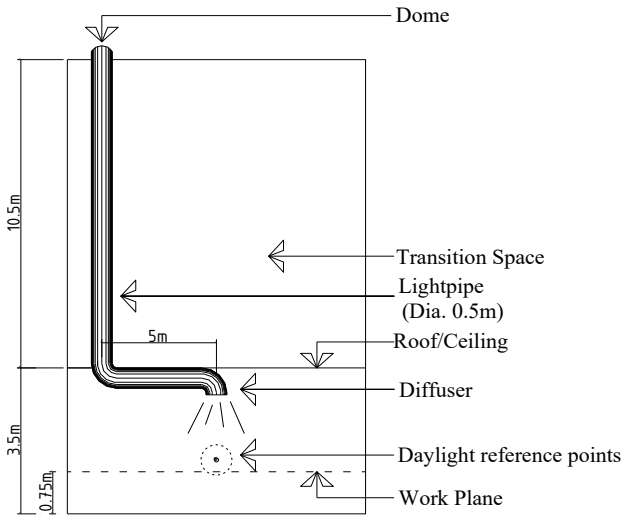


Figure 5.93: Section of simulation model 05(c)

Table 5.49: Daylighting distribution at illumination plane for case 05(c)

Point	A	B	C	D	E	F	G	H	I	J
a	2	2	2	2	2	2	2	2	2	2
b	2	4	7	11	16	16	12	7	5	4
c	2	5	9	18	33	35	20	10	5	4
d	2	6	11	29	64	72	35	13	6	4
e	2	6	13	40	124	144	50	15	7	4
f	2	6	13	40	124	144	50	15	7	4
g	2	6	11	29	64	72	35	13	6	4
h	2	5	9	18	33	35	20	10	5	4
i	2	4	7	11	16	16	12	7	5	4
j	2	4	5	7	9	9	7	5	4	3

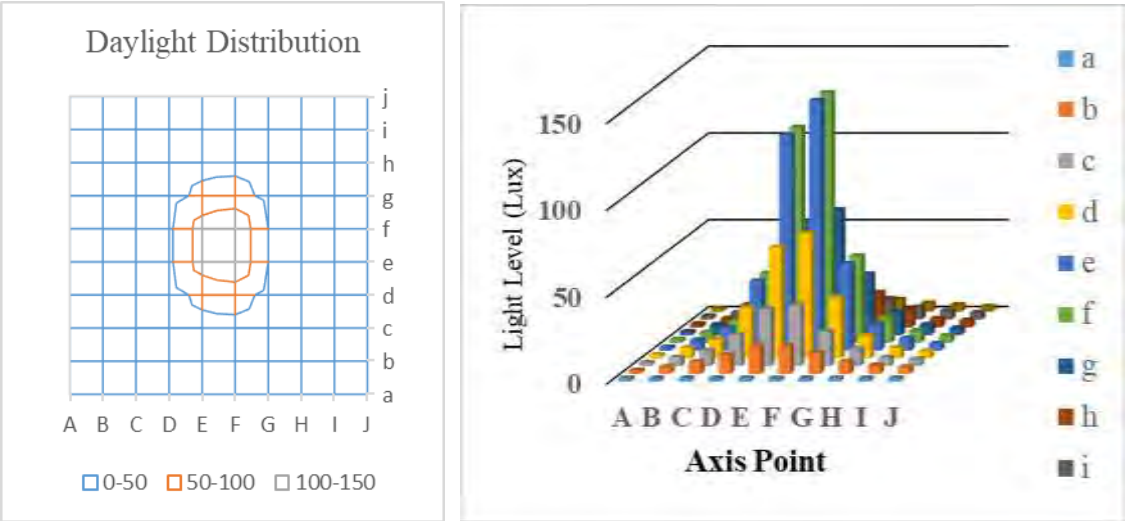


Figure 5.94: Daylighting distribution at illumination plane for case 05(c)

Table 5.49 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the installed light pipe. Figure 5.94 shows that daylight only illuminate the space under the diffuser and constantly decrease at the periphery area. The brightest level of light 144 lux found at the space under the diffuser and the light found at the periphery area was very low (less than 50 lux).

Light Level (Lux)	Value
Min	2
Max	144
Avg	18.2
Median	7
SD	28.5

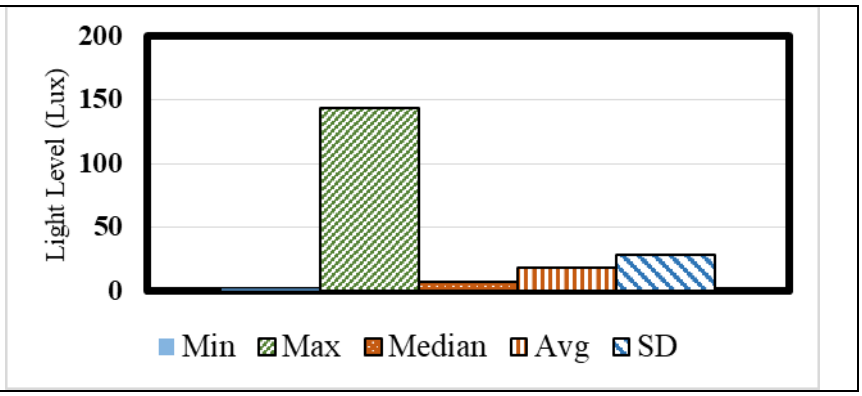


Figure 5.95: Daylighting distribution data analysis for case 05(c)

The minimum light was only 2 lux. The average light was 18.2 lux and the standard deviation was 28.5 lux (Figure 5.95). The median was 7 lux. The uniformity ratio below the light at workplane was 0.37 which was very poor comparing with the standard (≥ 0.60).

While considering only the illuminance level at the central part-f (Table 5.49), it has generated a curve line which indicate that the highest light found at 5m away from center of the space under the diffuser (Figure 5.96) and the amount of light decreases with the distance of the diffuser.

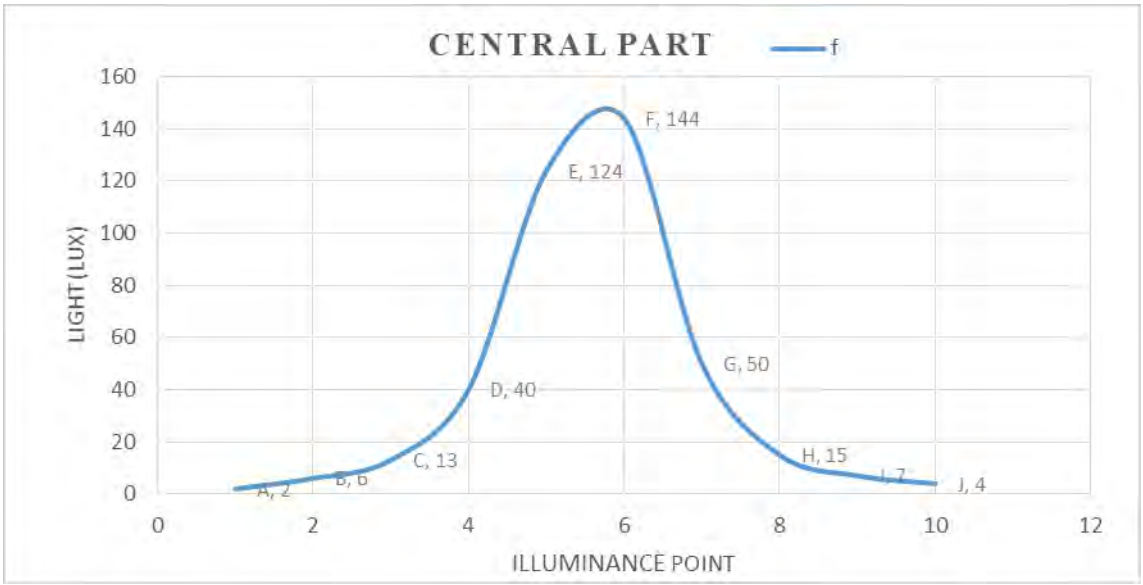


Figure 5.96: Daylighting distribution at central part (f) for case 05(c)

IV. Case 5(d): Pipe Length 14.0m

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model. There was one (1) bended light pipe which diameter was 0.50m with a transition space (height 14.0m-four floor) and with one dome and diffuser (Table 5.50). The dome of light pipe was set at one edge of the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the diffuser of the light pipe at the center position (Figure 5.84 and 5.97). Horizontal distance was 5m between dome and diffuser.

Table 5.50: Simulation model parameters for case 05(d)

Case	Pipe Diameter	**Pipe Length**	Number of Pipe	Presence of Window
05(d)	0.50m	**14.0m**	01	No

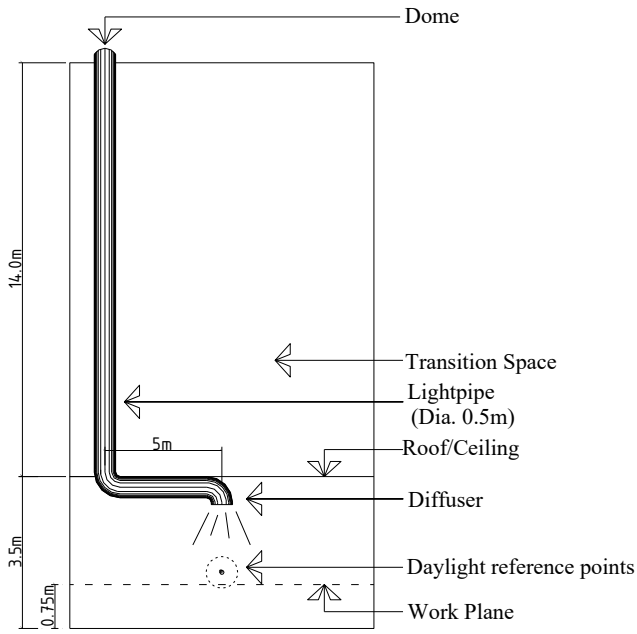


Figure 5.97: Section of simulation model 05(d)

Table 5.51: Daylighting distribution at illumination plane for case 05(d)

Point	A	B	C	D	E	F	G	H	I	J
a	2	2	2	2	2	2	2	2	2	2
b	2	4	7	11	16	16	12	7	5	4
c	2	5	9	18	33	35	20	10	5	4
d	2	6	11	29	64	72	35	13	6	4
e	2	6	13	40	124	134	50	15	7	4
f	2	6	13	40	124	134	50	15	7	4
g	2	6	11	29	64	72	35	13	6	4
h	2	5	9	18	33	35	20	10	5	4
i	2	4	7	11	16	16	12	7	5	4
j	2	4	5	7	9	9	7	5	4	3

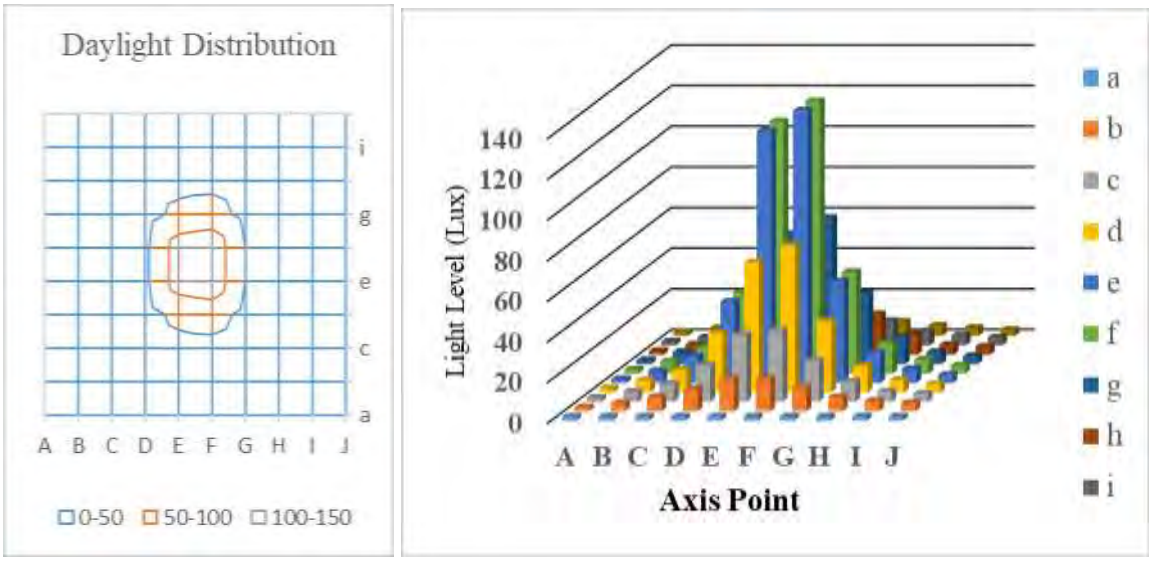


Figure 5.98: Daylighting distribution at illumination plane for case 05(d)

Table 5.51 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by the installed light pipe. Figure 5.98 shows that daylight only illuminate the space under the diffuser and constantly decrease at the periphery area. The brightest level of light 134 lux found at the space under the diffuser and the light found at the periphery area was very low (less than 50 lux). The minimum light was only 2 lux. The average light was 18 lux and the standard deviation was 27.7 lux (Figure 5.99). The median was 7 lux. The uniformity ratio below the light at workplane was 0.37 which was very poor comparing with the standard (≥ 0.60).

Light Level (Lux)	Value
Min	2
Max	134
Avg	18
Median	7
SD	27.7

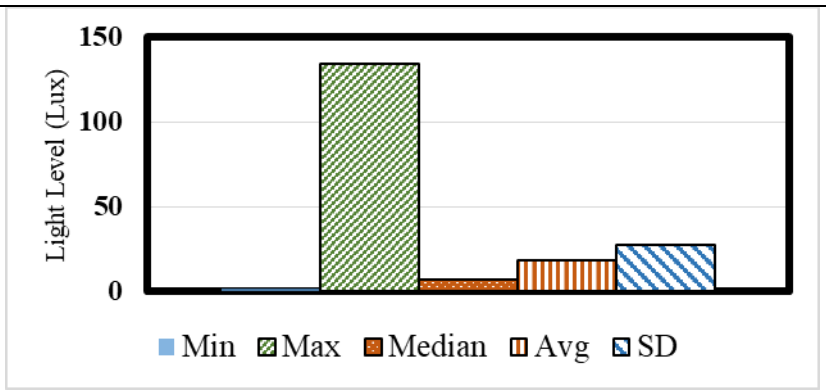


Figure 5.99: Daylighting distribution data analysis for case 05(d)

While considering only the illuminance level at the central part-f (Table 5.51), it has generated a curve line which indicate that the highest light found at 5m away from center of the space under the diffuser (Figure 5.100) and the amount of light decreases with the distance of the diffuser.

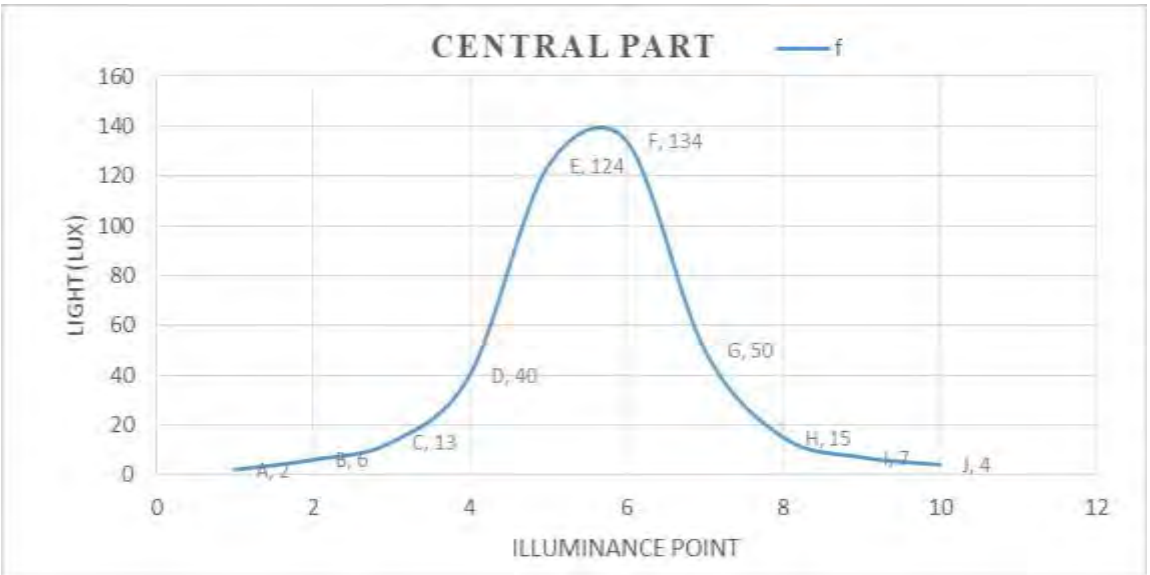


Figure 5.100: Daylighting distribution at central part (f) for case 05(d)

V. Comparative Analysis

Table 5.52 show the lighting level at the central part (f) of the illuminance plane for every variation for different length of bending light pipes with **Model 01** (The deep part of the office floor). From these data, it is observed that the difference of amount of daylight entered by lightpipe of different length are very minimum. Daylight entered into the office space at the same ratio by the time (hour). Highest light found under the diffuser and it has decreases with the distance from diffuser (Figure 5.101). Maximum daylight entered by the lightpipe of 3.5m length and minimum light found by the lightpipe of 14.0 m length.

The **uniformity ratio** below the light at workplane found 0.37 for all cases.

Table 5.52: Daylighting distribution at central part (f) of illumination plane for bended lightpipe of different length

Length	A	B	C	D	E	F	G	H	I	J
3.65m	3	6	13	41	137	158	51	16	7	4
7.30m	2	6	13	40	134	155	50	15	7	4
10.95m	2	6	13	40	124	144	50	15	7	4
14.60m	2	6	13	40	124	134	50	15	7	4

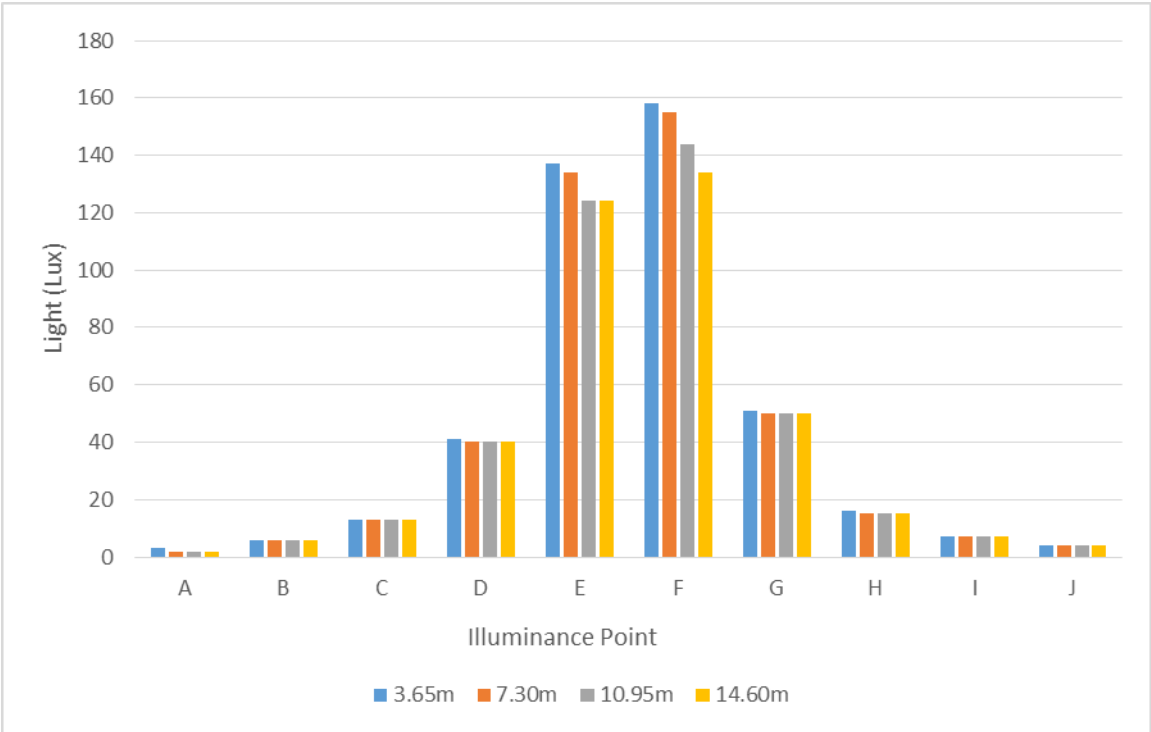


Figure 5.101: Daylighting variation for different length of lightpipes

5.7.2 Lighting Simulation with Different No. of Bending Lightpipes

I. Case 6(a): One(1) Pipe

This model simulation criteria and results were similar to the case 05(a) –Page 149.

II. Case 6(b): Two(2) Pipes

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model. There were two (2) bended lightpipes which diameter was 0.50m with a transition space (height 3.5-one floor) and with two domes and two diffusers (Table 5.53). The domes of light pipes were set at one edge of the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the diffusers of the light pipes at the center position (Figure 5.102). Distance between two diffusers was 8m.

Table 5.53: Simulation model parameters for case 06(b)

Case	Pipe Diameter	Pipe Length	**Number of Pipe**	Presence of Window
06(a)	0.50m	3.5m	**02**	No

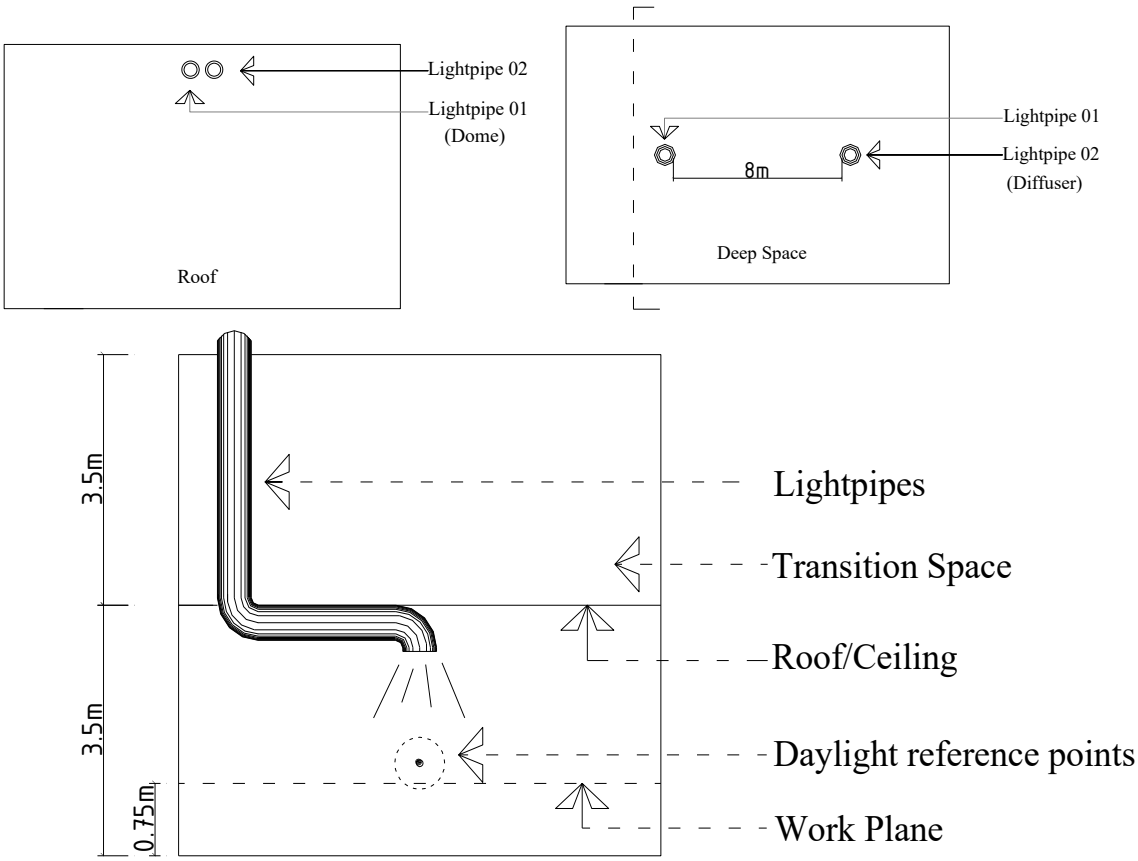


Figure 5.102: Plans and section of simulation model 06(b)

Table 5.54: Daylighting distribution at illumination plane for case 06(b)

Point	A	B	C	D	E	F	G	H	I	J
a	5	5	5	5	5	5	5	5	5	5
b	11	15	19	18	15	14	17	19	16	11
c	14	25	37	32	21	20	29	38	28	16
d	19	45	85	61	30	27	54	87	53	22
e	23	71	172	106	38	34	87	176	88	27
f	24	76	191	114	39	35	93	196	94	28
g	20	52	105	73	32	29	63	107	62	23
h	15	30	46	37	23	22	34	47	33	17
i	11	17	22	20	16	15	19	23	18	12
j	9	11	13	13	12	11	13	13	12	9

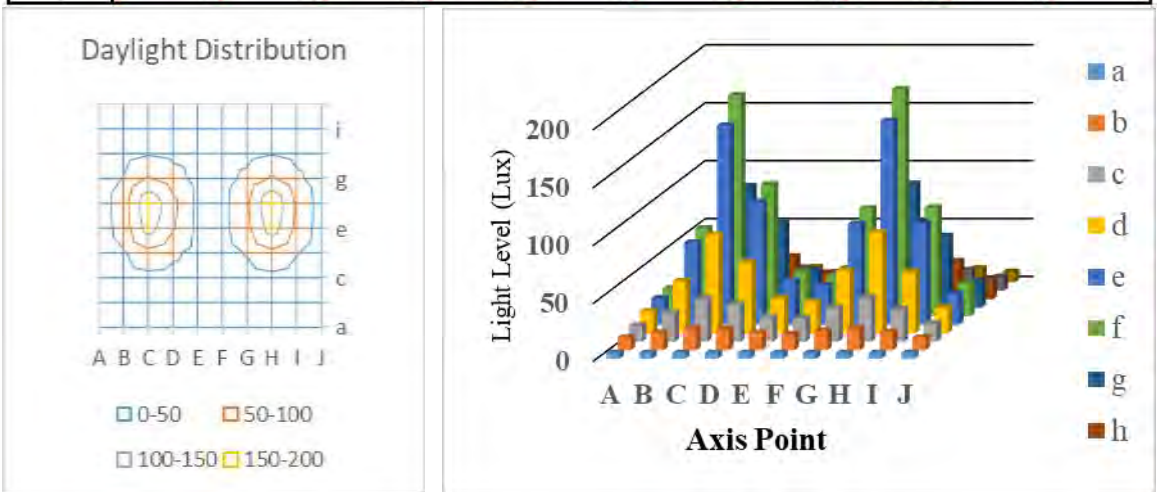


Figure 5.103: Daylighting distribution at illumination plane for case 06(b)

Table 5.54 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by two light pipes installed at the ceiling level with 0.5m distance. Figure 5.103 shows that daylight have illuminated the space under the diffusers which were 8m away from each other and constantly decrease at the periphery area. The brightest level of light 196 lux found at the space under the diffuser and the light found at the periphery area was very low (less than 50 lux).

Light Level (Lux)	Value
Min	5
Max	196
Avg	38.2
Median	23
SD	40.2

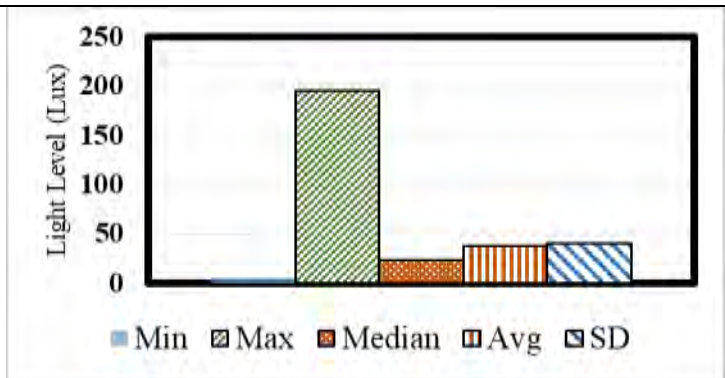


Figure 5.104: Daylighting distribution data analysis for case 06(b)

The minimum light was only 5 lux. The average light was 38.2 lux and the standard deviation was 40.2 lux (Figure 5.104). The median was 23 lux. The uniformity ratio below the light at workplane was 0.45 which was very poor comparing with the standard (≥ 0.60).

While considering only the illuminance level at the central part-f (Table 5.54), it has generated a curve line which indicate that the highest lights found under the diffusers (Figure 5.105) and the amount of light decreases with the distance of the diffusers.

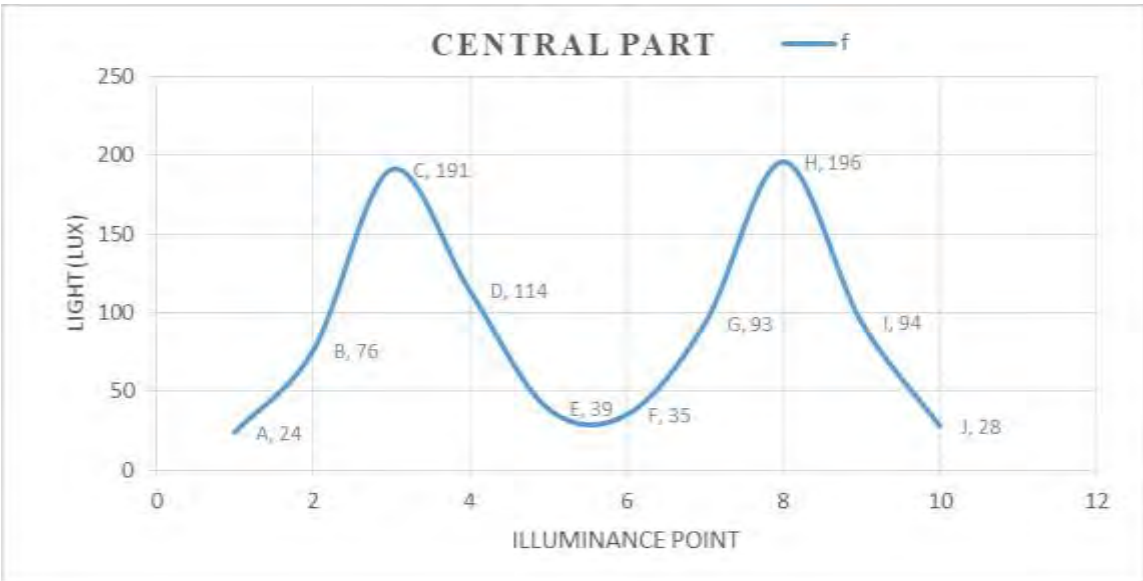


Figure 5.105: Daylighting distribution at central part (f) for case 06(b

III. Case 6(c): Three (3) Pipes

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model. There were three (3) bended lightpipes which diameter was 0.50m with a transition space (height 3.5m-one floor) and with three domes and three diffusers (Table 5.55). The domes of light pipes were set at one edge of the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the diffusers of the light pipes at the center position (Figure 5.106). Distance between the diffusers were 4m.

Table 5.55: Simulation model parameters for case 06(c)

Case	Pipe Diameter	Pipe Length	**Number of Pipe**	Presence of Window
06(b)	0.50m	3.5m	**03**	No

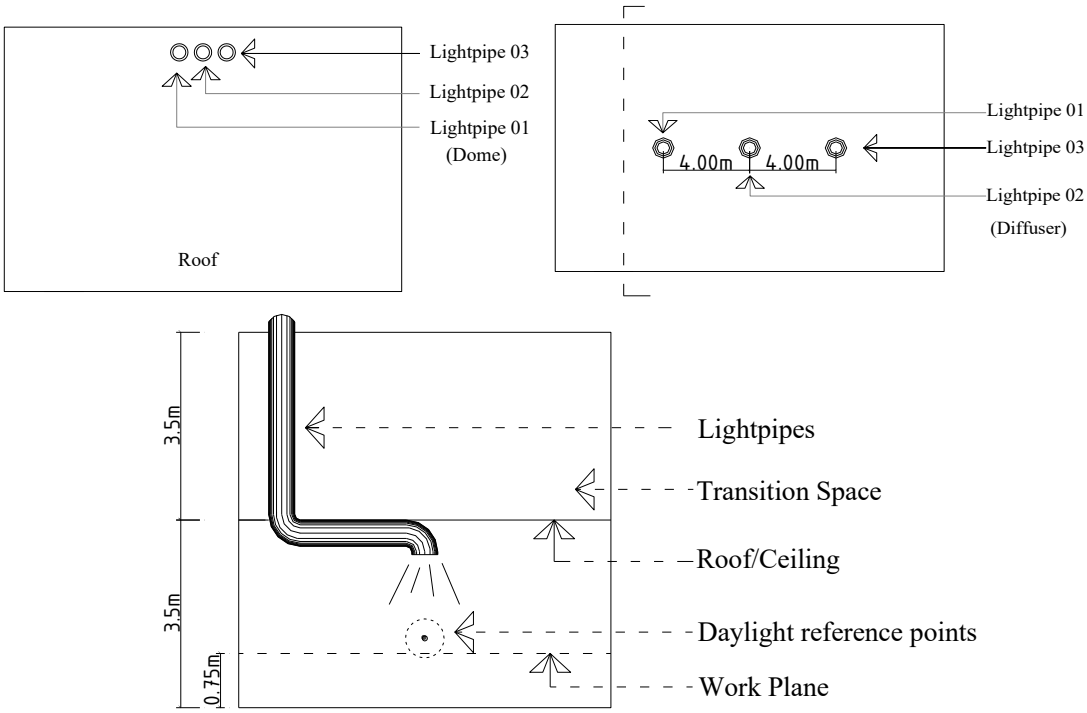


Figure 5.106: Plans and section of simulation model 06(c)

Table 5.56: Daylighting distribution at illumination plane for case 06(c)

Point	A	B	C	D	E	F	G	H	I	J
a	8	8	8	8	8	8	8	8	8	8
b	12	18	24	26	27	28	26	24	19	13
c	16	29	44	46	49	50	46	45	32	18
d	21	49	94	87	95	100	85	97	57	24
e	25	75	182	132	175	180	134	188	92	30
f	26	80	201	142	188	196	143	208	98	31
g	22	56	114	101	113	119	98	118	66	26
h	17	33	53	55	58	60	54	55	37	19
i	13	20	27	30	32	32	30	28	22	14
j	10	13	15	17	17	17	17	16	14	11

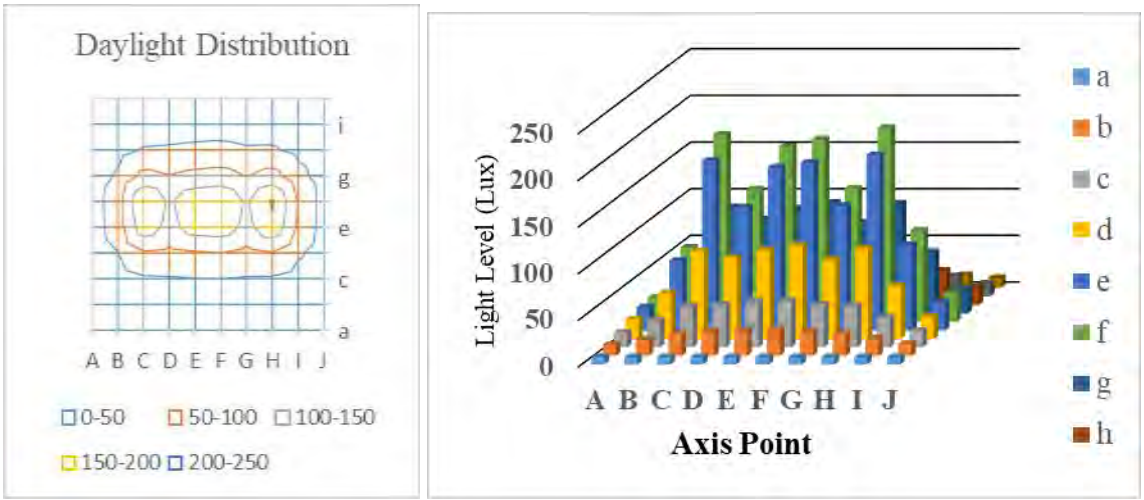


Figure 5.107: Daylighting distribution at illumination plane for case 06(c)

Table 5.56 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by three light pipes installed at the ceiling level in a group. Figure 5.107 shows that daylight have illuminated the space under the diffusers which were 8m away from each other and constantly decrease at the periphery area. The brightest level of light 208 lux found at the space under the diffuser and the light found at the periphery area was very low (less than 50 lux). The minimum light was only 8 lux. The average light was 55.8 lux and the standard deviation was 53.2 lux (Figure 5.108). The median was 30.5 lux. The uniformity ratio below the light at workplane was 0.58 which was very close to the standards (≥0.60).

Light Level (Lux)	Value
Min	8
Max	208
Avg	55.8
Median	30.5
SD	53.2

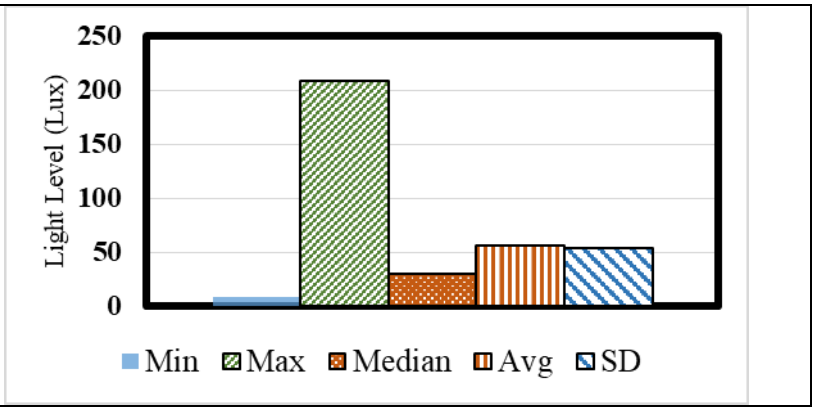


Figure 5.108: Daylighting distribution data analysis for case 06(c)

While considering only the illuminance level at the central part-f (Table 5.56), it has generated a curve line which indicate that the highest lights found under the diffusers (Figure 5.109) and the amount of light decreases with the distance of the diffusers.

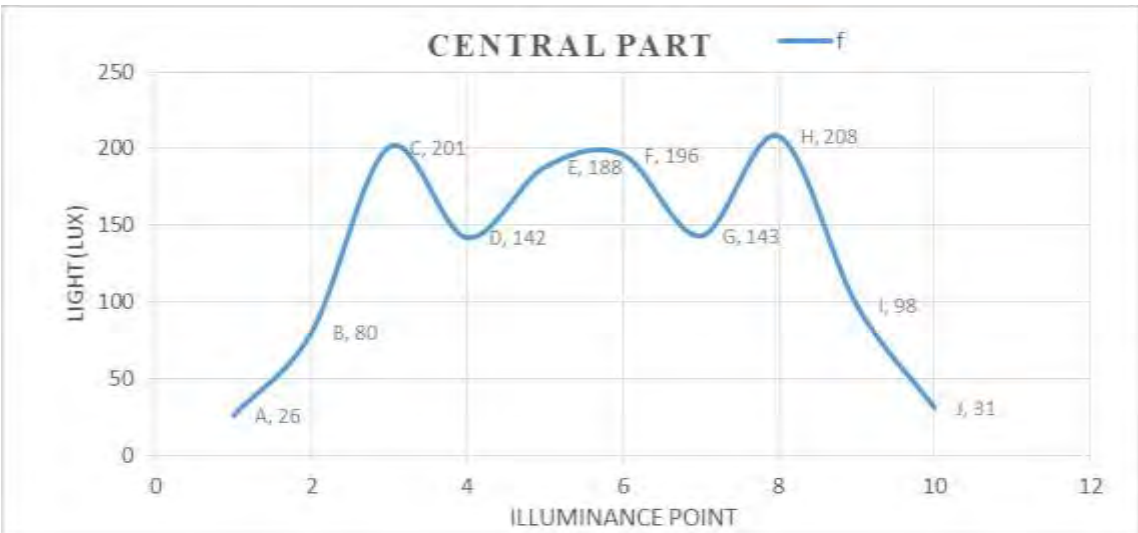


Figure 5.109: Daylighting distribution at central part (f) for case 06(c)

IV. Case 6(d): Six(6) Pipes

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model. There were six (6) bended lightpipes which diameter was 0.50m with a transition space (height 3.5m-one floor) and with six domes and six diffusers (Table 5.57). The domes of light pipes were set at one edge of the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the diffusers of the light pipes at the center position (Figure 5.110). Distance between the diffusers were 5m by length and 4m by width.

Table 5.57: Simulation model parameters for case 06(d)

Case	Pipe Diameter	Pipe Length	**Number of Pipe**	Presence of Window
06(c)	0.50m	3.5m	**06**	No

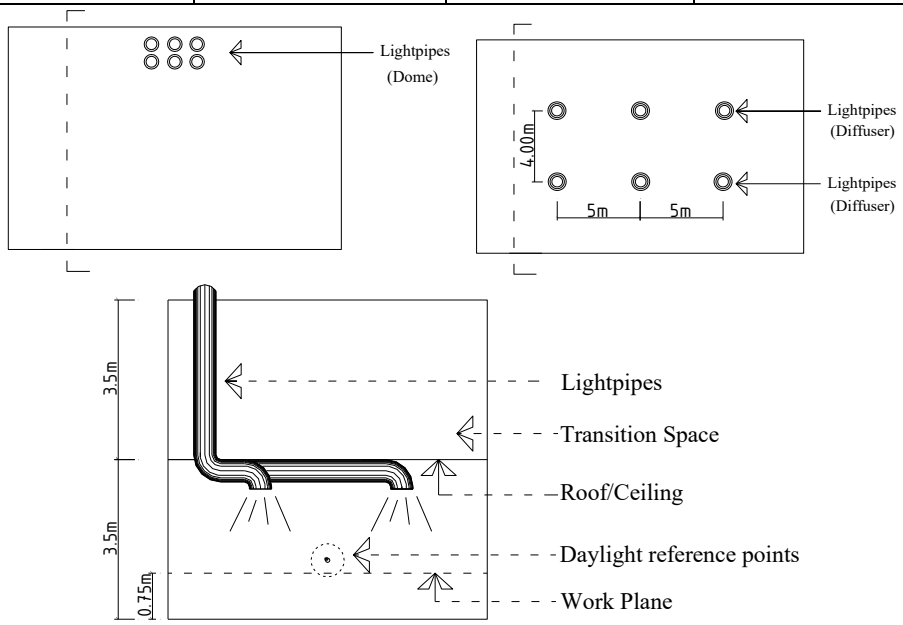


Figure 5.110: Plans and section of simulation model 06(d)

Table 5.58: Daylighting distribution at illumination plane for case 06(d)

Point	A	B	C	D	E	F	G	H	I	J
a	15	15	15	15	15	15	15	15	15	15
b	34	68	127	115	126	133	112	131	79	37
c	39	94	217	170	197	215	161	225	113	44
d	40	95	207	169	193	208	161	214	113	45
e	39	78	135	120	141	146	118	139	88	43
f	39	75	124	114	133	137	114	128	84	43
g	40	90	186	159	179	191	152	192	106	45
h	39	98	229	177	206	225	167	237	118	45
i	35	76	121	111	116	126	106	126	79	39
j	20	29	56	37	42	44	36	39	34	22

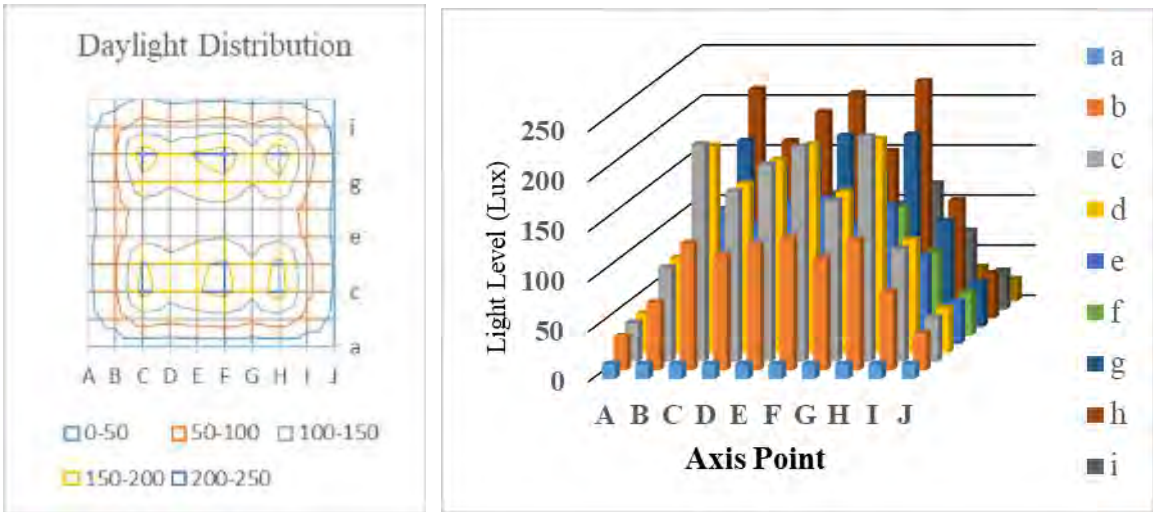


Figure 5.111: Daylighting distribution at illumination plane for case 06(d)

Table 5.58 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by six lightpipes installed at the ceiling level in a group. Figure 5.111 shows that daylight have illuminated the space under the diffusers which were 5m away from each other and constantly decrease at the periphery area. The brightest level of light 237 lux found at the space under the diffuser and the light found at the periphery area was low (less than 50 lux). The minimum light was only 15 lux. The average light was 102 lux and the standard deviation was 64.8 lux (Figure 5.112). The median was 109 lux. The uniformity ratio below the light at workplane was 0.65 which met the standards (≥0.60).

Light Level (Lux)	Value
Min	15
Max	237
Avg	102
Median	109
SD	64.8

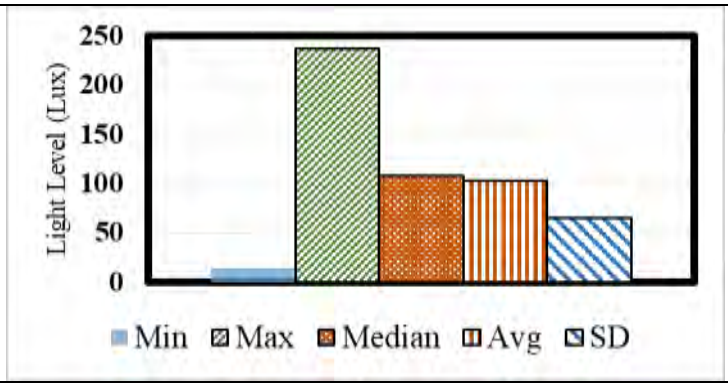


Figure 5.112: Daylighting distribution data analysis for case 06(d)

While considering only the illuminance level at the central part-f (Table 5.58), it has generated a curve line which indicate that the highest lights found under the diffusers (Figure 5.113) and the amount of light decreases with the distance of the diffusers.

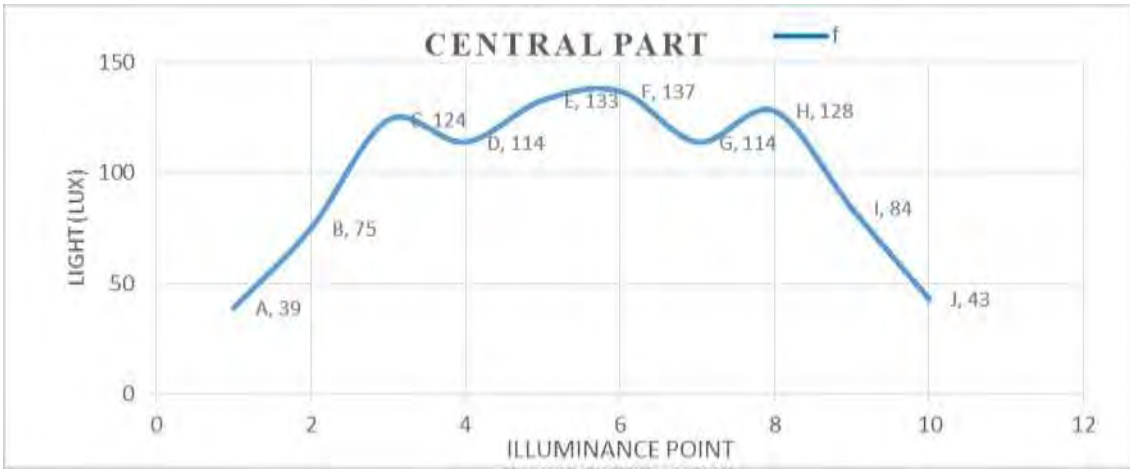


Figure 5.113: Daylighting distribution at central part (f) for case 06(d)

V. Case 6(e): Nine(9) Pipes

This model was created only with the internal (open office area) space, there was no opening at the side wall of the model. There were nine (9) bended lightpipes which diameter was 0.50m with a transition space (height 3.5m-one floor) and with nine domes and nine diffusers (Table 5.59). The domes of light pipes were set at one edge of the top roof (top of the transition space) and the ceiling (bottom of the transition space) contained the diffusers of the light pipes at the center position (Figure 5.114). Distance between the diffusers were 5m by length and 3m by width.

Table 5.59: Simulation model parameters for case 06(e)

Case	Pipe Diameter	Pipe Length	**Number of Pipe**	Presence of Window
06(e)	0.50m	3.5m	**09**	No

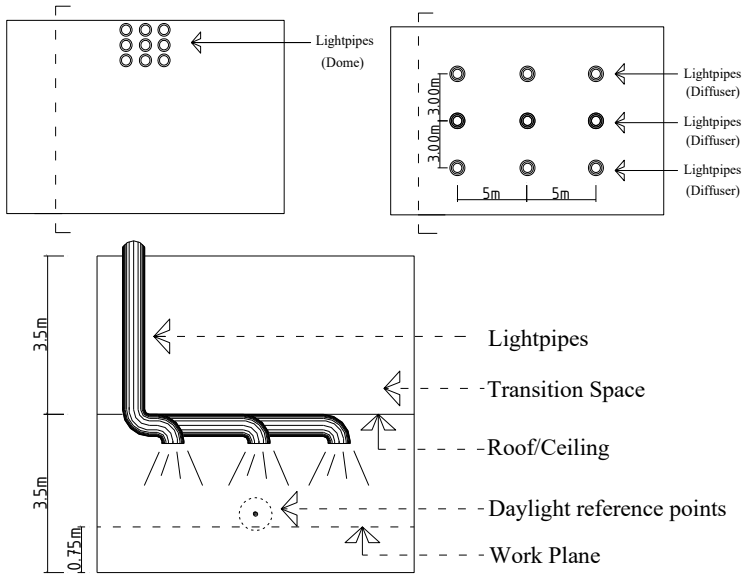


Figure 5.114: Plans and section of simulation model 06(e)

Table 5.60: Daylighting distribution- at illumination plane for case 06(e)

Point	A	B	C	D	E	F	G	H	I	J
a	23	23	23	23	23	23	23	23	23	23
b	23	96	174	123	182	160	119	164	82	38
c	23	135	277	190	281	236	187	260	112	45
d	23	149	285	213	296	256	208	268	124	50
e	23	168	307	228	318	273	223	289	151	52
f	23	179	312	230	322	276	225	293	172	52
g	23	159	284	215	296	257	209	267	125	50
h	23	138	282	195	287	241	192	265	114	46
i	23	101	187	131	195	170	128	176	86	39
j	23	42	74	74	83	76	70	68	45	31

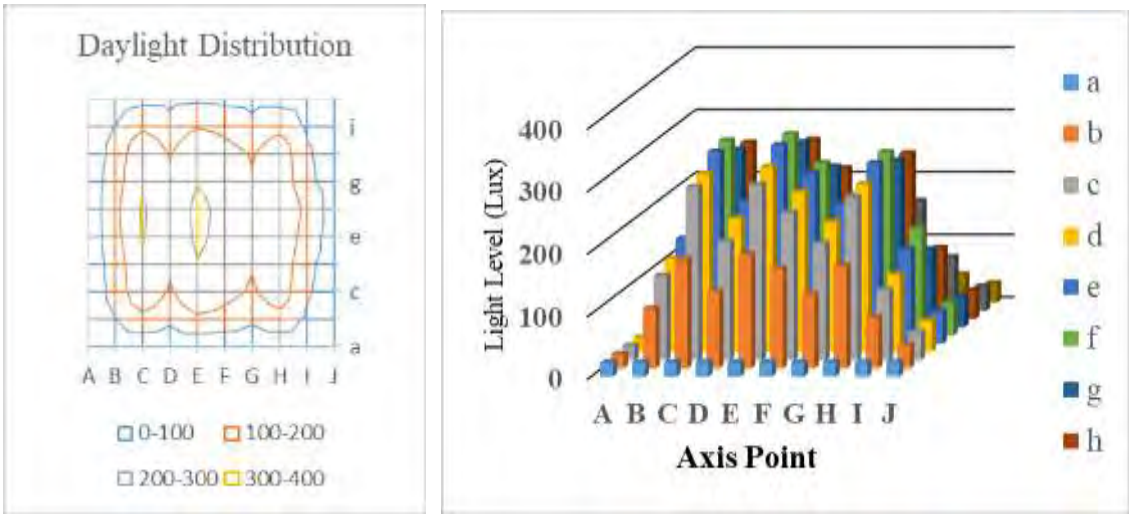


Figure 5.115: Daylighting distribution at illumination plane for case 06(e)

Table 5.60 shows the light level at the 100 point of the illuminance plane of Model 01 at 12.00pm. This light was penetrate by nine light pipes installed at the ceiling level. Figure 5.115 shows that daylight have illuminated the space under the diffusers and gradually decrease at the periphery area. The brightest level of light 322 lux found at the space under the diffuser and the light found at the periphery area was lower than the center.

Light Level (Lux)	Value
Min	23
Max	322
Avg	146
Median	144
SD	98.3

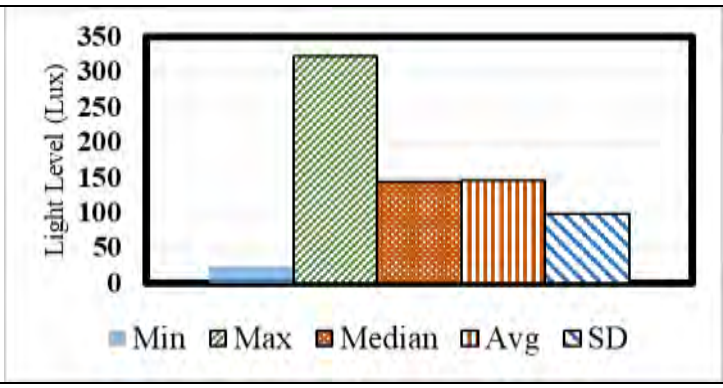


Figure 5.116: Daylighting distribution data analysis for case 06(e)

The minimum light was only 23 lux. The average light was 146 lux and the standard deviation was 98.3 lux (Figure 5.116). The median was 144 lux. The uniformity ratio below the light at workplane was 0.77 which was higher than the standards (≥0.60).

While considering only the illuminance level at the central part-f (Table 5.60), it has generated a curve line which indicate that the highest lights found under the diffusers (Figure 5.117) and the amount of light decreases with the distance of the diffusers.

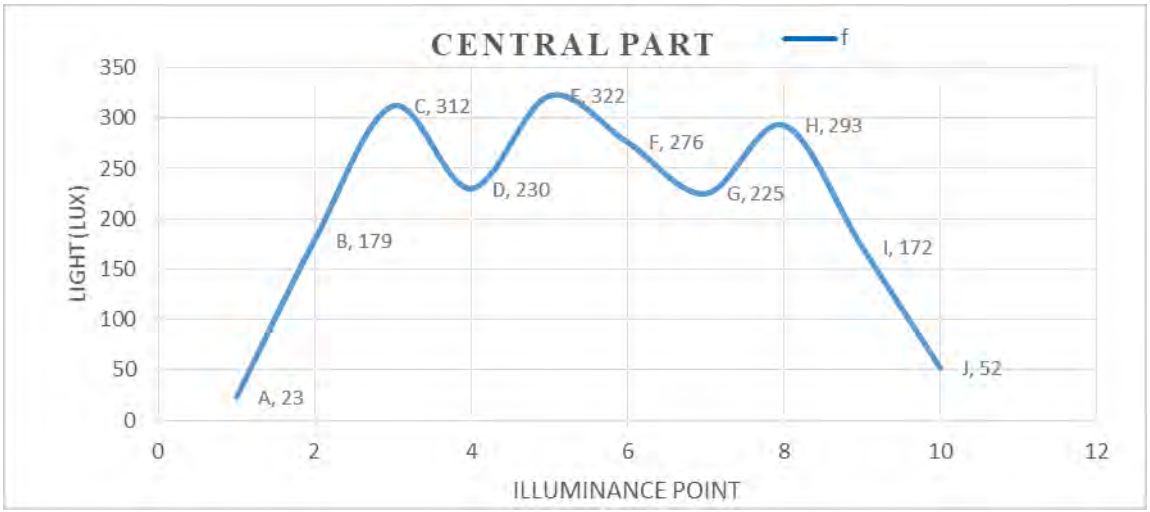


Figure 5.117: Daylighting distribution at central part (f) for case 06(e)

VI.Comparative Analysis

Table 5.61: Daylighting distribution at illumination plane of central part (f) for bended lightpipe of different nos (model 01)

Point	A	B	C	D	E	F	G	H	I	J
1 Pipe	3	6	13	41	137	158	51	16	7	4
2 Pipes	24	76	191	114	39	35	93	196	94	28
3 Pipes	26	80	201	142	188	196	143	208	98	31
6 Pipes	39	75	124	114	133	137	114	128	84	43
9 Pipes	23	179	312	230	322	276	225	293	172	52

Table 5.61 show the lighting level at the central part (f) of the illuminance plane for every variation for different light pipe numbers with **Model 01**(The deep part of the office floor). From these data, it can be calculate the maximum, minimum and average value (Table 5.62). From the table it is observed that amount of daylight increase significantly with the increasing number of light pipes (Figure 5.118).

Table 5.62: Daylighting distribution data analysis (model 01)

Option	Max	Min	Avg
1 Pipe	158	3	19.5
2 Pipes	196	5	38.2
3 Pipes	208	8	55.8
6 Pipes	237	15	102
9 Pipes	322	23	146

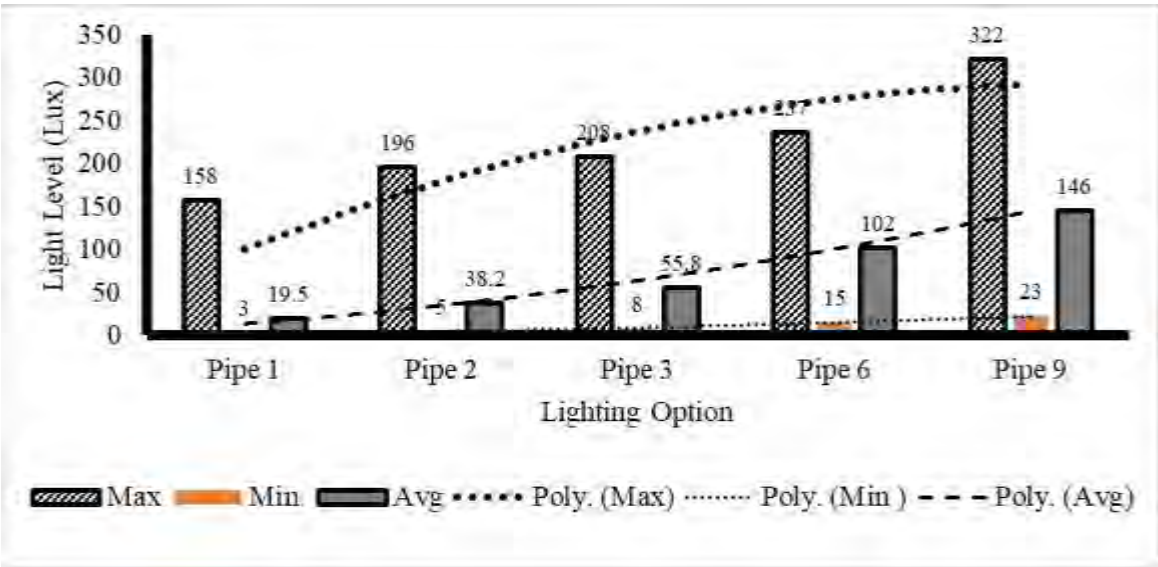


Figure 5.118: Daylighting distribution data analysis (model 01)

Though maximum light was found with nine (9) bending lightpipes in maximum illumination point of the illuminance plane, but as maximum points illumination were higher than 300 lux (standard light level) and the highest light level found 708 lux, it may create overlighting and glare. The average light level was 344 lux. Simulation with Six (6) bending lightpipes has given more acceptable light according to the standard illumination level, though it also have some over illuminated points. Average lights with one pipe to three pipes simulations were not meet the standard lighting level.

VII. Uniformity Ratio

The uniformity ratio found for different nos of lightpipes has stated at the Table 5.63. Here we found that the ratio has increased with the increasing nos of lightpipes. But the uniformity ratio of 06 pipes and 09 pipes have met the standards of the ratio most accurately which is ≥0.60%.

Table 5.63: Uniformity ratio for model 01

Pipe No.	1 Pipe	2 Pipes	3 Pipes	6 Pipes	9 Pipes
Uniformity Ratio	0.37	0.45	0.58	0.65	0.77

5.7.3 Lighting Simulation with Bending Lightpipes and Windows

I. Case 7(a): Three (3) Pipes with Windows

This model was created with the entire floor as surveyed floor area. There were openings at the side walls of the model and the opening height was 2.4m (Model 02). There were three (3) light pipes (0.50m diameter) with a transition space (height 3.5m-one floor) and with three domes and three diffusers (Table 5.64). The domes of light pipes were set at one edge of the top roof (top of the transition space) in the building core area and the ceiling (bottom of the transition space) contained the diffusers of the light pipes at the center position (Figure 5.119). Distance between the diffusers were 5m. The daylighting performance of 3 bending lightpipes, with side window was observed from the model.

Table 5.64: Simulation model parameters for case 07(a)

Case	Pipe Diameter	Length	**Number of Pipe**	**Presence of Window**
07(a)	0.50m	3.5m	**03**	**Yes**

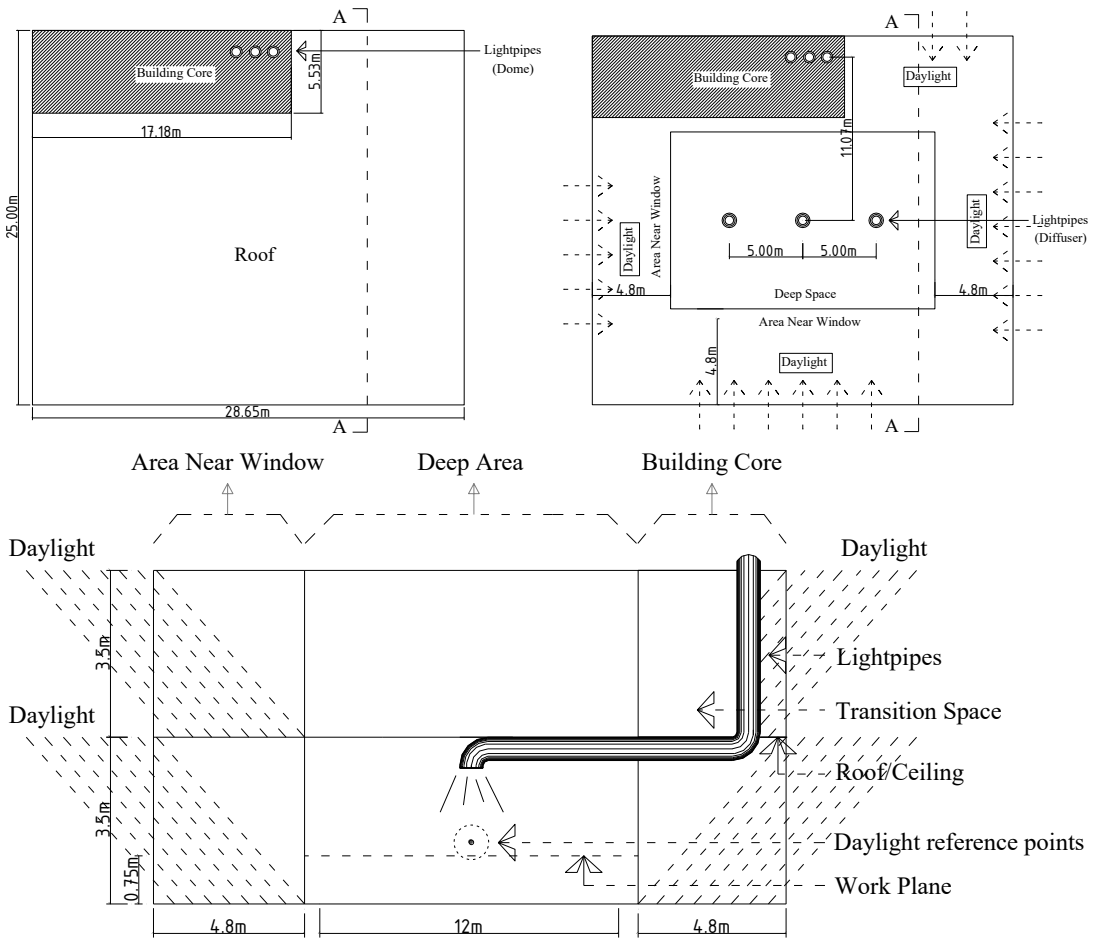


Figure 5.119: Plans and section of simulation model of 07(a)

Table 5.65: Daylighting distribution at illumination plane for case 07(a)

Point	A	B	C	D	E	F	G	H	I	J
a	141	141	141	141	141	141	141	141	141	141
b	145	145	174	254	294	299	292	253	315	141
c	145	204	167	166	190	189	172	193	453	141
d	164	352	194	189	187	269	195	191	247	141
e	159	278	207	195	265	231	188	169	162	141
f	160	381	209	195	250	268	183	161	152	141
g	162	372	206	196	188	263	181	158	150	141
h	165	281	200	191	194	216	176	157	149	141
i	152	222	300	340	327	205	196	155	146	141
j	142	146	149	148	147	146	145	144	143	141

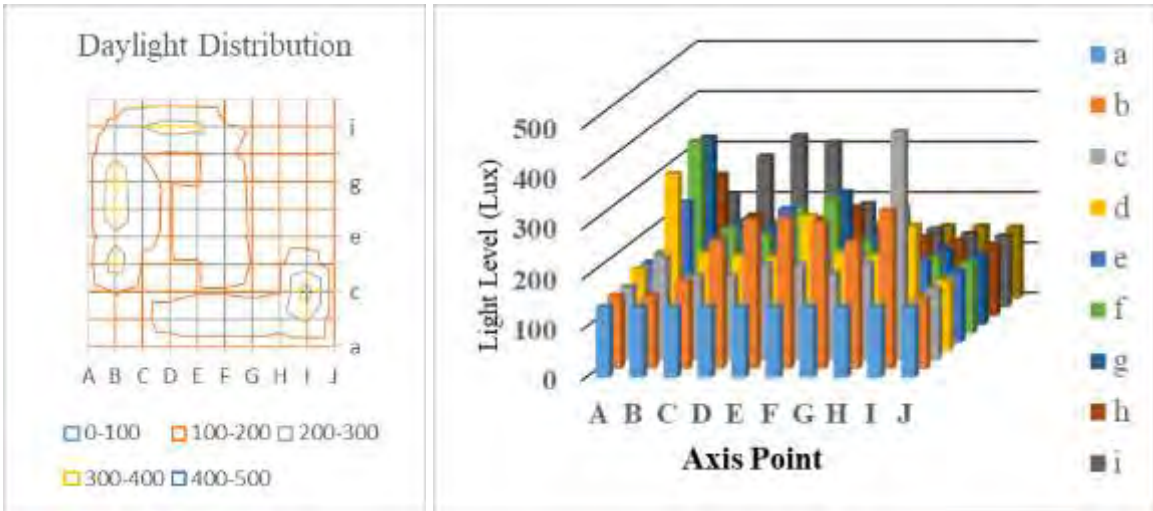


Figure 5.120: Daylighting distribution at illumination plane for case 07(a)

Table 5.65 shows the light level at the 100 point of the illuminance plane of Model 02 (whole office area) at 12.00pm. This light was penetrate by the installed light pipes and by window at the periphery area. Figure 5.120 has shown that this daylight illuminate the overall area of the office.

LIGHT Level (Lux)	Value
Min	141
Max	403
Avg	194
Median	173
SD	62.7

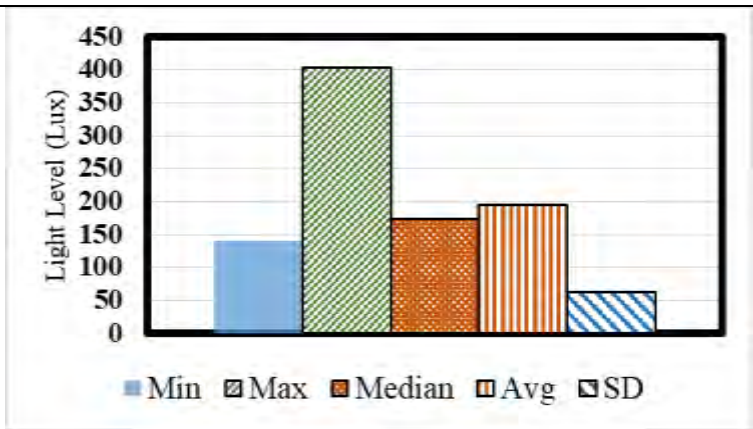


Figure 5.121: Daylighting distribution data analysis for case 07(a)

The brightest level of light 403 lux found near side window. The minimum light was 141 lux. Also found the average light was 194 lux and the standard deviation was 62.7 lux (Figure 5.121). The median was 173 lux. The uniformity ratio below the light at workplane was 0.72 which was very near to the standards (≥0.60).

While considering only the illuminance level at the central part-f (Table 5.65), it has generated a curve line with multiple pick points which indicate that the adequate light found more than one space (Figure 5.122). The lighting was little poor at the edge of the simulated area.

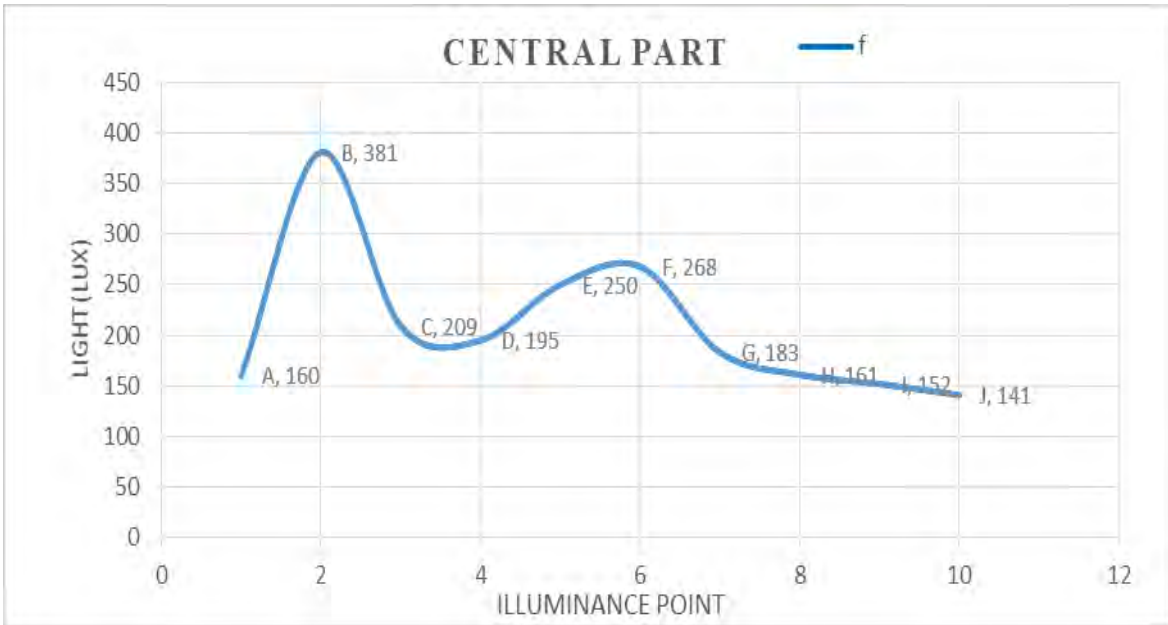


Figure 5.122: Daylighting distribution at central part (f) for case 07(a)

5.8 Comparative Analysis of Straight and Bending Pipe

Table 5.66: Daylighting distribution at illumination plane of central part (f) for diffetrent simulations (model 02)

Point	A	B	C	D	E	F	G	H	I	J
3 Straight Pipes +Window	160	431	240	217	295	272	185	161	152	141
3 Bended Pipes +Window	160	381	209	195	250	268	183	161	152	141

Table 5.66 show the lighting level at the central part (f) of the illuminance plane for three (3) lightpipes along with windows by **Model 02** (full area of the office floor). From these data, it can be calculate the maximum, minimum and average value (Table 5.67). From the table it is observed that same amount of daylight entered near window. But straight light has penetrated more amount of light (10%) than the lightpipes of bending position.

Table 5.67: Daylighting distribution data analysis (model 02)

Option	Max	Min	Avg
3 Straight Pipes +Window	474	141	214
3 Bended Pipes +Window	403	141	194

Uniformity Ratio

The uniformity ratio found for different nos of lightpipes has stated at the Table 5.68. The uniformity ratio of 03 straight pipes with window found 0.65 while the ratio for 03 bended lightpipes found 0.72. As the uniformity-created by a general lighting scheme should be better than 0.6 or 0.8 according to the German DIN norm and the UK CIBSE guidelines, respectively, both of the results has met German DIN norm, but slightly short with UK CIBSE guidelines.

Table 5.68: Uniformity ratio for model 02

Pipe No.	3 Straight Pipes +Window	3 Bending Pipes +Window
Uniformity Ratio	0.65	0.72

5.9 Implementation of Duel Ducting System

For almost all office buildings, working hours coincide with daylight hours, and HVAC systems are installed. Both DLSs and HVAC manufacturers have targeted offices as a major market (Mayhoub et.al. 2011). For the studied building, the designed HVAC system has assessed, the applicable DGS has studied and the integration of the two systems has been proposed.

From the simulation study, it has been observed that light can travel by bending lightpipe which was collected by the dome at the roof and can illuminate at the deep space of the office building where direct sunlight cannot reach. As every office building have already installed HVAC ducting system for heating and cooling, the light pipes can easily travel to the space where direct daylight cannot reach along with the HVAC ducting shaft. Wherever air only is transported, the specified air ducts will use, but when both air and light are transported, the dual ducts are used. The dual ducting system may be implemented by two ways-firstly by using single duct for both air and light and secondly two separate duct use for air and light in a single network.

5.9.1 By Using Single Duct for Air and Light

The lightpipes and AC ducts can be merged in one pipe network as illustrated in Figure 5.123. The horizontal air ducts need to be slightly re-routed in order to join the roof mounted collectors. The spacing distance needs to be modified to suit the new layout of the light and air outlets and to allow proper locations for the light collectors on the roof. Duel duct may be channel as single air duct when there will be no light outlet. Wherever the ducts are extended, an air stopper could be used after the last air outlet. This could be made up of clear glass or acrylic to allow the passage of light only and to avoid any possible drop in the air pressure due to the duct's added volume.

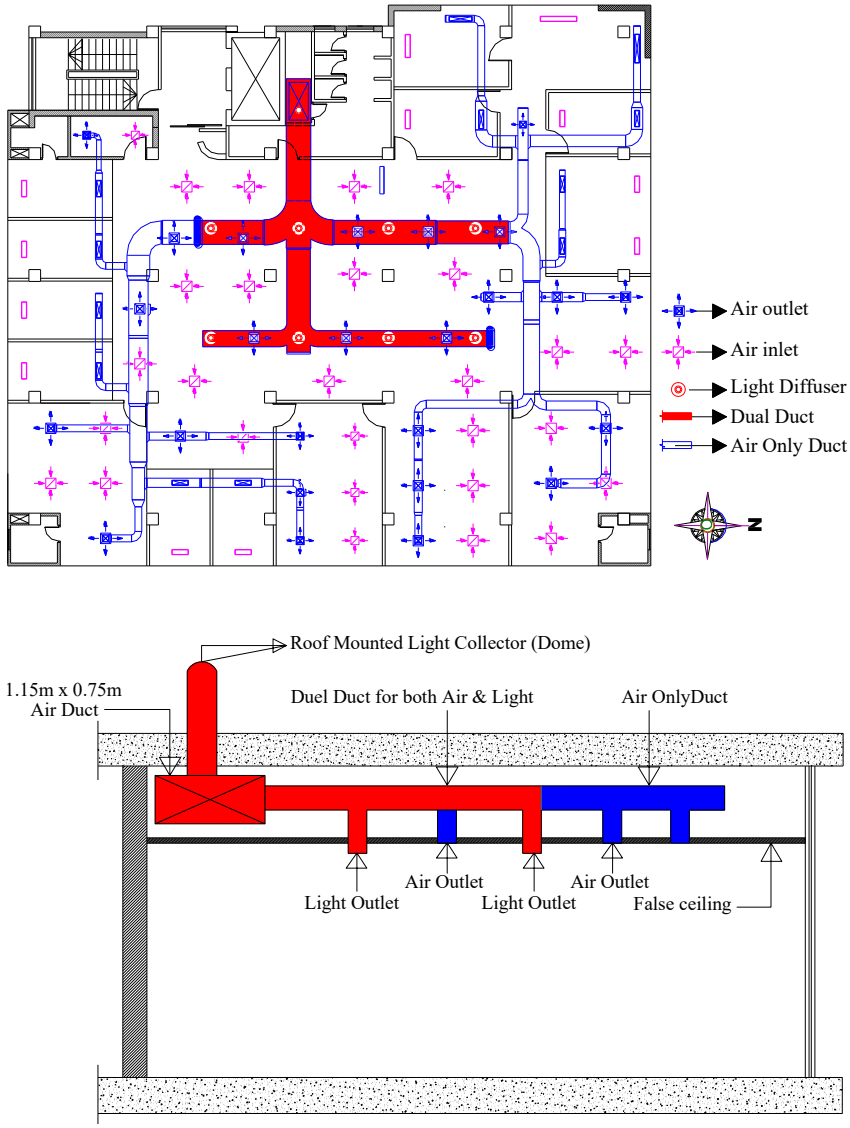


Figure 5.123: Conceptual plan and section of dual ducting system using single duct for both air and light

5.9.2 By Using Separate Ducts for Air and Light

The lightpipes and AC ducts can be integrated in one network by using separate pipes as illustrated in Figure 5.124. This system will be used in ICU of any hospital or such spaces where high risk of contamination have to be prevented. This system also used with VRF AC system. The vertical air ducts and roof mounted light collectors both travel separately at the service duct in a single network. Both of the pipe networks are aligned together at the upper part of the ceiling under roof in a different height for free movement of two networks. Again the spacing distance needs to be modified to suit the new layout of the light and air outlets and to allow proper locations for the light collectors on the roof.

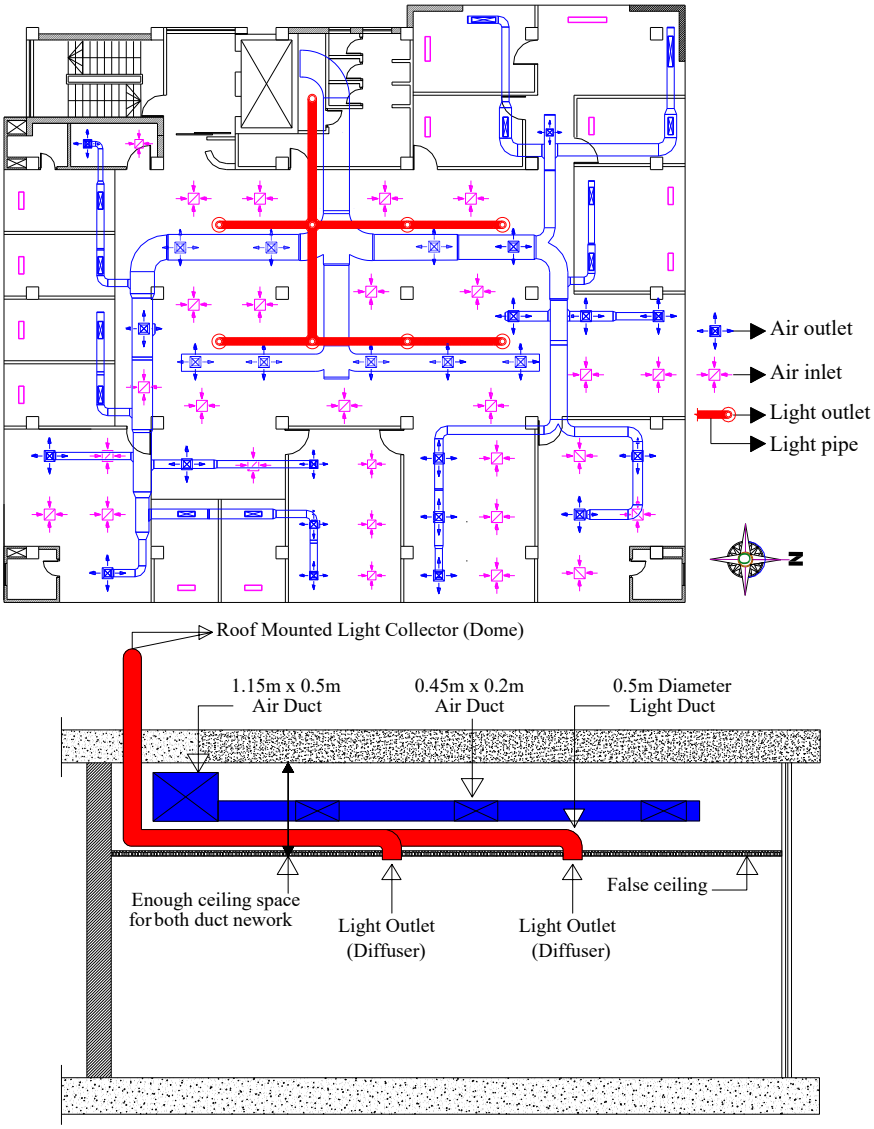


Figure 5.124: Conceptual plan and section of dual ducting system using separate ducts for air and light

5.9.3 Operational Requirements

Apart from the duct's functions, some challenges associated with the duct installation and operation need to be considered (Mayhoub, 2014).

- Attention has to be paid to the condensation risk. Precipitation of the air particulates on the inner surfaces of the ducts and the diffuser fins mitigates the system illumination efficiency dramatically. Regular maintenance of the air filter or even the use of anti-dust materials are practical solutions for this problem. Air filters are already used in the HVAC systems to improve the indoor air quality and maintain system efficiency.
- The thermal and acoustic insulation of the HVAC ducts may be effected with a dual function duct, transferring and distributing daylight both at once. Whilst the duct body is insulated, the light-only aperture can be double-glazed.
- Fire protection is already considered in the HVAC systems and needs to be considered in the DLS. Suitability of the used techniques in HVAC systems with the DLS needs to be investigated.
- As very little changes required in the air-duct size and length, this may have an small impact on air velocity and consequently on thermal comfort. For instance, air pressure losses due to the additional extensions to connect the ducts with the building envelope might occur. This can be avoided by recalculating the air velocity. The air stopper could also be used to prevent air from reaching unwanted spaces.

5.10 Critical Findings

The following observations found after performance analysis of this experimental parametric study:

- The maximum daylight enters at 12.00 pm (2015 Lux) to 01.00 pm (1228 Lux) by a single straight lightpipe.
- As the penetrated light increases with the increasing diameters of lightpipe, maximum light found with the lightpipe of 0.50m diameter.
- As the penetrated light decreases with the increasing length of lightpipe, maximum light found with the minimum length of lightpipe which was 3.5m.

- Amount of daylight increase significantly with the increasing number of light pipes but only lightpipes (9 nos.) are not enough to achieve the standard level of illumination for office table task. The combination of artificial light and lightpipe will give the proper lighting environment at the deep space.
- Light can travel both vertically and horizontally by bended lightpipes (angle 90^0) with small illuminance changes (10%) compare to the straight lightpipes.
- The uniformity ratio met the standard for the simulation with three (3) lightpipes and windows.
- The highest amount of daylight penetrate when window and lightpipe presents together.
- The illuminance were higher under the lightpipes and light degrease at the edge of the space.

5.11 Conclusion

This chapter has discussed the third and the forth objectives of the study. The third objective of the research which was to identify effective configuration of lightpipe of the office space to ensure standard illumination levels of daylight at task plane in the context of Dhaka. To achieve the objective, this chapter has discussed the output of the simulation of different configuration of light pipes to ensure standard illumination levels of natural daylight at task plane. The forth objective was to integrate lightpipe with HVAC system in office buildings to develop the dual ducting system in working spaces of office buildings. To achieve the objective simulation of lightpipes in bending position have done and discussed the implementation of dual ducting system. Existing DGS i.e. lightpipe system have the potential to provide efficient daylighting within buildings. However, they do face some challenges that can be summarized as reducing the initial cost and increasing the ease of integration into buildings. Both challenges can be overcome to great extent by the integration of DGS and HVAC systems, which could be achieved through the consideration of many factors such as the design of the duct network layout, the selection of the ducting materials, the development of the output devices and the development and improvement of many operating aspects.

CHAPTER SIX: RECOMMENDATION AND CONCLUSION

Preamble

Achievement of the Objectives

Suggestion for Future Research

6.1 Preamble

The first chapter of this thesis introduces the research. Chapter 2 provides the theoretical basis of this research and provides a clear understanding of office building, daylight and its components, lightpipe, dual ducting system and different national and international standards. The third chapter described the methodologies, selection of simulation tools and the detail steps applied for the simulation study in this thesis. It also describe parameters of simulation tools, modeling options and evaluation process. Chapter 4 provides the field survey and selection of office building and simulation space. Some experiments with scale models also described in this Chapter. In Chapter 5, twenty eight (28) different cases (different configurations and situations) of lightpipes of two models were evaluated under four criteria through dynamic daylight simulation to find out the most feasible luminous configuration through window and lightpipes. That chapter also describe the implementation of dual ducting system. This current chapter will summarize the research by discussing the achievements of the objectives and recommend some indicative suggestions to improve the daylighting condition of the deep space of the office building. It will also provide some suggestions for future research.

6.2 Achievement of the Objectives

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

6.2.1 Lightpipes-The Effective Way of Daylighting Strategies

The first objective was to find out the possible daylighting strategies to improve the daylighting condition in office building where direct sunlight can't reach through opening. In order to achieve this objective 10 offices of Dhaka city was investigated to observe the lighting condition for deep spaces of these office buildings. It shows that 25% to 40% of the office spaces are fully and 15% to 20% of the spaces are partly lake of daylight. It also found that the height of floor, ceiling, opening (lintel to seal height) are directly related for inclusion of daylight in office buildings. At the deep spaces, the effect of daylight is extremely low (85%-100%) or no daylight, due to distance or lack of opening. Work without daylight as well as with artificial light for a long time had an inverse health impact to the employees. Lightpipes are effective devices used to bring that

daylight to the back of deep plan buildings. Lightpipes are considered a median to transport light into deep spaces that do not have direct access to the outside. Lightpipes have a great potential to reduce electricity use in buildings (Figure 6.1). Daylight usage is a cost efficient strategy to reduce electric lighting consumption.

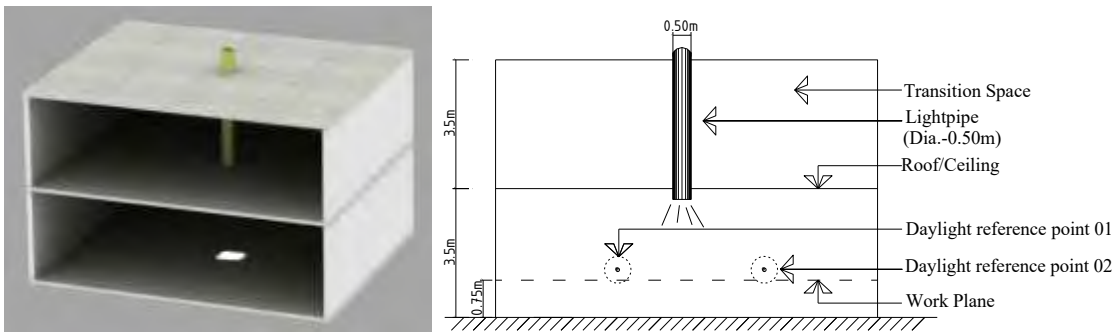


Figure 6.1:Lightpipe- conceptual 3D and section

6.2.2 Observe the Daylight Inclusion Pattern

The second objective was to observe the daylight inclusion pattern in different space of the office by side opening and by lightpipe where daylight cannot enter by window and roof. In order to achieve this objective an experimental study with scaled model of the selected space was conducted. Daylight enters at the peripheral side of the office building by side window (if there is no obstructions) at any floor. Penetration of daylight is also possible with roof openings at the top floor, but it is not possible for the intermediate floor. Straight lightpipe can be used where there is no obstruction at the upper floor of the target space. Light can be entered by bending (angle 90^0) of lightpipe where there are some obstructions at the upper floor of the target space (Figure 6.2).

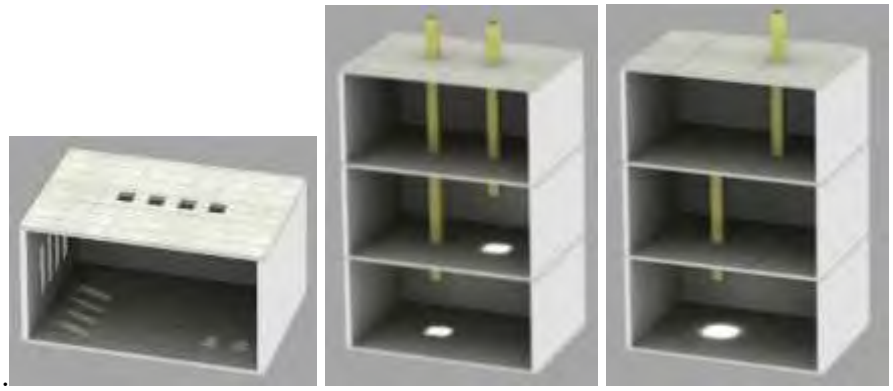


Figure 6.2: Daylight Inclusion by window, roof opening and lightpipes

6.2.3 Effective Configuration of Lightpipe

The third objective was to identify effective configuration of lightpipe of the office space to ensure standard illumination levels of daylight at task plane in the context of Dhaka. To achieve this objective, experimental parametric study was done by varying different parameters, such as lightpipe diameter, lightpipe length, lightpipe number and lightpipe performance with the presence or absent of the side window. It was found that the maximum light enters at 12.00 am (2015 Lux) to 01.00 pm (1228 Lux) under the lightpipe at working plane by a single straight lightpipe. Maximum light found with the lightpipe of 0.50m diameter as the penetrated light increases with the increasing diameters of lightpipe. As the penetrated light decreases with the increasing length of lightpipe, maximum light found with the minimum length of lightpipe which was 3.5m. Amount of daylight increase significantly with the increasing number of light pipes. Study under this research shows only lightpipes (even 9 nos.) are not enough to achieve the BNBC standard level (450 Lux) of illumination for office table task. The combination of artificial light and lightpipe will give the proper lighting environment at the deep space. The highest amount of daylight penetrate when window and lightpipe act together (Figure 6.3).

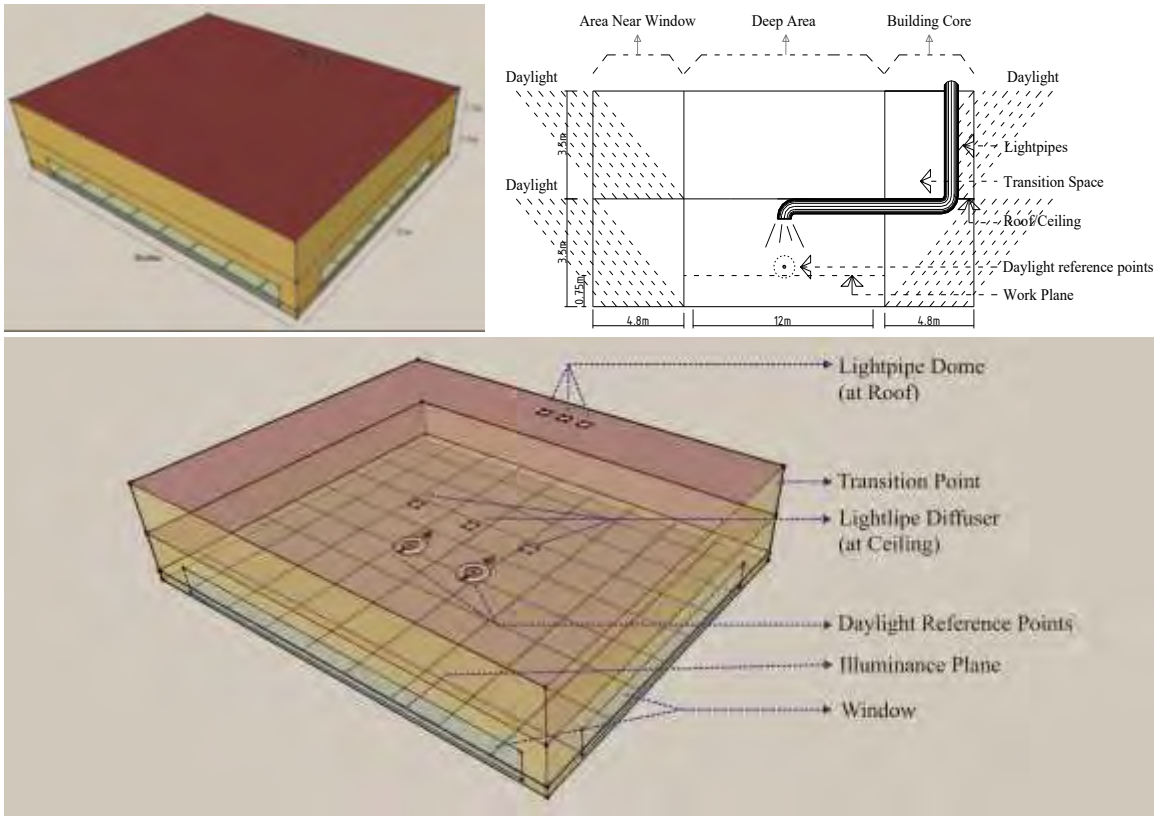


Figure 6.3: Daylight Inclusion by window and lightpipes(Section and Isometric Vew)

6.2.4 Develop the Dual Ducting System

The forth objective was to integrate light pipe with HVAC system in office buildings to develop the ducting system in working spaces of office buildings. Daylight guidance systems use lightpipes to distribute daylight, which occupy significant amounts of spaces and management tools. The integration of light ducts and heating, ventilation and air conditioning ducts is a promising solution. After defining the space HVAC ducting system and air outlets have reviewed. As the light has entered by dome at roof, it has channeled by vertical and horizontal lightpipes and the lightpipes can be merged with HVAC ducts. Dual ducting system could be an effective solution by overcoming some challenges and difficulties for the improvement of the luminous environment of the office spaces in the context of Dhaka.

Single ducts can be used for both light and air ventilation (Figure 6.4). The lightpipes and AC ducts can be integrated in one network by using separate ducts in some special cases (Hospital and VRF system) (Figure 6.5).

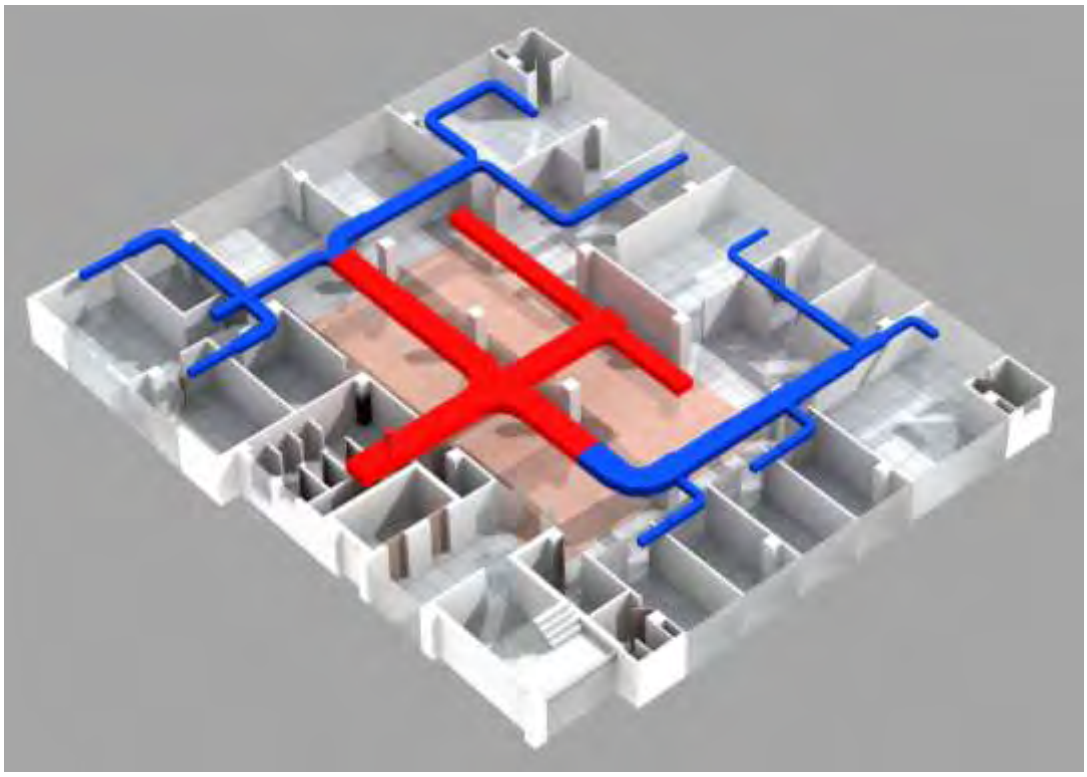


Figure 6.4: Conceptual Dual Ducting System using single duct for case building (Isometric Vew)

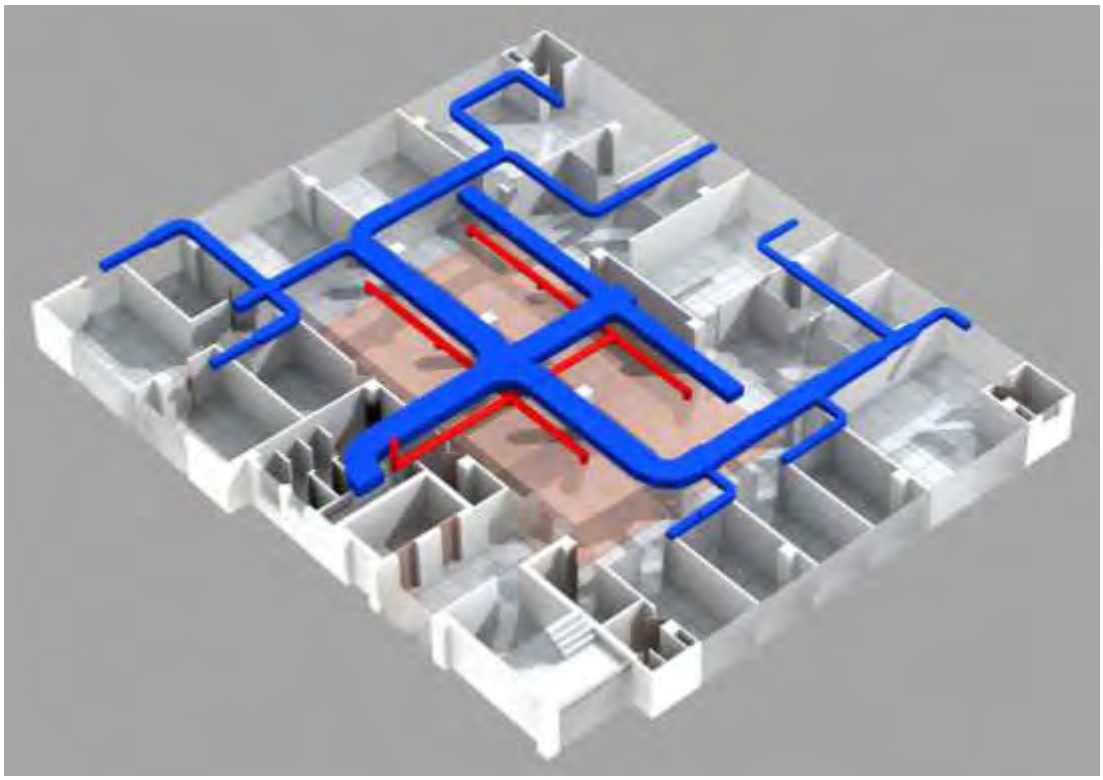


Figure 6.5: Conceptual Dual Ducting System using separate ducts for case building (Isometric Vew)

6.3 Suggestions for future research

Some of the important areas that need to be explored in future with the special reference to daylighting in deep spaces of office buildings are following:

- The study is to find out the performance of lightpipe for improving the luminous condition of the deep spaces of office buildings where direct sunlight cannot be reached. Change of the parameters, or relationship among different geometrical elements such as window size, sunshade and light selves may yield variation in the results generated in the investigation. This can be study in further research.
- The study concentrates only on the intermediate floor of office buildings. Top floor or ground floor of other types of buildings need to be analyzed further.
- The study concentrates only on the deep spaces of office buildings with open type seating arrangement, where employee use only artificial light and have

no or limited opportunity to use direct sunlight. The result for the other types of spaces, such as individual room, service area, and corridor need further research.

- In the study simple type of lightpipe consists of dome, diffuser and pipe and use the pipe of one material were considered. More research need for complex or other types of lightpipes, for example façade mounted lightpipe or lightpipe of fiber optics.
- More exercises with HVAC designs are required to assess the duct's re-routing difficulties and effects.
- Economic return, payback, life cycle of lightpipes etc are beyond the scope of the research. These can be study in further research.

It is expected that the research can be used as a basis for further research to investigate other aspects as described above of the illumination condition in the deep spaces of office buildings in context of Dhaka.

BIBLIOGRAPHY

Agrawala, Shardul, et al. *"Development and climate change in Bangladesh: focus on coastal flooding and the Sundarbans",* OECOD, France. 2003.

Available form http://apps1.eere.energy.gov/buildings/energyplus/cfm/ weather_ data3.cfm/ region=2_ asia_ wmo_region_2/country =BGD/cname= Bangladesh.

Ahmed, Z.N. (1987). *The Effects of Climate on the Design and Location of Windows in Bangladesh*. M. Phil. diss., Sheffield City Polytechnic.

Ahmed, Z.N. and Joarder, M.A.R. (2007). *An Observation on Daylight Inclusion in the Lighting of Offices in Dhaka*. Protibesh, 11(1): pp. 51-61.

Ahmed, K. (1995). *Approaches to Bioclimatic Urban Design for the Tropics with Special Reference to Dhaka, Bangladesh.,* Architectural Association School of Architecture, London, U.K.

Aman, J. (2017). *Impact of windows for daylighting on thermal comfort in architecture design studios in Dhaka*. Unpublished M.Arch Thesis. Department of Architecture, BUET, Dhaka.

Aizenberg JB. *Principal new hollow light guide system ''Heliobus'' for daylighting and artificial lighting of central zones of multi-story buildings: Proceedings of Right Light 4*, Copenhagen, Denmark, 19–21 November, 1997: 239–243

A.G.S.(2000). *Architectural Graphic Standards*. John Wiley & Sons, Inc. New York.

Bodart M. and Deneyer A., **"***A guide for the building of daylight scale models",* PLEA2006 - The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland, 6-8 September 2006.

Bodart M, Deneyer A., De Herde A., Wouters P, *"Design of a new single-patch sky and sun simulator"*, Lighting Research and Technology 38 (1), pp 73-89, 2006.

Bangladesh Meteorological Department (2017), Combined climatic data for the year 2016. Climate Division. Agargaon. Dhaka.

B. Malet-Damour, H. Boyer, A.H. Fakra, M. Bojic, *"Light Pipes Performance Prediction: inter model and experimental confrontation on vertical circular light-guides",* 2013 ISES Solar World Congress.

Bokel, R.M.J. (2007, September). *The effect of window position and window size on the energy demand for heating, cooling and electric lighting. In Building Simulation* (Vol. 10). Delft: BS.

B.N.B.C. (1993), Bangladesh National Building Codes, Housing and Building Research Institute and Bangladesh Standards and Testing Institute, City Art press Ltd, Dhaka, p.8-7

Baker, N. & Steemers, K. (2002), *Daylight Design of Buildings*, James & James Ltd., William Road, London, p.31-38.

Baker N., Fanchiotti A., Steemers K., *Daylighting in architecture; a European Reference Book*, James and James, London,1993.

Baker N., Steemers K., *Daylight Design of Buildings*, James and James, London, 2002.

B.N.B.C. (1993), Bangladesh National Building Codes, Housing and Building Research Institute and Bangladesh Standards and Testing Institute, City Art press Ltd, Dhaka, p.8-7

Boyce, P. R. (1998), *Why Daylight?* Proceedings of Daylighting Õ98: An International Conference.

Bell, J. & Burt, W. (1995) Designing buildings for daylight, Published by Construction Research Communications Ltd, BRE publications.

Chowdhury S.(2014), *Study of thermal performance of building envelope of ready made garments factories in Dhaka*. Unpublished M.Arch Thesis. Department of Architecture, BUET, Dhaka.

Commission International de l'Eclariage. *Tubular Daylight Guidance Systems*, CIE Technical Report 173. Vienna: CIE, 2006.

Carpenter Norris Consulting. *Solar light pipe in Washington, DC. Detail. Building with Light* 2004; 4: 327–329.

Cannon-Brookes S.W.A., *Simple scale models for daylighting design: analysis of sources of error in illuminance prediction,* Lighting Research and Technology, 29 (3), p135-142, 1997.

CIBSE, (1999). Lighting Guide 10: Daylighting and window design, Year: 1999, ISBN 0-900953-98-5, Publisher: CIBSE.

DJ Carter and MAl Marwaee, *"User attitudes toward tubular daylight guidance systems",* School of Architecture, University of Liverpool, Liverpool, UK (July 2008).

Dyala Sami Asad, *Investigating the effect of Light Pipes, as Daylight Strategy,on Employee Performance Levels in High-Rise Office Buildings in the UAE*, Dissertation submitted in partial fulfilment of M. Sc Sustainable Design of the Built Environment, The Faculty of Engineering, The British University in Dubai, 2009.

Dehoff, P. (2002). *The impact of changing light on the well-being of people at work. In Proceedings of Right Light*, 5 (pp. 374-351).

Debnath K. Biswajit, "*A parametric study of biomimetic design of high rise office building façades in view of optimizing natural ventilation potential in the humid tropics",* Unpublished M.Arch thesis dissertation, Dept. of Architecture, BUET, 2011.

Du, J. and Sharples, S., (2009). *Computational simulations for predicting vertical daylight levels in atrium buildings*. 11th International IBPSA Conference, Glasgow,Scotland, 27-30 July.

Energy Research Group (1994), *Daylighting in Buildings,* A Thermie Programme Action, School of Architecture, University College Dublin, Richview, Clonskeagh, Dublin 14, Ireland,p.3.

Evans. M. (1980). Housing Climate and Comfort. The Architectural Press., London.

Energy Information Administration. (2007). Intenational emissions data: Energy Related Carbon Emissions. Available from http://www.eia.doe.gov/environmental.html.

Edmonds, I. R. & Greenup, P. J. (2002). Daylighting in the tropics. Solar Energy, 73(2), 111-121. doi: http://dx.doi.org/10.1016/S0038-092X(02)00039-7

Freewan, A. A. (2010). *Maximizing the lightshelf performance by interaction between lightshelf geometries and a curved ceiling. Energy Conversion and Management*, 51(8), 1600-1604. doi: http://dx.doi.org/10.1016/j.enconman.2009.09.037

Freewan, A. A., Shao, L. & Riffat, S. (2008). *Optimizing performance of the lightshelf by modifying ceiling geometry in highly luminous climates.* Solar Energy, 82(4), 343-353. doi: http://dx.doi.org/10.1016/j.solener.2007.08.003

Figueiro, G. M. (2002). *Daylight and Productivity - A Field Study. Proceedings of 2002 ACEEE Summer Study on Energy Efficiency in Buildings*. Washinngton DC: American Council for an Energy-efficient Economy.

Garcia Hansen, Veronica and Edmonds, Ian (2003), Natural illumination of deepplan office buildings: light pipe strategies. In: ISES Solar World Congress 2003, 14-19 June 2003, Göteborg, Sweden.

Hossain, M. and Ahmed, K. S., *Illumination Conditions and Visual Comfort in Production Spaces of Ready-Made Garments Factories in Dhaka.* IACSIT International Journal of Engineering and Technology, 5(5), 2013.

Haque S.T. (2015). "*Assessment of HVAC Load in light zones to determine energy efficient shading for tall office buildings of Dhaka",* Unpublished M.Arch Thesis. Department of Architecture, BUET, Dhaka.

Harteb Puleo, S., & Leslie, R. (1991). *Some effects of sequential experience of windows in human response*. Journal of the IES, 20(1), 91-99.

Hafiz, R. (2000). "*High-Rise Residential Buildings and the Urban Environment: A Study in Dhaka*," In Architecture, City, Environment: Proceedings of PLEA 2000, James and James (Science Publishers) Ltd, Cambridge, United Kingdom, p. 369.

Iqbal, A and Khan, M. (2005). *Tall buildings in the urban context of Dhaka city*, in CTBUH 7th World Congress. Council on Tall Buildings and Urban Habitat, Newyork.

Islam, S.[Chief Editor], (2006) Banglapedia National Encyclopedia of Bangladesh, Asiatic Society of Bangladesh(Online). Available: http://www.banglapedia.net/HT/A_0291.HTM (2007, June.

Iqbal, M. (2015). *Incorporation of Useful Daylight In Luminous Environment of RMG Factories by Effective Use of Skylights In Context of Dhaka*. Unpublished M.Arch Thesis. Department of Architecture, BUET, Dhaka.

Ibarra, D. I. and Reinhart, C. F., (2009). *Daylight factor simulations – "how close do simulation beginners really get?"* 11th International IBPSA Conference, Glasgow, Scotland, 27-30 July.

IESNA, (2000). *The IESNA Lighting Handbook*, Ninth Edition. Illuminating Engineering Society of North America, New York, USA.

International Energy Agency (IEA), Daylight in buildings, *A source book on daylighting systems and components*, a report of the IEA SHC Task 21 / ECBCS Annex 29, Lawrence Berkeley National Laboratory, Berkeley, USA, 2000.

Islam, S.(Chief Editor), (2006),Banglapedia National Encyclopedia of Bangladesh, Asiatic Society of Bangladesh(Online). Available: http://www.banglapedia.net/HT/A_0291.HTM [2007. June 25).

Jackson, Q., Daylighting in Schools: A New Zealand Perspective, M.S. School of Architecture, Victoria University of Wellington. 2006. pp. 10.

Joarder, M.A.R. (2007). "*A Study of Daylight Inclusion in Luminous Environment of Offices in Dhaka City",* Unpublished M.Arch Thesis. Department of Architecture, BUET, Dhaka.

Joarder, A.R., Ahmed, Z.N., Price, A. and Mourshed, M. (2009). *A simulation assessment of the height of light shelves to enhance daylighting quality in tropical office buildings under overcast sky conditions in Dhaka, Bangladesh.* IBPSA 2009 - Int. Build. Perform. Simul. Assoc. pp1706–1713.

Joarder, M.A.R. (2011). *Incorporation of therapeutic effect of daylight in the architectural design of in-patient rooms to reduce patient length of stay (LoS) in hospitals.* Doctoral dissertation. Loughborough University, UK.

Joarder, M.A.R and Price, A.D.F. (2013a). Impact of daylight illumination on reducing patient length of stay in hospital after coronary artery bypass graft surgery. Lighting Research & Technology. 45 (3): pp. 435–449.

Joarder, M.A.R, and Ahmed, Z.N. (2013b). Daylighting inside Glass Box: Responsiveness of Interior Design to External Facade. Athens: ATINER'S Conference Paper Series, No: ARC2013-0556, pp.5-23.

Joarder, M.A.R and Price, A.D.F. (2012a). Impact of Climate Change on the Constructed Luminous Environment: An Evaluation for the Hospital In-patient Rooms Located in London. The International journal of the Constructed Environment, 2 (3): pp. 219-232.

Joarder, M.A.R. and Price, A.D.F. (2012b). Therapeutic Daylight for Hospital Patients: A Search for the Benchmarks. Proceedings of the First European Conference on Design 4 Health 2011, 13 - 15 July 2011, Sheffield UK, pp 159-174.

Joarder, M.A.R and Price, A.D.F., (2012c). Daylight Simulation in Architectural Practice: Shading Design for Hospitals in London. International Seminar on Architecture: Education, Practice and Research, 02 - 04 February, Dhaka, Bangladesh, pp 436-451. 126

Joarder, M.A.R., (2011). Incorporation of Therapeutic Effect of Daylight in the Architectural Design of In-patient Rooms to Reduce Patient Length of Stay (LoS) in Hospitals. Doctoral thesis. Loughborough University, UK.

Joarder, M.A.R, Price, A.D.F. and Mourshed M.M. (2010). Access to Daylight and Outdoor Views: A comparative study for therapeutic daylighting design. World Health Design, 3 (1): pp. 62-69.

Joarder, M.A.R, Ahmed, Z.N., Price, A.D.F. and Mourshed M.M. (2009a). A Simulation Assessment of the Height of Light Shelves to Enhance Daylighting Quality in Tropical Office Buildings under Overcast Sky Conditions in Dhaka, Bangladesh. 11th International Building Performance Simulation Association Conference and Exhibition, 27-30 July (IBPSA, 2009), Glasgow, UK, pp. 1706-13.

Joarder, M.A.R Price, A.D.F. and Mourshed M.M. (2009b). The Changing Perspective of Daylight Design to Face the Challenge of Climate Change. 3rd CIB International Conference on Smart and Sustainable Built Environments, 15-19 June (SASBE, 2009), Delft, The Netherlands, (CD).

Joarder, M.A.R (2009e). A Survey on Daylighting Potentiality in the Offices of Dhaka Bangladesh. Global Built Environment Review (GBER), 7(1): pp 5-22.

Joarder, M.A.R, Ahmed, Z.N., Price, A.D.F., and Mourshed M.M. (2009c). Daylight Simulation for Sustainable Urban Office Building Design in Dhaka, Bangladesh: Decision-making for Internal Blind Configurations. 2nd International Conference on Whole Life Urban Sustainability and its Assessment, 22-24 April (SUE-MoT 2009), Loughborough, UK, pp. 218-41.

Joarder, M.A.R, Price, A.D.F., and Mourshed M.M. (2009d). A Systematic Study of the Therapeutic Impact of Daylight Associated with Clinical Recovery. HaCIRIC PhD workshop, 2nd Annual International Conference of the Health and Care Infrastructure Research and Innovation Centre, Improving healthcare infrastructures through innovation, 1-3 April (HaCIRIC, 2009), Brighton, UK, pp. 25-31.

Koenigsberger, O.H., Iingersoll, T.G., Mayhew, A. & Szokolay, S.V. (1997), *Manual of Tropical Housing and Building, Climatic Design*, Orient Longman Ltd, Chennai, p.142.

Koenigsberger, O.H., Ingersoll, T.G., Mayhew, A., Szokolay, S.V. (1973), *Manual of Tropical Housing and Building Design*, Part 1, Orient Long man.

Kim, G.(1998), *Projecting Energy Savings from Daylighting in Partitioned Open Plan Spaces*, CIB World Building Congress, Sweden, June 9-11.

Khodulev, A.B. and Kopylov. E.A., (1996). *Physically Accurate Lighting Simulation Computer Graphics Software*. Keldysh Institute of Applied Mathematics.

Khan, M. (2012), Effects *of high rise apartments on the housing situation of Dhaka city*, J. Innov. Dev. Strateg. 6, 124–129.

Khan, M.N.Z.I. (2005), *Rethinking Learning Spaces: in warm-humid climatic context with special reference to Dhaka, Bangladesh*, MA Dissertation (unpublished), Environment and Energy Studies Programme, Architectural Association Graduate School, London, p.63.

Kittler R., *An historical review of methods and instrumentation for experimental daylight research by means of models and artificial skies*, Proceedings of the 14th CIE session, Brussels: Commission Internationale de l'Eclairage, 1959.

Lean, G., D. Hinrichsen, and A. Markham, *Atlas of the environment*. Arrow Books Ltd. 1990(22)

M.S. Mayhoub, D.J. Carter, *"How Hybrid Lighting Systems can be integrated into Building Design?"* 28th Conference, Opportunities, Limits & Needs Towards an environmentally responsible architecture, Lima, Perú 7-9 November 2012.

M.S. Mayhoub, D.J. Carter, *"The costs and benefits of using daylight guidance to light office buildings"*, Building and Environment Vol. 46: 2011, pp. 698-710.

MS Mayhoub, *"Dualducting: An innovation to increase the use of daylight in buildings",* Lighting Res. Technol. Vol. 47: 2015; pp. 712–729

Mondal, MAH and Denich, M. (2010). '*Assessment of renewable energy resources potential for electricity generation in Bangladesh*'. Renewable and Sustainable Energy Reviews, 14(8), pp 2401–2413.

Mondal, M. Abdul Latif. *"Our Cities: 15th Anniversary Special".* The Daily Star. 2006. [Accessed 27 September 2006]

Master Planning Organization (MPO), M.o.I., *Water Development* and Flood Control, Government of the People's Republic of Bangladesh, Dhaka., National Water Management Plan: Phase II, Final Report. 1991 (25)

NARM, (2009). *Natural daylight design through roof lighting*, UK: National Association of Skylight Manufacturers.

Philips, D. (2000), *Lighting Modern Buildings*, Architectural Press, Oxford, pp. 20-47.

Phillips, D. (2004), *Daylighting: Natural Light in Architecture*, Architectural Press, 200 Wheeler Road, Burlington, p.1-6.

Perez, R., Seals, R. and Michalsky, J., (1993). *All-Weather Model for Sky Luminance Distribution – Preliminary Configuration and Validation.* Solar Energy, 50(3), pp. 235-245.

Perez, R., Ineichen, P., Seals, R., Michalsky, J. and Stewart, R., (1990). *Modeling daylight availability and irradiance components from direct and global irradiance.* Solar Energy, 44(5), pp. 271 – 289.

PSL, (2007), *Energy saving by replacement of magnetic ballasts with electronic ballasts in readymade garments (RMG) factories in Bangladesh*, Prokaushali Sangsad Limited, Final Report, GTZ Progress Bangladesh.

Phillips, D. (2004) *Daylighting: Natural Light in Architecture, Architectural Press, 200 Wheeler Road*, Burlington, p.40.

Pank, W., Girardet, H. & Cox, G.(2002) op.cit., p.62.

Reinhart, C.F. (2002), *Effects of interior design on the daylight availability in open plan offices,* Conference Proceedings of the ACEEE Summer Study on Energy Efficient Buildings, Pacific Grove,CA.,U.S.A.,August 2002, pp.1-12.

Reinhart, C.F. and Fitz, A., (2006). *Findings from a survey on the current use of daylight simulations in building design* .Energy and Buildings. 38(7): 824–835.

Reinhart, C.F., Mardaljevic, J. and Rogers, Z., (2006). *Dynamic Daylight Performance Metrics for Sustainable Building Design.* Leukos, vol. 3, no.1, pages7–31.

Reinhart, C.F. and Galasiu, A., (2006). *Results of an Online Survey of the Role of Daylighting in Sustainable Design. NRC-IRC Report. Reynolds Number*. Available from http://www.grc.nasa.gov/WWW/k-12/airplane/reynolds.html. [Accessed 10 March 2014].

Rahman A. (2007), *Performance Evaluation of Shading Devices Used In Tall Office Buildings of Dhaka City,* Unpublished M.Arch Thesis. Department of Architecture, BUET, Dhaka.

Rahman, M.S. and Mowla, Q. (2003). '*Socio- spatial impacts of the growth of high- rise apartment in Dhaka'*. Jahangirnagar Planning Review. 27(Part- II: Social Science), 66–77.

Robbins, C.L. (1986) *Daylighting Design and Analysis*, Van Nostrand Reinhold Company,New York, chapter 1.

Sharmin, T. (2011). Study of the luminous environment in architecture design studios of Bangladesh. M.Arch Thesis. Department of Architecture, BUET, Dhaka.

SunCentral System. Sun Central system, technical data sheet. Retreived March 2014, from http://www.suncentralinc.com/products/suncentral-system-new

SunPortal. Sunportal products. Retrieved March 2014, from http://www.thesunportal.com/product-sunportal-cs.php

Thanachareonkit A., Scartezzini J.L., Andersen M, *"Comparing daylighting performance assessment of buildings in scale models and test modules"*, Solar Energy 79, p 168-182, 2005.

Sharmin, T., *A study of the luminous environment in Architecture design studios of Bangladesh*. M.Arch thesis dissertation, Dept. of Architecture, BUET, 2011.pp. 8.

"Weatherbase: Historical Weather for Dhaka, Bangladesh". Available from www.weatherbase.com. [Accessed 15 December 2008]

Wilson, J.R. and Corlett, N., *Evaluation of human work*. Third edition .Taylor and Francis, 2005.

Ward. G. and Shakespeare. R., (1998). *Rendering with Radiance: The Artand Science of Lighting Visualization*. Morgan Kaufman, San Francisco.

Zohir, S. C. and Paul-Majumder, P. *Garment Workers in Bangladesh: Economic, Social and Health Condition*, Dhaka: Bangladesh Institute of Development Studies, 2008.

APPENDIX

Appendix A: Key Findings

Appendix B: Meteorological Data of Dhaka

Appendix C: Surveyed Office Data

Appendix D: Questionnaire Survey

Appendix E: Instrumentation

Appendix F: Definition of key Terms and concepts

Appendix G: EnergyPlus Simulation Result 1

Appendix H: EnergyPlus Simulation Result 2

Appendix I: CDF Actual Frequency Distribution

Table A: Summary of the key findings of the research in relation to the objectives, methodologies and concerned chapters.

Objective	Methods	Chapter	Key findings
Objective 1: To establish the potential of lightpipe in office building where direct sunlight cannot reach through openings.	Field Survey	Chapter 4	The height of floor, ceiling, opening (lintel to sill height) are directly related for inclusion of daylight in office buildings. At the deep spaces, the effect of daylight is extremely low or no daylight, due to distance or lack of opening. Work without daylight as well as with artificial light for a long time had an inverse health impact to the employees. Lightpipes are effective devices used to bring that daylight to the back of deep plan buildings. Lightpipes have a great potential to reduce of electricity use in buildings.
Objective 2: To observe the daylight inclusion pattern in different space of the office by side opening and by lightpipe where daylight cannot enter by window and roof.	Experimental Study	Chapter 4	Daylight enters at the peripheral side of the office building by side window (if there is no obstructions) at any floor and roof opening at the top floor, but it is not possible for the intermediate floor. Straight Light pipe can be used where there is no obstruction at the upper floor of the target space. Light can be enter by bending of lightpipe where there are some obstructions at the upper floor of the target space.
Objective 3: To identify effective configuration of lightpipe of the office space to ensure standard illumination levels of daylight at task plane in the context of Dhaka.	Daylight simulation analysis by EnergyPlus	Chapter 5	The maximum light enters at 12.00 am by a single lightpipe. Highest daylight penetrated by the straight lightpipe of 0.50m diameters and 3.5m length. Nine (9) lightpipe allows maximum penetrated daylight. But only lightpipes are not enough to achieve the standard level of illumination for office table task. The combination of artificial light and lightpipe will give the appropriate lighting environment at the deep space.
Objective 4: To integrate lightpipe with HVAC system in office buildings to develop the ducting system in working space of office buildings.	Theoretical Study	Chapter 5	The integration of light ducts and heating, ventilation and air conditioning ducts is a promising solution. Dual ducting system could be an effective solution by overcoming some challenges and difficulties for the improvement the luminous environment of the office spaces in the context of Dhaka.

Table B.1: Monthly Highest Maximum Temperature in Dhaka, Bangladesh

Bangladesh Meteorological Department
Climate Division
Agargaon,Dhaka-1207

MONTHLY HIGHEST MAXIMUM TEMPERATURE IN CELCIUS .

STATION	YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.
Dhaka	1983	28.1	31.7	36.2	37.7	36.4	35.6	34.4	33.6	33.1	33.6	32.8	28.8
Dhaka	1984	27.2	33.0	38.0	37.6	35.8	35.8	32.5	35.4	34.5	34.0	31.8	30.0
Dhaka	1985	29.4	32.4	37.1	35.8	35.1	35.0	34.3	34.7	35.0	35.5	33.3	30.6
Dhaka	1986	30.0	32.3	39.5	38.0	37.2	36.8	34.5	36.0	34.5	33.9	33.1	29.0
Dhaka	1987	29.8	35.0	39.0	39.5	38.0	37.0	34.1	34.7	34.6	35.1	33.0	29.2
Dhaka	1988	29.2	32.8	37.0	39.0	36.2	36.8	35.2	34.1	36.0	35.1	33.0	29.3
Dhaka	1989	27.9	32.6	37.2	38.4	39.4	36.5	34.1	35.5	35.3	35.4	33.4	30.0
Dhaka	1990	28.2	30.4	34.6	34.5	35.4	34.2	32.7	35.3	34.8	34.0	32.8	28.6
Dhaka	1991	28.0	33.0	36.8	37.2	34.2	34.0	35.0	36.2	34.5	37.0	30.2	29.3
Dhaka	1992	27.4	28.0	36.6	39.2	36.2	35.8	33.8	35.2	35.0	34.6	33.5	27.8
Dhaka	1993	28.6	32.0	34.6	37.0	35.0	34.3	33.2	33.3	35.3	33.6	30.8	29.1
Dhaka	1994	29.1	31.0	35.2	37.6	36.1	34.8	34.0	34.1	35.0	34.5	33.0	29.8
Dhaka	1995	29.2	30.8	38.8	39.0	38.0	36.6	33.5	34.7	35.6	34.6	34.2	28.6
Dhaka	1996	29.2	32.0	37.6	38.4	36.5	35.5	34.1	35.5	37.5	35.4	33.7	30.3
Dhaka	1997	27.6	31.3	35.6	34.7	36.2	35.5	34.4	37.5	34.0	34.0	33.7	29.0
Dhaka	1998	27.3	30.8	34.8	35.7	37.5	35.8	34.1	34.6	36.2	35.7	33.6	30.3
Dhaka	1999	29.4	35.7	39.6	37.6	37.5	36.6	35.6	34.0	34.6	34.6	32.4	29.7
Dhaka	2000	28.7	28.2	34.0	35.1	36.6	35.2	35.2	35.0	34.4	34.9	32.5	27.3
Dhaka	2001	28.0	31.4	35.8	37.5	35.0	33.8	34.0	34.0	34.2	34.8	32.0	28.4
Dhaka	2002	28.2	33.5	35.5	34.3	35.4	34.4	35.2	34.1	35.0	34.2	32.0	29.5
Dhaka	2003	27.5	31.6	34.0	36.2	36.3	36.7	35.3	35.1	34.2	34.0	32.1	29.2
Dhaka	2004	27.5	32.8	35.7	35.2	38.1	35.2	34.5	34.6	34.0	34.5	31.1	29.4
Dhaka	2005	28.5	32.1	35.6	37.0	36.4	36.6	33.7	34.0	35.1	34.6	31.4	29.0
Dhaka	2006	28.2	35.9	38.5	37.1	36.8	35.0	35.6	35.2	35.7	34.7	32.6	30.1
Dhaka	2007	28.8	30.8	36.7	35.9	37.5	35.9	34.8	35.9	34.9	35.6	31.8	28.2
Dhaka	2008	29.0	30.6	34.6	36.9	36.7	35.4	34.0	36.0	34.8	34.8	32.3	29.0
Dhaka	2009	28.1	33.9	36.0	39.6	37.8	36.5	35.7	34.3	35.3	35.8	33.9	29.0
Dhaka	2010	29.0	31.2	37.3	37.9	36.9	35.8	35.1	35.1	34.0	35.7	33.2	29.7
Dhaka	2011	27.8	31.0	34.5	35.8	35.3	36.0	35.4	35.0	36.2	34.5	32.4	30.0
Dhaka	2012	28.5	33.0	37.3	37.1	36.2	36.7	34.3	34.5	36.5	34.4	32.4	28.5
Dhaka	2013	28.1	32.4	36.0	37.0	37.1	36.4	34.6	35.0	35.7	****	****	****

Table B.2: Monthly Highest Minimum Temperature in Dhaka, Bangladesh

Bangladesh Meteorological Department
Climate Division
Agargaon,Dhaka-1207

MONTHLY LOWEST MINIMUM TEMPERATURE IN DEG. CELCIUS.

STATION: Dhaka

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JUNE	AUG.	SEP.	OCT.	NOV.	DEC.
1983	10.0	7.8	15.8	17.9	20.7	21.9	23.9	23.1	24.3	18.7	16.2	9.4
1984	9.6	11.5	14.2	18.2	18.9	22.9	23.3	23.6	22.2	23.2	15.7	11.2
1985	11.6	12.3	17.1	18.2	19.6	22.8	23.4	24.8	23.8	19.7	15.9	11.9
1986	10.6	12.8	16.1	18.3	20.7	22.7	23.9	25.1	21.4	20.6	15.3	11.7
1987	8.8	12.8	16.2	18.9	18.9	24.4	24.2	22.6	23.3	19.6	15.8	12.1
1988	9.6	11.7	16.9	18.9	21.7	22.7	25.0	24.9	24.4	20.9	15.6	13.1
1989	6.8	11.6	14.6	20.6	21.1	22.1	24.4	25.3	24.4	19.8	15.6	11.0
1990	10.7	15.0	15.0	15.5	20.9	23.5	25.0	24.7	24.0	20.0	15.7	13.2
1991	10.0	14.2	18.4	19.0	20.0	22.8	24.6	24.6	23.4	21.6	15.4	10.3
1992	10.8	13.0	17.8	20.2	19.0	23.0	24.0	24.3	23.6	19.0	15.0	9.7
1993	7.2	11.4	13.7	19.0	19.8	23.1	23.0	24.6	24.2	19.2	15.5	10.6
1994	9.0	11.5	14.0	18.0	20.5	23.2	25.0	24.0	23.0	20.0	15.0	9.9
1995	6.5	10.2	14.5	17.7	22.8	23.1	23.6	23.2	24.5	19.2	14.6	11.3
1996	9.0	11.0	15.4	19.0	21.5	21.5	24.5	24.2	24.5	20.6	13.6	11.1
1997	7.8	9.0	17.2	17.0	21.1	22.4	24.4	25.0	22.5	19.0	15.8	10.6
1998	7.8	10.6	13.5	17.7	20.8	24.7	24.8	24.6	24.9	21.5	16.2	11.4
1999	9.4	11.5	15.2	21.2	20.6	24.3	24.3	24.7	24.3	22.0	15.1	11.0
2000	10.0	13.2	15.4	18.0	19.5	23.8	24.0	23.6	23.0	19.3	16.8	13.4
2001	9.8	12.4	16.6	20.9	19.9	24.0	24.0	22.5	21.5	19.7	15.5	12.6
2002	11.2	11.5	15.8	16.6	19.4	22.0	22.8	23.3	22.0	18.3	17.5	11.7
2003	8.1	14.2	13.5	17.8	19.6	22.5	23.4	24.2	23.5	23.0	14.0	13.2
2004	10.7	10.4	16.3	18.5	20.2	22.4	21.5	24.8	22.7	21.5	15.8	11.5
2005	11.4	11.5	19.0	19.6	19.7	22.5	24.0	24.3	23.8	20.8	16.0	12.2
2006	10.4	15.4	16.3	20.2	20.4	22.3	24.6	22.7	23.8	21.8	13.3	12.6
2007	9.6	12.6	15.0	18.1	22.5	22.0	23.4	24.2	24.5	19.5	16.8	11.3
2008	10.5	10.8	16.5	19.6	20.3	22.5	24.6	23.6	24.4	18.0	16.3	13.0
2009	11.1	12.2	15.8	20.4	21.6	22.6	24.4	24.3	24.5	20.6	15.2	11.4
2010	9.6	12.0	18.4	20.8	21.3	23.2	25.3	25.0	24.8	21.5	16.6	11.0
2011	8.2	13.0	16.0	20.2	21.3	23.2	23.9	24.5	23.7	22.0	17.2	11.0
2012	10.5	12.2	18.3	19.0	20.5	23.2	25.2	24.4	24.9	20.3	14.8	9.6
2013	7.2	14.0	16.7	19.8	20.0	22.0	24.5	24.5	24.2	****	****	****

Table C: Surveyed Office Data

Sl. No.	Name of the Office	Story	Surveyed Floor	Floor Height (m)	Ceiling Height (m)	Lintel Level (m)	Sill Level (m)	Opening Height (m)	Work Plane Height (m)	Partition Height (m)	Illumination Level (Lux)	
											With Artificial Light	Without Artificial Light
1	Opsonin Chemical Industries Ltd.	09	5th	3.00	2.1	2.1	0	2.1	0.75	1.2	400	30
2	Akiz House	14	4th	3.66	2.75	2.75	0	2.75	0.75	1.06	360	50
3	Pubali Bank Ltd. Credit Divition	15	7th	3.00	2.1	2.1	0.75	1.35	0.75	1.2	160	25
4	Markentile Bank Ltd.	22	12th	3.66	2.4	2.4	0.75	1.35	0.75	1.06	310	20
5	Renata Ltd. Inter.Business Divition	02	1st	3.35	2.75	2.75	0.75	1.35	0.75	1.2	435	60
6	Bangladesh Bank, Head Office	31	24h	3.20	2.1	2.1	0.75	1.35	0.75	1.2	275	80
7	BASF Bangladesh Ltd.	11	7th	3.66	2.75	2.4	0	2.4	0.75	1.2	420	30
8	I-Pay Office	19	13th	3.66	2.75	2.75	0	2.75	0.75	0	450	10
9	IFIC Bank Ltd., Progoti Saroni Branch	15	1st	3.35	2.1	2.1	0	2.1	0.75	1.2	300	70
10	Nafi Tower	20	5th	3.66	2.4	2.4	0	2.4	0.75	1.2/1	275	45

Part A

1. Building Name:
2. Type:

Highrise	Lowrise		
1 side open	2 side open	3 side open	4 side open
Top Floor	Intermediate Floor	Ground Floor	
Designed as office building		Turned as office	

3. Location:
4. Orientation:
5. Access Road: Name: Width:
6. Land Configuration:
7. Land Area:
8. No. of Floors:
9. Office Name:
10. Client:
11. Typology:
12. Location of the office in the building:
13. Total Floor Area:
14. Layout Type:
15. No. of stuff:
16. Dimension of activity spaces:

	Lobby	Corridor	Individual Room	Open Office space	Meeting Room
Space Dim					
Window					

17. Opening of the spaces:

Height			Type	Material	Shading
Sill	Lintel	Opening			

18. Ceiling height:
19. Average height of work plane:
20. Average height of interior partition walls:
21. Type of cooling system:
22. Check list:

Site Plan	Window Section	Photographs: Front, Surroundings, All Spaces		
Floor plan	Elevation	Interior Layout	Exterior Layout	HVAC Layout

Part B

1. Office Name:
2. Name:
3. Designation:
4. Age:
5. Gender:

Male	Female

6. Workspace Area:

Beside Window	Near Window	Away from Window	Near Deep Space	Deep Space

7. Which of the following best describes your personal workspace

Enclosed private office	Cubicles with partitions above standing eye level
Cubicles with partitions below standing eye level	Other (please specify)

8. Workspace Lighting Environment

Natural Daylight	Artificial Light

9. Overall, is the lighting comfortable?

Yes	No

10. Are you able to see out a window while sitting in your workspace?

Yes	No

11. Can you control the nearby artificial lights in your personal workspace?

Yes	No

12. On a typical day, how long are you in your personal workspace?

More than 6 Hours	4-6 Hours	2-4 Hours	Less than 2 hours

13. Health Symptom:

Headache	Eye Irritation	Fatigue	None

Table E.1: The instruments used in field study

Sl	Tool/Equipment/ Component	Manufacturer/ Origin	Instrument	Specification & details:
1	Dr. Meter LX1330B	China		The Digital Light meters are used in the fields of lighting research and scenic design, in order to determine the optimum light level. They are used in the general field of lighting, where they can ensure proper light levels.
2	Hand Held maxima-minima temperature meter Thermo Hydrometer	China		The thermo hygrometer measures both humidity of the air and temperature of the air. The thermo hygrometer measures different ranges of humidity and temperature depending on the model.
3	Digital Camera	Canon Inc., Japan		A digital camera (or digi-cam) is a camera that encodes digital images and videos digitally and stores them for later reproduction.
4	Analog Compass	China		A compass is a navigational instrument that shows directions in a frame of reference that is stationary relative to the surface of the Earth.

Daylight

Daylight is the light received from the sun and the sky, which varies throughout the day, as modified by the seasons and the weather.

Skylight

Skylight is the light received from the whole vault of the sky as modified by the weather and time of day, ignoring sunlight.

Sunlight

Sunlight is the light received directly from the sun, as opposed to that derived from the sky.

Illuminance

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 metre (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.

Luminance

Luminance is the quantitative expression for the amount of light reflected by a surface in a specific direction. A more familiar word is “brightness”, although this term must, strictly speaking, be reserved to describe the subjective impression of luminance on the eye. The luminance of a surface is determined by the illuminance on the surface in question and its reflective properties. Luminance is expressed in candelas per square metre (cd/m^2), referred to as the unit. In Imperial units the unit is the foot-lambert, which is candelas per square foot (cd/ft^2). Other units are – lambert, stilb, apostilb, blondel, skot.

Luminous flux

Luminous flux is the total amount of light radiated by a light source per second. A more familiar term would be “light output". It is expressed in lumens (lm).

Luminous intensity

Luminous intensity is the luminous flux radiated by a light source in a specific direction. Luminous intensity is expressed in candelas (cd).

Radiance

Radiance is power (energy flux) emitted per unit area into a cone having unit solid angle. The unit is W/m2/sr.

Normal Distribution

The normal distribution (also known as Gaussian) is a very commonly occurring continuous probability distribution, a function that tells the probability that any real observation will fall between any two real limits or real numbers, as the curve approaches zero on either side. Normal distributions are extremely important in statistics and are often used in the natural and social sciences for real-valued random variables whose distributions are not known. The normal distribution is immensely useful because of the central limit theorem, which states that, under mild conditions, the mean of many random variables independently drawn from the same distribution is distributed approximately normally, irrespective of the form of the original distribution: physical quantities that are expected to be the sum of many independent processes (such as measurement errors) often have a distribution very close to the normal. The Gaussian distribution is sometimes informally called the bell curve. However, many other distributions are bell-shaped (such as Cauchy's, Student's, and logistic). The terms Gaussian function and Gaussian bell curve are also ambiguous because they sometimes refer to multiples of the normal distribution that cannot be directly interpreted in terms of probabilities. A normal distribution is

$$f(x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

The parameter μ in this definition is the mean or expectation of the distribution (and also its median and mode). The parameter σ is its standard deviation; its variance is therefore σ2. A random variable with a Gaussian distribution is said to be normally distributed and is called a normal deviate.

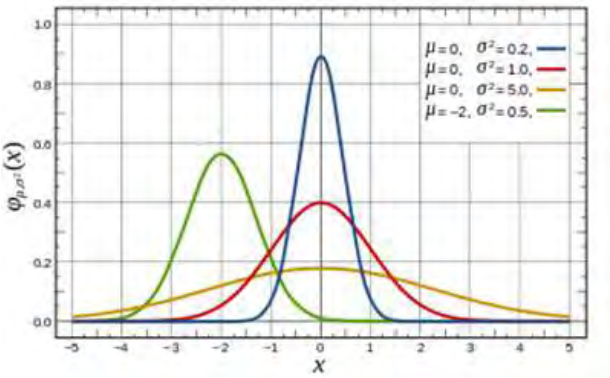


Figure F.1: Probability density function

If μ = 0 and σ = 1, the distribution is called the standard normal distribution or the unit normal distribution, and a random variable with that distribution is a standard normal deviate. The normal distribution is the only absolutely continuous distribution all of whose cumulates beyond the first two (i.e., other than the mean and variance) are zero. It is also the continuous distribution with the maximum entropy for a given mean and variance.

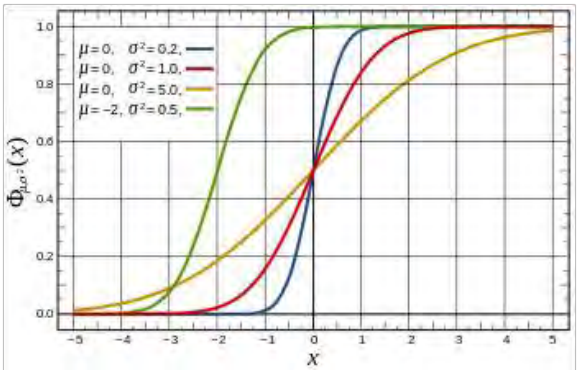


Figure F.2: Cumulative distribution function

The normal distribution is a subclass of the elliptical distributions. The normal distribution is symmetric about its mean, and is non-zero over the entire real line. As such it may not be a suitable model for variables that are inherently positive or strongly skewed, such as the weight of a person or the price of a share. Such variables may be better described by other distributions, such as the log-normal distribution or the Pareto distribution.

The value of the normal distribution is practically zero when the value x lies more than a few standard deviations away from the mean. Therefore, it may not be an appropriate

model when one expects a significant fraction of outliers—values that lie many standard deviations away from the mean — and least squares and other statistical inference methods that are optimal for normally distributed variables often become highly unreliable when applied to such data. In those cases, a more heavy-tailed distribution should be assumed and the appropriate robust statistical inference methods applied. The Gaussian distribution belongs to the family of stable distributions which are the attractors of sums of independent, identically distributed distributions whether or not the mean or variance is finite. Except for the Gaussian which is a limiting case, all stable distributions have heavy tails and infinite variance.

Standard Deviation:

In statistics and probability theory, the standard deviation (SD) (represented by the Greek letter sigma, σ) measures the amount of variation or dispersion from the average. A low standard deviation indicates that the data points tend to be very close to the mean (also called expected value); a high standard deviation indicates that the data points are spread out over a large range of values.

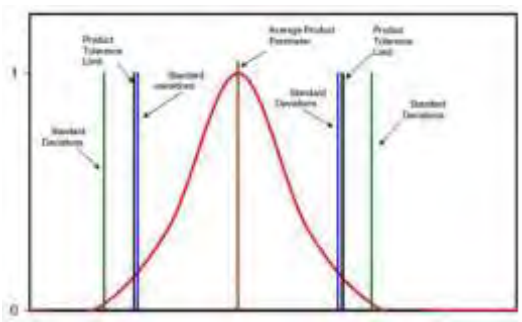


Figure F.3: Normal curve and standard deviation

Here the operator E denotes the average or expected value of X. Then the standard deviation of X is the quantity:

$$\sigma = \sqrt{\mathrm{E}[(X-\mu)^2]}$$

In other words the standard deviation σ (sigma) is the square root of the variance of X; i.e., it is the square root of the average value of (X − μ) 2.

Median:

In statistics and probability theory, the median is the numerical value separating the higher half of a data sample, a population, or a probability distribution, from the lower half. The median of a finite list of numbers can be found by arranging all the observations from lowest value to highest value and picking the middle one (e.g., the median of {3, 3, 5, 9, and 11} is 5). If there is an even number of observations, then there is no single middle value; the median is then usually defined to be the mean of the two middle values [1] [2] (the median of {3, 5, 7, 9} is (5 + 7) / 2 = 6), which corresponds to interpreting the median as the fully trimmed mid-range.

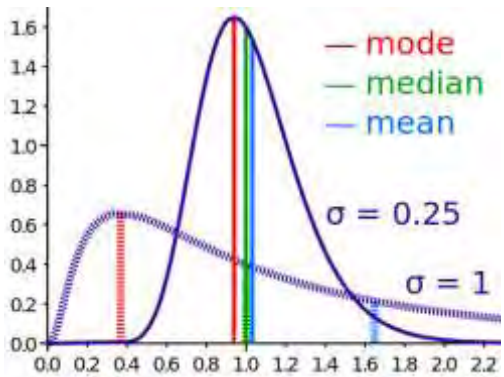


Figure F.4: Comparison of mean, median and mode of two log-normal distributions with different skewness

Table G.1: Case No. 04(b)

Time	PIPE 1:Tubular Daylighting Device Transmitted Solar Radiation Rate [W](Hourly)	PIPE 1:Tubular Daylighting Device Pipe Absorbed Solar Radiation Rate [W](Hourly)	PIPE 1:Tubular Daylighting Device Beam Solar Transmittance [](Hourly)	PIPE 1:Tubular Daylighting Device Beam Visible Transmittance [](Hourly)	PIPE 1:Tubular Daylighting Device Diffuse Solar Transmittance [](Hourly)	PIPE 1:Tubular Daylighting Device Diffuse Visible Transmittance [](Hourly)	ZONE 1:Daylighting Reference Point 1 Illuminance [lux] (Hourly)	ZONE 1:Daylighting Reference Point 2 Illuminance [lux] (Hourly)
1.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
4.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
5.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
6.00	0.0100	2.7356	0.0000	0.0000	0.0047	0.0030	29.3280	29.1508
7.00	0.0373	21.8987	0.0000	0.0000	0.0042	0.0039	157.6614	156.9143
8.00	0.0412	48.6837	0.0000	0.0000	0.0034	0.0046	195.0210	193.9880
9.00	0.0451	73.1281	0.0000	0.0000	0.0034	0.0062	195.7500	194.5033
10.00	0.0480	92.2247	0.0000	0.0000	0.0034	0.0090	180.2236	178.9952
11.00	0.1188	104.8078	0.0000	0.0195	0.0082	0.0144	160.3300	159.4245
12.00	3.0103	107.4828	0.0000	0.4497	0.2060	0.0207	188.4411	195.0971
13.00	1.0954	108.3416	0.0000	0.2745	0.0750	0.0186	196.8116	200.0575
14.00	0.0559	101.2446	0.0000	0.0070	0.0039	0.0122	236.2578	234.2318
15.00	0.0494	86.3030	0.0000	0.0000	0.0036	0.0079	301.9925	298.8907
16.00	0.0400	65.1837	0.0000	0.0000	0.0031	0.0056	342.6449	337.7428
17.00	0.0410	39.3558	0.0000	0.0000	0.0036	0.0043	334.1131	325.9774
18.00	0.0311	13.5776	0.0000	0.0000	0.0044	0.0038	226.3287	217.0731
19.00	0.0023	0.4792	0.0000	0.0000	0.0024	0.0014	6.8578	6.2600
20.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
21.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
22.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
23.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
24.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Appendix H: EnergyPlus Simulation Result 2 (Sample Data of Illuminance Plane)

Table H.1: Case No. 04(b)

06/07 06:00	(4.75;4.23)=	(7.59;4.23)=	(10.44;4.23)=	(13.28;4.23)=	(16.13;4.23)=	(18.97;4.23)=	(21.82;4.23)=	(24.66;4.23)=	(27.51;4.23)=	(30.35;4.23)=
(4.75;4.23)=	28	28	28	28	28	28	28	28	28	28
(4.75;7.44)=	31	37	45	61	72	79	94	1130	1361	28
(4.75;10.66)=	31	53	42	40	42	46	57	102	1388	28
(4.75;13.88)=	31	84	47	38	37	37	40	46	60	28
(4.75;17.09)=	31	90	49	39	35	34	34	33	32	28
(4.75;20.31)=	31	91	50	39	35	33	32	31	30	28
(4.75;23.53)=	34	92	52	41	37	34	32	31	30	28
(4.75;26.75)=	39	82	59	52	45	39	34	31	30	28
(4.75;29.96)=	52	97	133	136	115	70	39	31	29	28
(4.75;33.18)=	28	29	812	812	812	812	29	29	29	28
06/07 07:00	(4.75;4.23)=	(7.59;4.23)=	(10.44;4.23)=	(13.28;4.23)=	(16.13;4.23)=	(18.97;4.23)=	(21.82;4.23)=	(24.66;4.23)=	(27.51;4.23)=	(30.35;4.23)=
(4.75;4.23)=	153	153	153	153	153	153	153	153	153	153
(4.75;7.44)=	163	186	221	288	329	351	387	4009	4868	153
(4.75;10.66)=	162	254	208	201	207	221	260	424	5064	153
(4.75;13.88)=	163	386	230	195	188	189	200	227	292	153
(4.75;17.09)=	162	409	241	196	182	177	176	175	171	153
(4.75;20.31)=	164	413	245	198	182	174	169	165	161	153
(4.75;23.53)=	171	412	249	205	188	177	169	163	160	153
(4.75;26.75)=	188	360	269	242	219	195	175	164	159	153
(4.75;29.96)=	221	378	514	535	474	318	197	165	158	153
(4.75;33.18)=	154	158	9131	9131	9130	9128	156	155	155	153
06/07 08:00	(4.75;4.23)=	(7.59;4.23)=	(10.44;4.23)=	(13.28;4.23)=	(16.13;4.23)=	(18.97;4.23)=	(21.82;4.23)=	(24.66;4.23)=	(27.51;4.23)=	(30.35;4.23)=
(4.75;4.23)=	190	190	190	190	190	190	190	190	190	190
(4.75;7.44)=	199	225	266	348	391	406	420	480	1151	190
(4.75;10.66)=	198	311	254	245	249	259	290	427	1440	190
(4.75;13.88)=	201	467	281	239	229	230	241	273	359	190
(4.75;17.09)=	198	495	295	240	224	218	216	216	212	190
(4.75;20.31)=	200	499	299	242	223	214	209	204	199	190
(4.75;23.53)=	205	494	300	249	230	218	209	202	198	190
(4.75;26.75)=	215	416	309	282	262	238	216	203	197	190
(4.75;29.96)=	233	371	517	555	517	380	244	204	195	190
(4.75;33.18)=	191	195	17665	17664	17663	17661	193	193	192	190

Table H.1: Continued

06/07 09:00	(4.75;4.23)=	(7.59;4.23)=	(10.44;4.23)=	(13.28;4.23)=	(16.13;4.23)=	(18.97;4.23)=	(21.82;4.23)=	(24.66;4.23)=	(27.51;4.23)=	(30.35;4.23)=
(4.75;4.23)=	191	191	191	191	191	191	191	191	191	191
(4.75;7.44)=	197	222	262	346	387	397	396	397	758	191
(4.75;10.66)=	197	312	254	243	245	251	269	354	1007	191
(4.75;13.88)=	201	468	282	238	228	227	235	264	351	191
(4.75;17.09)=	197	495	295	241	224	218	216	217	213	191
(4.75;20.31)=	199	499	299	243	224	215	210	206	201	191
(4.75;23.53)=	202	491	298	248	230	219	210	204	199	191
(4.75;26.75)=	208	404	299	276	260	239	218	205	198	191
(4.75;29.96)=	217	323	458	503	483	378	246	205	196	191
(4.75;33.18)=	191	196	18075	18075	18074	18072	194	193	193	191
06/07 10:00	(4.75;4.23)=	(7.59;4.23)=	(10.44;4.23)=	(13.28;4.23)=	(16.13;4.23)=	(18.97;4.23)=	(21.82;4.23)=	(24.66;4.23)=	(27.51;4.23)=	(30.35;4.23)=
(4.75;4.23)=	176	176	176	176	176	176	176	176	176	176
(4.75;7.44)=	181	203	239	321	358	366	361	337	550	176
(4.75;10.66)=	181	289	233	223	225	228	239	294	739	176
(4.75;13.88)=	186	432	258	219	209	208	213	236	315	176
(4.75;17.09)=	181	457	270	221	206	200	199	200	197	176
(4.75;20.31)=	182	460	273	223	206	198	193	190	185	176
(4.75;23.53)=	185	452	272	227	212	202	194	188	183	176
(4.75;26.75)=	189	368	271	252	239	221	202	189	183	176
(4.75;29.96)=	193	279	401	447	435	352	229	189	181	176
(4.75;33.18)=	176	181	10697	10697	10696	10694	179	178	178	176
06/07 11:00	(4.75;4.23)=	(7.59;4.23)=	(10.44;4.23)=	(13.28;4.23)=	(16.13;4.23)=	(18.97;4.23)=	(21.82;4.23)=	(24.66;4.23)=	(27.51;4.23)=	(30.35;4.23)=
(4.75;4.23)=	154	154	154	154	154	154	154	154	154	154
(4.75;7.44)=	158	179	210	290	327	333	328	294	429	154
(4.75;10.66)=	159	264	208	199	201	203	209	247	569	154
(4.75;13.88)=	165	402	231	195	192	189	188	205	274	154
(4.75;17.09)=	159	427	243	198	188	182	177	177	175	154
(4.75;20.31)=	160	430	246	199	188	180	172	168	163	154
(4.75;23.53)=	162	421	244	203	195	185	173	166	162	154
(4.75;26.75)=	165	337	242	225	216	199	180	167	161	154
(4.75;29.96)=	168	242	355	401	394	324	206	167	159	154
(4.75;33.18)=	155	160	2764	2763	2762	2761	158	157	156	154

Table H.1: Continued

06/07 12:00	(4.75;4.23)=	(7.59;4.23)=	(10.44;4.23)=	(13.28;4.23)=	(16.13;4.23)=	(18.97;4.23)=	(21.82;4.23)=	(24.66;4.23)=	(27.51;4.23)=	(30.35;4.23)=
(4.75;4.23)=	141	141	141	141	141	141	141	141	141	141
(4.75;7.44)=	145	165	194	274	314	320	312	273	366	141
(4.75;10.66)=	146	255	197	197	222	220	203	223	474	141
(4.75;13.88)=	2189	402	224	210	333	304	196	192	247	141
(4.75;17.09)=	2184	429	237	216	310	286	189	169	163	141
(4.75;20.31)=	2184	431	240	217	295	272	185	161	152	141
(4.75;23.53)=	2186	422	236	217	334	298	182	158	150	141
(4.75;26.75)=	2188	331	230	222	236	217	177	157	149	141
(4.75;29.96)=	152	222	330	380	377	315	196	156	147	141
(4.75;33.18)=	142	147	149	148	148	146	145	144	143	141
06/07 13:00	(4.75;4.23)=	(7.59;4.23)=	(10.44;4.23)=	(13.28;4.23)=	(16.13;4.23)=	(18.97;4.23)=	(21.82;4.23)=	(24.66;4.23)=	(27.51;4.23)=	(30.35;4.23)=
(4.75;4.23)=	166	166	166	166	166	166	166	166	166	166
(4.75;7.44)=	170	191	217	296	337	344	337	298	370	166
(4.75;10.66)=	170	294	224	218	233	232	223	243	461	166
(4.75;13.88)=	35171	467	253	226	295	276	211	212	263	166
(4.75;17.09)=	35165	496	267	231	281	264	204	191	187	166
(4.75;20.31)=	35166	499	270	232	272	255	200	184	177	166
(4.75;23.53)=	35167	489	266	233	298	273	199	182	175	166
(4.75;26.75)=	35169	382	258	244	248	231	199	182	174	166
(4.75;29.96)=	177	246	352	406	404	345	225	181	172	166
(4.75;33.18)=	167	172	174	173	172	171	170	169	168	166
06/07 14:00	(4.75;4.23)=	(7.59;4.23)=	(10.44;4.23)=	(13.28;4.23)=	(16.13;4.23)=	(18.97;4.23)=	(21.82;4.23)=	(24.66;4.23)=	(27.51;4.23)=	(30.35;4.23)=
(4.75;4.23)=	231	231	231	231	231	231	231	231	231	231
(4.75;7.44)=	234	257	283	360	404	412	407	369	435	231
(4.75;10.66)=	235	388	295	279	278	279	283	307	520	231
(4.75;13.88)=	62055	614	330	279	267	263	263	275	326	231
(4.75;17.09)=	62050	646	346	283	265	257	253	253	251	231
(4.75;20.31)=	62050	649	349	285	266	256	250	245	241	231
(4.75;23.53)=	62052	637	344	288	272	261	251	244	239	231
(4.75;26.75)=	62054	498	331	307	296	280	260	246	239	231
(4.75;29.96)=	241	313	422	483	482	424	299	248	237	231
(4.75;33.18)=	231	236	5150	5149	5148	5147	234	233	233	231

Table H.1: Continued

06/07 15:00	(4.75;4.23)=	(7.59;4.23)=	(10.44;4.23)=	(13.28;4.23)=	(16.13;4.23)=	(18.97;4.23)=	(21.82;4.23)=	(24.66;4.23)=	(27.51;4.23)=	(30.35;4.23)=
(4.75;4.23)=	296	296	296	296	296	296	296	296	296	296
(4.75;7.44)=	299	326	354	432	479	488	484	446	513	296
(4.75;10.66)=	300	511	378	352	349	349	354	380	603	296
(4.75;13.88)=	61385	823	427	356	337	331	332	344	397	296
(4.75;17.09)=	61381	859	446	362	336	325	321	320	318	296
(4.75;20.31)=	61381	862	448	364	337	325	318	313	308	296
(4.75;23.53)=	61383	846	441	365	342	329	320	312	306	296
(4.75;26.75)=	61386	645	416	382	369	352	331	315	306	296
(4.75;29.96)=	307	383	499	574	577	519	383	319	304	296
(4.75;33.18)=	296	301	14026	14025	14024	14023	300	299	298	296
06/07 16:00	(4.75;4.23)=	(7.59;4.23)=	(10.44;4.23)=	(13.28;4.23)=	(16.13;4.23)=	(18.97;4.23)=	(21.82;4.23)=	(24.66;4.23)=	(27.51;4.23)=	(30.35;4.23)=
(4.75;4.23)=	333	333	333	333	333	333	333	333	333	333
(4.75;7.44)=	337	369	402	480	528	538	533	495	567	333
(4.75;10.66)=	338	663	450	407	397	394	399	427	665	333
(4.75;13.88)=	46634	1116	523	418	387	377	376	389	444	333
(4.75;17.09)=	46630	1154	545	425	387	372	365	363	359	333
(4.75;20.31)=	46631	1157	547	427	388	371	362	355	349	333
(4.75;23.53)=	46633	1137	533	424	391	375	364	355	348	333
(4.75;26.75)=	46635	806	481	435	420	402	379	360	348	333
(4.75;29.96)=	345	425	550	649	662	604	455	368	346	333
(4.75;33.18)=	334	340	19235	19235	19234	19232	338	337	337	333
06/07 17:00	(4.75;4.23)=	(7.59;4.23)=	(10.44;4.23)=	(13.28;4.23)=	(16.13;4.23)=	(18.97;4.23)=	(21.82;4.23)=	(24.66;4.23)=	(27.51;4.23)=	(30.35;4.23)=
(4.75;4.23)=	320	320	320	320	320	320	320	320	320	320
(4.75;7.44)=	324	362	400	471	513	522	516	479	548	320
(4.75;10.66)=	325	881	504	423	399	390	390	416	644	320
(4.75;13.88)=	26115	1500	609	445	395	376	371	381	432	320
(4.75;17.09)=	26112	1537	632	454	396	372	361	356	350	320
(4.75;20.31)=	26113	1538	632	453	395	370	357	348	341	320
(4.75;23.53)=	26114	1510	606	442	394	373	360	349	340	320
(4.75;26.75)=	26117	915	496	436	420	404	381	358	342	320
(4.75;29.96)=	332	406	535	669	704	656	499	378	340	320
(4.75;33.18)=	321	326	15492	15492	15491	15489	326	325	324	320

Table H.1: Continued

06/07 18:00	(4.75;4.23)=	(7.59;4.23)=	(10.44;4.23)=	(13.28;4.23)=	(16.13;4.23)=	(18.97;4.23)=	(21.82;4.23)=	(24.66;4.23)=	(27.51;4.23)=	(30.35;4.23)=
(4.75;4.23)=	212	212	212	212	212	212	212	212	212	212
(4.75;7.44)=	214	247	284	334	359	362	355	327	375	212
(4.75;10.66)=	215	4229	3848	323	289	274	270	285	445	212
(4.75;13.88)=	7538	4700	3940	345	289	266	257	261	297	212
(4.75;17.09)=	7537	4719	3955	351	289	263	250	244	238	212
(4.75;20.31)=	7537	4724	3954	348	286	260	246	238	231	212
(4.75;23.53)=	7538	4697	3919	327	278	259	248	239	232	212
(4.75;26.75)=	7540	648	351	304	296	288	272	252	236	212
(4.75;29.96)=	219	270	369	500	552	529	405	283	235	212
(4.75;33.18)=	212	216	5567	5567	5567	5566	216	215	214	212
06/07 19:00	(4.75;4.23)=	(7.59;4.23)=	(10.44;4.23)=	(13.28;4.23)=	(16.13;4.23)=	(18.97;4.23)=	(21.82;4.23)=	(24.66;4.23)=	(27.51;4.23)=	(30.35;4.23)=
(4.75;4.23)=	6	6	6	6	6	6	6	6	6	6
(4.75;7.44)=	6	8	10	13	14	15	14	12	15	6
(4.75;10.66)=	6	99	76	13	11	10	9	10	19	6
(4.75;13.88)=	62	124	81	14	11	9	9	9	11	6
(4.75;17.09)=	62	125	82	15	11	9	8	8	8	6
(4.75;20.31)=	62	125	82	14	11	9	8	8	7	6
(4.75;23.53)=	62	123	79	13	10	9	8	8	7	6
(4.75;26.75)=	62	29	14	11	11	11	10	8	7	6
(4.75;29.96)=	6	9	15	23	27	26	18	11	7	6
(4.75;33.18)=	6	6	51	51	51	51	6	6	6	6

Table I.1: CDF Actual Frequency Distribution

Pipe 1	Pipe 2	Pipe 3	Pipe 6	Pipe 9	pipe+no Win	Pipe3+Win	No Pipe+Win	Actual Frequency (%)
2	5	6	16	24	3	141	16	0.01
2	5	6	16	24	3	141	17	0.02
2	5	6	16	24	3	141	17	0.03
2	5	6	16	24	3	141	18	0.04
2	5	6	16	24	3	141	30	0.05
2	5	6	16	24	3	141	35	0.06
2	5	6	16	24	3	141	36	0.07
2	5	6	16	24	3	141	40	0.08
2	5	6	16	24	3	141	50	0.09
2	5	6	16	24	3	141	61	0.1
3	9	11	30	24	3	141	65	0.11
3	10	12	33	24	3	141	66	0.12
3	11	13	35	24	3	141	70	0.13
3	12	14	36	24	3	141	72	0.14
4	12	14	39	24	3	141	78	0.15
4	12	14	40	24	3	141	80	0.16
4	12	15	40	24	3	141	85	0.17
4	12	15	41	24	3	141	88	0.18
4	12	17	41	24	3	141	89	0.19
4	12	17	41	43	3	142	90	0.2
4	13	18	41	50	3	143	90	0.21
4	13	18	42	50	3	144	92	0.22
4	13	18	45	57	3	145	95	0.23
4	14	19	45	58	3	145	110	0.24
4	14	19	45	62	4	146	120	0.25
4	15	19	46	62	4	146	122	0.26
4	15	20	47	64	4	147	125	0.27
4	16	20	47	65	4	147	127	0.28
4	16	20	51	67	4	148	129	0.29
4	16	20	57	74	4	148	132	0.3
4	16	21	71	95	4	149	133	0.31
4	16	22	78	99	4	149	134	0.32
5	16	22	79	102	4	150	135	0.33
5	17	23	79	104	4	152	135	0.34
5	17	25	79	107	4	152	136	0.35
5	18	25	80	108	4	156	138	0.36
5	18	25	81	110	4	157	138	0.37
5	18	26	82	110	4	158	139	0.38
5	18	27	82	115	4	159	139	0.39

Table I.1: Continued

Pipe 1	Pipe 2	Pipe 3	Pipe 6	Pipe 9	pipe+no Win	Pipe3+Win	No Pipe+Win	Actual Frequency (%)
6	19	27	85	117	5	160	139	0.4
6	19	27	87	126	5	161	139	0.41
6	20	27	87	129	5	162	139	0.42
6	20	28	92	139	5	163	140	0.43
6	20	29	92	140	5	165	140	0.44
6	21	29	94	146	5	165	140	0.45
6	21	29	98	147	5	165	140	0.46
6	21	30	98	151	5	169	141	0.47
7	22	31	101	154	5	177	141	0.48
7	22	31	110	165	5	182	142	0.49
7	23	31	116	165	6	185	142	0.5
7	23	32	117	165	6	189	143	0.51
7	24	33	118	169	6	192	143	0.52
7	24	33	119	174	6	194	143	0.53
8	24	33	122	174	6	196	144	0.54
8	26	34	127	175	6	196	145	0.55
9	26	38	129	177	6	197	145	0.56
9	28	46	129	178	7	197	145	0.57
9	28	47	131	180	7	203	147	0.58
9	29	48	131	187	7	210	149	0.59
10	29	48	132	191	7	216	150	0.6
10	30	51	133	193	8	217	151	0.61
11	30	51	133	199	8	217	152	0.62
11	30	52	135	204	8	217	153	0.63
11	30	55	136	212	8	220	154	0.64
11	30	56	136	236	9	222	155	0.65
12	32	57	138	238	9	222	156	0.66
12	33	57	138	241	10	222	158	0.67
13	34	58	140	243	10	223	160	0.68
13	35	59	142	255	10	224	165	0.69
13	35	60	144	257	10	230	180	0.7
14	36	62	146	258	11	236	181	0.71
15	38	69	152	261	12	236	181	0.72
15	39	78	152	263	12	237	183	0.73
15	39	83	157	264	12	240	188	0.74
16	41	88	158	273	13	247	189	0.75
17	47	90	161	275	13	255	190	0.76
18	47	95	162	276	15	272	190	0.77
18	48	97	165	277	17	273	196	0.78
19	54	99	167	279	17	274	206	0.79
21	54	100	167	280	19	286	217	0.8

Table I.1: Continued

Pipe 1	Pipe 2	Pipe 3	Pipe 6	Pipe 9	pipe+no Win	Pipe3+Win	No Pipe+Win	Actual Frequency (%)
27	54	101	173	280	30	295	218	0.81
29	55	102	175	286	31	298	223	0.82
30	63	104	177	288	33	304	242	0.83
31	64	105	184	288	34	310	250	0.84
32	64	117	185	294	36	312	268	0.85
36	73	119	193	297	37	314	268	0.86
36	73	123	198	297	37	315	274	0.87
38	75	124	200	302	39	320	297	0.88
39	78	139	200	304	40	330	305	0.89
40	78	148	204	305	40	331	306	0.9
48	89	148	214	306	45	333	306	0.91
50	90	158	215	308	49	334	311	0.92
66	90	171	216	310	117	366	317	0.93
72	96	185	222	314	125	377	323	0.94
80	96	187	223	317	132	380	325	0.95
89	108	189	225	318	141	402	326	0.96
125	110	196	233	329	142	422	362	0.97
137	117	204	234	334	143	429	368	0.98
144	181	208	238	340	168	431	373	0.99
159	201	216	246	344	169	474	469	1