PERFORMANCE OF INTERNAL VENETIAN BLIND CONFIGURATIONS FOR DAYLIGHTING OFFICE SPACES IN CONTEXT OF DHAKA

By

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ABSTRACT

Most of the offices in Dhaka are located in high-rise buildings with deep plan layout due to constraint of space in urban areas. Contemporary glazed envelope technology in commercial buildings help to create a visual contact with the outside and lets daylight to enter especially in deep plan offices. In most cases high-rise commercial buildings do not use efficient shading elements. As a result, excessive daylight enters inside the office space causing glare, irregular daylight distribution, solar heat gain and visual and thermal discomfort. Shading elements reduce glare issues, provide improved illumination distribution, and ideally can also increase the daylighting penetration into the active work spaces. Internal venetian blinds are common type of shading system which consist of separate louvers and arranged equidistant from each other. It reflects light efficiently and ensures homogeneity of daylight illuminance by adjusting the louver angles while allowing view to the outdoors.

The aim of this research is to identify the characteristics of internal blinds to enhance the interior luminous environment of office spaces in the context of Dhaka. In order to study the performance of internal blind configurations, an active portion of workspace area of the case office floor is selected for simulation study, which has glass exterior walls on three of its sides. Different parameters of the venetian blind is studied, e.g. the slat geometry, configuration of slats and the distance between slats for each orientation. For this analysis, Useful Daylight Illuminance (UDI) is considered as the performance metric. Climate based dynamic daylight annual simulation is done using DAYSIM simulation program. The data from the simulation procedure is critically analyzed and compared with the base case when there is no blind provided.

The results suggested that for south, east and west orientations, internal venetian blinds with “inverted V” louver geometry at 45^{o}angle is the most feasible for enabling optimal indoor illuminance. In terms of distance between slats, 160mm is suitable for south façade whereas for east and west directions, 70mm provides the best performance among the studied options. This research proposes feasible configurations for internal venetian blind that are suitable for high-rise buildings with glazed façades in three orientations (south, east and west) to ensure sustainable building design.

Keywords: Daylight; Simulation; Internal venetian blind; Glazed facade; Office spaces.

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List of Abbreviations

BUET	Bangladesh University of Engineering & Technology
DoA	Department of Architecture
BNBC	Bangladesh National Building Code
CBDM	Climate-Based Daylight Modelling
CIE	International Commission on illumination
CES	Centre for Energy Studies
CIBSE	Chartered Institution of Building Services Engineering
CRI	Colour Rendering Index
CRI	Color Rendering Index
DAmax	Maximum Daylight Autonomy
DA	Daylight Autonomy
DDS	Dynamic Daylight Simulation
DF	Daylight Factor
DSF	Double Skin Facade
GMT	Greenwich Mean Time
IESNA	Illuminating Engineering Society of North America
IEA	International Energy Agency
IGU	Insulated Glass Unit
LEED	Leadership in Energy and Environmental Design
NOAO	National Optical Astronomy Observatory
PV	Photovoltaic
PVB	Polyvinyl Butyral
SHGC	Solar Heat Gain Co-efficient
SAD	Seasonal Effective Disorder
UDI	Useful Daylight Illuminance
UVR	Ultraviolet Radiation
UV	Ultra Violet

CHAPTER: ONE

INTRODUCTION

Preamble

Statement of the problem

Aim and Objectives of the study

Overview of research methodology

Scope and Limitations

Structure of the thesis

Summary

INTRODUCTION

1.1 Preamble

The modern envelope technologies often encourage adoption of large transparent facades in different orientations for commercial buildings. A building envelope acts as the interface between the exterior and the interior environment of building (Berardi and Anaraki, 2015). Large glazed aperture allows penetration of daylight, protection from climatic factors and creates a positive psychological effect on people because of the openness of the space (Hammad and Hijleh, 2010; Lavin and Fiorito, 2017). Daylighting is considered as one of the effective strategies to maintain a comfortable indoor environment and to provide great opportunities for energy savings in buildings (Moazzeni and Ghiabaklou, 2016). The sustainable approach in architecture and other disciplines, demand for the improvement of user's comfort and reduction of energy consumption in the built environment (Cellai, et al., 2014).

Daylight inside an interior space creates two types of luminous areas: daylight or light zone; and artificial light or dark zone. Light zone is created when there is abundance of daylight, whereas, dark zone refers to absence of daylight (Trisha, 2016). Excess amount of daylight inclusion can cause visual discomfort and glare. Glare can reduce workers performance and excessive light may also contribute to increment in the energy consumption (Zakhour, 2015), as daylight is the form of radiant energy that comes from the sun so when it enters through the glass facade, huge percentage of it is transformed into thermal energy. As a result, the internal temperature increases and this creates load on the heating, ventilation, and air conditioning (HVAC) system and lots of energy consumption occurs (Soud and Hossain, 2017). It is important for building professionals to maintain a comfortable luminous environment as well as reduce energy consumption.

In most office buildings, less attention is provided to the interdependence of the indoor and outdoor environment (Joarder, 2009). As a consequence, the portion closer to window receives daylight, whereas, most of the office spaces depend on artificial light. In addition to that, majority of glazed facade commercial buildings do not use appropriate interior shading elements. The glass envelopes are often exposed to direct sunlight and gains immense amount of heat (Trisha and Ahmed, 2017). Having a full control over daylight is possible through implementing of an optimum interior shading system which would result in optimization of passive solar heating in winter as well as reduce solar gain in summer (Kontadakis, et al., 2017). Interior shading devices on the glazed envelope can act as a passive means to change the property of daylight and let diffused light to enter inside the office spaces. This will enhance the quality of daylight in office spaces and become more energy efficient (Kim, et al., 2015). Interior shading elements with efficient design and parameters should be selected to address the said issues.

Depending on the climate and direction of the building aperture, performance of a shading device will differ (Lim, et al., 2017). Internal venetian blind that is a common type of interior shading element, has the distinctive ability to adjust the slat angles in order to allow view to outside as well as ensuring glare protection (Tzempelikos, 2008). Internal venetian blinds are cost effective, easy to install and take up minimum amount of space inside a room (Joarder, et al., 2011; Tzempelikos, 2008). This opens up limitless possibilities of external façade design to designers and reduces the construction cost as well (Ye, et al., 2016). To maintain comfortable luminous environment inside commercial office spaces, strategies for controlled daylight penetration are essential in the climatic context of Dhaka (Joarder and Ahmed, 2007).

1.2 Statement of the problem

The dense urban environment and lack of open space in Dhaka has led the commercial buildings with deep office plans having less access to daylight (Trisha and Ahmed, 2017). Glazed envelopes enhance the illuminance inside office spaces and increase the exterior views (Berardi and Anaraki, 2015). Admittance of daylight inside a space depends on the natural determinants e.g., orientation, altitude of sky, daylight quality and other factors such as detail of glazing, aperture size and shading devices (Hammad and Hijleh, 2010; Lavin and Fiorito, 2017). Reduction of glazed surface can increase the dependence on artificial lighting in office spaces. The global energy consumption is increasing at an unprecedented rate every year. In terms of global energy consumption, 38% of energy is used for building in which lighting takes up the highest ratio of 22% (Choi, Lee and Kim, 2014).

In most cases, buildings with glazed facades in different orientations, allows immense amount of daylight to penetrate causing visual and thermal discomfort, excessive heat and glare (Ochoa and Capeluto, 2006). The implication of inefficient interior shading system design results in uneven distribution of daylight inside work spaces. The dynamic nature of daylight causes the light inside an interior space to shift drastically. This continuous shifting nature of lighting causes eye fatigue and in longer run this can eventually lead to reduced visual output (Shishegar and Boubekri, 2016). The absence of daylight in active workspaces has negative impact on psychological health of office employees, lowers productivity, increases their frequency of making mistakes and the percentage of absenteeism also rises (Jamrozik, et al., 2019).

Internal shading elements reduce glare issues, provide better illumination distribution, and ideally also increase the daylighting penetration into the active work spaces. Shading glazed facades affect the property of incident radiation of sun rays (Kim, Leigh, Kim and Cho, 2015). The selection of appropriate configurations for internal shading system to a great extent depends on the climate of a country as well as the orientation of the building. Dhaka has a composite climatic condition, so both overcast as well as clear sky conditions persist throughout a year. Internal venetian blinds are adjustable and moveable so they can respond to dynamic weather conditions. The selection of effective design for internal shading system in consideration with climate and orientation becomes challenging (Joarder, 2009). In some cases, designers neither contemplate on the geometric configurations of the internal venetian blind nor take into account about the effectiveness of the system on daylight penetration for different orientations (Ochoa and Capeluto, 2006). It is necessary to develop an effective configuration of internal venetian blind for various orientations that would provide balance between glare controls, respond to seasonal variation in natural light and can be used efficiently with the building envelopes (Choi, Lee and Kim, 2014).

This research attempts to ensure comfortable luminous environment, for air-conditioned office buildings in Dhaka, with glass façade in three critical orientations (i.e., South, East and West) (BNBC, 2020; Joarder, et.al, 2012). Parameters such as, standard illumination level up to maximum depth and glare-free workspaces, are evaluated to determine performance of internal venetian blinds in office space.

1.3 Aim and Objectives of the study

The aim of this research is to identify the characteristics of internal venetian blinds to enhance the quality of interior luminous environment of office spaces in the context of Dhaka. To achieve this aim, following objectives have been developed.

Objective 01: To evaluate the effectiveness of internal venetian blind as shading system to ensure appropriate illuminance level inside deep plan office buildings.

Objective 02: To select appropriate types of internal venetian blind in context of Dhaka.

Objective 03: To identify the best parametric configuration of internal venetian blind for different orientations.

1.4 Overview of research methodology

Chapter 3 describes a detail research methodology which is followed in this research. This section provides a brief outline of the research methodology. This is a simulation-based research. An active portion of workspace area of the case office floor is selected for simulation study, which has glass exterior walls on south, east and west orientations. A flow diagram of the research process is shown in Figure 1.1, which incorporates the main research methods: literature review, case study and simulation analysis. A brief description of the methods for this study is described as follows.

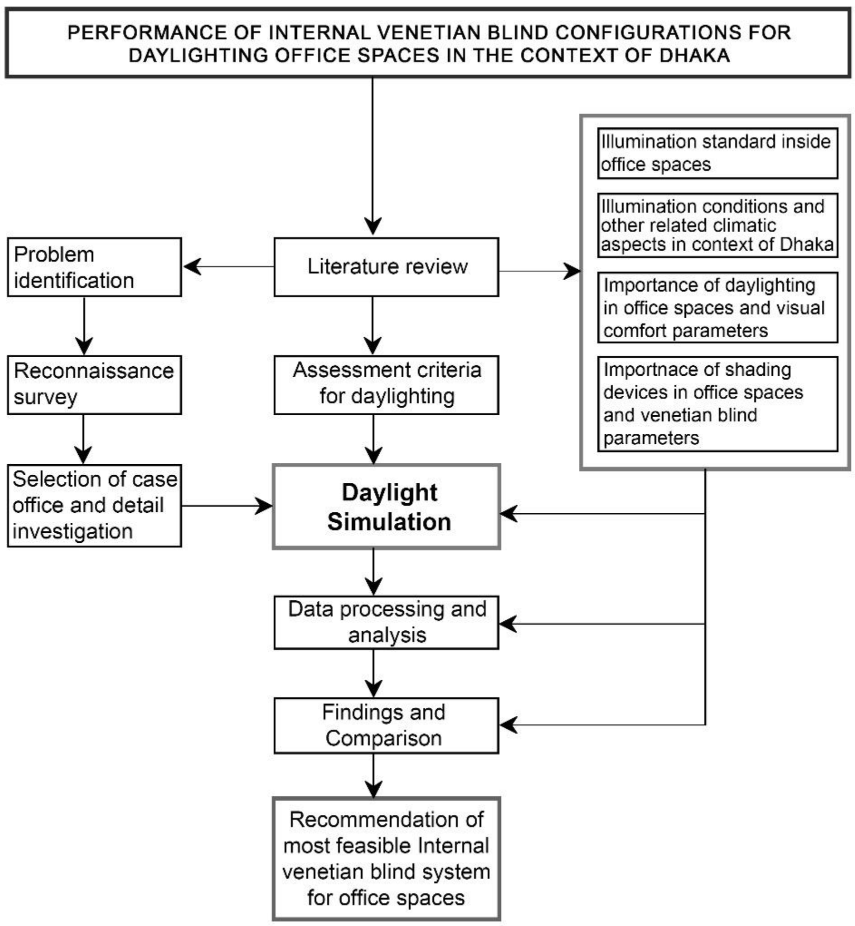


Figure 1.1: Flow diagram for overall methodology of the research process

Literature review is done to get an overview of the past studies from books and verified documents (e.g., research papers, standards, codes and websites) that are relevant to this research. Illumination conditions and related climatic issues for Dhaka as well as other contexts are studied from published sources. An understanding of the daylight situation, strategies, properties and configurations of venetian blind, their influence on daylight distribution and standards for active work spaces is compiled to provide a knowledge base for this research.

Physical survey is conducted to create a model for case office space for detailed study. Actual measurement of office space is taken and characteristics of window configurations, floor, ceiling materials are recorded for simulation analysis.

An active portion of workspace area of the case office floor is identified for **simulation study**, which has glass exterior walls on three orientations. Different parameters of the venetian blinds are studied, e.g., the slat geometry, configuration of slats and the distance between slats for each orientation. Findings from the physical survey and the mentioned design variants are used to create simulation model. The models are analyzed with DAYSIM program to find out the performance of various venetian blind configurations for different orientations throughout the year.

Finally, the **analysis and comparison** of the simulation results helped to identify the effective blind configurations for office space with glass facades at three orientations (e.g., South, East, and West). The findings will help to ensure standard illuminance level in office spaces for different seasons round the year in the context of Dhaka.

1.5 Scope and Limitations

This study concentrates on the influence of internal venetian blind configurations for different orientations on daylight performance in office spaces in the climatic context of Dhaka. It is recognized that, numerous environmental factors are connected with the illumination issues inside a space. Along with visual performance, daylight inclusion is also linked to; unwanted heat, ventilation, sound transmission, energy consumption, safety, privacy, view, all these factors are beyond the scope of this research. This study is limited to the penetration of sufficient daylight inside the office space.

The study focused mainly on the slat geometric configurations and slat distance. Other geometric parameters such as angle of inclination, dimension, material property and other parameters are beyond the scope of this research. In order to evaluate the performance of blind parameters for a particular orientation, openings in other orientations are kept unobstructed during the simulation analysis. The findings from this research are feasible for high-rise buildings with glass façade in three orientations (South, West and East). The interior space is considered vacant for this simulation study; different partition layout, furniture arrangements as well as presence of suspended ceiling can affect the output to a certain extent. The presence of any type of peripheral shading might affect the result. It is essential to carry out post occupancy study in the office space to find out the effectiveness of proposed venetian blind configurations. Human collaboration factor was not part of this study, which can be conducted to study the effect of blind parameters in real scenario. The performance of blind also depends on operation of blind configurations; a study can be conducted to monitor the usage of interior blind in office space in correspondence to weather condition. The blind configurations were not studied in correspondence to view allowance, so the recommended configurations might affect outside view as well.

Daylight penetration not only improves the visual performance but is also related to aesthetics, energy consumption (electric lighting, mechanical heating and cooling), heat loss and gain, sound transmission, glare control, ventilation, economics, safety, security and subjective concerns of view and privacy. In the short time available, the consequence of daylight penetration on energy savings, ventilation, view, heat, comfort and efficiency of occupants are however beyond the scope of this thesis. Considering the time and resource limitation, the present work focuses mainly on daylight penetration inside office space due to different internal venetian blind configurations to meet the required illumination level in context of Dhaka.

1.6 Structure of the thesis

This study is organized into five chapters. This section provides an overview of all the chapters, shown in the Figure 1.2.

Chapter 1 is a brief introduction of the research and describes subjects that might be necessary for understanding the research, problem statement with the aim, objectives, brief methodology and limitations.

Chapter 2 discusses the literature review based on established research and published sources. It helped to form the base of this research, made it easier to understand many aspects which are relevant to this study and helped to fulfil the knowledge gaps. In addition to that, it explored the climatic context of Dhaka with focus on the daylighting condition.

Chapter 3 describes the methodology of this research in detail. It also established the criteria for selection of the case space and details about the field survey. This chapter provided detail description about the fixing criteria for investigation and simulation metrics. To evaluate the performance of internal venetian blind configurations for different orientations in office spaces, few parameters are considered, such as, standard illumination level up to a maximum depth, uniform distribution of daylight and glare-free workspaces.

Chapter 4 illustrates detail description of the simulation procedure. Simulation is conducted following dynamic metrics, which generally uses the daylight co-efficient (DC) approach. Data from the field survey is used to generate the physical model in software. The dynamic-climate based daylight simulation program, DAYSIM is used to compare the impacts of design variants on the indoor daylighting situation.

Chapter 5 discusses and analyses the data from simulation to find out the result for different orientation. The findings of the research and recommendation of the feasible architectural design strategies will help to develop comfortable luminous environment for office spaces. The research ended by identifying other research areas that need further investigations to be done.

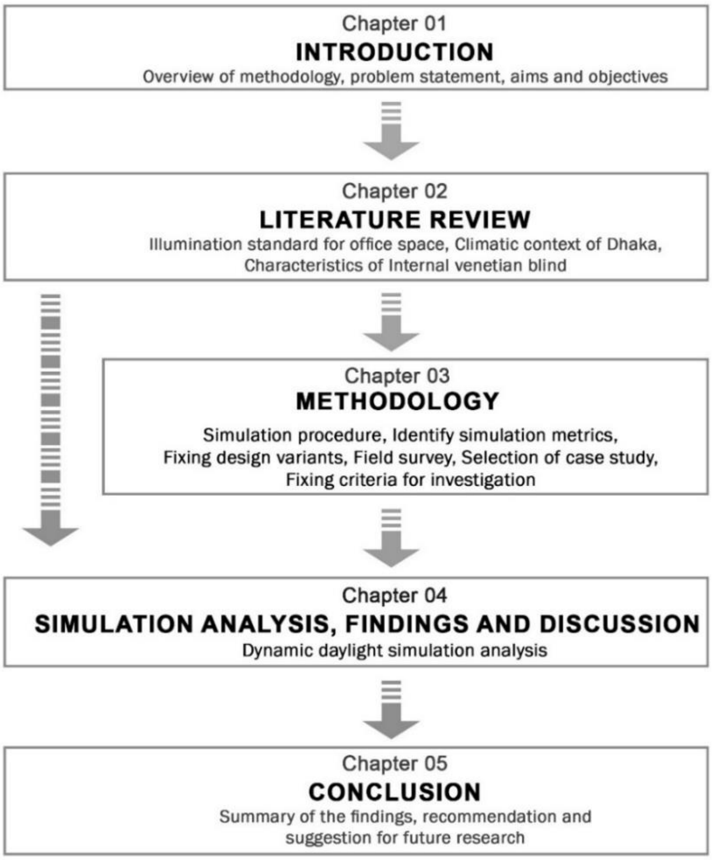


Figure 1.2: Organization of chapters and structure of the thesis

1.7 Summary

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

Daylighting and high-rise buildings

Daylight and glass façade

Solar control and shading devices

External and Internal shading devices

Illumination standards for office spaces

Key-findings

Summary

LITERATURE REVIEW

2.1 Preamble

The first chapter introduces the research. This chapter discusses the outcome of the literature review to describe the basic information which is required to create an effective luminous environment inside office spaces by selecting appropriate venetian blind configurations for different orientations in the climatic context of Dhaka. There are four major parts in this chapter. The first part presents a brief discussion on the significance of daylight in office buildings and its impact on office work. The second part studies different types of glazing systems and curtain wall façade and how they can contribute to solar heat gain and daylight transmission. Part three discusses different types of effective shading systems that are available and their appropriate orientations in the climatic context of Dhaka. Part four focuses on types of internal shading systems in detail, especially on types and mechanisms of different venetian blind configurations. Different possibilities of blind configurations and how they can effectively enhance the luminous environment inside office space were also discussed in this part. The last part points out the national and internal standard illumination requirements for office spaces. At the end, the key findings of the chapter have been highlighted to identify some parameters of venetian blind configurations, which will help to support the decisions setting criteria for simulation exercises. The methodology for simulation studies is discussed in next chapter, developed with respect to the outcome of this chapter.

2.2 Daylighting and high-rise buildings

Before the discovery of artificial lighting, building design used to depend on the climatic parameters and daylight condition of a place to achieve required amount of lighting levels for visual purpose. Light enables people to perform and without it, the building would stop to perform (Phillips, 2000). The continuous changing nature of daylight can change something stationary to dynamic. The manipulation of this dynamic element has enabled architects to create various atmospheres which trigger different emotional responses (Baker, et. al, 1993; Baker, et al, 2014). In addition to that, by creating a direct connection with the dynamic perpetually evolving outdoor illumination, daylight helps to create visually stimulating environment, adds drama and excitement to the architecture, as well as the aesthetics of the space (Boyce, et.al, 2003).

The nature of daylight is variable and due to its spectral composition, daylight provides better illumination inside an interior space than artificial lighting. Human eye responds to daylight stimulus, while the same stimulus is not achieved with artificial light. The use of daylight during the peak hours cuts the demand for artificial light and makes the building more energy efficient. As a result, an overall sustainable result is achieved by reducing the non-renewable energy and replacing it with solar energy. Daylight also has significant impact on the psychological and physiological health of occupants, which in return improves the productivity and reduces absenteeism. The effective admittance of daylight also increases the rental price or the value of the building due to energy saving and improved workplace health (Goulding, et. al, 1992).

High-rise can be characterized as the buildings with lower footprints compared to total built-up space, have a large façade because of its height, smaller roof area than external wall area and have a complex structural system in comparison to low-rise buildings (Yeang, 1991). In a study, buildings above six-storey are considered as the high-rise buildings in Dhaka, considering the fire escape provision and walk-up limit (Ahmed, 2007). Bangladesh National Building Code (BNBC, 2020) states that, Buildings of ten stories and above must have the provision for at least two fire stairs and they must lead directly to an outdoor or safe space. Considering these aspects, buildings of 10 stories and more are considered as high-rise building for study under this research.

High-rise buildings have external facades more exposed to direct sunlight and other climatic factors. The facades often do not get shading from the surrounding buildings in comparison to mid-rise or low-rise buildings (Ahmed, 2007). As a result, climate and orientation need to be specially considered while designing high-rise buildings. Buildings use about 48% of the energy consumed and among them 40% is used in the operation of the buildings (Rahman, 2018; Hassan, et.al, 2014). Significant amount of operational cost can be saved through the implication of climate and context friendly design elements (Trisha, 2016). The dominant idea of transparency and dematerialization evolved from the extensive use of glass on external façade of tall buildings. Glass is a light-weight building fabric, which can absorb temperature fluctuations. However, the high transmission property and particularly solar radiation transmission properties can create uncomfortable thermal and lighting environment inside. As a result, overheating can occur during the summer and heat loss can occur during winter seasons (Beevor, 2010). The façade of high-rise buildings must be multifunctional, to intercept direct beam of radiation and deliver diffuse light to the deepest corner of the interior space (Ubbelohde, et. al, 2002).

Daylighting can be defined as controlled penetration of natural light inside a space (direct sunlight and diffuse skylight) to reduce dependence on artificial lighting and to save energy for lighting as well as cooling (Konis, 2013). Due to the constraint of land and urban density of Dhaka, the commercial sector has shifted to deep plan office buildings design (Ahmed, 2007). Daylight penetrates inside an interior space through simple apertures on the envelope through the windows or skylights. Lighting from windows decreases simultaneously with distance away from the aperture, reaches passively up to 4m to 6m, which is known as the passive zone. Spaces further away from the passive zone depend on artificial lighting for illumination and can create a great contrast between light zones (Beltran, et. al, 1997). Daylight inside an interior space creates two types of luminous areas: daylight or light zone and an artificial light or dark zone. Light zone is created when there is abundance of daylight, whereas, dark zone refers to absence of daylight (Trisha, 2016). Skylight is considered as an effective technique for uniform daylight distribution on work plane level inside the spaces as long as the ceiling is designed accordingly and does not allow glare. Illumination from skylights can only reach the top floors and rest of the floors depends on side lights. Multi-storey buildings can introduce atrium or light wells throughout the building to illuminate the interior space. This strategy of daylight penetration not only reduces floor area but also creates more façade and this is only applicable for newly constructed buildings (Beltran, et. al, 1997; Nasersharifi, et al, 2014). According to BNBC (2020), in order to achieve effective illumination solely from daylighting, spaces more than 14m in depth should have window openings of at least 35% of external wall area of the space.

2.2.1 Daylighting in deep plan offices

Few factors such as increase in urban land prices, advent in air conditioning systems, development in structural design methods, invention of artificial lighting and low-cost electricity together, has made deep plan buildings popular in modern office design. Deep plan buildings are considered as buildings with unobstructed open plan more than 17m deep (PSADE, 1976). A passive zone is considered as the area inside a building which is naturally ventilated as well as daylit. The passive zone depth is limited to twice the ceiling height (Baker and Steemers, 2014). In other words, a building can be truly defined as a deep plan building, if it exceeds the passive zone as shown in Figure 2.1.

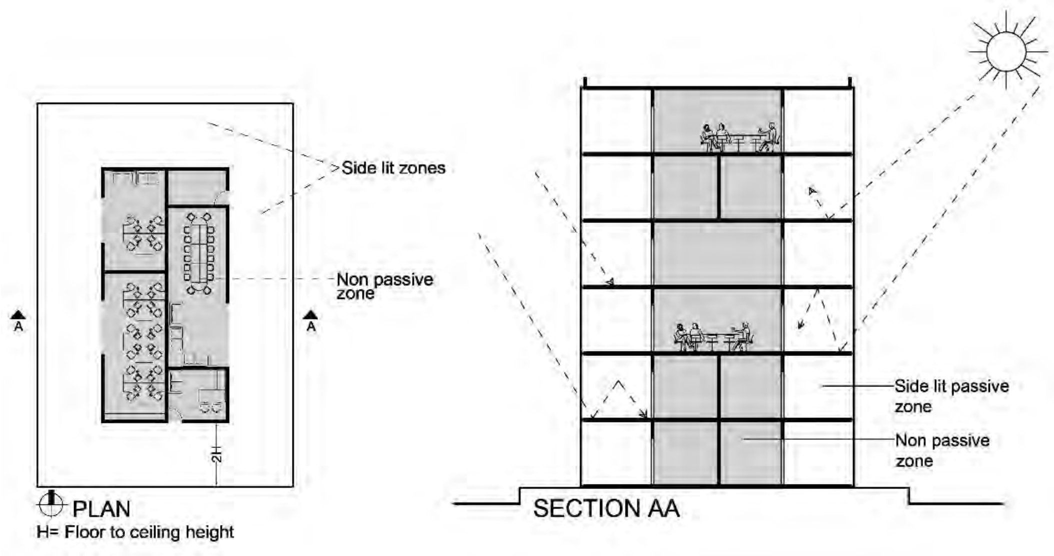


Figure 2.1: Passive and non-passive zones in commercial buildings (after, Baker and Steemers, 2000)

The non-passive zone needs to depend completely on artificial lighting and ventilation. Daylight guiding systems installed on building envelopes can re-direct light up to 8m to 10m inside the area and for further distances more complex lighting devices need to be placed (Baker, Steemers and Franchiotti, 1993).

Deep plan buildings are preferred by developers because they maximize the ratio of built-up area to site area and net usable space to gross building space. These ratios determine the number of stories of a building, which affects the total cost of the building. Modern offices prefer to have different facilities under same roof for ease of working and facilitate communication among workers. The availability of artificial lighting and mechanical ventilation has enhanced the growth of deep plan office design (Phillips, 2000).

Deep plan offices often have huge difference in the level of illuminance between perimeter and central zones, creating contrast and puts strain in eyesight. Commercial buildings with large windows result in glare problems near the perimeter zone, as a result building use blinds and this eventually reduces natural light to the deep areas. The arrangements of small offices alongside the perimeter will block the daylight distribution into the interior spaces, hence office layout and partitioning are also vital for daylight optimization (Boyce, Hunter and Howlet, 2003; Goulding, Lewis and Steemers, 1992).

2.2.2 Impact of daylight on occupants' health

Daylight has always been known for not only improving visual performances, but also makes the occupants to feel more relaxed, comfortable, stimulated, and less depressed (Katabaro, et.al, 2019). Psychological and physiological pressure, such as, fatigue, eyestrain, nausea, anxiety, back pain, shoulder pain, neck pain, lethargy, lack of concentration, even daytime sleeping and visual discomfort for video display terminal (VDT) workers are associated with adequate amount of light on the working plane (Pauley, 2004). Providing adequate amount of light depends on many factors such light color, illuminance uniformity, distribution, color rendering, nature of light (artificial or natural), flicker and glare control (Veitch and Newsham, 1998). The minimum illuminance level on task plane for certain tasks need to be ensured for uniformity and appropriate illuminance level (Katabaro, et.al, 2019).

Daylight in work environment helps to improve the physiological aspects of occupants by regulating the cardiac rhythm and synthesizing vitamin D, while restraining the harmful impact of artificial lighting (Pauley, 2004). Studies showed that, office employers having long time exposure to daylight had longer hours of sleep at night, better quality of sleep, more physically active and enjoy quality life compared to workers with no exposure to daylight (Boubekri, et. al., 2014). Office which lacks sufficient daylight, occupants most likely suffer from headaches, eyestrain and seasonal effective disorder (SAD). Headaches are one of the commonly faced health problems faced by occupants in most offices. Eyestrain is associated to spectrum of light present in the work environment and the ability of eye to refocus. Appropriate adjustment of daylighting in office spaces provides effective spectrum of light to eye (Edwards and Torcellini, 2002). Psychological studies have shown that, daylight in workplaces meet the need for contact with outside world through daylight aperture in building. Daylight enhances the connection of nature with building occupants hence helps to improve their mood (Gelfand and Freed, 2010).

Mainly two aspects of daylight affect humans: intensity of light exposure and exposure to ultraviolet component of light (Baker and Steemers, 2014). In addition to illuminating a space and providing visual comfort, daylight is also important for non-visual influence on workers' biological processes. The intensity of daylight which enters an occupant's eye activates the specific neural pathway which helps in the regulation of circadian rhythm (Brainard and Glickman, 2003). Receiving adequate daylight at morning keeps the internal body clock in sync with the Earth's 24hour rational cycle. As a result, it is important for office spaces to have provision for adequate amount of daylight. Absence of adequate daylight will slow down the circadian cycle and melatonin production will occur at wrong times of the day, leading to lethargy and drowsiness. Disruption in melatonin rhythm for prolonged periods can lead to chronic fatigue, depression, reproductive anomalies and even cancer (Stevens and Rea, 2001).

Table 2.1: Daylight and human body (Shishegar and Boubekri, 2016)

Natural light and human body			
Physical		Psychological	
Improves	Decreases	Improves	Decreases
Vitamin D	Cancer Possibility	Mood	Depression
Visual system	Abnormal bone formation	Mental performance	Stress
Circadian Rhythms		Alertness	Sadness
Sleep quality		Brain activity	Violent behaviour

Daylighting consists of ultraviolet components which has detrimental as well as beneficial effects on humans. Less exposure to ultraviolet component can lead to vitamin D deficiency, while, over exposure can cause skin cancer especially to people with light skin complexion (Lucas and Ponsonby, 2002). UV exposure also helps in the defence against microbes and stimulates the immune system. The glazing envelope in commercial office buildings cuts down the essential ultra violet B component from entering indoors (Baker and Steemers, 2014). Office workers who spend maximum daylight hours inside the office spaces are being deprived from the useful daylight components which are affecting their physiological as well as psychological health tremendously. Table 2.1 shows the physiological and psychological benefits of daylighting on occupants inside a building (Shishegar and Boubekri, 2016).

According to the Illuminating Engineering Society (IES, 2013), daylighting is referred to as the art and practice of allowing beams of sunlight, diffused skylight and reflected light from the exterior to the interior spaces to meet the lighting requirements and reduces the electric loads. In comparison to daylighting, artificial light provides constant light. Sun has the highest color rendering index (CRI) value and generates broad spectrum of light to provide wide range of wavelength to recognize maximum colors (Sharp et al., 2014). CRI provides scale of value with highest value up to 100; sun having the highest value of 100. Sun has the best color rendering quality and the poor rendering quality has the value of 60. Artificial light source with higher CRI value has better ability to render colors accurately. Most of the commercial spaces use artificial lighting which is associated with some harmful effects on the occupants. For example, the flicker of fluorescent lights induces rapid involuntary eye movement, which results in fatigue and strain (Baker and Steemers, 2014).

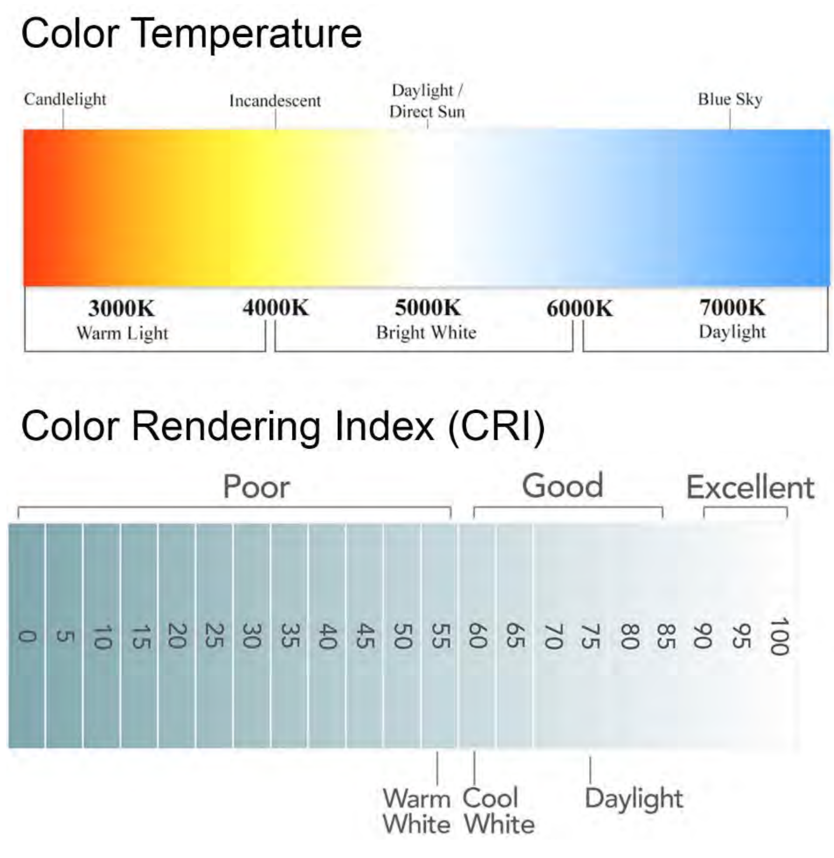


Figure 2.2: Color Rendering Index value and Spectrum for daylight and artificial light. (Source: LUMENS,2020)

The difference in artificial light intensity, timing and spectrum can aggravate the effects of cardiac dysfunction to occupants. Studies also show that exposure to artificial light in built environment increases the risk of breast cancer in women (Stevens and Rea, 2001). There are various studies being conducted to match the characteristics of daylight with artificial lighting, most importantly the wavelength distribution of daylight.

2.2.3 Impact of daylight on occupants' productivity

Productivity of an individual is defined as the ability to improve work production either by quantity or quality of a service or product which needs to be delivered (Boyce, et.al, 2003). Studies have shown that the presence of adequate amount of daylighting in an office space can effectively increase the productivity of workers to a great extent and hence increases the finances of an organization (Gelfand and Freed, 2010). Offices having occupants working in daylight and full spectrum are reported to have less absenteeism, good health condition, financial savings, increased productivity, work involvement, motivation, and better preference. A negative mood setting can cause distractions and discomfort, whereas, positive mood is associated with better communication among co-workers and efficiency (Heerwagen, 2000). Studies performed in an office building in Sunnyvile California have shown that a replacement of ambient artificial lighting with daylight and use of additional desk lamp for task lighting, have reduced absenteeism by 15% while increased productivity by 15% (Edwards and Torcellini, 2002). Many factors are associated with the productivity of workers in an office space, which are stress, health, job satisfaction, peoples' personalities and office management. Psychological studies show that physical environment also affects workers' satisfaction and well-being, which eventually affects the productivity (Baker and Steemers, 2014).

Study conducted by Juslen and Tenner (2005) shows that, use of new lighting mechanism affects the productivity of workers by at least 10 various mechanisms, which are, visual performance, visual comfort, visual ambiance, interpersonal relationships, biological clock, stimulation, job satisfaction, problem solving, variability and change in the environment. Daylight also helps to increase attention and alertness during the post –lunch period and is seen to be useful for increasing alertness for repetitive and mundane tasks (Robbins, 1986). A study performed by Tennesen and Cimprick (1995) found out that occupant having views to daylight and vegetation are more attentive towards their work during office hours (Heerwagen, 2000). Series of studies are carried out in California to find out the relation between office workers and outside view with daylighting. A call centre with 100 workers was examined and their performance of taking each call was measured. It was found that offices having view to outside performed 6%-12% better than offices with no view (Heschong, 2003).

The performance of office workers can be affected significantly by visual comfort, changes in mood and alertness as well. The job satisfaction of office workers can be greatly affected by higher visual comfort, alertness and well-being, which in turn enhances the productivity. A study conducted by Borisuit and his colleagues on 25 office workers proved that workers have tremendously higher visual acceptance scores under daylighting than artificial light, in spite of having no outside views. It was observed that, subjective alertness and physical well-being decreased for both the lighting condition during afternoon, but workers felt sleepy earlier under electric light in comparison to daylighting condition (Borisuit, et.al, 2014). Another study by Boubekri and others (2014) studied the effect of daylight exposure on workers' productivity by considering subjective health, physical activity, sleep quality and well-being. It showed that, workers in offices with no daylight have low scores with respect to physical activity, vitality and sleeping quality in comparison to offices with windows. The workers with sufficient amount of daylight also sleep in an average of 46 minutes longer during the day compared to their counterparts (Boubekri, et.al, 2014).

Daylight inside an office space can definitely increase the performance of workers but this involves few other factors as well. Factors such as heat gain and glare must be avoided for a comfortable environment inside the workplace and this must be an integrated part of the design (Shishegar and Boubekri, 2016).

2.2.4 Daylight and visual comfort

Visual comfort is a fundamental requirement for office spaces. The criteria of visual comfort differ with the type of activity and the sensory perception of the office environment. In active office spaces visual comfort must be achieved to improve workers' productivity and well-being (Giarma, Tsikaloudaki and Aravantinos, 2017). Visual comfort is usually the main factor which has a significant role in meeting lighting requirements. The requirements can be achieved by daylight and artificial light.

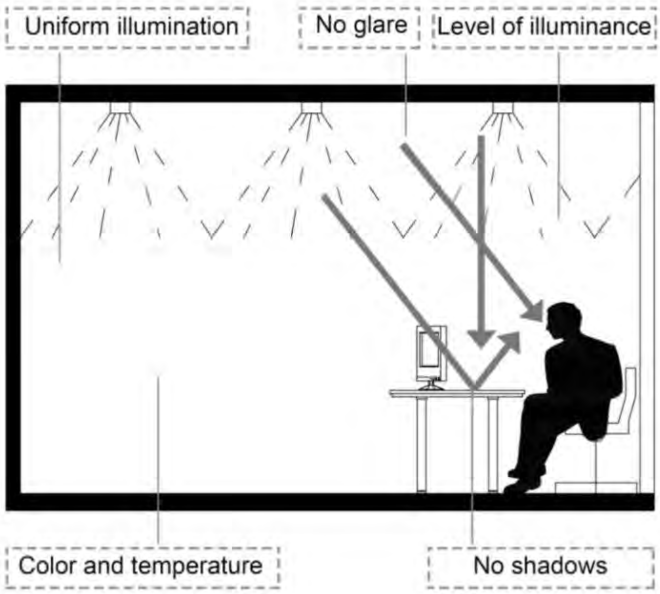


Figure 2.3: Factors affecting visual comfort inside office space.
(after, Abdelhakim,2019)

The optimization of daylighting can be achieved by careful fenestration design and maximizing the percentage of aperture area (Erell, Kaftan and Garb, 2014). Increasing the glazing area might allow immense amount of daylight to enter that causes glare. In addition to that, the use of excessive artificial lighting in active work spaces increases the energy consumption of the building. As a result, it is necessary to maintain strategies to fulfill visual comfort as well as energy efficiency. In an office space visual comfort can be achieved by the following factors (Figure 2.3) (Carli, Giuli and Zecchin, 2008).

- Access to the outdoors
- Appropriate illuminance and light direction
- Homogenous distribution of daylight throughout the active area
- Appropriate contrast
- Glare control
- Appropriate color rendering

The intensity of daylight varies constantly depending on the geographical location of the building, day, season and even the time of the day (Boyce, Hunter and Howlett, 2003). As a consequence, for an aesthetically pleasing space to provide optimum visual comfort is a sophisticated design challenge.

2.2.5 Daylight and glare control

The essential features for a luminous environment in an office building are even distribution of light, adequate amount of light on the working plane and prevention of glare (Hopkinson, 1972). In deeper plan office buildings, the glass façade with high clerestory windows allows maximum daylight, while lead to excess reflections, causing glare. Glare is produced when the presence of a light source makes it difficult to distinguish objects. Direct glare occurs when the light source is directly on the line of vision or it is reflected from the surface with high reflectance. Glare is referred to as the visible noise which often interferes with observer's visual performance (Hopkinson, 1972). It is the measurement of an observer's physical discomfort level, which results from contrast in the field of view. Hence it depends on the luminance distribution seen by the observer (Reinhart, Mardaljevic and Rogers, 2013). Factors that affect glare are the following (Figure 2.4) (Lechner, 2014).

- **Luminance of light source:** Tolerable luminance by direct observation is 7,500cd/m^2.
- **Location of light source:** Glare occurs when the light source is within 45-degree of the observer's line of sight and can be reduced by increasing the angle. Figure 2.3 shows the possible ways to avoid glare.

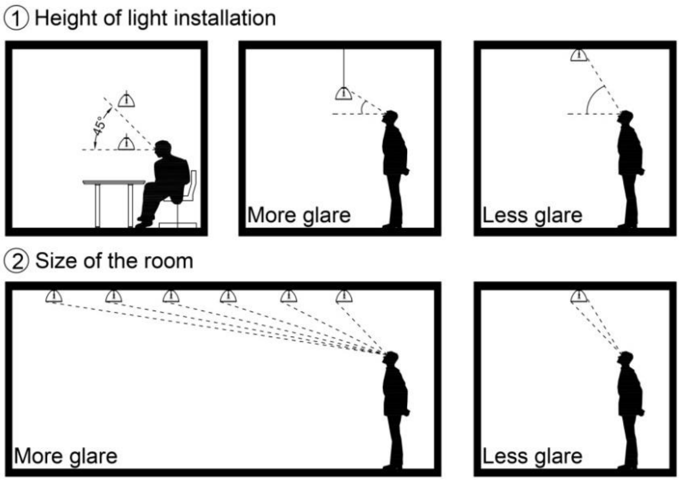


Figure 2.4: Factors affecting Glare (after, ilocis.org, 2011)

Glare can be classified in two ways: first one is how it affects the observers and the second one is to consider it from the position of the light source. While categorizing glare by its impact on observer, there are three subcategories: Disability Glare, Discomfort Glare and Veiling Glare (Figure 2.5) (Lechner, 2014).

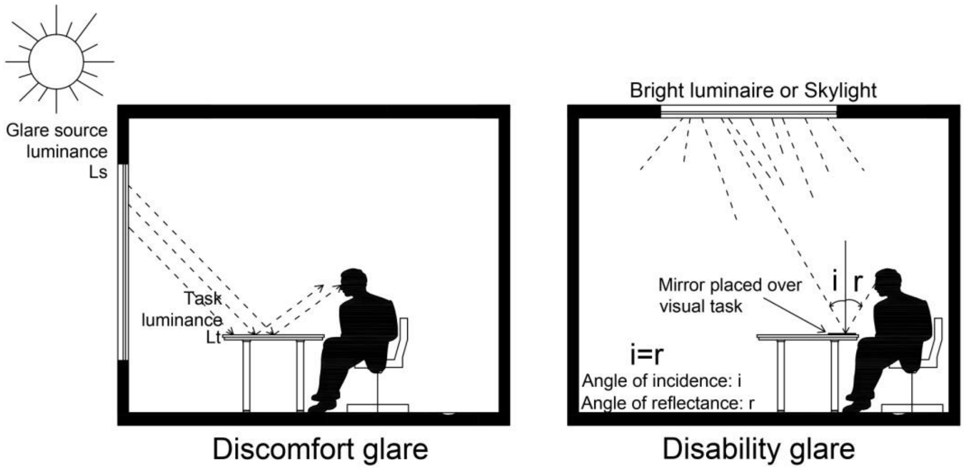


Figure 2.5: Discomfort and Disability Glare (after, Florida solar energy center, 2007)

- **Disability Glare** creates a situation which reduces the contrast of retinal image and measurably impairs vision because of the presence of bright light source (Bangali, 2019). Disability glare occurs when the daylighting enters through the large window opening. This not only occurs because of brightness and large window aperture but also because of intensity of light source.

- **Discomfort Glare** creates a less severe situation than disability glare. This type of glare is non-uniform or highly distributed brightness, which causes difficulties but does not hamper visibility. The increase of brightness, size and prominence of light source can transform the discomfort glare into disability glare (Tuaycharoen and Tregenza, 2007).
- **Veiling Glare** occurs when the bright light is reflected from the surface with high reflectance. This glare diminishes the contrast and reduces visibility. Discomfort glare does not show any observable effects initially, so it is hard to recognize disability and veiling glare (Hopkinson, 1972).

It is fundamental to quantify glare and classify types of glare in order to improve the visual comfort of workers and avoid direct sunlight on work plane and visual field of observers. Glare Index (GI) is the numerical expression of quantifying glare present in an area. It is derived from luminous distribution in the visual field of view of an observer (Jakubiec and Reinhart, 2011).

There is a quatity called discomfort glare constant (g) which is

$$g = 0.45 \times \frac{L_s^{1.6}}{L_B} \frac{\omega^{0.8}}{P^{1.6}}$$

In this relation

L_s = luminance of source of glare

L_B = average luminance of the background source

P = Position constant. This gives an indication of the position of where the light index is located in the field of view. P is small when light is in the field of view.

$$\omega = \frac{\text{Area of Glare Source}}{(\text{Distance from source})^2} = \text{solid angle of glare}$$

Glare from all the source is additive

So,

Glare Index (GI) = $10\log_{10}(g_1 + g_2 + g_3 + \ldots\ldots)$

The value of glare index is affected by the intensity of glare source, brightness and size of the source in the visual field. Glare Index value below 10 is imperceptible; the value between the range 16-22 is within acceptable range, while, value greater than 28 is intolerable. It is recommended to keep direct sunlight away from vertical task planes such as computer screens and horizontal task planes, i.e., working desk, to prevent glare.

The luminance distribution in field of view should be controlled for visual comfort. The visual field consists of three parts mainly: the central field, immediate background and the surrounding environment (Ahmed, 2014). The International Energy Agency (IEA, 2000) recommends, the luminance ratio in central: immediate: environment should be 5:2:1. The condition of glare occurs when the ratio exceeds 10:3:1. Glare does not only depend on the sky condition, rather it also depends on the placement of working desk and visual plane of observer (Jakubiec and Reinhart, 2011). To maintain an efficient luminous environment, it is needed to take into account about the interior layout and furniture placements as well to avoid effects of glare.

2.3 Daylight and glazed façade

The intensity and amount of solar radiation falling on glazed surface varies throughout the day and year. In Bangladesh, maximum proportion of solar gains occurs during the monsoon and pre-monsoon periods through the south facing windows. Maximum amount of solar gains inside a building occurs through direct radiation through glazed facades or windows. This creates greater depth of direct sunlight zone inside a building which usually stays towards the outer periphery of a building (Rahman and Ahmed, 2008).

Glazing technology has improved tremendously in the past decades, so most of the commercial buildings are adopting extensive glass fenestration systems. This improved technique enhances the aesthetics of a building but it gets difficult to ensure energy-efficiency and optimum comfort level for the users (Jin and Overend, 2016). The high-performance, energy efficient glazing systems feature double or triple glazing units with specialized transparent coatings and insulating gas sandwiched in between the panes, that reduces energy loss through glass (Alam and Islam, 2017). The incident solar radiation on the glass surface partly gets reflected partly gets transmitted inside the space and the rest portion is absorbed in to the glass thickness (Figure 2.6).

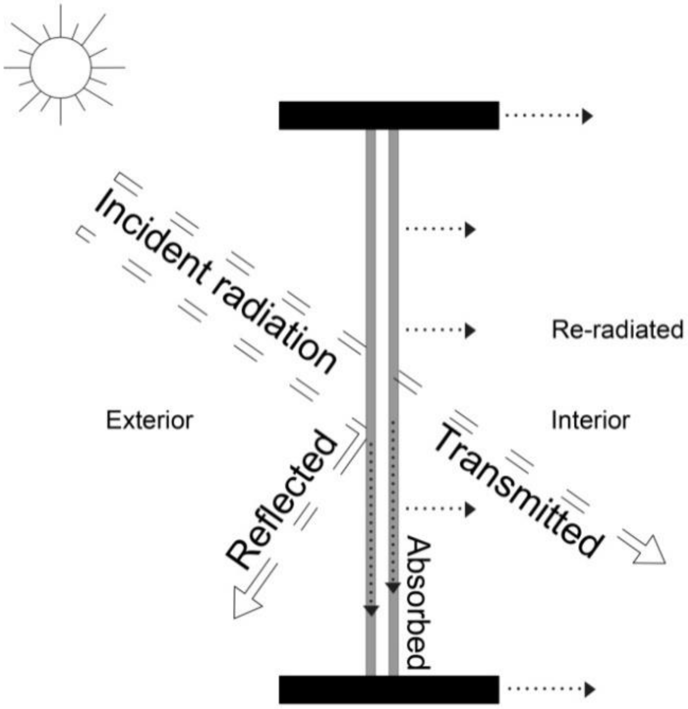


Figure 2.6: Solar radiation transmittance through glass (after, Aminuddin et al., 2012)

The absorbed radiation depends on the thickness and type of glazing, while the reflected portion depends on the glass surface and solar incidence angle. The absorbed radiation raises the temperature of glass and this heat reaches the room surfaces by convection or radiation, hence room temperature increases (Rahman, 2007). Glass usually transmits short wave radiation but they are opaque to long wave radiation. The gained solar radiation gets trapped within the glass which causes the internal temperature to rise. The solar heat gain is directly proportional to the surface area of the exposed glass, so the larger the glass area, the greater will be the solar heat gain. For this reason, it is considered disadvantageous to use curtain glass façade in tropical climates (Trisha, 2015).

2.3.1 Curtain glass fenestration

Curtain walls form the outer envelope of a building and it is the non-structural part often attached to the main structure, and deal with the weather conditions. They can resist water and air infiltration, seismic forces, their own dead-loads and sway induced by wind pressure (Figure 2.7) (Kubba, 2012). The selection of glazing type for the building envelope is crucial as they have great impact on the performance of the daylighting system.

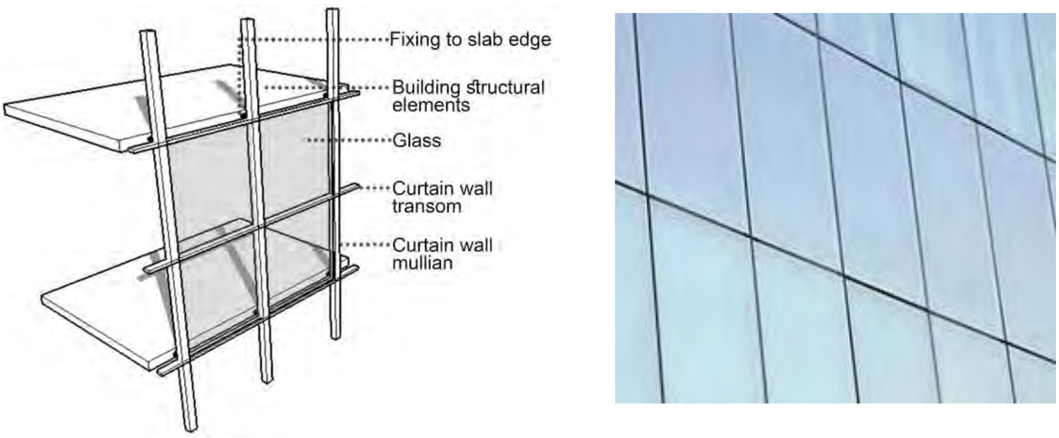


Figure 2.7: Curtain glass façade (after, Kassem, et.al. 2015)

The characteristics of glazing unit determine the intensity, directionality and amount of daylight entering inside a space (Kassem and Mitchell, 2015). Clear single pane glass allows high daylight transmission and high radiation transmission as well. Various types of advanced glazing systems are introduced to reduce the solar gain but they cause loss of subsequent amount of daylight inside a space. The amount of reflected radiation can be increased significantly by adding thin metallic coating on the surface, which still allows certain portion of radiation to penetrate inside. The percentage of reflectance of a glass depends on the thickness and reflectivity of the coating. Reflective glazing is effective to block solar radiation inside while maintaining the view (Rahman, 2007). These glasses can block the desirable winter radiation as well and reduces light transmission inside the space (Figure 2.8). Tinted or reflective glasses are suitable for blocking diffused sky radiation and glare control in humid regions. In terms of shading purposes, glazing with lower transmittance value is effective (Lechner, 2014). Visible transmittance of glazing ranges from above 90% for uncoated water-white clear glass to less than 10% for highly reflective coatings on tinted glass. A typical double-pane insulated glass unit (IGU) has a visible transmittance of around 78% (Santana, Jarimi, Carrasco and Riffat, 2020)

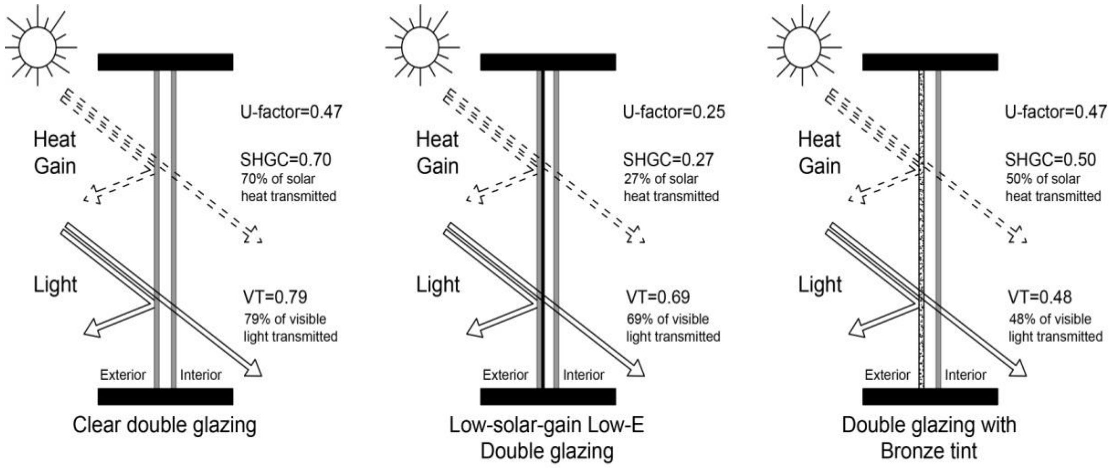


Figure 2.8: Heat gain values for different double-glazing units (after, commercial windows.org, 2000)

The optimum daylight factor for office spaces is around 2% (Kermani, Nasrollahi and Mahdavinejad, 2018). A study on different types of glasses showed that green, bronze and green reflective glasses are effective enough to ensure adequate daylight factor inside office space. Green-reflective glass in south orientation proved to be the effective material to provide daylight factor of 2.05%-2.06% in the climate of India (Kumar and Babu, 2017). Other study in the climatic context of India concluded that bronze, green and bronze-reflective glasses can reduce the heat gain by 2.52%, 3.83% and 6.46% respectively in comparison to clear glass window (Kumar, Saboor and Babu, 2017b). Study in the context of Bangladesh revealed that by using double clear glass, double low-E opaque glazing and double low-E clear (argon) glazing, energy transfer can be reduced by a considerable amount. A combination of appropriate overhang or side fin with single clear pane glazing for any orientation is found to be more effective than only depending on advanced glazing (double clear, low-E glazing) (Alam and Islam, 2017).

It is found that buildings that has glazing units with high U-value and solar reflectance but lower shading co-efficient will have significantly lower cooling load and total energy usage. This type of glazing systems poses good potential to mitigate the impact of global warming on built environments (Guan, 2011). Low-e-glazing transmits higher ratio of visible to infrared radiation and selective low- E glass allow transmission of cooler daylight than other glazing types.

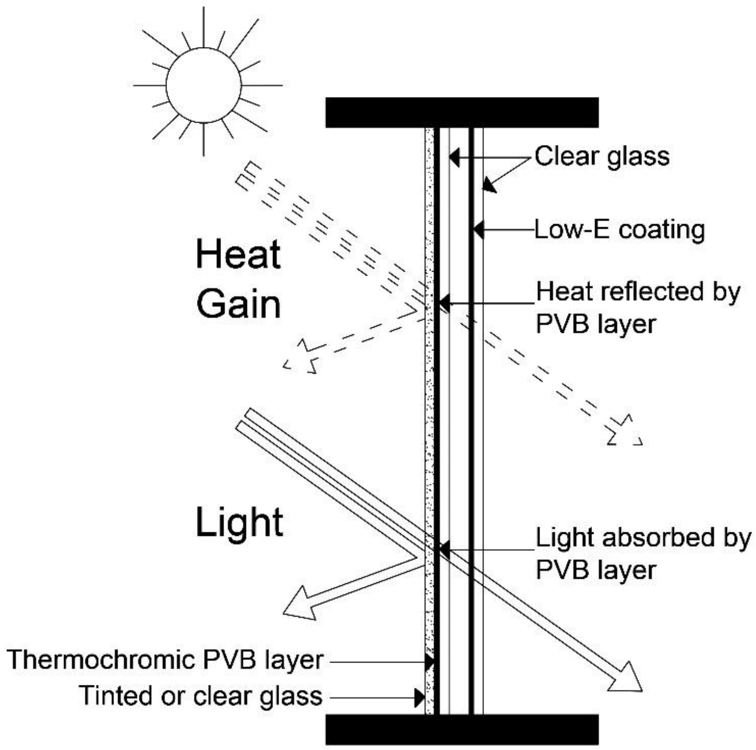


Figure 2.9: Characteristics of thermochromic glazing (after, commercial windows.org, 2011)

There are more advanced glazing systems available named responsive-e-glazing systems. They can adjust and respond according to the change in the climate, heat, availability of daylight to reduce overall energy consumption in comparison to other types of glazing units. There are two types of responsive-e-glazing systems available: active and passive. The active glazing systems can be operated according to the user’s need. Passive systems respond directly to environmental conditions such as availability of daylight such as photochromic or thermochromic (Figure 2.9) (Trisha, 2015).

2.4 Solar control and shading devices

2.4.1 Significance of shading devices

Daylight impacts on indoor lighting quality and has economic and bio-environmental advantages (Chan and Tzempelikos, 2013). An efficient daylighting system results from a combination of daylight responsive controlling system along with adequate daylight apertures. When the system can ensure adequate ambient lighting solely through daylight penetration, the load on electrical power for lighting can be reduced (Liu, 2013). There are various factors that affect the effectiveness of sun protection system such as solar shading solution (fixed or mobile), screen location with respect to frame (internal, external or intermediate), screen materials and finishing type (reflectance), façade exposition, geographical location and façade characteristics (Carletti, et. al, 2016). Each type of controlling system is modified to control certain aspect of solar radiation approaching towards the aperture, for instance problems related to solar gains and potential glare can be moderated by using overhangs, solar screens, venetian blinds, rollers and louvers. Daylighting system such as light shelf can re-direct light towards the ceiling and results in uniform distribution, reducing excessive illumination near the openings (Kontadakis, et. al, 2018). These systems use optical devices to generate reflection, refraction or total internal reflection of sunlight and skylight. The type and configurations of daylighting system should be selected depending upon the climate and contextual characteristics, for instance sky type and latitude of site (Omar, 2008).

An effective shading system must allow good solar protection in summer, while maintaining sufficient solar radiation during winter and not impeding natural ventilation and lighting. The most effective way of blocking solar heat gain is by preventing the transmission of shortwave radiation through the glass envelope by using external shading. The effectiveness of a shading system can be measured by the solar gain factor. The factor decreases with the effectiveness of shading system (Rahman, 2007). According to Steemers and Baker (2014), main purposes of shading systems are as followings.

- To prevent direct sunlight from falling, that might lead to temperature increment by 3 to 7 degrees.
- To reduce total solar energy from entering the interior space, thereby reducing the interior temperature of the room.
- To reduce illumination on surface
- To prevent glare formation.
- To ensure uniform illumination throughout the interior space, preventing contrast.

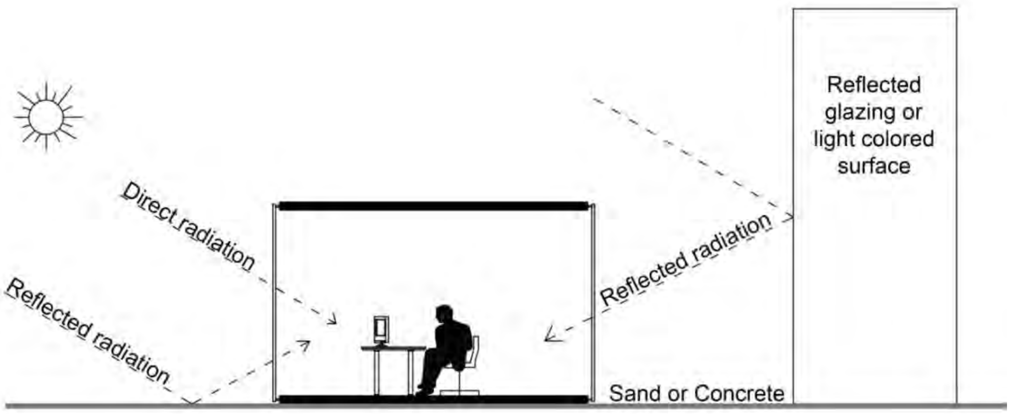


Figure 2.10: Total component of solar radiation (after, Lechner, 2009)

Solar radiation consists of three components: direct, diffuse and reflected radiation. So, it is fundamental to provide shading in order to avoid passive solar heating either from diffused, direct or reflected solar rays. Diffuse radiation is prominent in the sunny humid regions. For sunny regions, presence of excessive dust and pollution can result in diffused radiation. In regards to reflected solar radiation, it becomes difficult to control especially for areas in the south west regions where highly reflected surface and intense sunlight both co-exist. Urban areas are more prone to reflected radiation due to the presence of highly reflective surfaces such as concrete roads, glazed facades, and white walls (Figure 2.10). Reflective glazed surfaces allow intense solar radiation inside the indoor space (Lechner, 2014).

The selection of the types of shading systems depends on the overall solar load. The reflected radiation is most often controlled by reducing the solar reflection on reflective surfaces (Lechner, 2009). This can be done by introducing some buffers such as vegetation. Diffused sky radiation sometimes becomes unmanageable when they come from great exposure angle. Introducing additional indoor shading systems or shading within glazing can help to reduce the radiation to some extent (Shahwarzi, 2014). Controlled amount of solar radiation inside a space can help to provide high quality lighting, while at the same time reduce heat gain (Armaroli and Balzani, 2011).

Table 2.2: Classification of shading systems according to solar components (Omar,2008)

Shading systems using Diffuse Light	**Shading systems using Direct sunlight**	**Non-shading systems using Diffuse Light**	**Non-shading systems using Direct sunlight**
Louvers / Blinds	External Light Shelves	Anidolic ceiling	Laser-cut panels
Holographic Optical elements (HOE) Shading systems	Internal light shelf (redirecting daylight)	Zenithal Light guiding glass with HOEs	Prismatic panels
Optical shutters	Angular selective Skylight		
Automated Blinds			

The selection of any shading system also depends on the type of building and the climate. A building having elongated glazed façade in the north orientation will face the overheated period for shorter period of time. A building of similar characteristics having majority of glazed façade in south direction will experience at least twice or 3 times more over heated period (Armaroli and Balzani, 2011). It is necessary to incorporate shading systems depending on the micro-climate characteristics such as predominant sky type, nature of the building and latitude of building site. The nature of daylight varies greatly with climate and latitude. Table 2.2 shows the classification of shading systems according to their usage of solar radiation components. Louvers or internal blinds redirect sun rays and let diffuse light to pass towards the deeper parts of the interior space. Similarly, the angular characteristics of Anidolic ceilings re-directs direct sunlight and transmits diffused lights inside a space. On the other hand, external light shelf, changes the property of direct sunlight and reflects diffused sunlight to enter. Laser cut panels are usually placed at the exterior façade and due to their various patterns, they act as a barrier and do not allow direct sunlight to penetrate.

2.4.2 Orientation of shading systems

Orientation plays a critical role in the availability of daylight. According to the IEA (2000), the penetration to daylight inside a space varies with the strategies for determinants of daylight availability. Architectural features such as physical characteristics and geometrical configuration of daylight systems on glass faced commercial office building have great control over the luminance inside (Trisha, 2016). To the east and west direction, the sun usually stays at lower altitude which makes it difficult to shade the façade horizontally. Irrespective of climate, west or east glass façades are more prone to glare and solar heat gain problems. Particularly for the west façade, as maximum intensity prevails during the hottest time of the day. It is advantageous to have elongated façade of a commercial building towards north-south orientation.

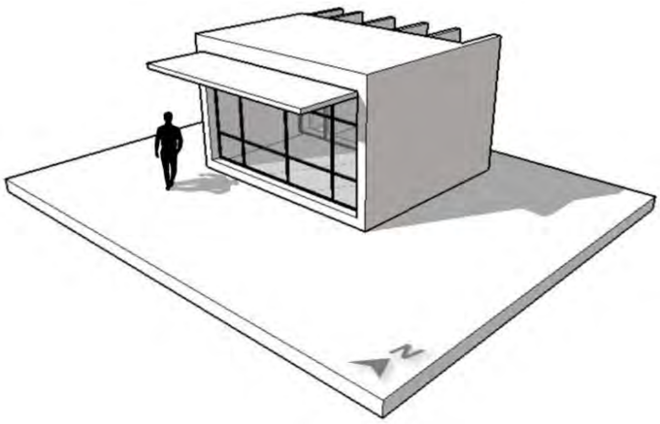


Figure 2.11: Different shading strategies for different orientations (after, Lechner,2014)

The sun's altitude during summer makes horizontal overhang shading systems extremely effective for south facades. For north facing windows, shading is necessary as the sun rises in north-east and sets north of west in hot climates. The lower altitudes of sun make horizontal overhang systems less effective so additional vertical fins are necessary for north facades (Figure 2.11) (Lechner, 2014).

In order to make an effective shading system, a combination of vertical and horizontal shading elements is needed to be utilized. Similar to a single massive overhang, cumulative number to miniature horizontal shading elements on a façade can have the same impact. These screens are composed to miniature louvers that efficiently obstruct the solar radiation and are nearly transparent not to block the view (Figure 2.12) (Kotey, et. al., 2009).

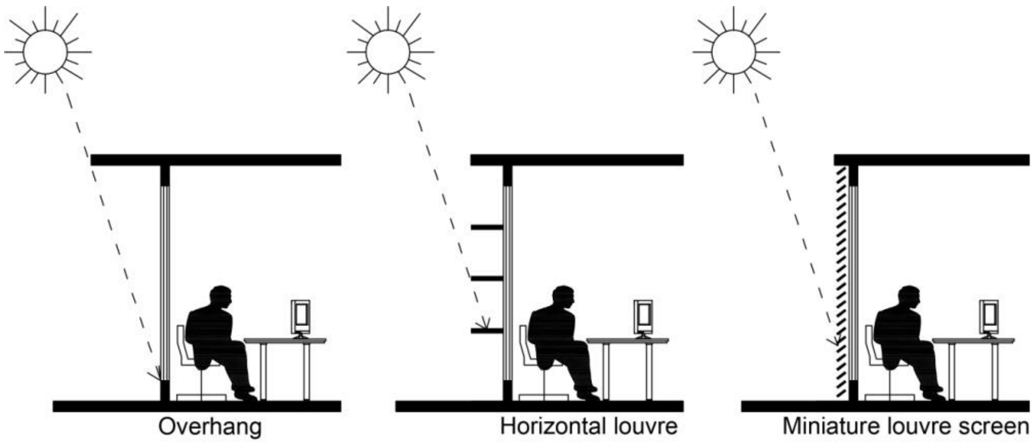


Figure 2.12: Shading effects with many miniature elements (after, Kotey, 2009)

2.5 External and Internal shading devices

The fundamental purpose of shading devices is to provide protection from direct sunlight especially during summer, while allowing solar gains in winter and keeping provision for natural ventilation (Rahman, 2007). Well-designed and effective shading systems have the ability to enhance daylighting inside a space. The selection of appropriate shading system depends on the orientation, location, climate, cooling and heating loads of the buildings and these factors need to be decided during design phase of a building (Trisha, 2015). The effective way of preventing solar gain is by reflecting and blocking the radiation before it reaches the glazed envelope. External shades also have ability to reduce the overall energy consumption of a building to some extent.

2.5.1 External shading devices

External shading devices are designed and installed on the external façade of the building. These form integral part of the building, which protects the glazing from direct solar radiation. External shading systems are not very effective in reducing the diffused and reflected solar components. These elements are expensive and often take up lots of space which sometimes gets difficult for building with small plot size to accommodate (Kotey, et. al., 2009). Depending on the integration system with glass façade, shading devices are classified into three broad categories. They are retractable or removable shading system, adjustable shading device and fixed shading system (Hans, 2006).

i. Retractable shading system

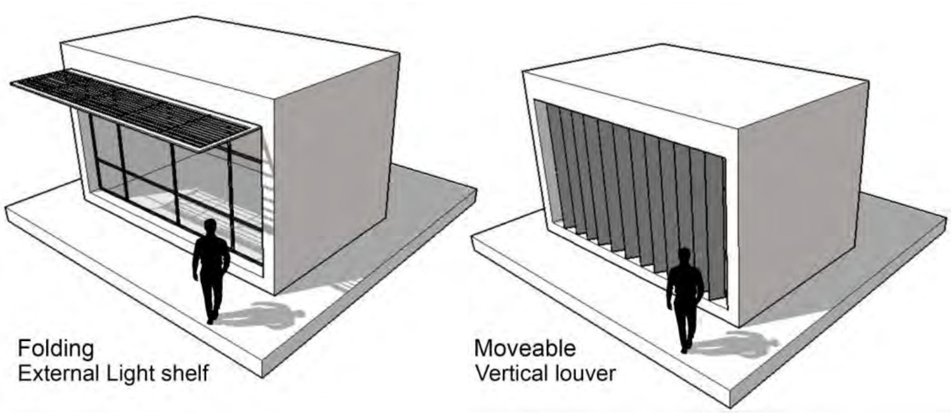


Figure 2.13: Examples of retractable shading system

This type of devices can be removed partially or completely from window aperture as shown in Figure 2.13. Active operation of this type of element is necessary as they might allow unwanted heat or glare inside the space if not effectively used during the time of huge light exposure (Rahman, 2007).

Retractable shading elements such as louvers or shutters are effective but can get expensive if they are automated (Trisha, 2015).

ii. Adjustable shading devices

Adjustable or moveable shading elements can be used either externally or internally. According to the thermal and visual comfort level of user, these systems can be operated manually or by using motors. The configurations of moveable devices can be changed so their performance is considered better than fixed shading systems. Their maintenance is expensive and gets difficult sometimes, especially for external shading devices such as awning systems, moveable fins, rotatable horizontal louvers or egg crate system with rotatable horizontal louvers (Figure 2.14). In terms of automated external adjustable devices, it is necessary to include provision for manual operation as well in case of power failure. In addition to that, automated shading systems require uninterrupted Wi-fi connectivity for operation, which needs to be ensured all the time. Manual operation can get inefficient at times if they are not operated actively (Rahman, 2007).

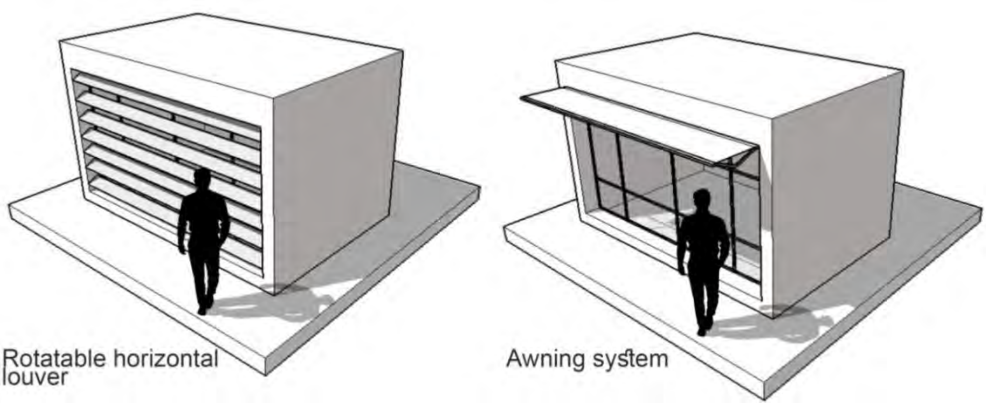


Figure 2.14: Examples of adjustable shading system

iii. Fixed shading devices

Fixed shading systems are an integral part of a building and most of the time used on the exterior façade as a visible architectural statement (Trisha, 2015).

These can act as structural element such as balconies, horizontal fins or light shelf or can act as non-structural elements as well for instance louvers, blinds, screens or canopies (Rahman, 2007) (Figure 2.15).

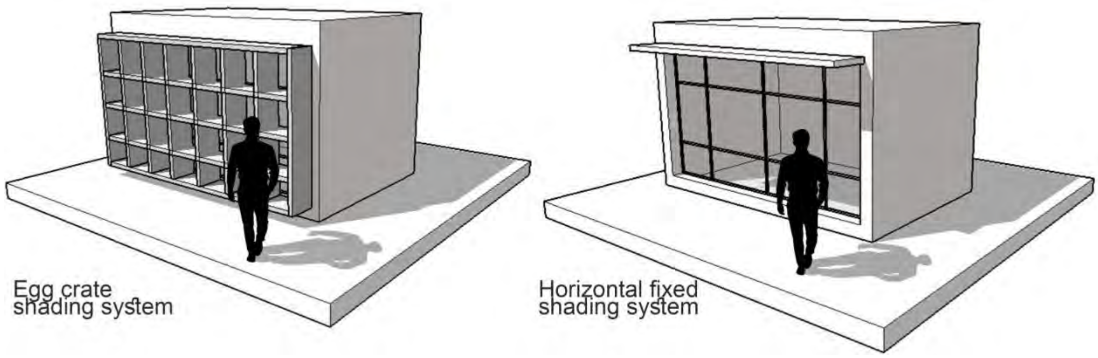


Figure 2.15: Examples of fixed shading system

Fixed shading systems are simple, need less maintenance and require less cost during construction. The system is static and permanent. So, any modification on the device configuration is difficult. Design and selection of the static shading device during construction phase are crucial in order to maintain optimum comfort level for users and ensure energy efficiency (Hans, 2006). Orientation and size of window opening with respect to solar angles throughout different times of the day need to be considered. Each orientation needs to be evaluated in terms of direct, diffused and reflected components of overall solar radiation in annual basis. Efficient geometric configuration and composition provides angular sensitivity to the shading elements for different orientations (Ahmed, 2014). There are mainly three types of fixed shading systems as discussed below.

a) Horizontal shading device

Horizontal devices are most suitable when the sun is positioned at a higher angle and opposite to the building façade such as south orientation. They obstruct direct sun radiation while allow low winter sun to enter and do not block any view (Trisha, 2015). The pattern of sun radiation is such that before noon the rays usually come from the south-east direction while it shifts towards south-west by afternoon. For designing a horizontal overhang, the sun radiation might outflank a device similar to width of the window. In case of narrow overhangs, sometimes additional vertical fins are required for solar protection (Figure 2.16) (Maurya, 2011).

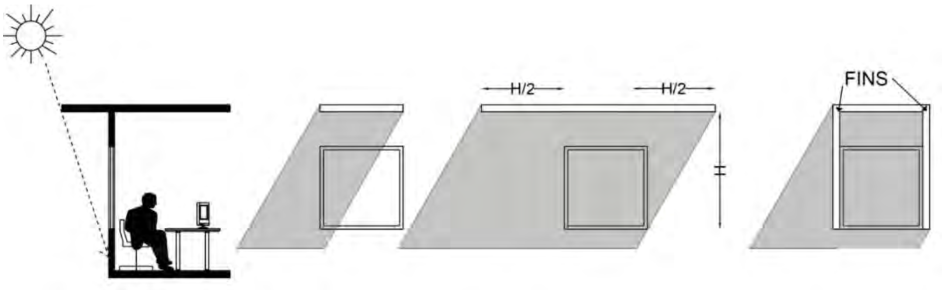


Figure 2.16: Horizontal overhang configuration (after, Maurya, 2011)

Horizontal louvers in horizontal plane are much effective than solid overhangs. They allow air to pass through them, hence reduces structural load. At the same time, louvers do not allow accumulation of hot air near the glazed façade during summer, so helps to ensure thermal comfort for indoors (Figure 2.17) (Galloway, 2004).

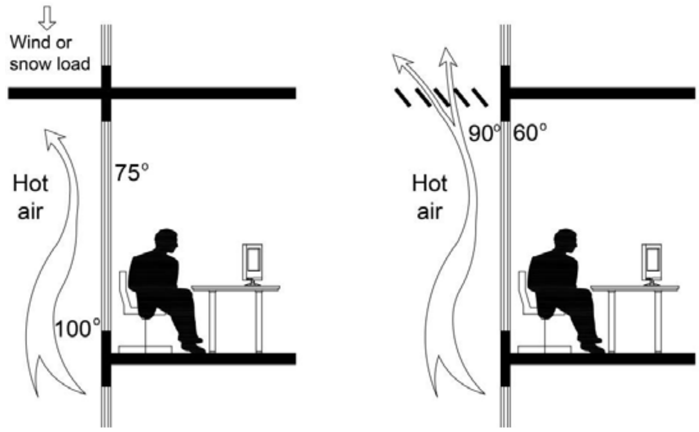


Figure 2.17: Horizontal louvered overhangs (after, Galloway, 2004)

b) Vertical shading device

Vertical shading system consists of louvers or fins in vertical position (Figure 2.18). Both the combination of narrow fins with close spacing and broader fins with wider spacing produces identical shadow patterns (Hans, 2006). These are feasible when the sun is positioned at either east or west façade of the window aperture. The vertical elements direct the view in a particular direction and sometimes block the view. Sometimes these elements can get undesirable as they cover almost the entire side of the window, so this factor needs to be considered during selection (Seraj, 2017).

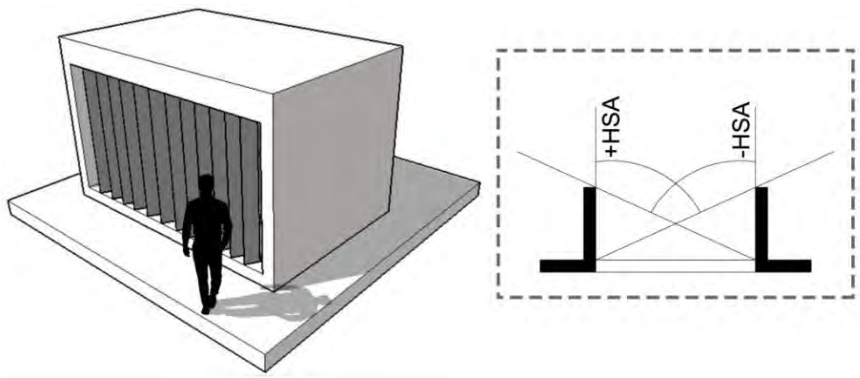


Figure 2.18: Configuration of vertical shading system

c) Egg-crate shading device

Egg-crate shading systems consist of both horizontal (louvers) and vertical (fins) elements (Figure 2.19). The horizontal elements control ground glare from reflected solar rays (Trisha, 2016; Rahman, 2007).

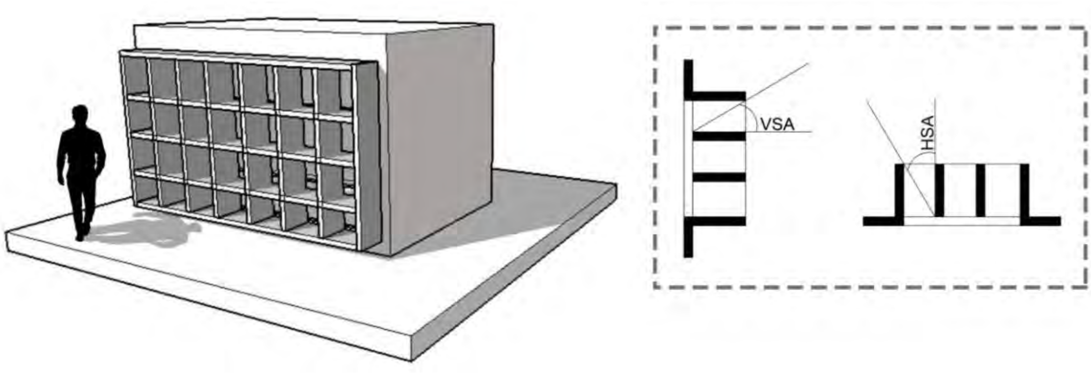


Figure 2.19: Configuration of egg-crate shading system

These are more suitable for east and west façades in hot climates. In very hot climate, these devices are feasible in south-east and south-west direction (Loutzenhiser, et. al., 2007). These are efficient to control both altitude and azimuth angle of solar rays (Seraj, 2017). For any context and sun penetration, the configuration of egg-crate system can be modified unless the height: depth and width: depth ratio is kept constant (Trisha, 2016).

2.5.2 Internal shading devices

Internal shading devices are adjustable and moveable so they can easily respond to dynamic weather conditions. Interior elements such as rolling shades, curtains, venetian blinds and shutters are cost efficient with respect to external shading devices (Trisha, 2015). These devices can also work additionally to stop solar radiation when the exterior devices get outflanked (Grondzik, et. al., 2011). In addition to that, interior shading devices helps to provide privacy, control glare, provide insulation and often enhance the aesthetics of a space. Internal shading devices also help to prevent the 'black hole' effect near the glazed façade during night (Galloway, 2004).

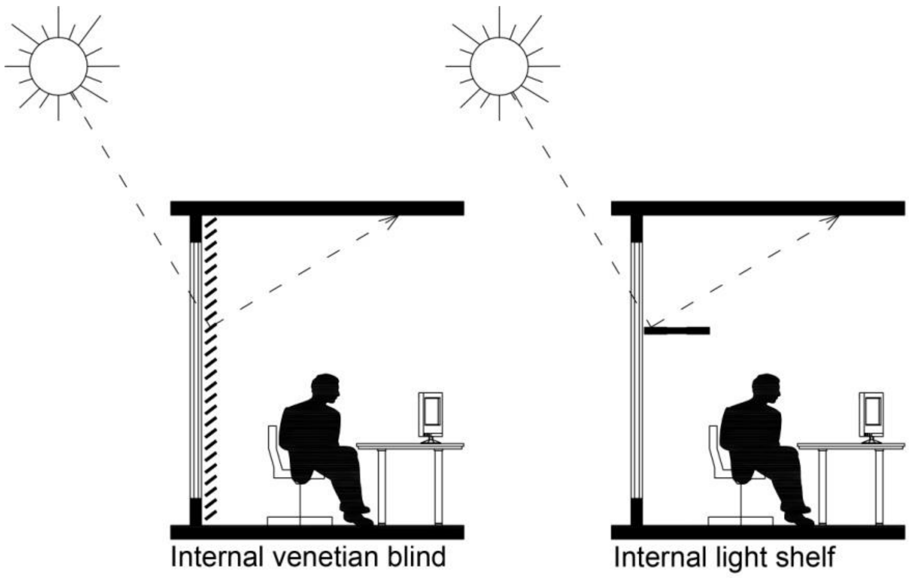


Figure 2.20: Interior shading devices (after, Grondzik et al., 2011)

Devices such as internal light shelf and venetian blind system can re-direct light inside the space that can enhance the quality of luminance environment (Figure 2.20) (Grondzik, et. al., 2011). On an average, the daily solar gain factor of single glazed unit is 72% without any type of shading. The figure reduces to 55% by the introduction of internal venetian blind system (Trisha, 2015). One of the drawbacks of internal shading systems are that since they are placed inside, the solar radiation remains indoors. In addition to that, it is not possible to block the radiation while at the same time admitting view to outdoors. This problem can be overcome by introducing bright color reflective coating on the surface facing towards glass, in order to reflect the radiation back through the glass. As a result, visible light pass through the glass easily and blocks maximum percentage of infrared radiation as their energy are absorbed. However, certain wavelength of infrared lights passes through the glass. (Omar, 2008). When internal shading devices are used in conjuction with external elements, it is recomemnded that the internal device should move up from window sill level. The external device will provide the shading and this will enable to provide view, privacy and daylighting (Palmero-Marrero and Oliveira, 2010).

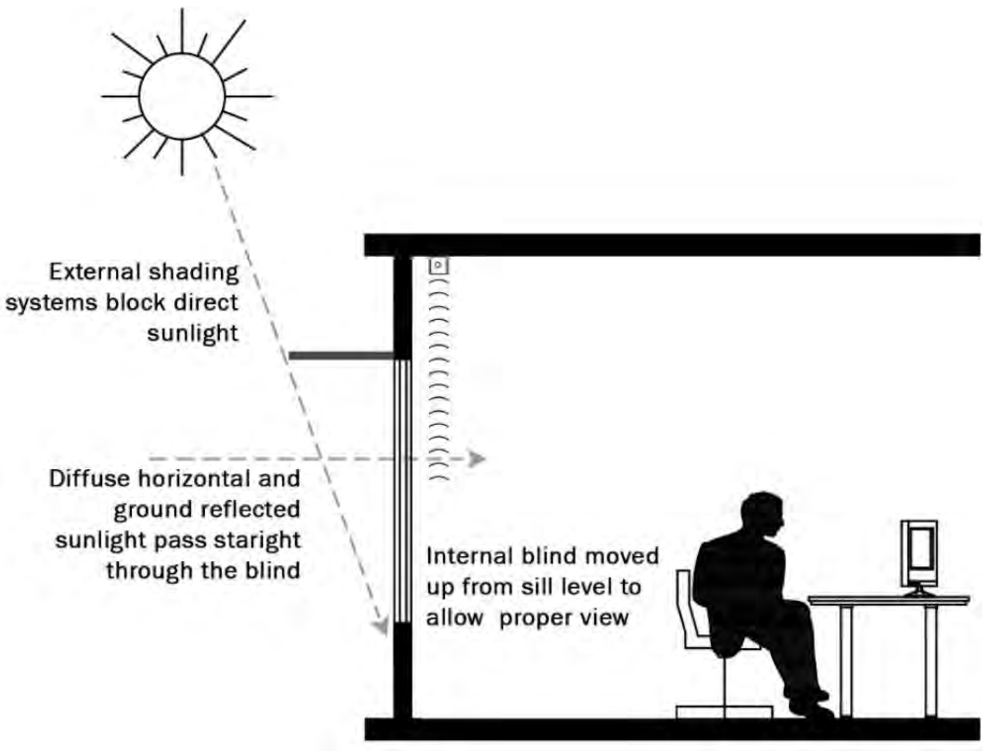


Figure 2.21: External shading system in conjunction with internal shading systems

a) Internal light shelf

Light shelf is a classic internal horizontal shading device. These are usually installed in a horizontal or inclined position above eye-level and are categorized into internal, external and mixed type (Figure 2.22). Light shelf is a light controlling system that directs daylight to the deeper parts of the room and helps to ensure energy efficiency (Lee, et al., 2018b; Moazzeni and Ghiabaklou, 2016). It blocks direct sunlight from flowing in order to prevent glare and illumination imbalance in indoor work spaces.

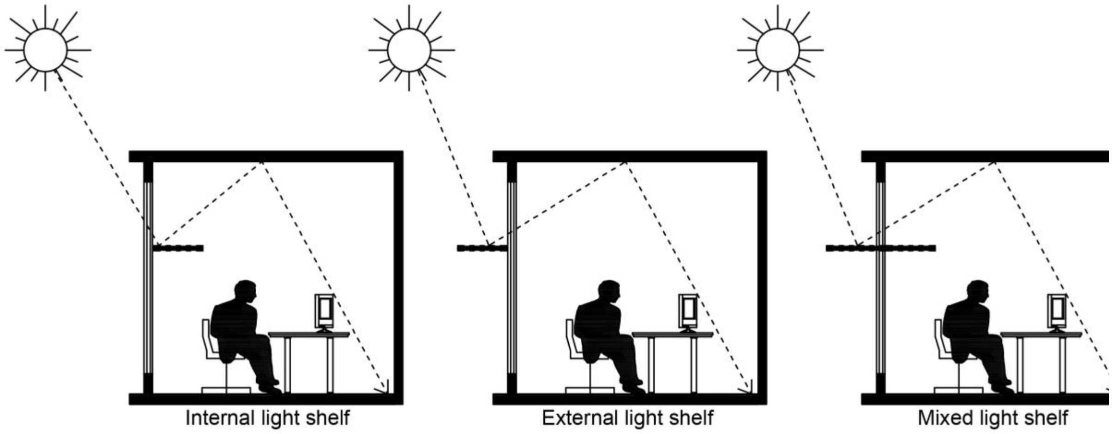


Figure 2.22: Types of light shelves depending on their location

Light shelf induces uniform distribution of light which improves overall indoor lighting quality and ensures comfortable environment for inhabitants (Kwon, et. al., 2014). External light enters into the interior space through reflection on surface of the walls or floor based on the reflector of light shelf, height of the ceiling, depth and shape of the interior space. The first light reflection occurs from light shelf reflector, so it is fundamental to consider the shape and parametric configurations of light shelf in order to determine the daylight performance (Lee, et. al., 2016a). Lowering the height of light shelf increases the possibility of light reflection on to the ceiling; hence the chance of glare also increases. The performance of a light shelf system varies to a greater extent in different climatic conditions, seasons, azimuth and altitude of the sun and can affect the energy consumption of a building. In regard to the overall illuminance inside a space, external light shelf performs better than interior light self. Internal light shelf takes up much space inside and are expensive as well (Trisha, 2015).

b) Internal venetian blind

Internal venetian blinds are a common type of shading system, extensively used in commercial buildings with transparent façades. The blinds have significant impacts on incident light and act as a visual barrier between the indoor and outdoor environment (Ye, et. al., 2016). A Venetian blind has the ability to reflect and transmit daylight inside spaces. In modern offices which have glazed envelopes, it is crucial to ensure privacy, allow sufficient daylight and at the same time provide glare protection. Venetian blind has that distinctive ability to adjust its slat angle in order to allow view to outside as well as ensuring glare protection (Tzempelikos, 2008). Internal blinds are cost effective, easy to install and takes up very little space inside a space (Ye, et. al., 2016; Joarder, et. al., 2009; Tzempelikos, 2008). This opens up limitless possibility of external façade design to designers and reduces the construction cost as well (Ye, et. al., 2016).

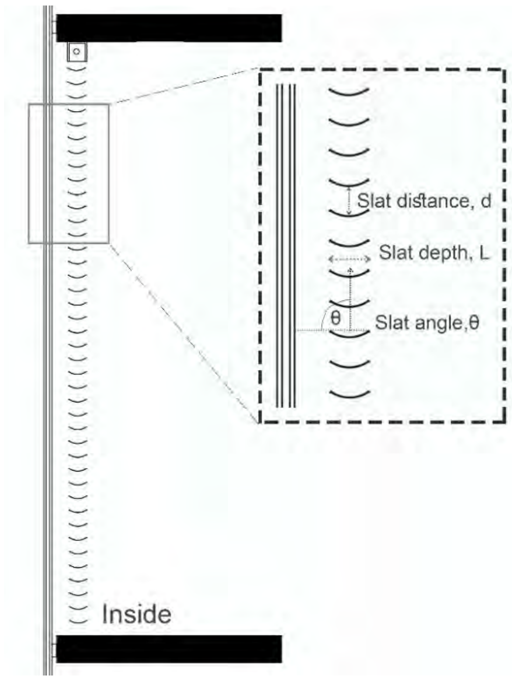


Figure 2.23: Schematic of internal venetian blind configuration (after, Nicoletti. et.al, 2020)

The screen consists of separate moveable slats, which are arranged equally, spaced from each other (Tzempelikos, 2008). There are few characteristic parameters of a blind configuration that affects their performance which are, slat depth ‘L’; distance between two consecutive slats ‘d’; the angle of slat inclination with the horizontal plane and normal (Figure 2.23). The shaded (slat) area and the viewing area depend on the slat geometry, rotation angle of slat and surface reflectance of slat material (Nicoletti, et. al., 2020). The optical properties of the system depend on several factors such as tilt angle, louver characteristics and solar incidence angle. Other parameters such as geometric configurations (size and shape) of slat, material and colour of slat have great impact on glare and view.

The absorbance, transmittance and reflectance property of the window aperture also affects the overall illuminance inside an office space (Tzempelikos, 2008). A research conducted on internal venetian blind concluded that these systems can become much more effective than external blinds if highly reflective materials are used for slats (Ye, et. al., 2016).

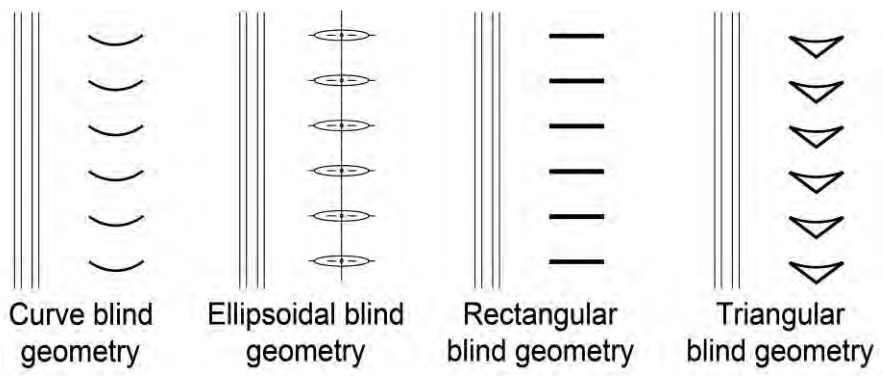


Figure 2.24: Different slat geometric configurations

In most cases the blind elements are made of various types of materials such as, painted galvanized steel, copper, wood, PVC or aluminium. In addition to that, there are various possible slat geometric configurations available, ranging from curve, ellipsoidal, triangular, gull-wing, diamond-shaped or rectangular especially for wooden slats (Ye, et. al., 2016) (Figure 2.24). The system is operated by a mechanism housed in upper casing and additional lateral support is provided by wires made of mostly aluminium (Figure 2.25).

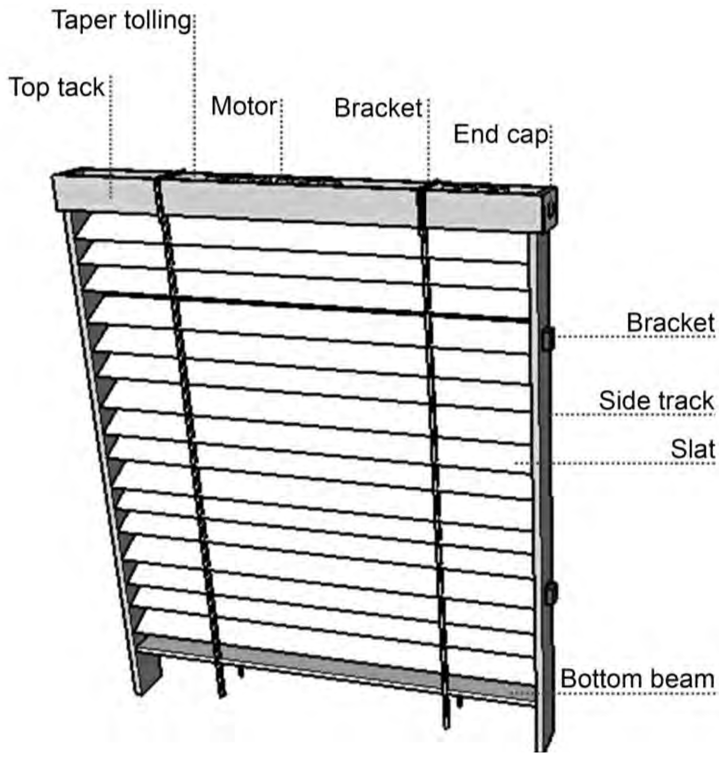


Figure: 2.25: Operating mechanisms of internal venetian blind

Venetian blind configurations control the incoming solar radiation annually by modifying the slats either manually or automatically (Ye, et. al., 2016; Joarder, et. al., 2009). Depending on the control mechanisms, blinds can be classified into three categories (Ye, et. al., 2016; Singh, et. al., 2016) (Figure 2.26).

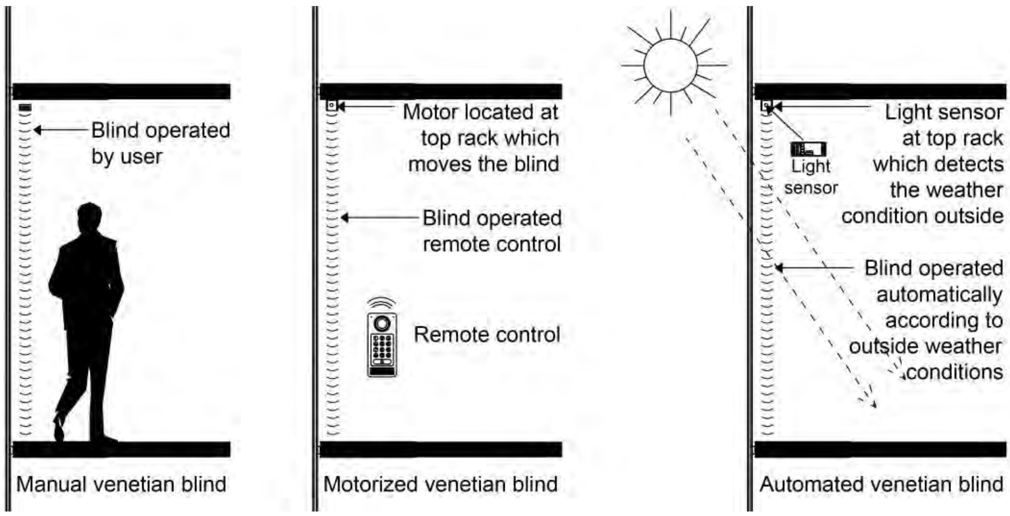


Figure 2.26: Classification of venetian blinds

- **Manual venetian blind:** These are the simplest ones which do not require any motorized device. These are usually operated by the users according to their comfort level.
- **Motorized venetian blind:** They are operated by a motor that can be controlled either by a remote or centralized system.
- **Automatic venetian blind:** These blinds are controlled by sensors depending on the weather and climate conditions outside. They require constant Wi-fi connectivity for operation.

There are various types of blinds available in the industry, such as vertical hung louver blind, venetian horizontal blind and blind in between double glass cavity (Figure 2.27). The vertical louver blinds give the flexibility to rotate individual louvers and move to a side when not needed. Similar to venetian horizontal blinds, vertical blinds come in various louver materials and are inexpensive. A study conducted between vertical louver blind and venetian blind revealed that, on annual basis venetian blinds provide better quality for visual environment (Joarder, et. al., 2009).

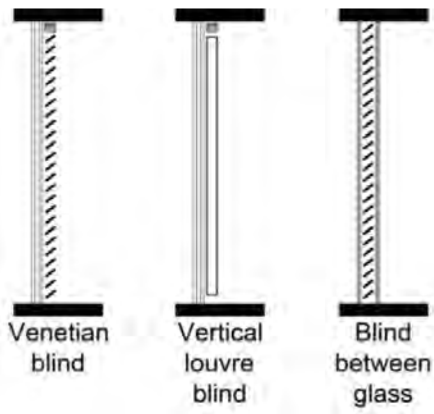


Figure 2.27: Types of internal blinds (after, A. G. S. 2000)

The performance of blind is linked to a great extent on human factors as well such as their satisfaction level, ease of usage and others. In the past, pilot study was conducted in office spaces examining the effects of manual blind system, semi-automatic blind system and automatic blind system in correspondence to user's satisfaction level. 14 office employees were tested for three hours in the morning and afternoon. The study showed that, almost 85% of people felt daylighting level to be comfortable using manual system and did not have any complaints regarding dimness, shadow, brightness or lighting distribution. However, user's satisfaction level is linked to many other factors such as source of glare, type of task, outdoor weather condition, operation of the daylighting system, brightness of the surfaces surrounding the task and others (Lee, Bartolomeo, Vine, and Selkowitz, 1998).

In order to improve the sustainability of a building, double skin façade (DSF) is being used in many commercial buildings. DSF generally consists of two separate glasses with air cavity in between. In most cases, the air gap is filled with solar shading devices such as venetian blinds to improve the performance of DSFs by minimizing the solar heat gain inside the building (Ji, et. al., 2008) (Figure 2.28).

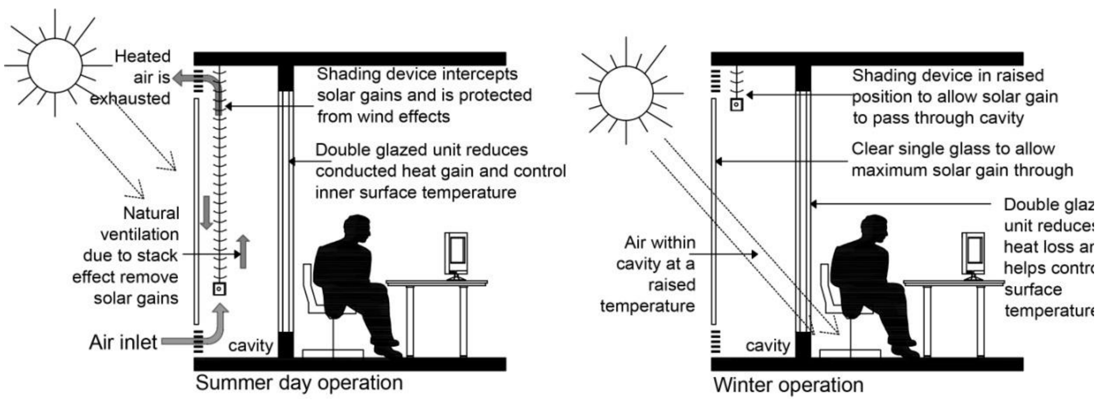


Figure 2.28: Characteristics of double skin façade (after, Ghaffarianhoseini, et al, 2016)

The mechanism inside DSF which is used for natural ventilation and slat angle rotation operation often makes the system expensive and difficult to operate. This system also limits the view in comparison to venetian blind (Gavan, et. al., 2007). Manual venetian blinds are easy to operate, inexpensive and their distinct characteristics allow enhancing the overall luminance inside a space.

As a result, this study intends to analyze the performance of various slat geometry for different orientations inside an office space.

2.6 Illumination standards for office spaces

2.6.1 Local Illumination standards

According to the BNBC (BNBC, 2020), the recommended values for illumination required in buildings of different occupancies, is based on activity types. The initial illuminance should be higher than the minimum recommended value to allow for the fact that the illuminance will inevitably drop below this value by the end of cleaning and revamping period. A gradual transition of brightness from one portion to another within the field of vision is recommended so as to avoid or minimize glare discomfort. The recommended illuminance value for office spaces is presented in Table 2.3 (BNBC, 2020).

Table 2.3: Recommended light levels for different space. (BNBC, 2020)

AREA OR ACTIVITY OFFICE SPACE	Illuminance(lx)
Entrance area and reception areas	150
Conference rooms and executive offices	300
General offices	300
Business machine operation	450
Drawing office	
General	300
Boards and Tracing	450
Corridors and lift cars	70
Stairs	100
Lift landings	150
Telephone exchanges	
Manual exchange rooms (on desk)	200
Main distribution frame room	150

According to BNBC (2020), 300lux illumination is recommended for general offices and for critical office works i.e., drawings, 450lux is recommended. Four essential features are determined by BNBC (2020) for an efficient lighting system: visual comfort through adequate illumination of the working surface; prevention of glare; avoidance of shadows; and ease of maintenance.

Table 2.4 shows the recommended brightness ratio for task in office work spaces (BNBC, 2020). In office spaces, to create a productive and comfortable working environment it is necessary to consider the impact of lighting on the walls and surrounding areas. It is recommended to avoid any kind of drastic changes in light levels within an office space, as this result in eye fatigue and reduction in productivity of the workers.

Table 2.4: Recommended brightness task ratios between task, adjacent sources and surroundings. (BNBC, 2020)

Recommendation	Requirement
Brightness	100cd/m^2
Brightness ratio: for high task of work brightness	3 to 1
Maximum ratio between work area and any remote area	10 to 1

2.6.2 International Illumination standards

According to The National Optical Astronomy Observatory (NOAO, 2015), factors that generally affect the effectiveness of illuminance are the quality and quantity of light, amount of flicker, amount of glare, contrasts and shadows. Each of the factors should be adjusted according to emergency, safety, operations and security. Table 2.5 shows the recommended illumination standards for office spaces according to NOAO (2015).

Table 2.5: Recommended illumination standard for office spaces. (NOAO, 2015)

OFFICE SPACE	Illuminance(lx)
Normal work station space, open or closed offices	500Lux
ADP (Automatic Data Processing) Areas	500Lux
Conference Rooms	300Lux
Training Rooms	500Lux
Internal Corridors	200Lux
Auditorium	150-200Lux

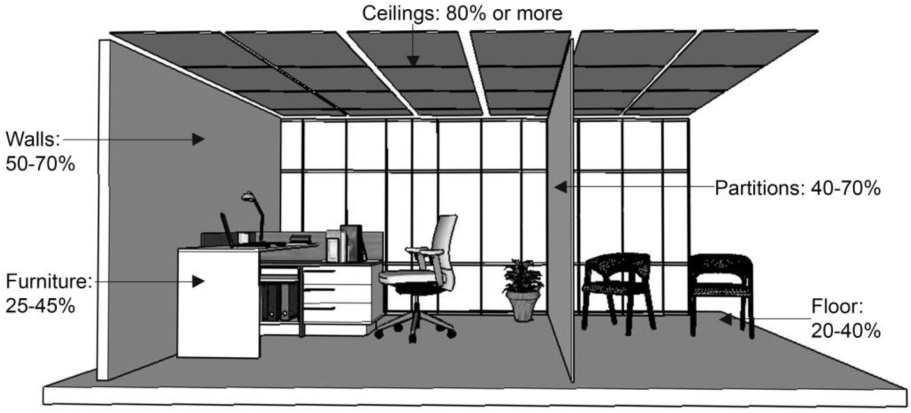


Figure 2.29: Reflectance recommended for room and furniture surfaces in offices. (after, IESNA, 2000)

The brightness difference of the surfaces makes an interior space visible. The absolute and spectral reflectance along with light distribution from the surfaces creates the brightness variation. According to IESNA (2000), the office interiors must be provided with appropriate lighting to avoid any glare and to improve visibility. For creating a comfortable, attractive and simulating office environment, it is necessary to provide sufficient variation of illuminance and avoid direct or reflected glare. Figure 2.29 shows the recommended reflectance percentage from surfaces inside an office space.

Table 2.6: Determination of illuminance categories. (IESNA 2000)

Categories of visual tasks	Areas or Activities	Illumination
Orientation and simple visual task In these spaces visual task is not important, such as public spaces.	Public spaces	30 lux (or 3fc)
	Simple orientation for short visit	50 lux (or 3fc)
	Working space where simple visual task is performed	100 lux (or 3fc)
Common visual task Visual task is important in these spaces. These tasks are found in commercial, residential and industrial applications.	Performance of visual task of high contrast and large size	300 lux (or 3fc)
	Performance of visual task of high contrast and medium size	500 lux (or 3fc)
	Performance of visual task of low contrast or small size	1000 lux (or 100 fc)
Special visual task Visual performance is of critical importance. These tasks are very specialized, including those with very small or very low contrast critical elements.	Performance of visual task near threshold (places such as operation theatres)	3000-10000lux (or 300-1000 fc)

IESNA (2000) recommends 300lux for visual task of moderately high contrast and large size, whereas, 1000lux for visual task of low contrast. As a result, for normal office desk work 300lux is recommended. Table 2.6 shows the recommended illumination conditions for different visual task situations. The recommended Illumination levels vary because of the characteristics of various visual tasks. For critical visual task, the recommended illumination level can be achieved by addition of supplementary task lighting.

2.7 Key- findings

a) Daylight has significant impact on the psychological and physiological health of office employees, which in return improves their productivity and reduces absentees.

b) Deep plan offices often have huge difference in the level of illuminance between perimeter and central zones, creating contrast and puts strain on eyesight. Commercial buildings with glazed envelops results glare problems near the perimeter zone, as a result building use internal shading device which reduce daylight to the deeper areas.

c) The standard illumination level for general office work plane is 300 lux and for critical office works i.e., drawings, 450lux is recommended (BNBC, 2020). In order to create attractive and simulating office environment, it is necessary to provide sufficient variation of illuminance and avoid direct or reflected glare (IESNA).

d) The type and characteristics of glazed units determine the intensity, directionality and amount of natural light entering inside a space. In order to provide shading to the interior space, glazing with lower transmittance value are effective.

e) Orientation and size of window opening with respect to solar angles throughout different climate of the year have great impact on the amount of daylight inclusion. Configurations for shading system with respect to orientations are essential to consider.

f) Among available types of internal blinds, venetian blinds are one of the most suitable to ensure effective visual environment on annual basis.

g) Internal venetian blind has great impact on the incident light which can protect the interior space from glare, at the same time allow sufficient amount of daylight inside, taking negligible amount of space.

h) The optical properties for internal blind configurations depend on several factors such as tilt angle, louver characteristics and solar incidence angle. Other parameters such as geometric configuration (size and shape) of slat, material and colour of slat have great impact on glare and view.

2.8 Summary

This chapter has discussed different aspects of daylight systems and the effectiveness of internal venetian blind on daylight enhancement inside an office space in commercial high-rise buildings with glazed façade. This chapter also elaborated how the daylighting level inside work spaces biologically stimulates and effects psychological health of employees. The available blind configurations which are being studied and their significance over other internal shading systems have also been described in this chapter.

The first objective of this research has been achieved in this chapter by evaluating the effectiveness of internal venetian blind as shading system to ensure appropriate illuminance level inside deep plan office buildings. Among available types of internal blinds, venetian blinds are one of the most suitable to provide quality visual environment on annual basis. Internal venetian blind has great impact on the incident light which can protect the interior space from glare, allow sufficient amount of daylight inside and takes small amount of space. According to the scope of this thesis, illumination standards for office spaces, impact of orientations on configurations of shading elements, performance of venetian blind with respect to overall illuminance, impact of glazing on daylighting inside office space have been discussed in this chapter. These aspects were studied depending on previous research and published sources.

The information and data of this chapter helped to be selective of the issues on which detail steps of methodology for simulation study has been developed in the next chapter.

CHAPTER: THREE

METHODOLOGY

METHODOLOGY

3.1 Preamble

This chapter illustrates the detailed framework for daylight simulation procedure which is followed in this research. The simulation procedure which is followed in this research helps to evaluate the efficiency of different types of internal venetian blinds and its parameters, and its impact on overall illuminance level and visual comfort inside office space. In practical life, there are many environmental and climatic factors that are interlinked with each other such as penetration of daylight is linked with solar heat gain. It is not possible to separate the impact of a single factor from others. Simulation helps to study the impact of a single factor, keeping other factors constant. During the simulation procedure, parameters are changed in order to identify the performance of a particular design variant. Depending on the findings from simulation, an efficient element is identified that will ensure appropriate daylight illuminance inside office space. The evaluated parameters of venetian blind configurations in this research are identified from literature study of the previous chapter. The model space was made using ECOTECT software and climate based dynamic daylight simulation tool DAYSIM is used to evaluate illuminance level and quality of daylight inside the case space.

This chapter includes detail description of the simulation methodology that is followed, including the parameters and detail blind configurations. The procedure helps to evaluate the performance of different blind configurations in terms of illuminance level in side office space within glass faced commercial buildings in Dhaka.

3.2 Methodology for Simulation Study

The simulation procedure that is followed in this research helped to identify effective parameters for internal venetian blind configurations for different orientations of office spaces with glazed envelopes in the context of Dhaka. The methodology flow diagram which is used for simulation study is shown in Figure 3.1.

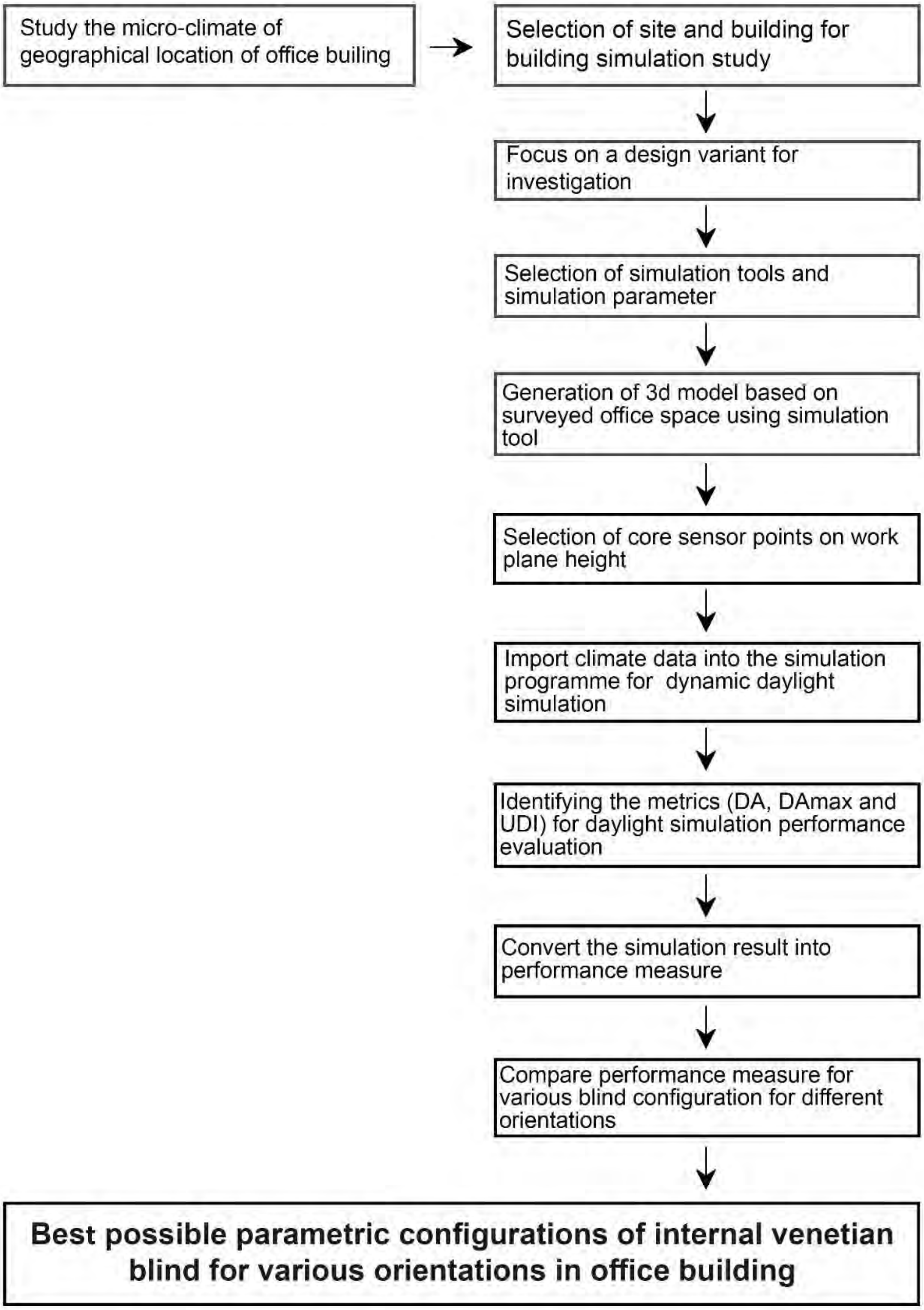


Figure 3.1: Flow diagram of the simulation process (after, Joarder 2011)

A detailed field investigation was carried out to study the selected case office space and the micro-climate surrounding the site. An appropriate simulation tool was selected to create the physical model based on the data and parameters as they are found during the field investigation. In the next step, another simulation tool was selected to evaluate the performance of venetian blind parameters for different orientations to ensure appropriate daylight level inside office space. A single blind configuration will not be effective for different orientations. North facades face continuous indirect sunlight and less solar heat gain during summer, while south facing windows gets intense direct and indirect sunlight (Omar, 2008). In the climatic context of Dhaka, North façade does not need any kind of shading element (Joarder and Price, 2012), so the research focused on the daylighting performance of South, East and West orientations.

The (Section 2.5.2) parameter for simulation process is followed from the literature review. For the evaluation procedure, the entire office space is divided equally to locate core sensor points. The evaluation is done by selecting some dynamic simulation metrics (e.g., DA, DAmax and UDI), developed from literature study. Finally, the parameters are analysed critically based on the evaluation metrics to find out the best possible parametric configurations for internal venetian blind in three different orientations.

3.2.1 Geographical location of office building

The climate of a place presents certain conditions which need to be addressed in order to create sustainable and climate-responsive buildings. There are certain criteria such as comfort, energy-efficiency and environment friendly material, results in a climate responsive building. Design of a building without any consideration of surrounding climate can cause enormous energy intakes inside indoor spaces, either to solve over-heating or insufficient illuminance (Rahman, 2007). This study is based on Dhaka and the geographic location is, longitudes: 90^0 to $90^0$30’ East and latitudes: $23^0$40’ to $23^0$55’ North. The following sections will discuss about the climatic aspect of Dhaka city and its potential for daylight design,

a. Micro-climate of Dhaka

The change in urban fabric and dense physical development of Dhaka differentiate its climatic characteristics from other cities in Bangladesh. The climate within the city in different areas may vary depending on topography, building density, orientation, building materials, building heights, proximity between buildings, and other factors (Ahmed and Joarder, 2007). The climate of Bangladesh is classified mainly into four distinctive seasons, winter, pre-monsoon, monsoon and post-monsoon.

Temperature remains cool and dry during winter, whereas, pre-monsoon is hot and dry and it remains hot and wet during post-monsoon season (Ahmed, 1995). The average relative humidity for Dhaka is 74% and it is highest for the months June, July, August and September, whereas, it is the lowest during February and March. The air temperature and radiation depend on the density of the surrounding, so relative humidity will vary with the change in the density of built form. Relative humidity is inversely proportional to temperature, provided with other conditions being constant. Relative humidity affects the clarity of the environment, hence affects the daylight quality. The rapid urbanization in Dhaka, which is associated with construction of roads and built structures, increases radiation of heat. This result in the development of heat island effect thus increases the use of energy for cooling purposes. The temperature differences between rural and urban areas are more divergent (Mridha, 2002).

b. Cloud coverage

The luminous environment inside an office space depends on the availability of sunlight, sunshine hours, quality and quantity of sunlight and sky condition throughout the year. Clear sky enhances the chance of solar radiation, hence increases the load on HVAC system (Ahmed and Joarder, 2007). In Dhaka, the condition of cloud coverage varies in various seasons. The sky remains clear (sunny with sun) and overcast during pre-monsoon period (Hot Dry). Monthly cloud coverage varies from 2 to 4 octa during pre-monsoon period and this indicates a mixed day condition, the sky remains both overcast and clear (sunny with sun) (Nandi, et.al, 2013). In winter (December-February) the sky stays mostly clear. However, the sky remains considerably overcast during warm-humid period (March-November) (Joarder, 2009).

Table 3.1: Sky condition of Dhaka throughout a year (Khatun, Rashid and Hygen, 2016)

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

The composite climate of Dhaka, where both overcast and clear sly condition stays in various seasons throughout the year, designers face difficulties to design. In mixed sky conditions, April has the dry weather with high solar altitude angle, maximum sunshine hours along with higher solar intensity. Table 3.2 shows the sky condition with respect to cloud coverage throughout a year in Dhaka. Fixed horizontal shading devices are suitable for overcast sky conditions, whereas, moveable vertical devices perform better in clear sky condition. Architects need to use critical strategies in order to cope with both the conditions while ensuring comfort to the occupants (Ahmed, 1995).

c. Sun shine hours

The tropical climate and latitude of Dhaka makes it a good recipient of solar energy. Monthly sunshine hours vary from 4.1 to 7.8 hours (Fatemi, 2012). The sunshine hours vary during different seasons depending on the length of the day. The amount of light received inside an interior space depends on the duration of sunshine, which in turn affects the sun light zone in interiors (Ahmed, 1994). In Dhaka, during April (pre-monsoon period) the sunshine hour is longest (Khan, Rahman and Hossain, 2012) and reaches to a minimum value in monsoon months. The sunshine hours start to increase steadily after monsoon months (Joarder, 2007).

d. Solar radiation

Solar radiation is considered as a sole factor which determines the climate of an area because it affects the density and temperature of air, which in turn changes the wind velocity, humidity and wind direction (Ahmed, 1995). The solar radiation is high for the hot and dry season (March, April and May) and it is highest in April. In the monsoon to post-monsoon period (July-November) due to the cloudy atmospheric condition, the solar radiation intensity reduces and remains fairly constant. In Dhaka, the average solar radiation per day ranges between 4.02 to 5.76 KWh/m^2, which is significant enough for solar energy extraction (Rahman, 2010).

Horizontal surfaces such the roof of buildings receives maximum amount of solar radiation in comparison to vertical façade of buildings. In case of high-rise buildings, the vertical surface area is larger than the horizontal area (roof surface), so only top floor is exposed to the incurring radiation from the roof. The tall buildings are more susceptible to over-heating through the vertical glazing surface as a result the issue of heat gain is significant especially when the sun is at lower angle. Sustainable strategies need to be developed for the vertical facades for high-rise buildings in tropical climates (Rahman, 2007).

e. Daylight illumination level

The intensity of direct sunlight varies with the sun's position and seasons throughout the day. For clear sky, the daylight can have intensity of 10-25% of direct sunlight (10,000lux to 1, 00,000lux). The intensity can be as low as 5%-10% of direct sun (5,000 to 10,000lux) for overcast sky condition (Joarder, 2007). Illumination level varies with change in latitudes; it is much brighter in the lower altitudes in comparison to higher altitudes (Ahmed, 2014). For Dhaka, the sky illuminance is approximately 10,000 to 12,000lux. Table 3.2 shows the illumination values of design sky for different latitudes globally (Evans, 1980). In Dhaka, the heat content is approximately 2 to 2.5% more for specified illuminance of daylight available in comparison to other European countries (Ahmed, 2014). So, for tropical climate such as, Dhaka, while considering daylight it must be weighed against heating as well to ensure energy efficiency of the buildings.

Table 3.2: Illumination value for design sky on horizontal surfaces (Source: Evans, 1980)

Overcast Sky	**Unit: lux**
Latitude 50^0-60^0	5000
Latitude 40^0-50^0	5000-6000
Latitude 30^0-40^0	6000-8000
Latitude 20^0-30^0	8000-10000
Latitude 10^0-20^0	10000-15000
Clear Sky (Sun altitude 15'min)	**Unit: lux**
All altitude	5000
Solar altitude 15^0	14000
Solar altitude 30^0	36000
Solar altitude 45^0	58000
Solar altitude 60^0	75000
Solar altitude 75^0	83000
Solar altitude 90^0	94000-110000

3.2.2 Selection of case space

a) Surveyed Office buildings

The purpose of this research is to evaluate the performance of internal venetian blind parameters for different orientations inside an office space in glazed faceted high-rise commercial buildings in Dhaka. Number of commercial high-rise buildings have increased in an unprecedented rate within last couple of years. In order to carry out daylight simulation analysis inside office space, four commercial office buildings were primarily surveyed in Dhaka (Table 3.3).

Table 3.3: Surveyed high rise office buildings in Dhaka

Name of office building	Establishment	Design Status	Orientation (Elongation)	Number of storeys
Venture Tower	2014	Completed	East West	12 storied
Shadhinata Tower	2011	Completed	East West	13 storied
MTB Center	2009	Completed	North South	6 Storied
Grameenphone Headquarter	2007	Completed	East West	9 storied

To maintain comfortable indoor luminous environment, it is fundamental to study human factors i.e., how the employees are responding to the visual environment and to carry out a post occupancy study. As a result, the buildings that were selected for survey was based on operational years. The mentioned surveyed four buildings were in operation for more than 6 years. This will broaden the scope for research and help to study the effectiveness of the recommended blind configuration from this research with consideration of different factors. Table 3.4 represents the layout of the surveyed office buildings and exterior pictures.

Table 3.4: The layout and exterior views of surveyed buildings

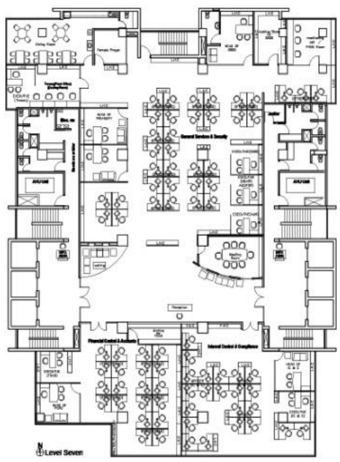
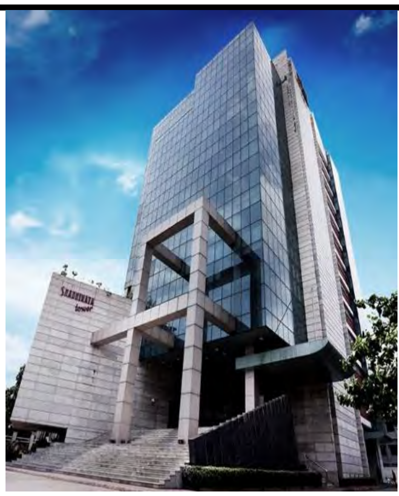
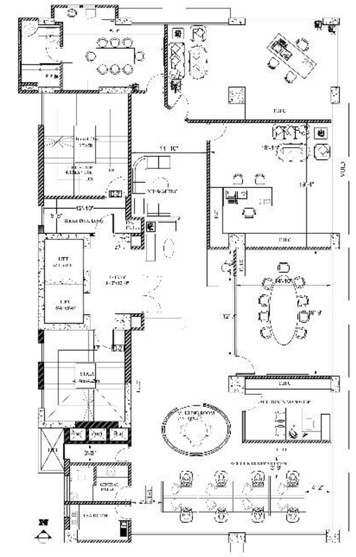
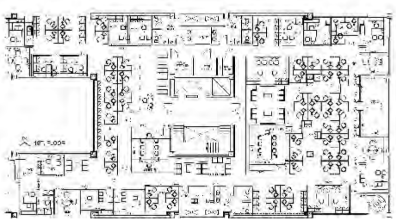
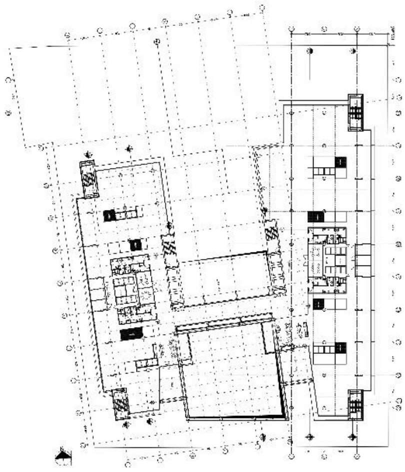
Name of Office Building	Layout	Exterior view
Shadhinata Tower		

Table 3.4: Continued

Venture Tower		
MTB Center		
Grameenphone Headquarter		

b) Selection criteria for office building

Certain criteria are considered while selecting the case building and site. Criteria that are followed are mentioned below.

a) It is ensured that the site is located within the urban context.
b) The commercial office building represents open plan office layout design in Dhaka.
c) The building façade had glazing on at least three sides, preferably South, East and West.
d) It is ensured that the building façade have plain curtain walls, i.e., without any ornamental elements or shading devices.
e) The commercial building is built according to the building construction regulations of 2008 of concerned authorities of Dhaka.
f) The internal layout had potential to allow ample penetration and distribution of daylight.
g) The commercial office buildings fall under the category of high-rise buildings i.e., 10 storey or above.

Surveyed office buildings in correspondence to selection criteria are shown in Table 3.5.

Table 3.5: Surveyed office buildings in correspondence to selection criteria

Criteria	Shadhinata Tower	Venture Tower	MTB Centre	Grameenphone Headquarter
a	✓	✓	✓	✓
b	✓	✓	✓	✓
c	✓	✕	✓	✓
d	✓	✕	✕	✕
e	✓	✓	✕	✕
f	✓	✓	✓	✓
g	✓	✓	✕	✕

c) Selection of the office building

Based on the mentioned criteria (Table 3.5) Shadhinata Tower falls under the category of all the selection criteria, so it is selected for simulation evaluation.

It is a 13 storied high-rise commercial office building with glass façade on three different orientations (South, East and West). The building is located near Bir Srestha Shaheed Jahangir Gate, Dhaka Cantonment. The building has 12m wide road on the south direction, 9m wide road on the west side, 3 storied building towards the east and 2 storied building at north side (Figure 3.2). In working days (5 days), the office hour starts at 10:00 AM and ends at 5:00 PM. Two different offices are located in seventh floor of the building: Trust Bank Limited and Bkash corporate office. Office floor of Trust Bank limited is selected as case space for simulation study.

Figure 3.2: Site and the surrounding area

d) Physical characteristics of the case space

The building has typical floor plans, except the ground floor which is mainly used for administrative purposes and waiting area. The seventh floor of the building is selected for simulation study as it represents typical office layout to the rest of the floors. The research intends to find out the impact of different venetian blind parameters on the illuminance inside office space, so an active portion of seventh floor is selected which has glass façade on the east, west and south orientations (Figure 3.3). The architectural features of the selected active office area as found during the physical survey are as following.

- **Total floor area** :1236.5 m^2
- **Selected active area** : 289 m^2
- **Window to floor ratio** :0.21
- **Work Plane height** :0.75m (2'-6")
- **Direction of windows** : East, West and South
- **External shading device** : None

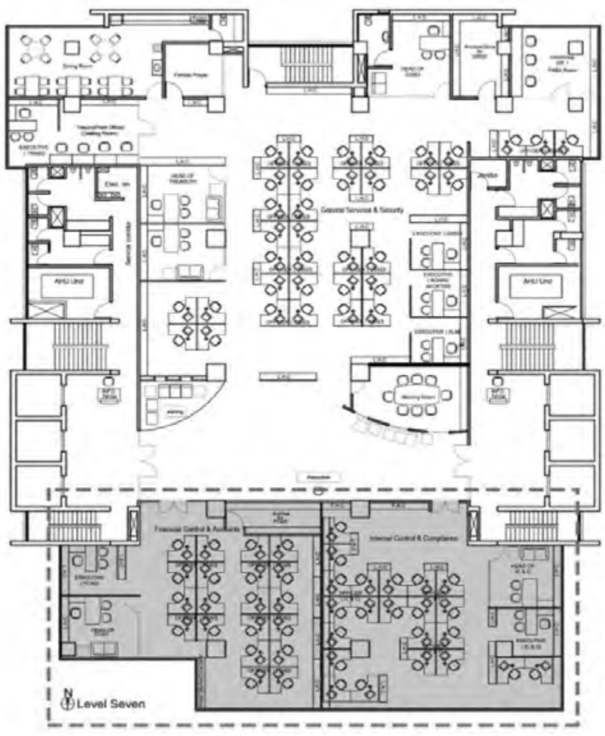


Figure 3.3: Location of active portion of office layout from 7th floor

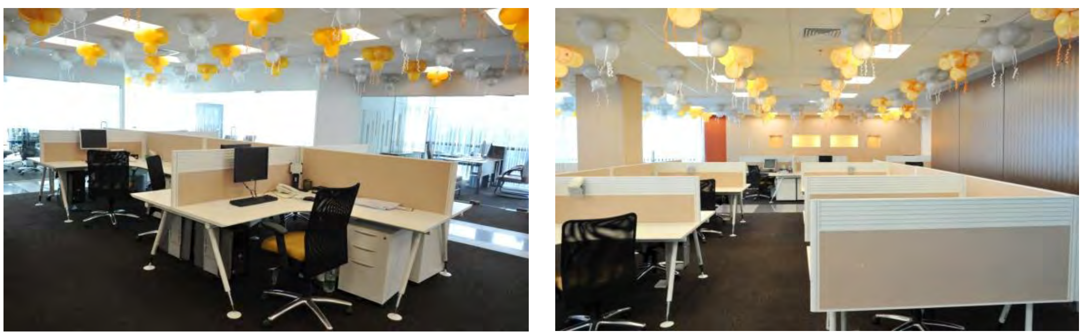


Figure 3.4: Images of interior space inside the study area

The interior image of the selected office area is shown in Figure 3.4. Field survey is carried out to find out the material characteristics and dimensions for simulation procedure. The detail survey for floor, suspended ceiling and partition wall of the selected space is shown in Figure 3.5. For interior finishing the following material characteristics are used.

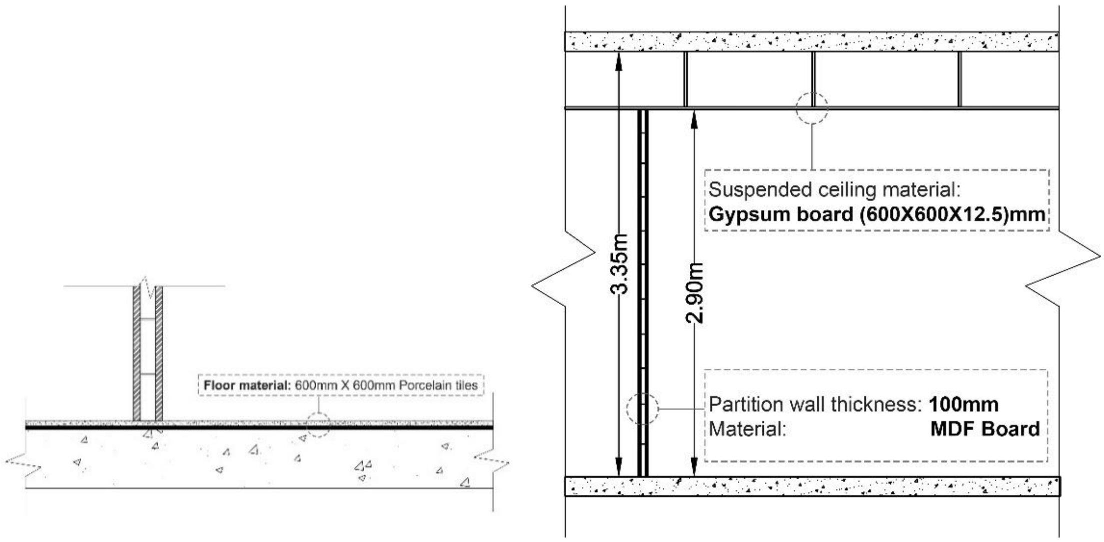


Figure 3.5: Detail of floor finish, partition wall and suspended ceiling

Floor finish: Mirror polished Porcelain tile (Color: Off-White)

Partition Wall: MDF Board Matt- finished wall (Color: Ivory)

Suspended Ceiling: Matt- finished Gypsum board (Color: White)

The selected active office space has glazed wall on east, west and south side on the exterior façade. The building did not have any kind of shading element on these facades; and the case space does not pose any peripheral shading from surroundings as there are enough set back in between buildings. As a result, abundance amount of daylight enters inside the space during office hours. The detail characteristics of glazed wall are shown in Figure 3.6.

External glazed wall: It consists of 6mm double glazed unit (DGU) with clear glass. The frame is made of aluminium.

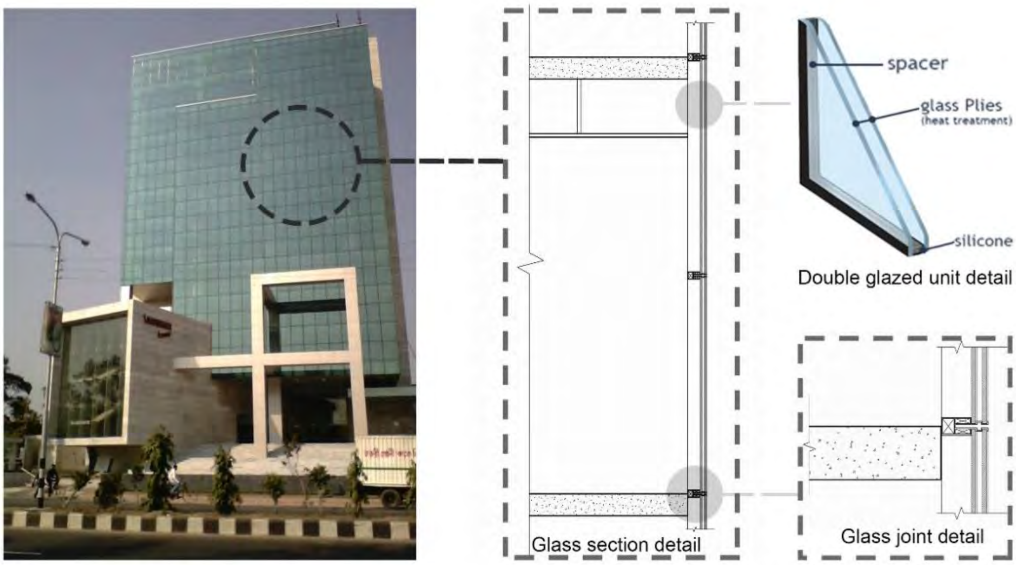


Figure 3.6: Detail of glazed unit in exterior façade

3.2.3 Decide on design variant

Internal venetian blind is identified as having a significant impact on incident light and act as a visual screen between the interior and exterior environment. In a study between two types of internal blinds (vertical and horizontal) for office spaces, it is found that horizontal internal venetian blind performs better in correspondence to luminance environment (Joarder, et al., 2009). There are many parameters of venetian blinds available that can greatly reduce the performance. This research intended to evaluate the performance of the following blind parameters (Section 2.5.2).

- Geometry of slat
- Configuration of feasible slat geometry
- Distance between slats

It is found from market survey in Dhaka that the commonly available width and separation distance of blind is 100mm (Joarder and Price, 2012). A combination of experimental and simulation study showed that internal venetian blind gets more effective by the use of highly reflective materials (Ye, et al., 2016). Figure 3.7 shows detailed blow-up for venetian blind used in the simulation study. For 3D model interface 100mm is selected for slat width and separation distance is kept 25mm (Carletti, et al., 2016) from the glazed façade. Aluminium with reflectance value 0.92 is selected as blind material. The specifications for blind configuration used for simulation study is shown in Table 3.6. During the simulation it is considered that the blind configurations are static and completely open. The evaluation of blind parameters in this research is done in three stages.

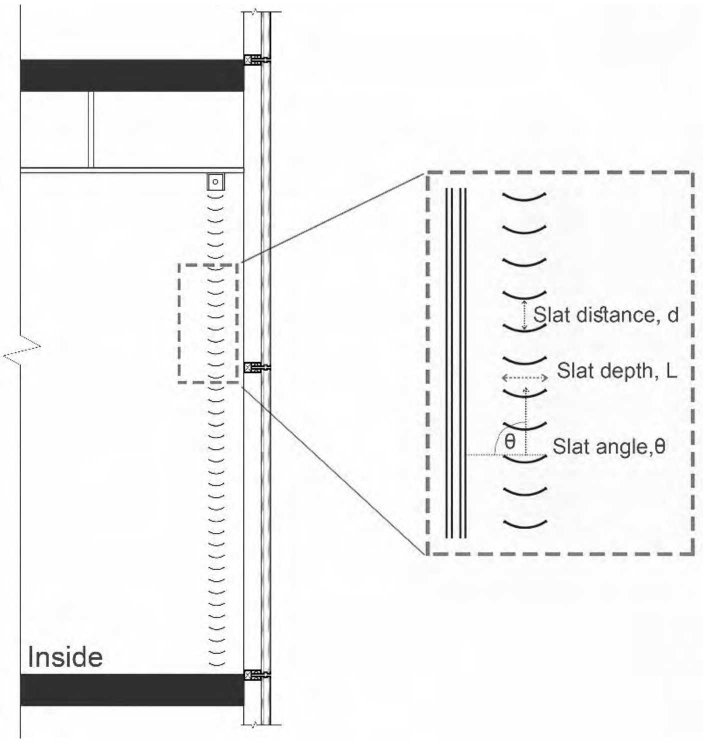


Figure 3.7: Blow-up detail for venetian blind configuration and specification

Table 3.6: Constant parameters of blind configurations used for simulation

Blind specification		
Blind width	a	100mm
Distance between slats	b	100mm
Separation distance between blind and glass facade	c	25mm
Blind material	Aluminium (Reflectance:0.92)	

The following slat characteristics were considered during this simulation research.

- Slats have negligible thickness
- Slats are opaque
- Slat surface is smooth and without any irregularities
- Edge effects are negligible

a) Stage 01: Evaluation of slat geometry

The first stage of simulation process involved evaluation of different slat geometry configurations for east, west and south orientations. The simulation outputs of geometries are then compared with the situation when there is no blind provided. Seven different geometries are studied as shown in Figure 3.8. A particular blind geometry is evaluated individually in three different orientations to identify its performance.

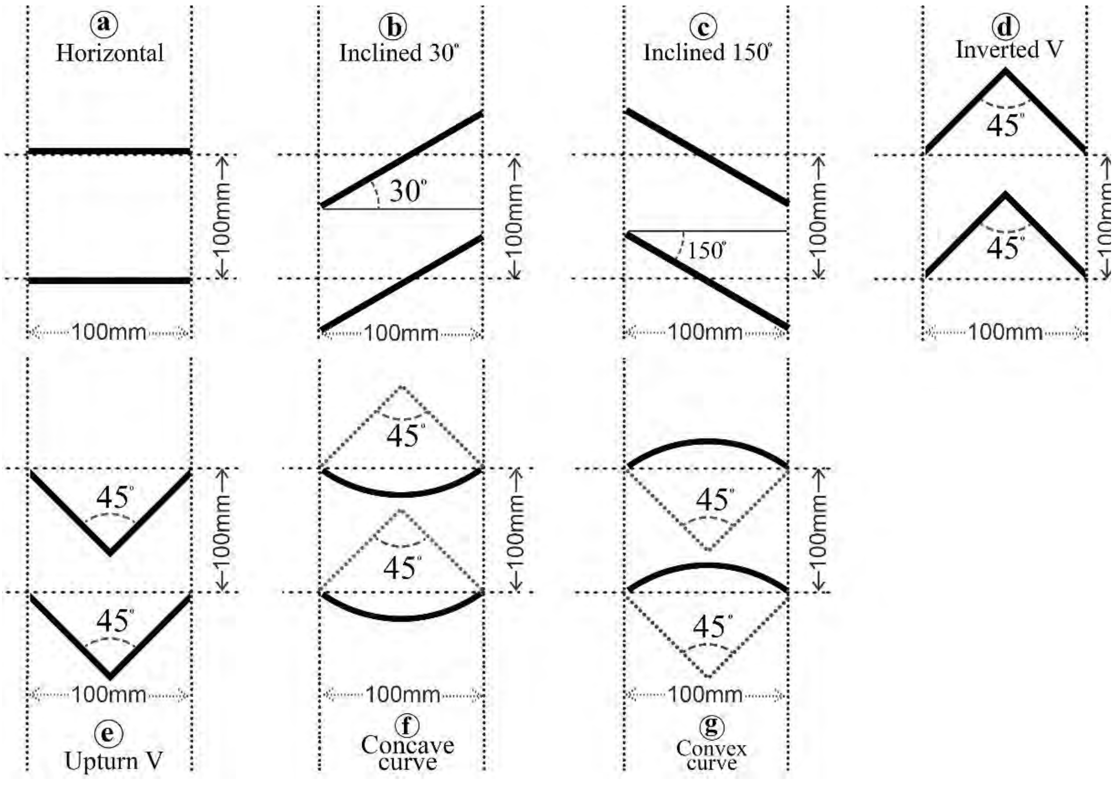


Figure 3.8: Blind geometries evaluated in stage 1 of simulation study

b) Stage 02: Evaluation of geometric configurations

The second stage of simulation involved evaluation of configurations for the best geometry found in the previous step. Same blind specifications are followed during this stage. Eight different vertex angles are selected for three different orientations as shown in Figure 3.9. Selected vertex angles for simulation are taken within 15^0 intervals and the angles are 15^0, 30^0, 45^0, 60^0, 75^0, 90^0, 105^0, and 120^0.

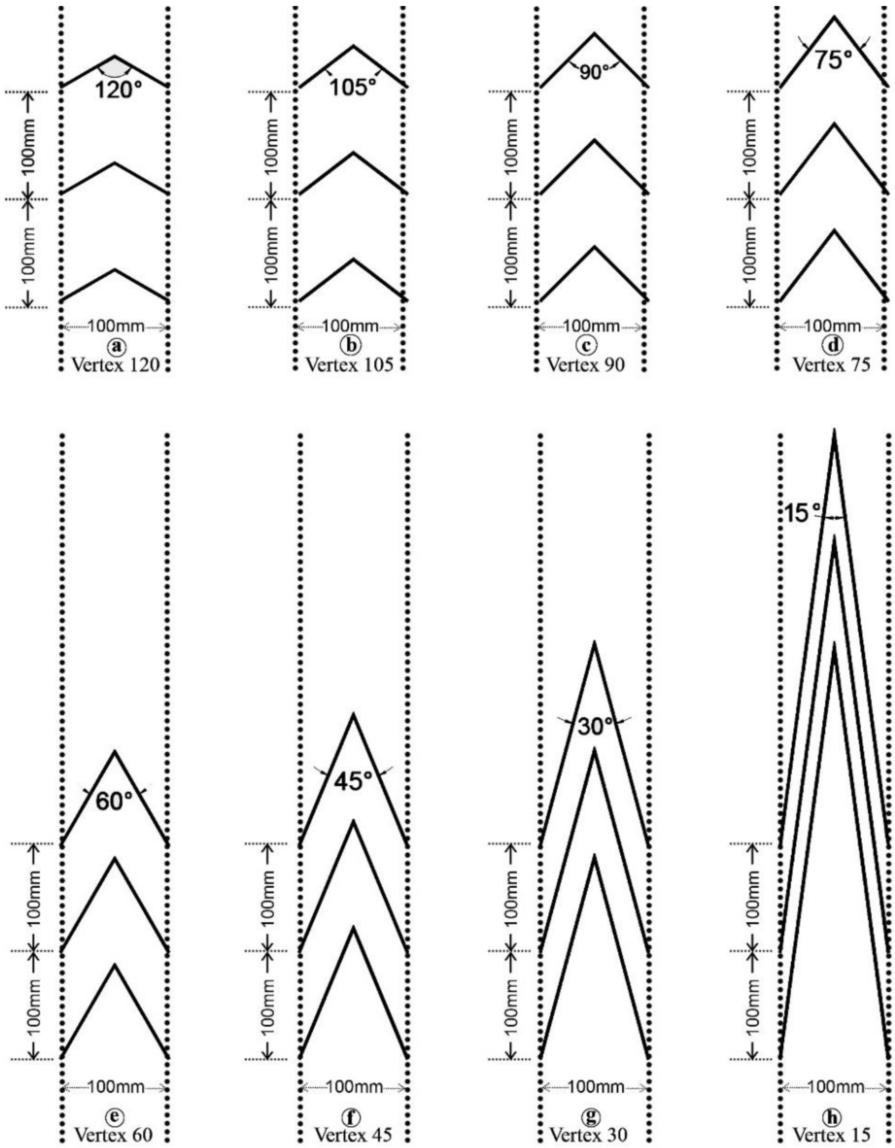


Figure 3.9: Geometric configurations evaluated in stage 2 of simulation study

c) Stage 3: Evaluation of distance between slats

In the last stage of simulation process, the gaps in between the slats are studied for three orientations. The best geometric shape and configuration from previous steps are used for this third step. Apart from the distance, other previous specifications are followed in this stage. Sixteen different variants are selected for the distance as shown in Figure 3.10.

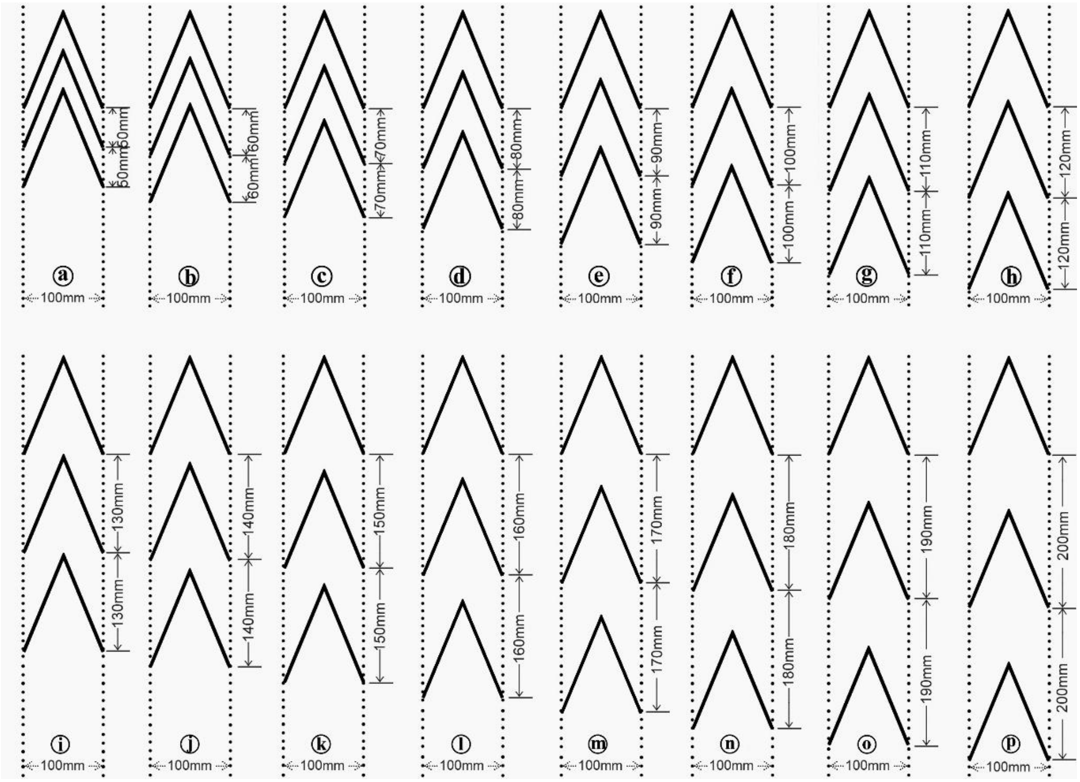


Figure 3.10: Separation distance evaluated in stage 3 of simulation study

3.2.4 Selection of simulation tool and simulation parameters

The rating tools help designers to analyse the daylight performance of a space for sustainable design (Leslie, Radetsky and Smith, 2012). The daylight simulation process is a type of computer-based calculation which helps to identify the effective illumination level inside a space under different sky conditions in annual basis (dynamic simulation) or under a selected sky condition (static simulation) (Reinhart, 2010). For both the type of simulation procedure, the model interface is made in the same way, however, different factors are considered from sky.

It is shown in many studies that overcast sky condition is the worst type of sky condition and it does not result in better daylight inside a space (Reinhart, Mardaljevic and Rogers, 2006). Design decision based on CIE overcast sky condition is considered logical for many locations such as Dhaka (Joarder, et. al, 2009), Hong Kong (Li, Lau and Lam) and Southern England (Enarun and Littlefair, 1995). The static simulation fails to analyse the annual performance as it can only evaluate under a single sky condition at a particular time. The dynamic nature of seasons requires year-round daylight evaluation in order to design a sustainable building (Mardaljevic, 2008).

Daylight coefficient (DC) concept depends on the sky illuminance distribution that varies with time. Under this approach, different properties of space are considered such as the geometry, material parameters, reflectance and transmittance of the window glass and its surrounding physical environment. If the sky luminance changes, the luminance inside the space will change in the same proportion (Leslie, Radetsky and Smith, 2012). Results developed by DC approach under a sky luminance will be theoretically equal to result created by sky simulator (Hu, Place, Konradi, 2012). The working process in DC approach occurs in two steps, at first DC is calculated then it is combined with different time varying luminance (Bourgeois, Reinhart and Ward, 2008). The dynamic daylight simulation uses a simple algebraic equation to calculate the daylighting levels in year basis considering dynamic nature of daylight outside with time variation from hours to minute. In a study by Reinhart and Herkel (2000) showed that in a comparison between six different dynamic simulation concepts, DC approach is most reliable and fast to identify illuminance change in a building.

In order to evaluate the luminance level inside a space, it is necessary to consider different sky conditions. The varying luminance from different parts of sky will have different effects at a particular point inside a room and at the same time, the variation will differ with times. The interior daylight luminance is not proportional to the outdoor daylight illuminance and the ratio varies greatly (Li, Lau and Lam, 2001). In order to design a sustainable building, it is necessary to allow adequate amount of daylight throughout the year under different sky conditions. Considering the above aspects, this study followed dynamic simulation procedure to identify the impact of blind parameters throughout the year.

A suitable daylight simulation tool is required to evaluate the effective parameter of blind configurations to ensure appropriate daylight illuminance inside office space. An effective simulation tool should have the following characteristics (Joarder, 2011).

- Able to create model interface for simple as well as complex geometries along with their surroundings.
- Have high prediction capability for indoor daylight distribution.
- Can provide results for climate-based daylight metrics, e.g., DA and UDI.

There are limited numbers of software available which can analyse the results from climate-based metrics, such as 3D SOLAR, GENELUX, LIGHTSWITCH WIZARD, S.P.O.T, LIGHT SOLVE and DAYSIM. In this research DAYSIM software is used to evaluate the performance of different blind configurations on indoor luminance. DAYSIM uses the DC approach (Tregenza and Waters, 1983) along with the RADIANCE (backward) ray tracer method considering all weather sky luminance models (Perez, et al., 1990). DAYSIM and RADIANCE are validated by many researchers as successful for daylighting analysis (Reinhart and Walkenhorst, 2001). DAYSIM program calculates the luminance level on discrete sensors, so the simulation parameters are slightly different from RADIANCE, which needs to be modified. However, setting the parameters at high level might slow the whole simulation procedure. The recommended parameter setting for daylight simulation analysis for complex geometries (Reinhart, 2010) are shown in Table 3.7.

Table 3.7: Utilized RADIANCE simulation parameters in DAYSIM (Reinhart, 2010)

Ambient bounces	Ambient division	Ambient sampling	Ambient accuracy	Ambient resolution	Specular threshold	Direct sampling
5	1000	20	0.01	300	0	0

3.2.5 Generation of 3D models and simulation parameters

In the initial stage, the 3d model of the selected space was created by ECOTECT software. Physical characteristics and material parameters for the space such as floor finish, partition walls, and outdoor-indoor conditions are kept similar as they are found during the physical survey. However, suspended ceiling was avoided in the 3D model, so the floor height was considered 3.35m which is the floor to ceiling height. The parameters for material finish used in 3D model are as follows.

- **Ceiling of office space:** White painted plaster (reflectance: 0.6).
- **Internal wall:** White painted brickwork (reflectance 0.6)
- **Floor: Off-**White porcelain tile finishes (reflectance: 0.5).
- **Glazing:** Double glazed with aluminum frame (reflectance: 0.78, U value: 2.35W/m^{2}K).
- **Partition wall**: Framed plasterboard (reflectance: 0.4)

When the 3D models are created, the interior space is considered vacant and without any kind of partitions, suspended ceiling and furniture, to avoid any hindrance from actual output as in previous studies (Joarder et al., 2009). It is also assumed that the peripheral glazing envelope is unshaded to avoid any kind of hindrance from daylight penetration. In addition to that, the upper and the lower floors are kept hidden to make the simulation process faster as they do not have any contribution to the simulation output shown in Figure 3.11.

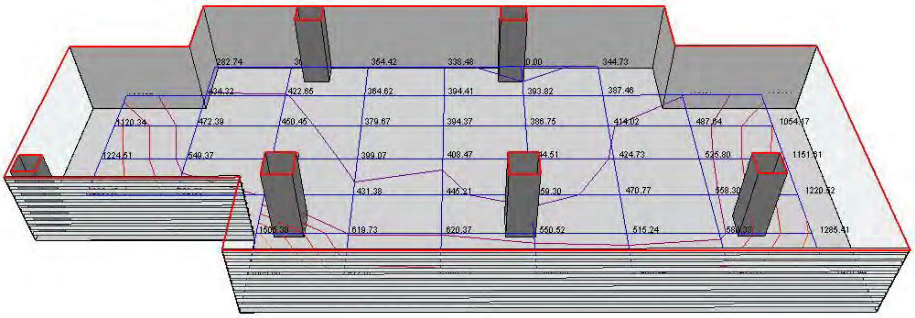


Figure 3.11: View of model used for simulation with a sample analysis

The simulation procedure is conducted in three phases and in each stage a particular design variant is evaluated for three different orientations. In order to evaluate the impact of a blind variant for a particular orientation, rest of the sides are kept exposed to light, i.e. without any blind. (Figure 3.12). For each stage, series of models are created depending on the number of configurations that are studied. In addition to that, a base model is also created to compare the overall output of simulation.

Figure 3.12: Location of internal venetian blinds for three orientations

The following parameters are followed to evaluate different design strategies.

Location: Dhaka, Bangladesh (longitude: 90.40° N; latitude: 23.80° E)
Calculation Settings: Full Daylight Analysis
Precision: High

Local Terrain: Urban
Window (dirt on glass): Average
Sky Illumination Model: CIE Overcast
Duration for simulation: Whole Year

3.2.6 Identifying sensor points

An active portion of the office floor layout on seventh floor is selected for the daylight simulation study. This floor has partition layout and furniture arrangements similar to most of the floors. The selected area is the main working zone for the entire floor area and remains active throughout the office hours (10:00 AM– 5:00 PM). According to the LEED v4 (2010) requirements and methods, for spaces greater than 14 square meters, measurements of maximum 3000mm square grid is recommended. Total five gridlines are set in XX’ axes which represents east-west direction and seven in YY’ axes which represents north-south direction (Figure 3.13).

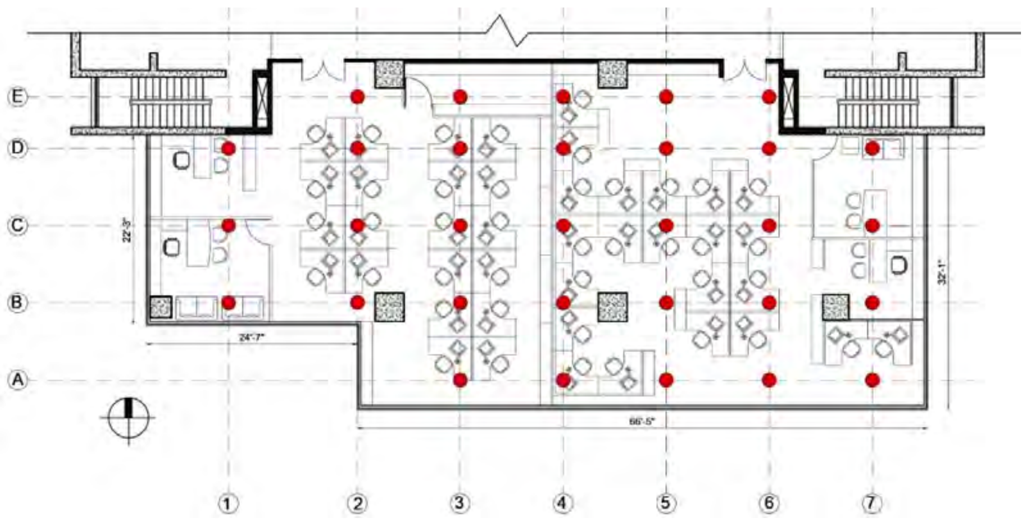


Figure 3.13: Location of core sensor points in the case space

The axis lines and core sensor points are placed at certain location so that they pass through the desks and important locations. The case space measures 289 square meters (3107sft), which is divided into 2700mm X 3600mm grids as shown in Figure 3.13. As the study intends to evaluate the overall illuminance level inside the office space, so the sensor points are considered as core sensor points. Total 31 core sensor points are created and the work plane height is set at 750mm above floor finish, which represents the standard desk height for office space (Joarder et al, 2009).

3.2.7 Identify metrics for simulation

The dynamic daylight metrics help to commute time series for illuminance and luminance in buildings (Reinhart and Walkenhorst, 2001). These time series can be used to find out the annual dynamic daylight performance metrics such as Daylight Autonomy (DA) and Useful Daylight Index (UDI) (Reinhart et al. 2006; Nabil and Mardaljevic, 2005). The simulation outputs are evaluated based on the following dynamic metrics to understand the performance of design variants throughout a year.

a) **Annual Daylight Autonomy (DA):** It is the metrics that is considered as the percentage of time of the year when the minimum illuminance required at a particular space is met by daylight alone (Reinhart and Walkenhorst, 2001). This metrics is often used to check the illuminance level at a particular point inside a space and represented as percentages. For office space, the standard illuminance on the work plane height is considered to be 300lux (BNBC, 2020). So, for the simulation analysis the minimum illuminance is set at 300lux. If the percentage of DA falls in between 80% and 100% then the daylight design is considered as excellent and in the context of Dhaka it is possible to achieve 80% DA level (Joarder, 2011).

b) **Maximum Daylight Autonomy (DAmax):** This metrics is based on illuminance-based glare analysis. It is considered as the percentage of occupied times when the daylighting level is 10 times greater than the design illumination, so appears as glare (Rogers and Goldman, 2006). The idea is to calculate DA_{max} using an illuminance threshold. So if the design illuminance at a particular place is 300lux, the DAmax will correspond to 3000lux. It is recommended that DA_{max} must not exceed 1%, for more than 5% of the floor area (CHPS, 2006).

c) **Useful daylight Index (UDI):** This metric determines when the daylight level is useful for the occupants and when they are not. Depending on preference of users in daylit office space, the UDI is categorized into three metrics (Nabil and Mardaljevic, 2005).
   - **$UDI_{<100}$ lux:** When the light level is below 100 lux, it is not considered as visible light, i.e., the place is considered to be too dark.
   - **$UDI_{100-2000}$ lux:** The daylight level between 100lux and 2000lux is regarded as useful daylight illumination range. An indoor space having UDI value lower than 2000lux is considered as good indoor luminous environment.
   - **$UDI_{>2000}$ lux:** Illumination value more than 2000lux is considered to be too bright. 2000lux is the upper threshold and value above this range is not preferable due to potential risk of overheating or glare.

During the simulation procedure in DAYSIM software, for the performance metrics same annual illuminance profiles are used which is based on US Department of Energy weather files (2008) for Dhaka.

3.2.8 Convert result into performance measure

The results for dynamic daylight simulation are generated for the core sensor points and presented in the form of a table. The illumination value for different performance metrics is then calculated from the table to get the annual output for the office space. The overall illumination inside the office space is evaluated based on the following criteria.

- Annual average DA% of the core sensor points
- Annual average DA_{max} % of the core sensor points

- Average annual UDI% ($UDI_{<100}$, $UDI_{100\text{-}2000}$, $UDI_{<2000}$) value of the core sensor points

Different types of overall rating systems are used in the past for dynamic performance metrics. One approach used by Reinhart (2006) for daylight autonomy calculations, which used core sensor points being concentrated on a central axis towards north-south direction. In this study the sensor points are set throughout the office space layout to evaluate the daylighting performance. The average values for the performance metrics are then presented in a table and rating points are assigned depending on their performance. As in this study three different parameters for blind configurations are studied for three different orientations, so range of parametric configurations for each stage is being studied. For stage 1 and stage 2, the rating points are given between 1 to 8 points and for stage 3 the rating points are assigned between 1 and 16. Highest point (8 or 16 points) means best performance, whereas, lowest point (1 point) indicates worst performance among the studied options. The score of each performance metric is then summed up to get the final score for ranking; higher the score, higher is the rank.

3.3 Summary

The detail methodology for simulation process including the selection procedure for case space is described in this chapter to provide a clear depiction of the daylight simulation procedure which is followed in this research. The next chapter describes the findings from simulation output and their analysis with respect to luminous environment based on the methodology developed in this chapter to find out the effective parametric configurations for venetian blinds.

CHAPTER: FOUR

SIMULATION ANALYSIS AND RESULTS

4.1 Preamble

The basic criteria and information required to carry out the simulation process is identified in chapter two and three. It helps to form an outline for the simulation study by mentioning standards for illuminance level. The third chapter identified different types of design variant and detail framework for the methodology that is followed in this research. This chapter critically analyses the simulation output in detail, based on the framework discussed in the previous chapters. In this chapter, the dynamic simulation procedure for the studied space is done in three phases considering three blind parameters for three different orientations. Initially the annual performance of a particular slat parameter is studied and then critically analysed to find out the best configuration. The best parameter from previous step is then evaluated with other variants, analysed and compared critically to identify the best possible outcome among the studied options. Finally, in the last step another parameter is evaluated considering the parametric aspects from previous steps to find out the most efficient parametric configurations of internal venetian blind configuration for different orientations in the context of Dhaka. The key findings along with the conclusion are presented in the next chapter.

4.2 Evaluation of internal venetian blind configurations

It is shown in many studies that internal blind configurations are one of the appropriate options for internal shading systems in the context of Dhaka. In Section 3.2.3, it is established that among two types of internal blind configurations, horizontal blind is more effective for office spaces in context of Dhaka. The evaluation of blind configurations for different orientations inside office spaces is done by comparing the performance metrics as discussed in Section 3.2.7. As the research focused on annual performance under different sky conditions, dynamic daylight simulation metrics is used. The office hours for the selected case office building start at 10:00 AM and ends at 5:00 PM and this time period are considered for the simulation process. The simulation parameters, blind specifications and material parameters for the studied space are kept constant for dynamic simulation process as discussed in the Sections 3.2.3, 3.2.4, and 3.2.5. The annual illuminance values on each sensor point are summed up to get an average value for each blind option for particular orientation to identify the efficient parametric configurations.

4.3 Dynamic daylight simulation results

The dynamic simulation process is divided into three stages; each part evaluates the performance of a particular blind parameter. In addition to that, each parameter is evaluated for three orientations separately. For each stage of simulation process a design variant for a particular blind parameter is evaluated three times for three orientations (South, East and West). The goal of the dynamic simulation analysis is to provide minimum 300lux at each sensor point at work plane height.

4.3.1 Simulation output and analysis for slat geometry

The first stage of dynamic simulation involved evaluation of slat geometry. Seven different design variants are studied for three orientations. The studied geometries are horizontal, 30^0 inclination, 150^0 inclination, inverted V, upturn V, concave curve and convex curve. Finally, the simulation outputs from the design variant are compared with the output from condition with no blind. The simulation outputs for design variants are evaluated against the performance metrics and given rating points based on their performance as described in Section 3.2.8.

a) Analysis for south orientation

South orientation is the elongated facade for the case office building and majority of the area is exposed to direct sunlight. The design variants are only applied in south direction and evaluated on the basis of their performance metrics. DA is defined as the percentage of occupied time when minimum illuminance is met by daylight (Section 3.2.7). It is shown in Figure 4.1 that the base case with no blind scored highest DA value (91.4%), while, inverted V slat geometry scored lowest point with 82.9% DA value. Rating points are assigned to the parameters (figure 4.1) based on their performance.

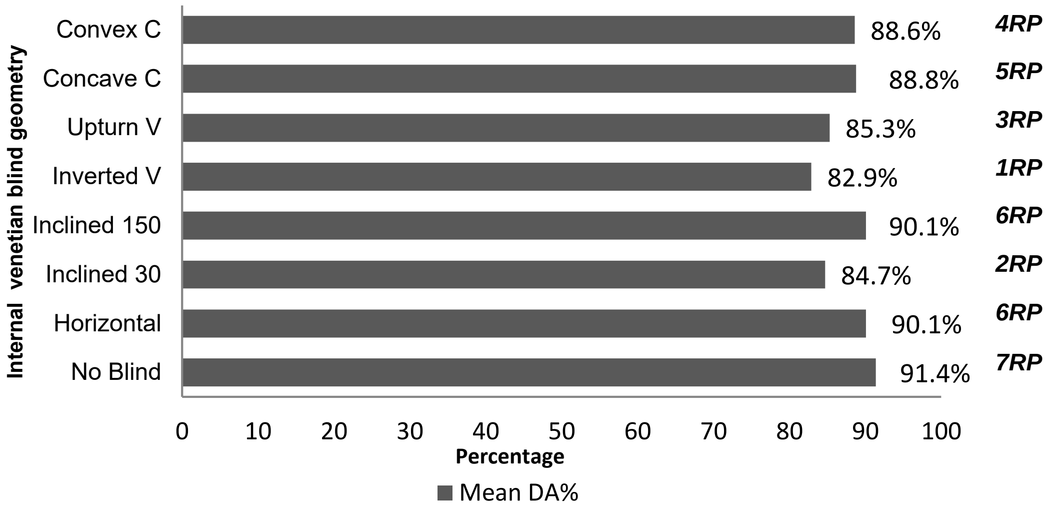


Figure 4.1: Mean DA% for different blind geometries for south orientation and base case with respective rating points (RP)

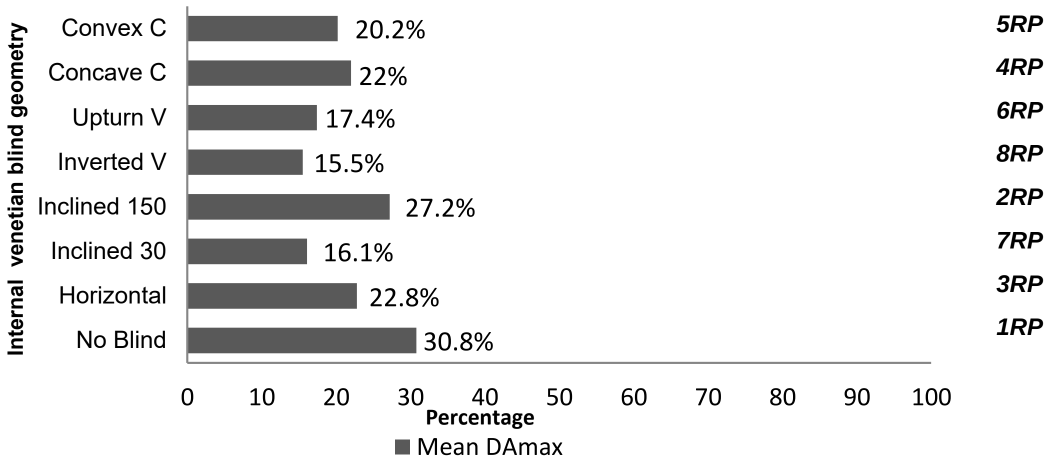


Figure 4.2: Mean DA_{max}% for different blind geometries for south orientation and base case with respective rating points (RP)

On the other hand, another performance metrics DA_{max} refers to the time when the daylight is ten times greater than the design illumination (Section 3.2.6). Figure 4.2 represents the mean DA_{max} percentage from the simulation output for different blind geometries. It shows that venetian blind with inverted V slat geometry performed better with lowest mean value (15.5%) whereas; slats inclined at 150^0 has the highest value (27.2%) among the studied geometric configurations, which indicates poor performance. The condition without blinds showed the highest mean percentage (30.8%) in comparison to the studied geometries, which indicates that the installation of internal blind is essential for the studied space.

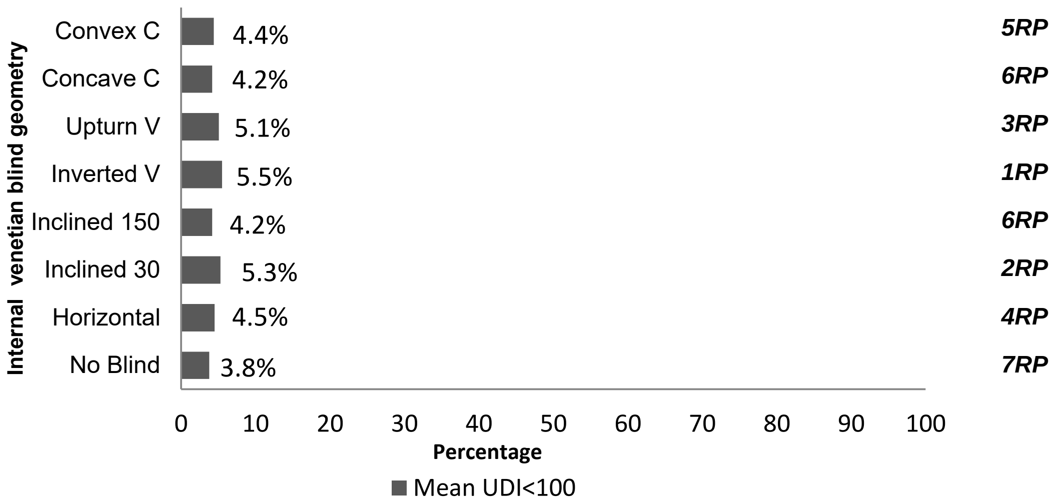


Figure 4.3: Mean $UDI_{<100}$ % for different blind geometries for south orientation and base case with respective rating points (RP)

$UDI_{<100}$ percentage indicates the range when the space is too dark. The mean $UDI_{<100}$ percentage for condition with no blind is the lowest (3.8%) and scored highest rating points (7point), while inverted V slat geometry scored lowest point (1point) with 5.5% value as shown in Figure 4.3. The result for $UDI_{<100}$ shows that, the space will have less illumination below the recommended range for blind with inverted V slat geometry.

In terms of $UDI_{100\text{-}2000}$, this indicates the percentage of occupied times when the daylight is useful. Depending on the performance, the variants are given scores as shown in Figure 4.4. On an average, inverted V geometry has the highest percentage (69.4%) of $UDI_{100\text{-}2000}$ and scored 8 rating points, whereas condition with no blind has the lowest value (54.5%).

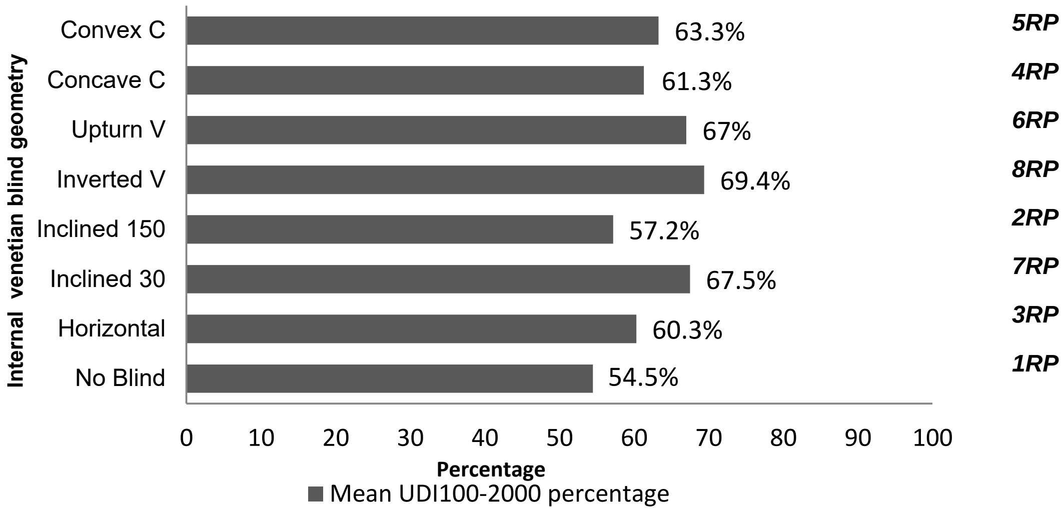


Figure 4.4: Mean $UDI_{100\text{-}2000}$% for different blind geometries for south orientation and base case with respective rating points (RP)

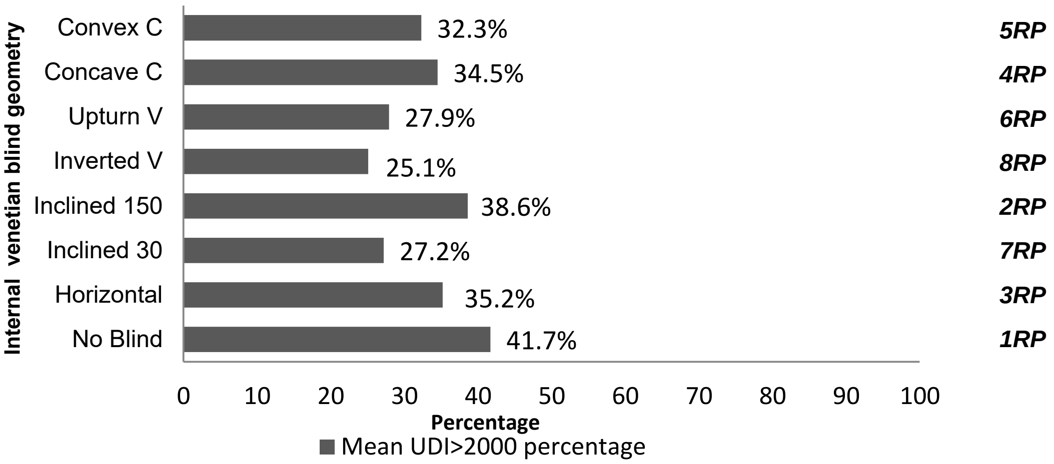


Figure 4.5: Mean $UDI_{>2000}$ % for different blind geometries for south orientation and base case with respective rating points (RP)

In regards to $UDI_{>2000}$ metrics which indicates glare, shows that slat with inverted V geometry with percentage 25.1% scored highest rating points shown in Figure 4.5. On the contrary, condition with no blind having value 41.7% scored lowest point, which means there will be glare throughout the year.

The studied geometries are given rating points for each performance metrics and the summation of the value for the points are used to determine final rank. It is shown in the Table 4.1 that inverted V slat geometry is ranked first with highest rating points, whereas, the condition with no blind is ranked lowest position. The rating points for DA% and UDI<$_{100}$% is lowest for inverted V geometry, however it scored highest rating points for the other performance metrics which gives a total rating point of 26. As a result, for south orientation blind with inverted V slat geometry is considered to be the best possible configuration based on the studied rating points.

Table 4.1: Dynamic simulation output with rating points and ranking of different slat geometry for south orientation

Slat geometry	***Value & Rating points (RP)***	***DA (%)***	***DA_{max} (%)***	***$UDI_{<100}$ (%)***	***$UDI_{100-2000}$ (%)***	***$UDI_{>2000}$ (%)***	***Total RP***	***Ranks***
No Blind	Value	91.4	30.8	3.8	54.5	41.7	**17**	**7**
	RP	**7**	**1**	**7**	**1**	**1**		
Horizontal	Value	90.1	22.8	4.5	60.3	35.2	**19**	**5**
	RP	**6**	**3**	**4**	**3**	**3**		
Inclined 30°	Value	84.7	16.1	5.3	67.5	27.2	**25**	**2**
	RP	**2**	**7**	**2**	**7**	**7**		
Inclined 150°	Value	90.1	27.2	4.2	57.2	38.6	**18**	**6**
	RP	**6**	**2**	**6**	**2**	**2**		
Inverted V	Value	82.9	15.5	5.5	69.4	25.1	**26**	**1**
	RP	**1**	**8**	**1**	**8**	**8**		
Upturn V	Value	85.3	17.4	5.1	67	27.9	**24**	**3**
	RP	**3**	**6**	**3**	**6**	**6**		
Concave curve	Value	88.8	22	4.2	61.3	34.5	**23**	**4**
	RP	**5**	**4**	**6**	**4**	**4**		
Convex curve	Value	88.6	20.2	4.4	63.3	32.3	**24**	**3**
	RP	**4**	**5**	**5**	**5**	**5**		

b) Analysis for east orientation

The simulation procedure for east orientation is using the same parameters and specifications as they are used for previous steps.

The mean DA percentage for different geometric configurations in east direction is shown in Figure 4.6 and assigned rating points based on their performance. The percentage for condition with no blind is the highest with 91.4%, so scored highest rating points (6 point). On the other hand, the value is lowest (90.1%) for blind configuration with inverted V, upturn V and 30^{O} inclination geometric configurations, so gained 1 rating point.

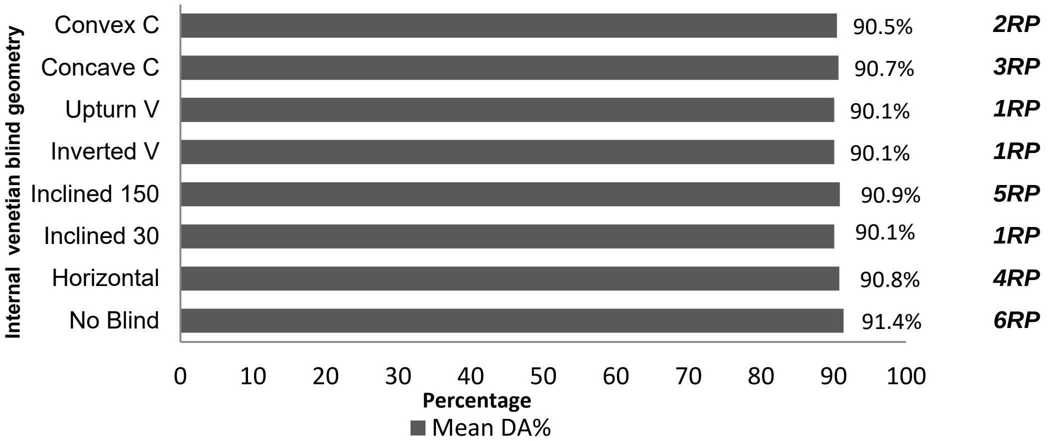


Figure 4.6: Mean DA% for different blind geometries for east orientation and base case with respective rating points (RP)

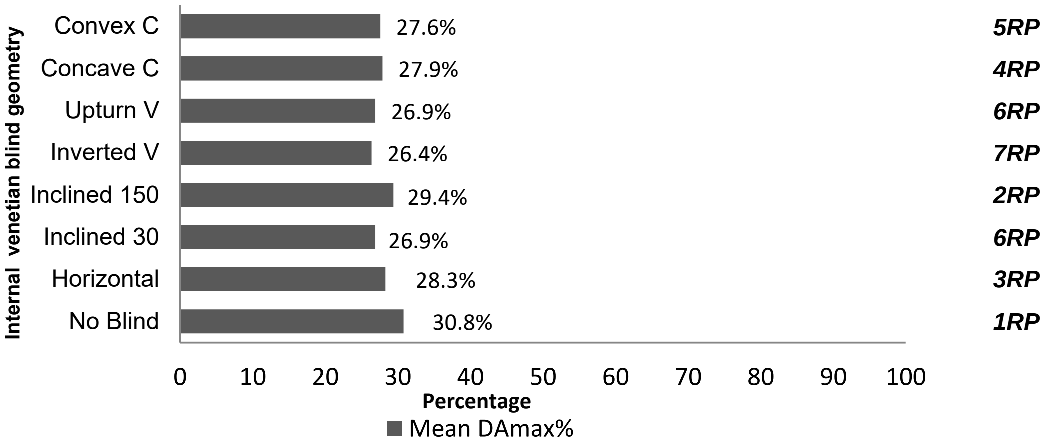


Figure 4.7: Mean DA_{max}% for different blind geometries for east orientation and base case with respective rating points (RP)

With respect to mean DA_{max} percentage, the condition with no blind has the highest value of 30.8% while the inverted V geometry has the lowest percentage (26.4%) as shown in Figure 4.7. Based on the performance of blind geometries, rating points were assigned. Inverted V geometry is given highest rating point (7point) in comparison to other geometries. On the contrary, the condition with no blind scored 1 point, which indicates glare.

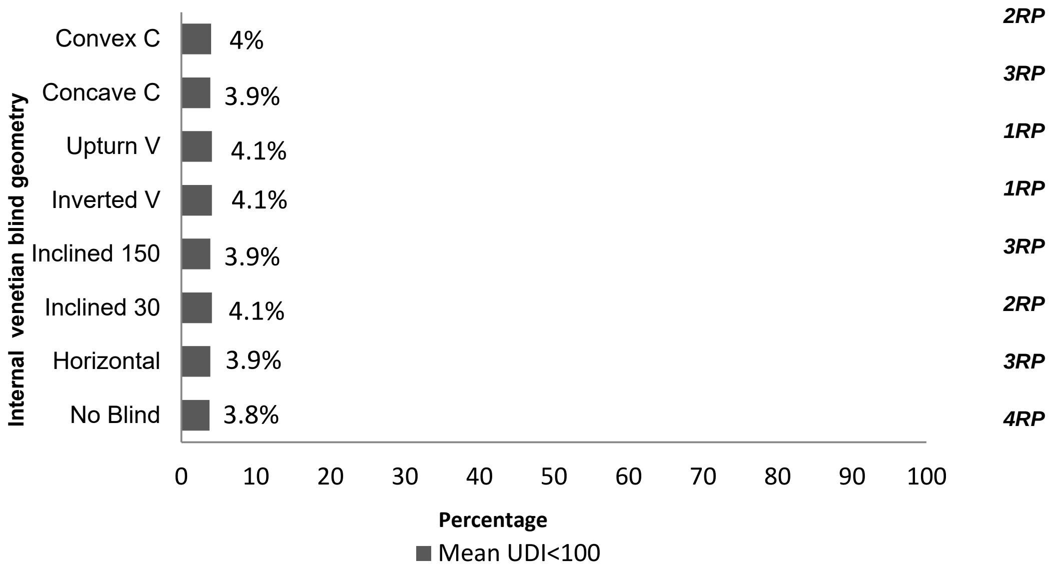


Figure 4.8: Mean $UDI_{<100}$ % for different blind geometries for east orientation and base case with respective rating points (RP)

On the other hand, the mean $UDI_{<100}$ percentage for Upturn V, Inverted V and 30^{O} inclination geometry is the highest (4.1%), so assigned with the lowest point (1point). The condition without blind is rated the highest rating points (4points) with a percentage of 3.8% (Figure 4.8).

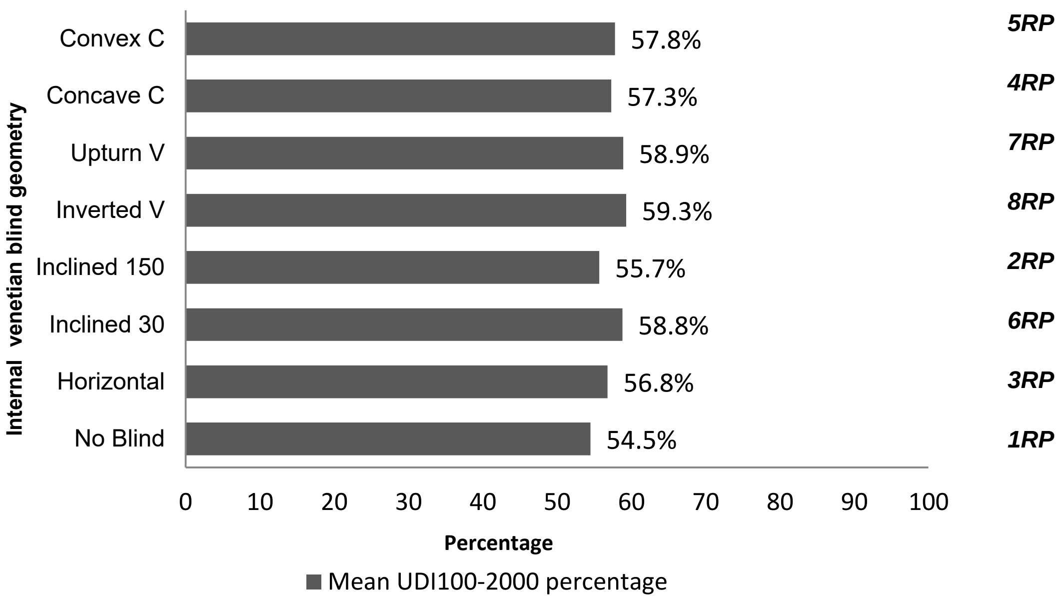


Figure 4.9: Mean $UDI_{100-2000}$% for different blind geometries for east orientation and base case with respective rating points (RP)

The mean $UDI_{100-2000}$ percentage for the studied design variants represented in Figure 4.9 shows that Inverted V geometry has the highest percentage of 69.4%. On the contrary, condition with no blind has the lowest percentage (54.5%). Inverted V geometry scored highest rating points (8 point) while, 1 point was assigned to the condition with no blind, which indicates poor performance.

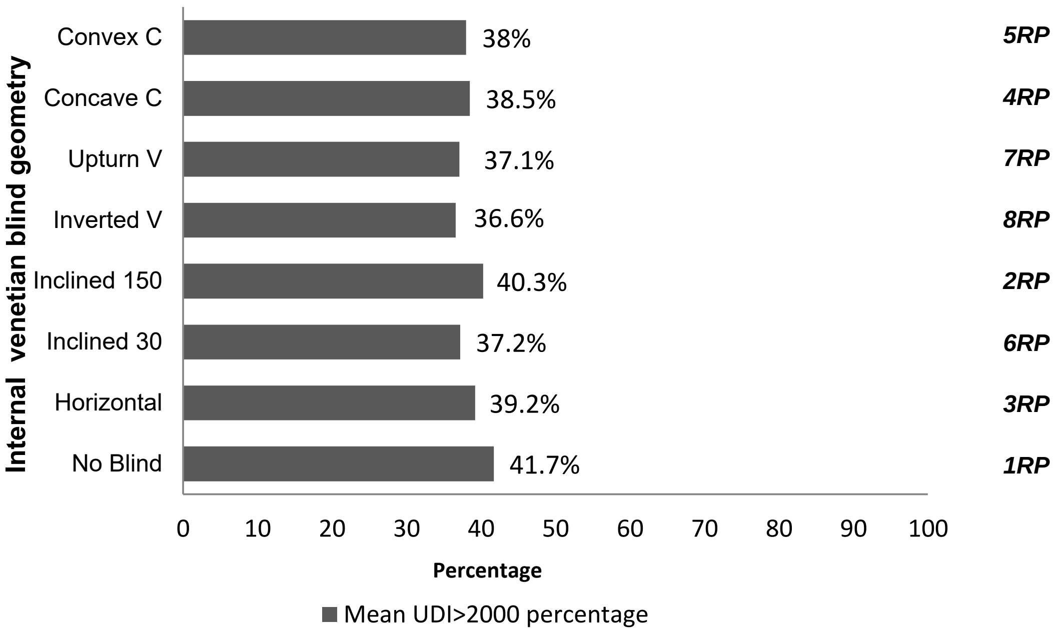


Figure 4.10: Mean $UDI_{>2000}$ % for different blind geometries for east orientation and base case with respective rating points (RP)

Finally, the analysis of last performance metrics $UDI_{>2000}$ in Figure 4.10 shows that, the inverted V slat geometry scored the highest rating point (8 points) with a percentage of 36.6%. The lowest rating point (1point) is assigned to condition with no blind configuration which had the percentage of 41.7%.

The comparison and analysis of the performance metrics in Table 4.2 showed that blind configuration with inverted V geometric configuration scored the maximum number of points (25 points) which is greater than any other studied options. So, it is ranked as first and considered as the best possible option for east orientation.

Table 4.2: Dynamic simulation output with rating points and ranking of different slat geometry for east orientation

Slat geometry	***Value & Rating points (RP)***	***DA (%)***	***DA_{max} (%)***	***$UDI_{<100}$ (%)***	***$UDI_{100-2000}$ (%)***	***$UDI_{>2000}$ (%)***	***Total RP***	***Ranks***
No Blind	Value	91.4	30.8	3.8	54.5	41.7	**13**	**8**
	RP	**6**	**1**	**4**	**1**	**1**		
Horizontal	Value	90.8	28.3	3.9	56.8	39.2	**16**	**6**
	RP	**4**	**3**	**3**	**3**	**3**		
Inclined 30	Value	90.1	26.9	4.1	58.8	37.2	**20**	**3**
	RP	**1**	**6**	**1**	**6**	**6**		
Inclined 150	Value	90.9	29.4	3.9	55.7	40.3	**14**	**7**
	RP	**5**	**2**	**3**	**2**	**2**		
Inverted V	Value	90.1	26.4	4.1	59.3	36.6	**25**	**1**
	RP	**1**	**7**	**1**	**8**	**8**		
Upturn V	Value	90.1	26.9	4.1	58.9	37.1	**22**	**2**
	RP	**1**	**6**	**1**	**7**	**7**		
Concave curve	Value	90.7	27.9	3.9	57.3	38.5	**18**	**5**
	RP	**3**	**4**	**3**	**4**	**4**		
Convex curve	Value	90.5	27.6	4	57.8	38	**19**	**4**
	RP	**2**	**5**	**2**	**5**	**5**		

c) Analysis for west orientation

In case of west orientation, the similar procedure is followed as that of south and east orientation. The simulation output for this stage is presented in Table 4.3 and scores were assigned based on the performance.

In terms of DA%, condition with no blind showed the highest percentage (91.4%) as shown in Figure 4.11. So, it was assigned highest rating points (6 point). On the other hand, two geometric configurations (Inclined 150 and Inverted V) showed the lowest percentages (89.9%), which led them to lowest score that is 1 point.

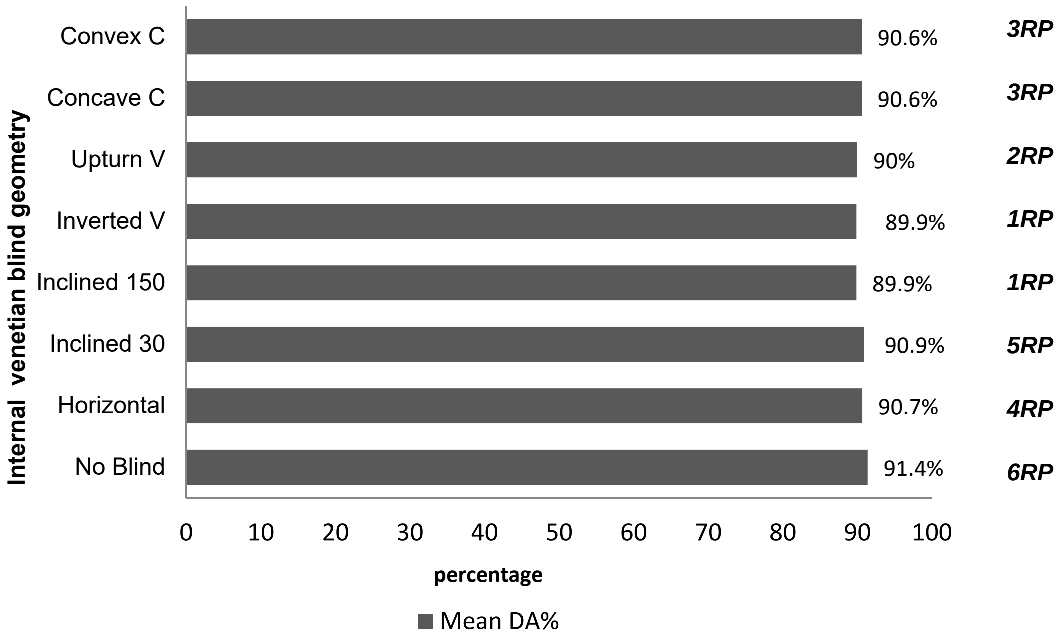


Figure 4.11: Mean DA% for different blind geometries for west orientation and base case with respective rating points (RP)

With regards to DA_{max} mean percentages, it is shown in Figure 4.12 that the percentage for geometry at 150^{O} inclination is the lowest (25%) and it is highest (30.8%) for the base condition. As a result, the condition with no blind configuration scored lowest rating points (1Point).

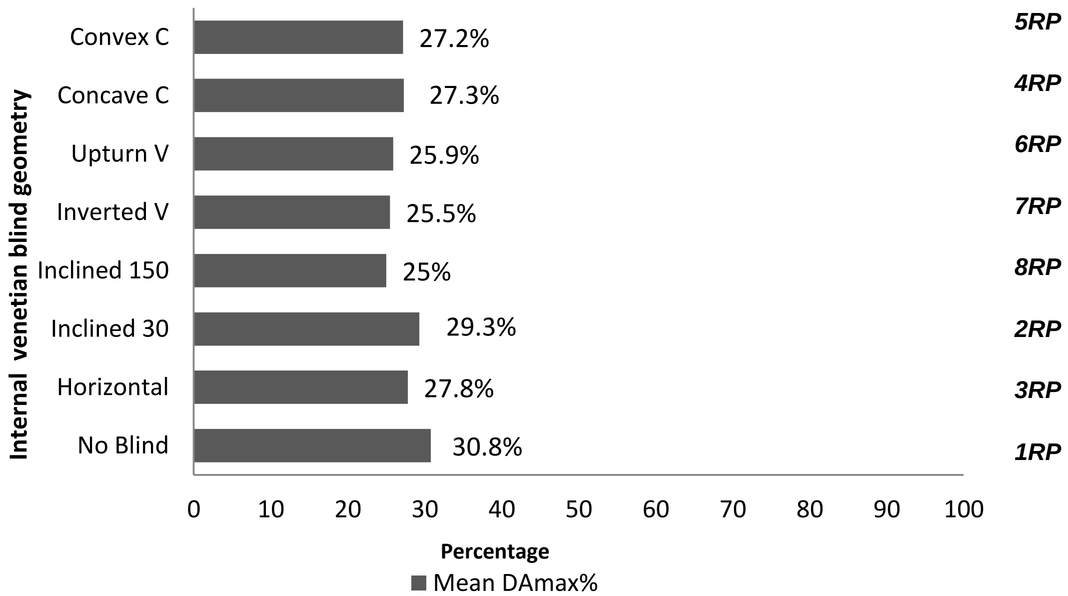


Figure 4.12: Mean DA_{max}% for different blind geometries in West orientation and base case with respective rating points (RP)

In terms of $UDI_{<100}$, inverted V, Upturn V and 150^{O} inclination blind geometry showed highest mean percentage (4.1%) in comparison to other geometries and scored lowest rating point (1point). Condition with no blind gained lowest percentage of 3.8%, hence scored highest rating points (Figure 4.13).

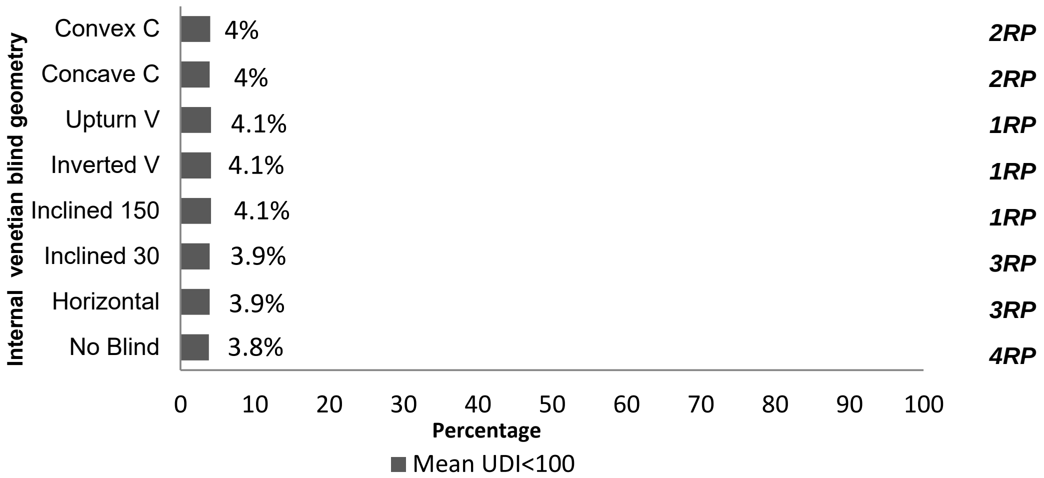


Figure 4.13: Mean $UDI_{<100}$ % for different blind geometries for west orientation and base case with respective rating points (RP)

Performance metrics $UDI_{100\text{-}2000}$ showed an opposite pattern as compared to the previous metrics. The condition with no blind showed the lowest percentage (54.5%) for $UDI_{100\text{-}2000}$, while blind with inverted V geometry gained highest rating points (8 points) with a percentage of 58.9% (Figure 4.14).

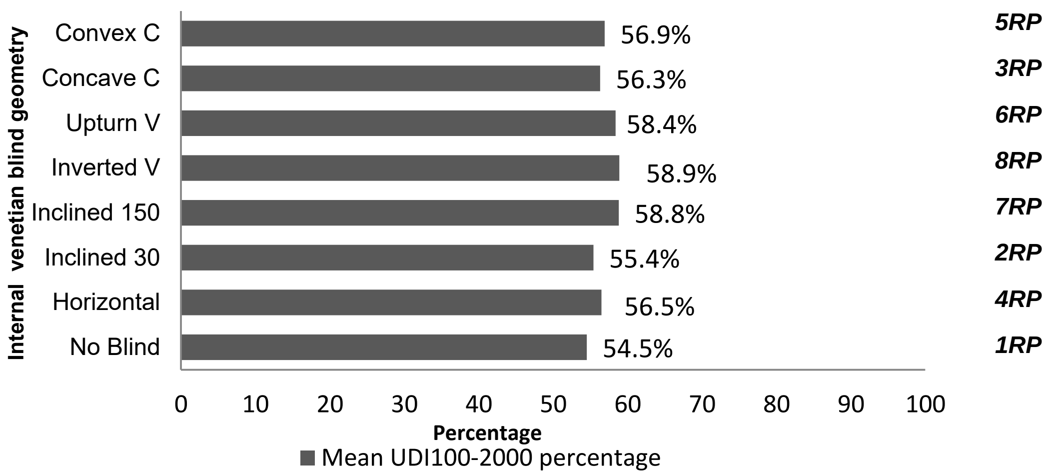


Figure 4.14: Mean $UDI_{100\text{-}2000}$% for different blind geometries for west orientation and base case with respective rating points (RP)

Similarly, for $UDI_{>2000}$ performance metrics, the condition with no blind gained the lowest rating points (1point) with a percentage of 41.7%. Blind with inverted V slat geometry showed the lowest percentage of 37%, hence scored highest rating points (8 point) (Figure 4.15).

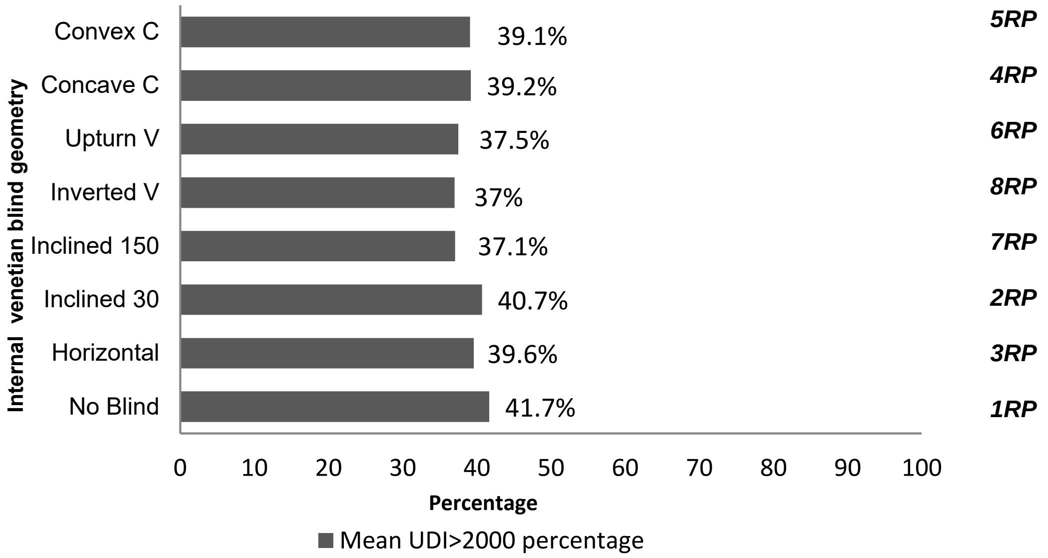


Figure 4.15: Mean $UDI_{>2000}$ % for different blind geometries for west orientation and base case with respective rating points (RP)

The summation of the rating points for the performance metrics showed that the blind configurations with inverted V slat geometry gained the highest rating point (25 point), than any other geometries. On the other hand, the condition with no blind scored lowest rating points of 13 points (Table 4.3). Hence, Inverted V slat geometry is ranked first position and considered as best possible configuration for west orientation in the studied space.

The analysis for the studied geometries for three different orientations based on the performance metrics identified the best possible geometric configurations of slats for blind configurations. Inverted V slat geometry is recognized as the effective option for three orientations in the studied space. It is necessary to study the exact configuration for the geometry in order to get appropriate result. So, the vertex angle for inverted V geometry is critically analysed in the next step.

Table 4.3: Dynamic simulation output with rating points and ranking of different slat geometry for west orientation

Slat geometry	***Value & Rating points (RP)***	***DA (%)***	***DA_{max} (%)***	***$UDI_{<100}$ (%)***	***$UDI_{100-2000}$ (%)***	***$UDI_{>2000}$ (%)***	***Total RP***	***Ranks***
No Blind	Value	91.4	30.8	3.8	54.5	41.7	**13**	**8**
	RP	**6**	**1**	**4**	**1**	**1**		
Horizontal	Value	90.7	27.8	3.9	56.5	39.6	**17**	**5**
	RP	**4**	**3**	**3**	**4**	**3**		
Inclined 30	Value	90.9	29.3	3.9	55.4	40.7	**14**	**7**
	RP	**5**	**2**	**3**	**2**	**2**		
Inclined 150	Value	89.9	25	4.1	58.8	37.1	**24**	**2**
	RP	**1**	**8**	**1**	**7**	**7**		
Inverted V	Value	89.9	25.5	4.1	58.9	37	**25**	**1**
	RP	**1**	**7**	**1**	**8**	**8**		
Upturn V	Value	90	25.9	4.1	58.4	37.5	**21**	**3**
	RP	**2**	**6**	**1**	**6**	**6**		
Concave curve	Value	90.6	27.3	4	56.3	39.2	**16**	**6**
	RP	**3**	**4**	**2**	**3**	**4**		
Convex curve	Value	90.6	27.2	4	56.9	39.1	**20**	**4**
	RP	**3**	**5**	**2**	**5**	**5**		

4.3.2 Simulation output and analysis for geometry configurations

The best possible slat geometry from previous step is evaluated varying the vertex angle for three different orientations in the second stage of dynamic daylight simulation. Eight different angles are studied which are 15°, 30°, 45°, 60°, 75°, 90°, 105° and 120° (Figure 3.9). The simulation parameters and procedure are kept similar to the previous steps.

a) Analysis for south orientation

The dynamic simulation outputs for the studied configurations for south orientation are generated in DAYSIM software. The result on each sensor points is calculated and the mean value for each performance metrics is presented in Table 4.4.

The mean percentage for DA shows that the vertex angle 120^0 has the highest percentage (87.2%) among all the studied angles (Figure 4.16). On the other hand, angle 15^0 and 30^0 are rated as the lowest points (1 point) with percentages of 61.9%.

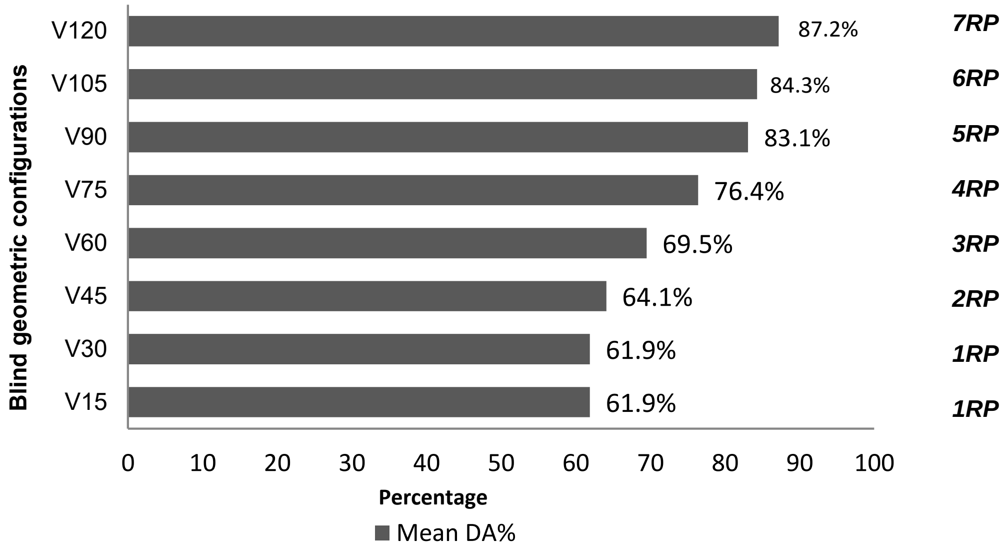


Figure 4.16: Mean DA% for slat geometric configurations for south orientation with respective rating points (RP)

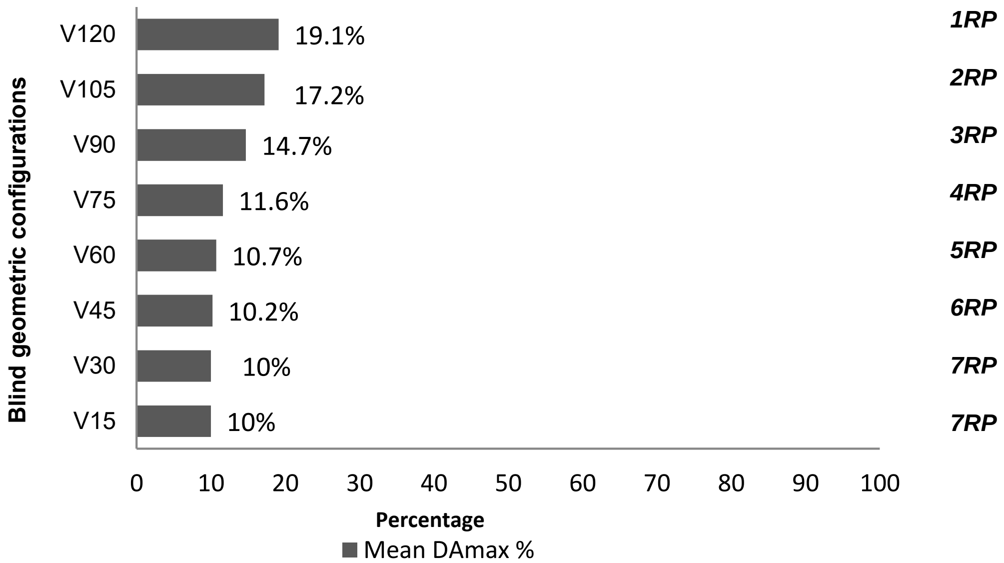


Figure 4.17: Mean DA_{max}% for slat geometric configurations for south orientation with respective rating points (RP)

In terms of mean DA_{max} percentage, the number shows a gradual rise in percentage starting from vertex angle 15^O onwards to 120^O angles, as shown in Figure 4.17. The highest percentage is observed for V120^{O} (19.7%), which is rated 1 point. Mean percentages for design variant V15^{O} and V30^{O} are the lowest (10%) among others; hence scored the highest rating points (7 point).

A completely different scenario is observed among rating points for the case of $UDI_{<100}$ metrics. V15^{O} scored the lowest rating points among others with a mean $UDI_{<100}$ percentage of 9.6% (Figure 4.18). The number of percentages kept gradually decreasing with the increase of angle. V120^{O} scored the highest rating points (8 point) with a mean $UDI_{<100}$ percentage of 4.6%.

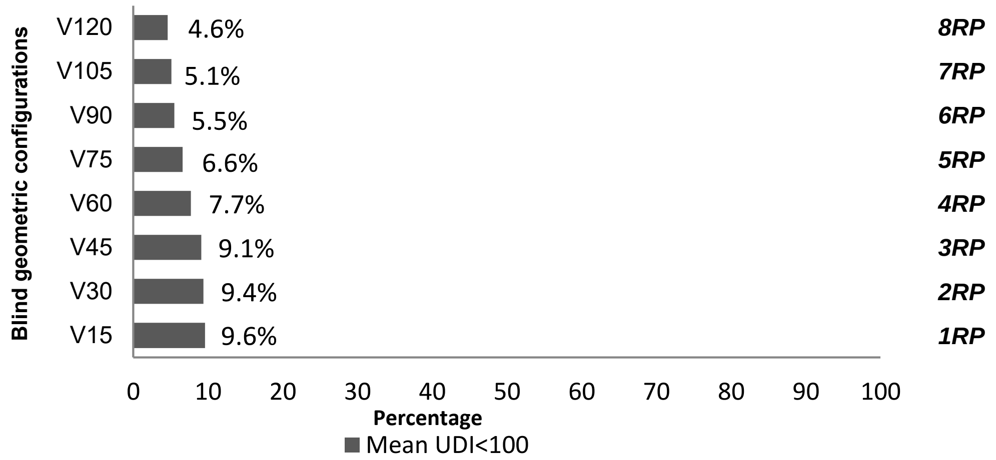


Figure 4.18: Mean $UDI_{<100}$ % for slat geometric configurations for south orientation with respective rating points (RP)

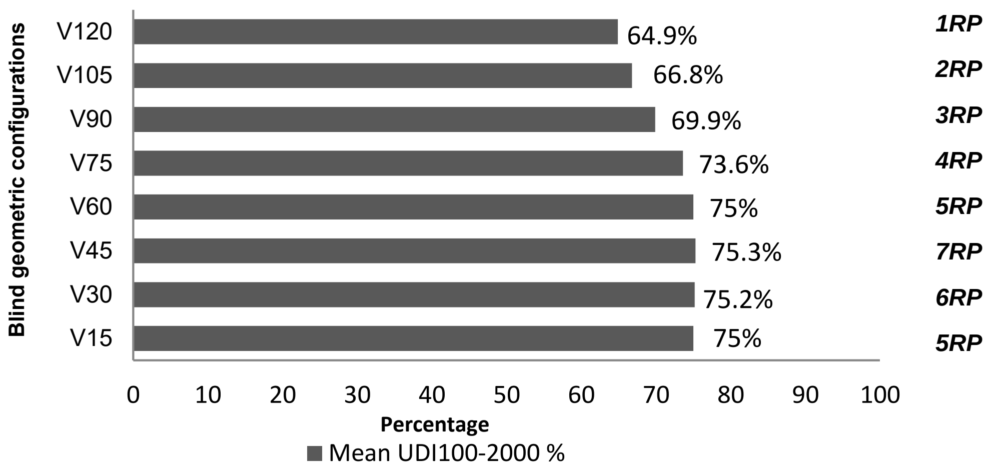


Figure 4.19: Mean $UDI_{100-2000}$% for slat geometric configurations for south orientation with respective rating points (RP)

With regards to performance metric $UDI_{100-2000}$ percentage, the highest rating point (7 point) is assigned to vertex angle of 45^{O} with a mean percentage of 75.3%. Among the studied angles, the lowest mean percentage is observed for $V120^{O}$ (64.9%) and assigned 1 rating point (Figure 4.19).

At last, for $UDI_{>2000}$% metric, lowest mean percentage is observed for vertex angle 15^{O} and 30^{O} which is 15.4% (Figure 4.20). $V120^{O}$ has the highest mean percentage and scored a rating point of 1 point. This means that, the office space will be subjected to higher glare percentage for blind with inverted V geometry having a vertex angle of 120^{0}.

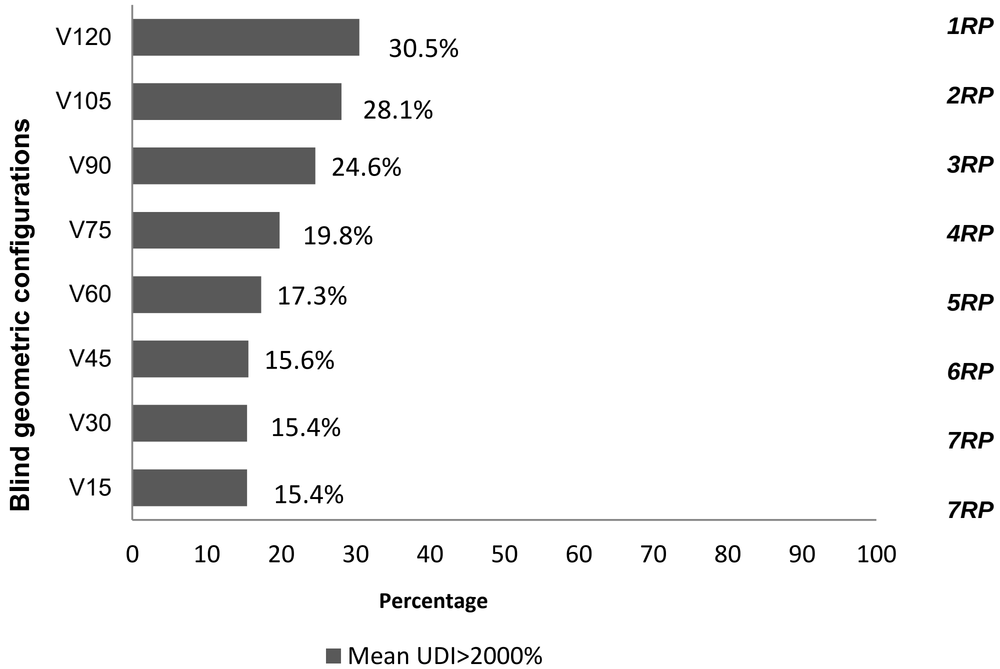


Figure 4.20: Mean $UDI_{>2000}$% for slat geometric configurations for south orientation with respective rating points (RP)

The vertex angles are rated individually for the performance metrics and finally a total rating point for the variants are generated (Table 4.4). Based on the rating points, final rank is developed, which shows that vertex angle of 45^{O} ranked first position, followed by $V30^{O}$, $V60^{O}$, and others respectively. As a result, for south orientations, inverted V slat geometry with vertex angle 45^{O} is considered most feasible than any other studied vertex angles.

Table 4.4: Dynamic simulation output with rating points and ranking of slat geometric configurations for South orientation

Inverted V slat geometry	***Value & Rating points (RP)***	***DA (%)***	***DA_{max} (%)***	***$UDI_{<100}$ (%)***	***$UDI_{100-2000}$ (%)***	***$UDI_{>2000}$ (%)***	***Total RP***	***Ranks***
V15^0	Value	61.9	10	9.6	75	15.4	**21**	**4**
	RP	**1**	**7**	**1**	**5**	**7**		
V30^0	Value	61.9	10	9.4	75.2	15.4	**23**	**2**
	RP	**1**	**7**	**2**	**6**	**7**		
V45^0	Value	64.1	10.2	9.1	75.3	15.6	**24**	**1**
	RP	**2**	**6**	**3**	**7**	**6**		
V60^0	Value	69.5	10.7	7.7	75	17.3	**22**	**3**
	RP	**3**	**5**	**4**	**5**	**5**		
V75^0	Value	76.4	11.6	6.6	73.6	19.8	**21**	**4**
	RP	**4**	**4**	**5**	**4**	**4**		
V90^0	Value	83.1	14.7	5.5	69.9	24.6	**20**	**5**
	RP	**5**	**3**	**6**	**3**	**3**		
V105^0	Value	84.3	17.2	5.1	66.8	28.1	**19**	**6**
	RP	**6**	**2**	**7**	**2**	**2**		
V120^0	Value	87.2	19.1	4.6	64.9	30.5	**18**	**7**
	RP	**7**	**1**	**8**	**1**	**1**		

b) Analysis for east orientation

The analysis from South orientation identified that inverted V geometry with vertex angle 45^O is the most feasible for both sides. The analysis for east orientation is done following the similar procedure as it is done for the previous sections. The rating and ranking for the studied vertex angles are presented in Table 4.5.

With regards to mean DA percentage, V105^O and V120^O have gained 90.3% which is the highest value in comparison to the other options (Figure 4.21). The mean percentage for V90^O (83.1%) is only 0.4% less than the last two options, which gives it a rating point of 5. On the contrary, V15^O and V30^O scored the lowest point (1point) with mean DA 88.5%.

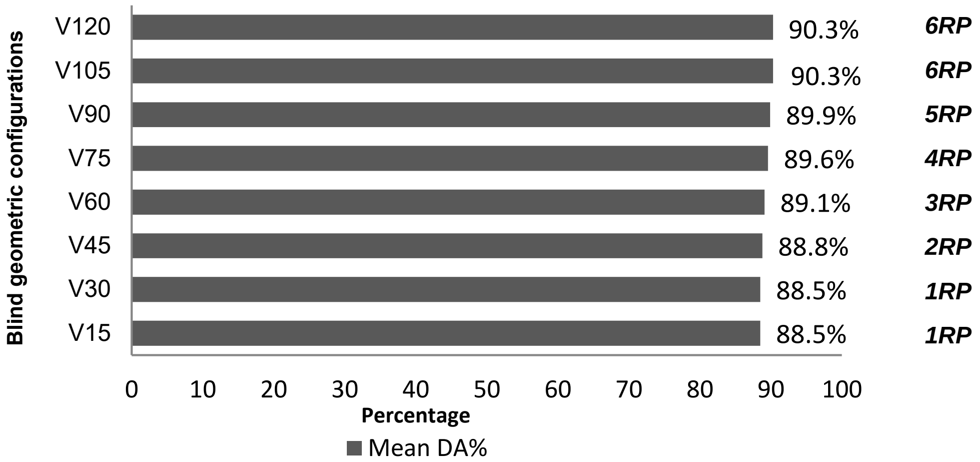


Figure 4.21: Mean DA% for slat geometric configurations for east orientation with respective rating points (RP)

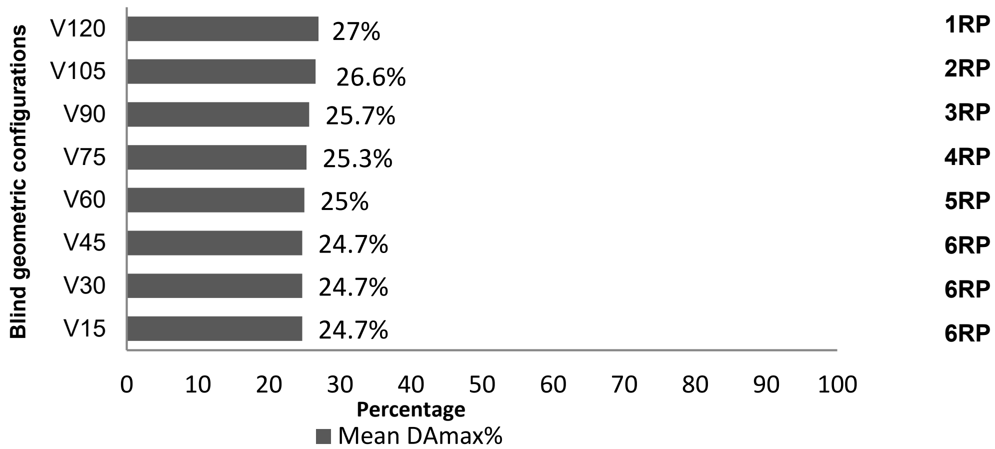


Figure 4.22: Mean DA_{max}% for slat geometric configurations for east orientation with respective rating points (RP)

The mean simulation output percentage for DA_{max} (Figure 4.22) shows that, the mean percentage for V15^{O}, V30^{O} and V45^{O} are the lowest, while V120^{O} has the highest value. The lowest rating point (1point) is assigned to V120^{O} based on its performance. The value indicates lighting performance for V15^{O}, V30^{O} and V45^{O} will be better than other vertex angles.

On the other hand, the mean percentage for $UDI_{<100}$ shows a little deviation between the studied options (Figure 4.23). The percentages kept increasing with decrease in angle. The lowest percentage is observed for V105^{O} and V120^{O} (4%) and assigned highest rating point (4 point) among other options.

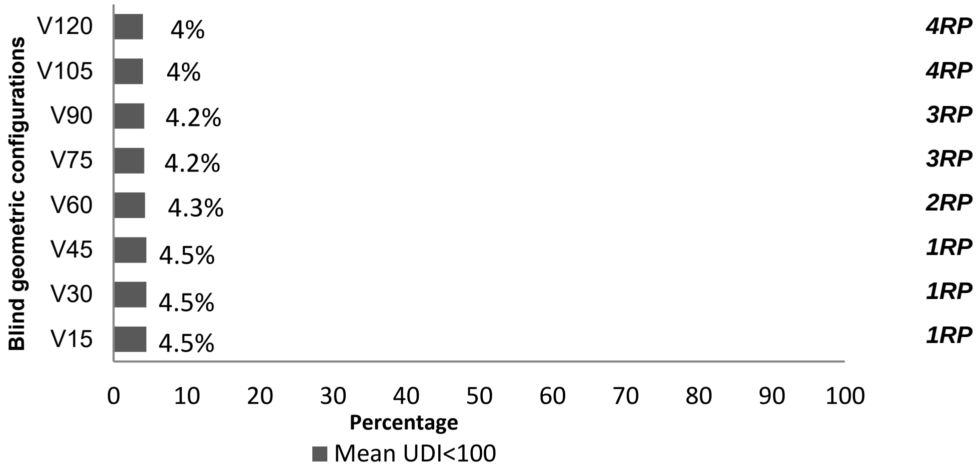


Figure 4.23: Mean $UDI_{<100}$ % for slat geometric configurations for east orientation with respective rating points (RP)

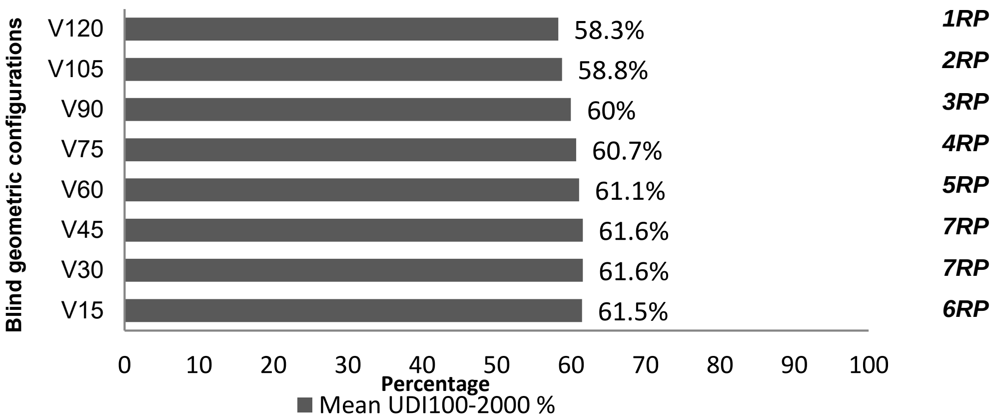


Figure 4.24: Mean $UDI_{100-2000}$% for slat geometric configurations for east orientation with respective rating points (RP)

In terms of mean $UDI_{100-2000}$ percentages, 61.6% is observed to be the highest mean value, which is achieved by V30^{O} and V45^{O} shown in Figure 4.24. After this point, the number for percentage kept decreasing with increase in angles. V120^{O} is assigned 1point whereas; V30^{O} and V45^{O} are given rating point of 7. This indicates that the installation of slat geometry with vertex angle of 30^{O} and 45^{O} will ensure illuminance level within comfortable range.

Finally, the last performance metrics $UDI_{>2000}$ indicates that V30^{O}and V45^{O} have the lowest mean percentage (33.9%) and rated with 7 points (Figure 4.25). On the other hand, V120^{O} scored 1point with mean $UDI_{>2000}$ 37.7%.

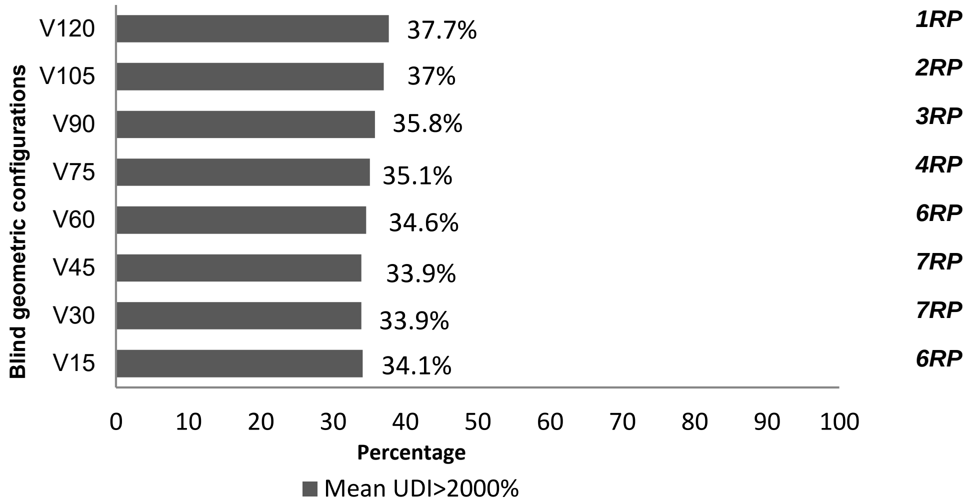


Figure 4.25: Mean $UDI_{>2000}$% for slat geometric configurations for east orientation with respective rating points (RP)

Table 4.5: Dynamic simulation output and ranking of slat geometric configurations for East orientation

Inverted V slat geometry	***Value & Rating points (RP)***	***DA (%)***	***DA_{max} (%)***	***$UDI_{<100}$ (%)***	***$UDI_{100-2000}$ (%)***	***$UDI_{>2000}$ (%)***	***Total RP***	***Ranks***
V15^{O}	Value	88.5	24.7	4.5	61.5	34.1	**20**	**3**
	RP	**1**	**6**	**1**	**6**	**6**		
V30^{O}	Value	88.5	24.7	4.5	61.6	33.9	**22**	**2**
	RP	**1**	**6**	**1**	**7**	**7**		
V45^{O}	Value	88.8	24.7	4.5	61.6	33.9	**23**	**1**
	RP	**2**	**6**	**1**	**7**	**7**		
V60^{O}	Value	89.1	25	4.3	61.1	34.6	**20**	**3**
	RP	**3**	**5**	**2**	**5**	**5**		
V75^{O}	Value	89.6	25.3	4.2	60.7	35.1	**19**	**4**
	RP	**4**	**4**	**3**	**4**	**4**		
V90^{O}	Value	89.9	25.7	4.2	60	35.8	**17**	**5**
	RP	**5**	**3**	**3**	**3**	**3**		
V105^{O}	Value	90.3	26.6	4	58.8	37	**16**	**6**
	RP	**6**	**2**	**4**	**2**	**2**		
V120^{O}	Value	90.3	27	4	58.3	37.7	**13**	**7**
	RP	**6**	**1**	**4**	**1**	**1**		

The mean percentages of all metrics for east orientation are presented in Table 4.5. The total rating point shows that V45^{O} scored the highest point among others and ranked 1st position based on the performance. On the other hand,

120^0 vertex angle is ranked 7^{th} position with lowest rating point of 13points. This indicates that, internal venetian blind with inverted V geometry having a vertex angle of 45^0 in east orientation, will show better performance in optimization of daylight inside office space.

c) Analysis for west orientation

The analysis and rating system for west orientation followed similar procedure as that of the previous sections. Table 4.6 presents the ranking of all vertex angles that are studied.

The analysis and comparison of mean DA percentages for the studied angles in west orientation shows that the value kept decreasing with decrease in angle size (Figure 4.26). The lowest percentage (88.3%) is observed for $V15^0$ and $V30^0$ whereas, the highest value is observed for $V120^O$ with a figure of 90.3%. Similarly, highest rating point (8 point) is assigned to angle with highest mean DA percentage and vice versa.

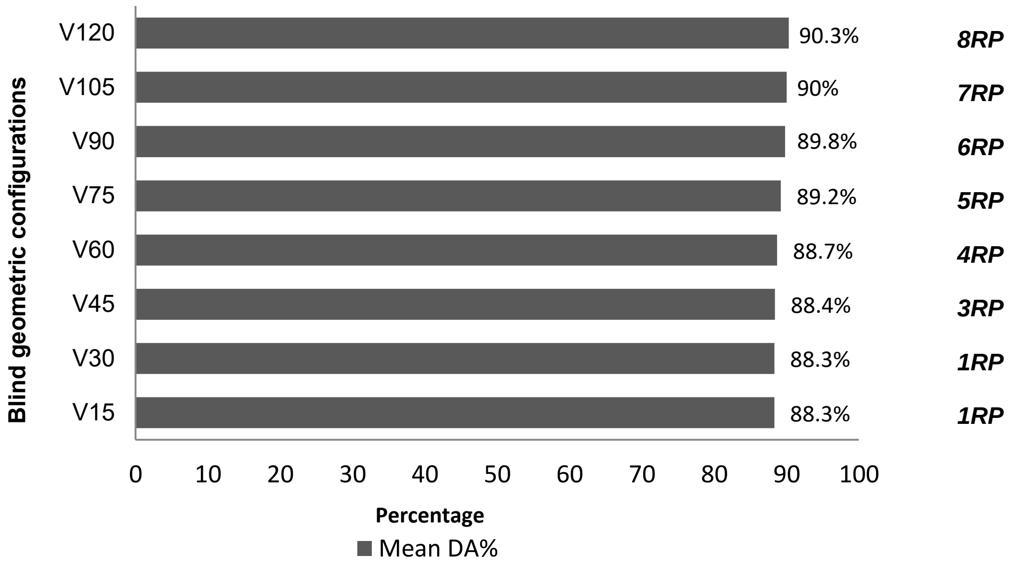


Figure 4.26: Mean DA% for slat geometric configurations for west orientation with respective rating points (RP)

The mean DA_{max}% for vertex angle 45^O is lowest (23%) (Figure 4.27) and scored 7 points, which is greater than other options. On the contrary, $V120^O$ scored the lowest rating point (1point) with a mean DA_{max} percentage of 26.5%.

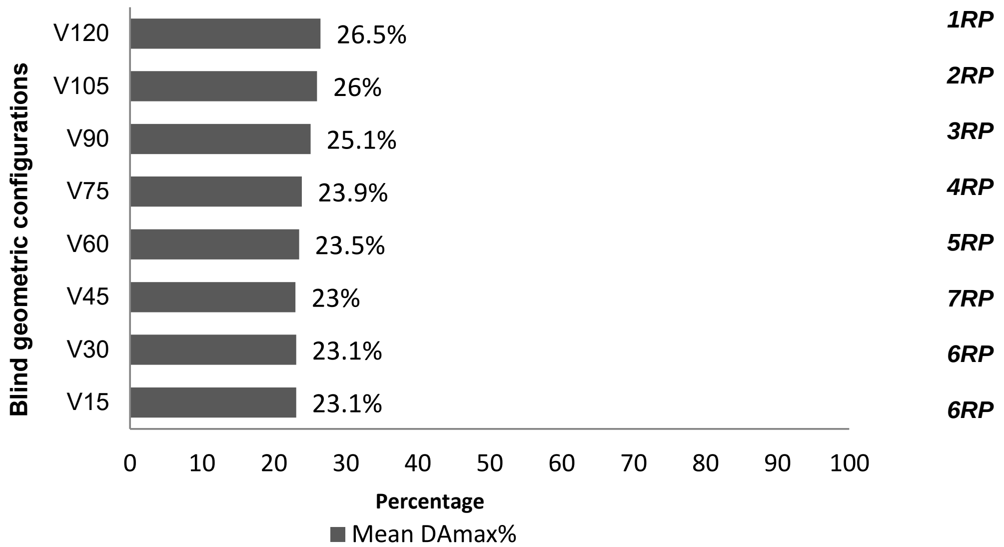


Figure 4.27: Mean DA_{max}% for slat geometric configurations for west orientation with respective rating points (RP)

On the other hand, mean $UDI_{<100}$ percentages are observed to be the lowest for V120° and V105° with a value of 4.1% (Figure 4.28). The second highest rating point (3 point) is secured by V90° with mean $UDI_{<100}$ percentages of 4.2%, which is followed by V60° and V75° with 2points. At last, the highest percentage (4.4%) is observed for V15°, V30° and V45° and assigned 1 point.

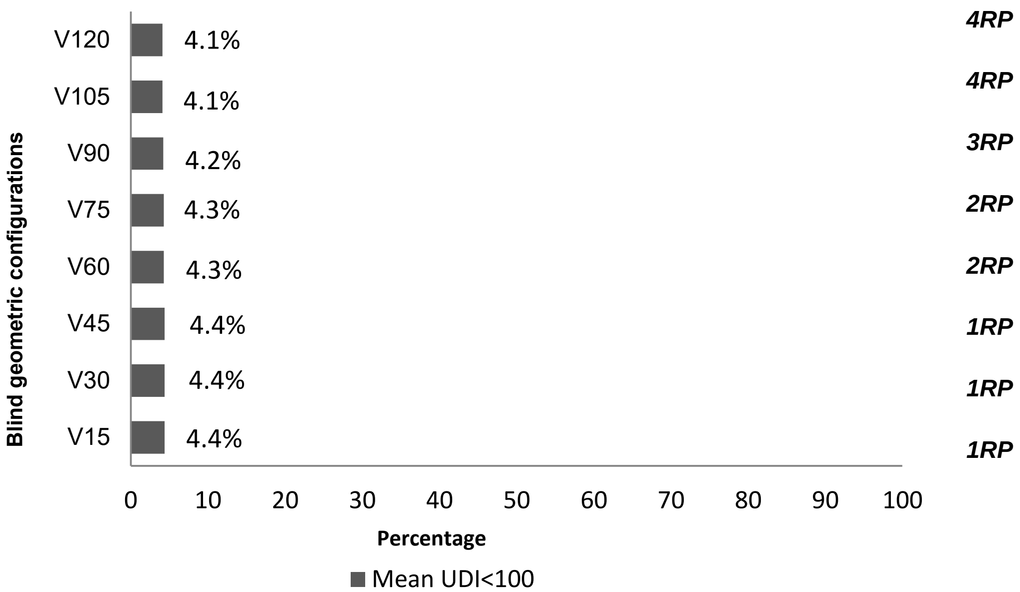


Figure 4.28: Mean $UDI_{<100}$ % for slat geometric configurations for west orientation with respective rating points (RP)

With respect to $UDI_{100-2000}$ mean percentage (Figure 4.29), $V45^{O}$ scored the highest rating point (8 point) with percentage of 62.4%. In comparison, the lowest percentage (57.8%) is observed for $V120^{O}$ and assigned 1 point.

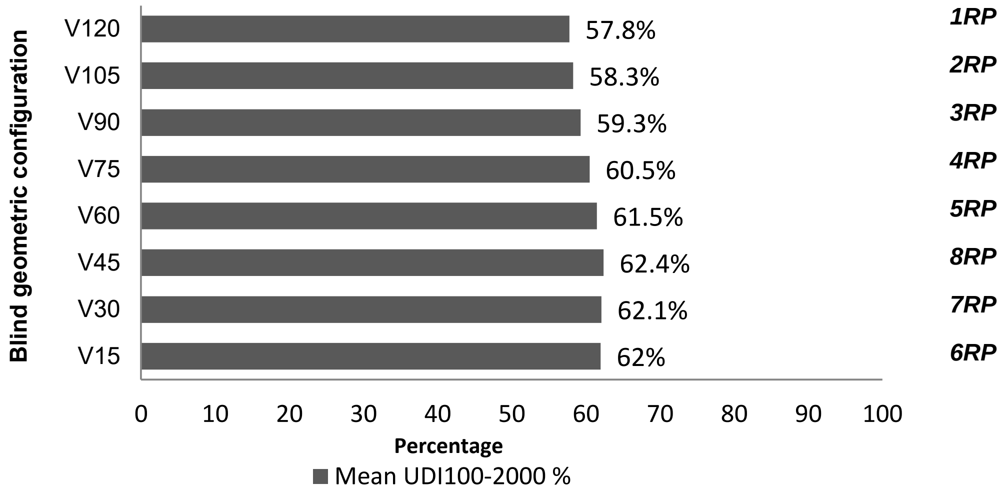


Figure 4.29: Mean $UDI_{100-2000}$% for slat geometric configurations for west orientation with respective rating points (RP)

Similar pattern in the rating points is observed for $UDI_{>2000}$ percentages as that is seen for the previous metrics. $V45^{O}$ scored the highest rating point (8 point) with a percentage of 33.2%, whereas, $V120^{O}$ scored the lowest point (1point) with 38.2% mean $UDI_{>2000}$% (Figure 4.30).

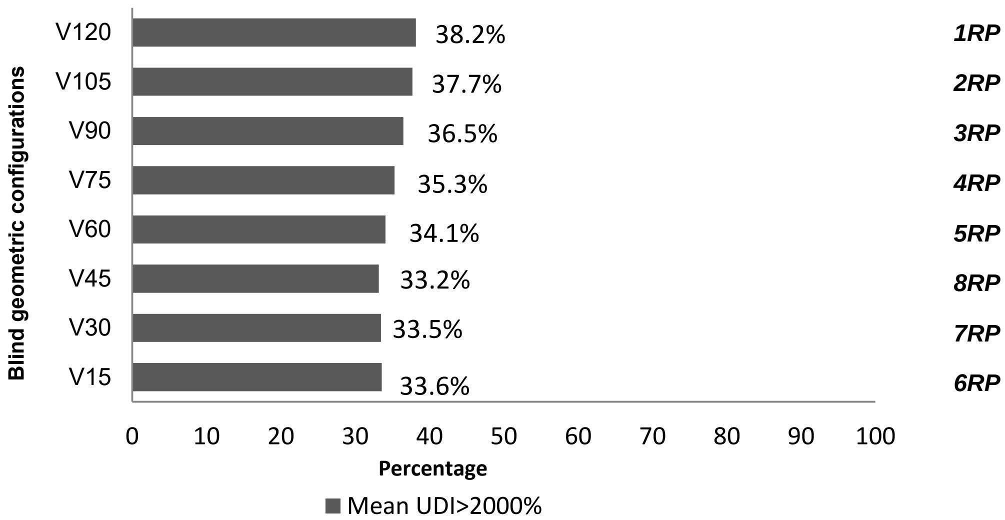


Figure 4.30: Mean $UDI_{>2000}$% for slat geometric configurations for west orientation with respective rating points (RP)

The summation of rating point showed that V45^{O} scored highest rating point in comparison to others, followed by V30^{O}, V60^{O}, V15^{O}, V75^{O}, V105^{O} and finally V120^{O} (Table 4.6). As a result, V45^{O} is ranked first position, which means this variant will perform better for west orientation. The analysis and comparison of the vertex angles identified that inverted V slat geometry with vertex angle of 45^{O} is the most feasible parameter for three of the orientations. The next stage analyses simulation output for separation distance between slats in order to identify the best possible parameter for different orientations.

Table 4.6: Dynamic simulation output with rating points and ranking of slat geometric configurations for West orientation

Inverted V slat geometry	***Value & Rating points (RP)***	***DA (%)***	***DA_{max} (%)***	***$UDI_{<100}$ (%)***	***$UDI_{100-2000}$ (%)***	***$UDI_{>2000}$ (%)***	***Total RP***	***Ranks***
V15^{0}	Value	88.3	23.1	4.4	62	33.6	**20**	**4**
	RP	**1**	**6**	**1**	**6**	**6**		
V30^{0}	Value	88.3	23.1	4.4	62.1	33.5	**22**	**2**
	RP	**1**	**6**	**1**	**7**	**7**		
V45^{0}	Value	88.4	23	4.4	62.4	33.2	**27**	**1**
	RP	**3**	**7**	**1**	**8**	**8**		
V60^{0}	Value	88.7	23.5	4.3	61.5	34.1	**21**	**3**
	RP	**4**	**5**	**2**	**5**	**5**		
V75^{0}	Value	89.2	23.9	4.3	60.5	35.3	**19**	**5**
	RP	**5**	**4**	**2**	**4**	**4**		
V90^{0}	Value	89.8	25.1	4.2	59.3	36.5	**18**	**6**
	RP	**6**	**3**	**3**	**3**	**3**		
V105^{0}	Value	90	26	4.1	58.3	37.7	**17**	**7**
	RP	**7**	**2**	**4**	**2**	**2**		
V120^{0}	Value	90.3	26.5	4.1	57.8	38.2	**15**	**8**
	RP	**8**	**1**	**4**	**1**	**1**		

4.3.3 Simulation output and analysis for distance between slats

The best possible slat geometry from previous steps is evaluated varying the separation gap in between the slats in the third stage of dynamic daylight simulation. Sixteen different dimensions for separation distance are studied starting from 50mm to 200mm with an interval of 10mm apart. In this section, the simulation output for the separation gaps is analysed for three orientations to identify the most feasible parameter for venetian blind configuration.

a) Analysis for south orientation

The rating and ranking value based on critical analysis for 16 different studied separation distance dimensions are presented in the Table 4.7. The performance of the dimensions is compared for different metrics to assign them rating points.

In terms of mean DA percentage, gap of 200mm showed good performance and assigned 16 rating points (Figure 4.31). Among the studied dimensions, the worst performance is observed for 50mm gap which has a mean DA percentage of 60.9%. The pattern for mean DA% showed that, the performance kept increasing with increase in gap dimension.

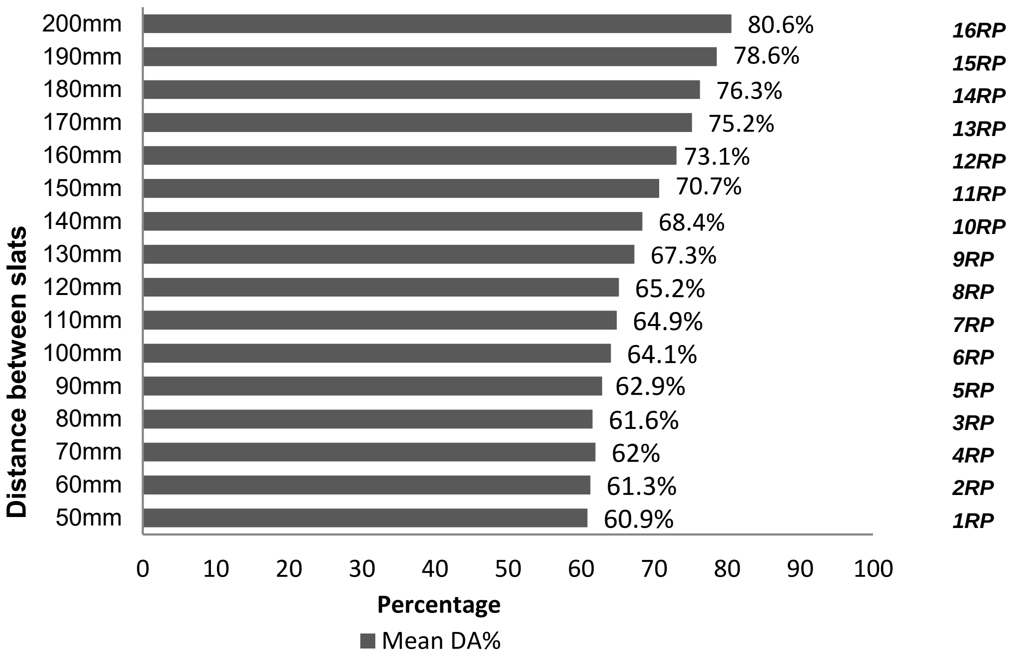


Figure 4.31: Mean DA% for distance between slats for south orientation with respective rating points (RP)

The mean DA_{max} percentage (Figure 4.32) shows that, 200mm scored the lowest rating point (1Point) with a mean DA_{max} 14.4%. Among the studied dimensions, very little deviation of only around 4.4% is observed. The lowest percentage is observed for 50mm and 60mm (10%) which are assigned 13 rating points.

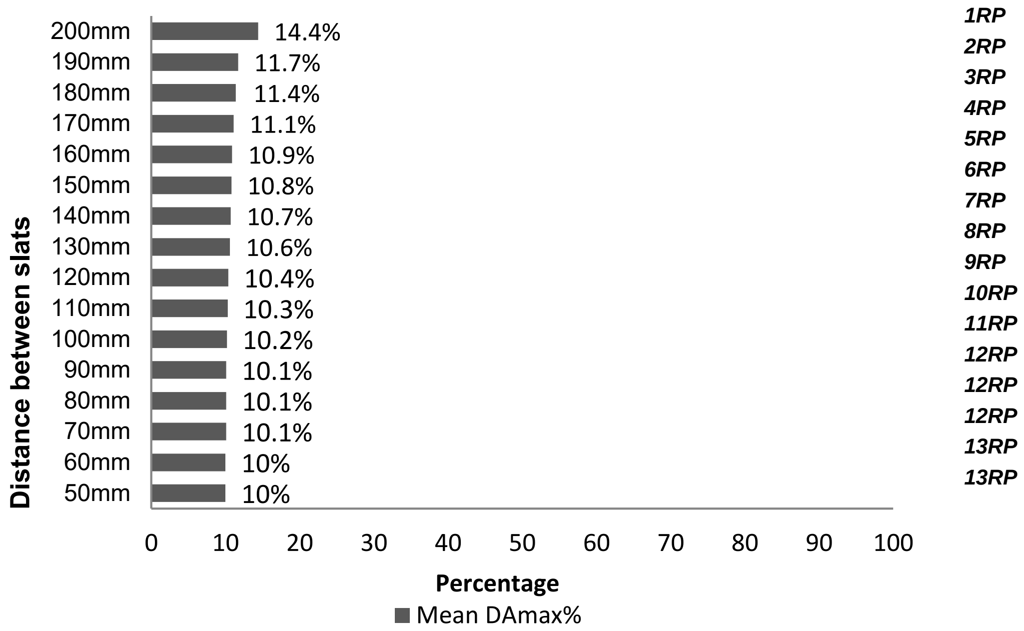


Figure 4.32: Mean DA_{max}% for distance between slats for south orientation with respective rating points (RP)

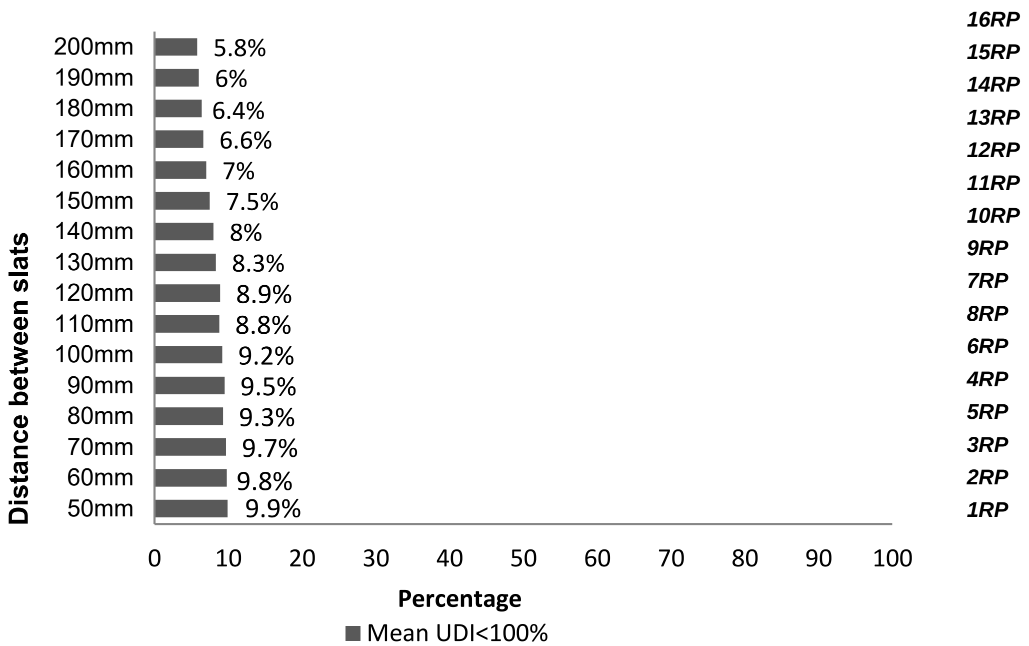


Figure 4.33: Mean $UDI_{<100}$% for distance between slats for south orientation with respective rating points (RP)

On the other hand, the mean $UDI_{<100}$ percentage shows a completely opposite pattern for the studied dimensions in comparison to the previous performance metrics. Figure 4.33 shows that, the rating point for 200mm is the highest (16 points) among studied options with a mean $UDI_{<100}$ 5.8%. The highest mean $UDI_{<100}$ percentage (9.9%) is observed for 50mm.

In regards to $UDI_{100-2000}$ percentage separation distance of 160mm gained the highest mean percentage (75.8%) (Figure 4.34), so rated the maximum rating points (12 point). 200mm scored the lowest rating point (1point) with a mean $UDI_{100-2000}$ 70.8%. This suggests that in consideration of mean $UDI_{100-2000}$% in south orientation, distance of 160mm in between the slats will show better daylighting performance in comparison to other studied options.

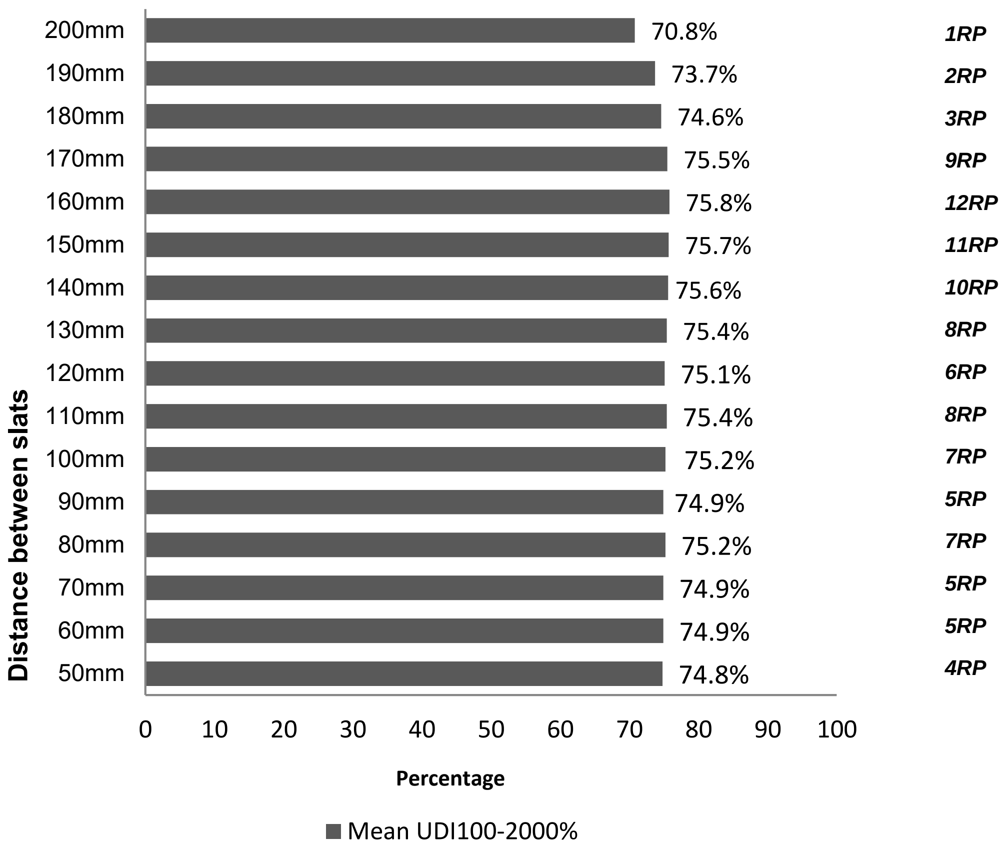


Figure 4.34: Mean $UDI_{100-2000}$% for distance between slats for south orientation with respective rating points (RP)

At last, the performance metric UDI$_{>2000}$% (Figure 4.35) indicates that distance of 200mm has the highest mean percentage (23.3%) and the percentage is lowest (15.3%) for 50mm, 60mm and 70mm. Based on the performance 50mm, 60mm and 70mm are assigned highest rating points (13point).

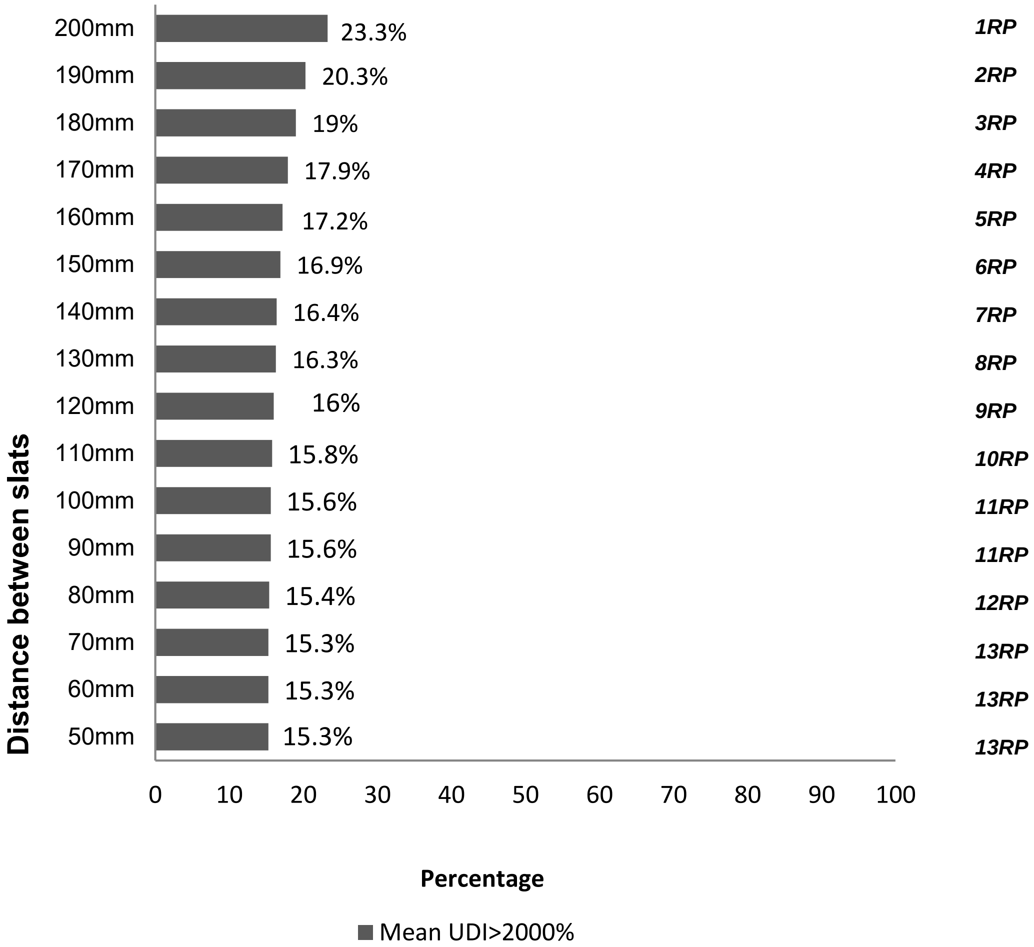


Figure 4.35: Mean UDI$_{>2000}$% for distance between slats for south orientation with respective rating points (RP)

Based on the rating points, final ranking for distance is done (Table 4.7). 160mm separation distance is ranked first position with highest rating point (46 points), whereas, the last rank is assigned to 50mm. So, for south orientation, blind configuration with inverted V slat geometry at 45^{O} vertex angle and having a separation distance of 160mm is most feasible than any other studied parameters.

Table 4.7: Dynamic simulation output with rating points and ranking of distance between slats for south orientation

Distance between slats	***Value & Rating points (RP)***	***DA (%)***	***DA_{max} (%)***	***$UDI_{<100}$ (%)***	***$UDI_{100-2000}$ (%)***	***$UDI_{>2000}$ (%)***	***Total RP***	***Ranks***
50mm	Value	60.9	10	9.9	74.8	15.3	**32**	**11**
	RP	**1**	**13**	**1**	**4**	**13**		
60mm	Value	61.3	10	9.8	74.9	15.3	**35**	**10**
	RP	**2**	**13**	**2**	**5**	**13**		
70mm	Value	62	10.1	9.7	74.9	15.3	**37**	**8**
	RP	**4**	**12**	**3**	**5**	**13**		
80mm	Value	61.6	10.1	9.3	75.2	15.4	**39**	**7**
	RP	**3**	**12**	**5**	**7**	**12**		
90mm	Value	62.9	10.1	9.5	74.9	15.6	**37**	**8**
	RP	**5**	**12**	**4**	**5**	**11**		
100mm	Value	64.1	10.2	9.2	75.2	15.6	**41**	**6**
	RP	**6**	**11**	**6**	**7**	**11**		
110mm	Value	64.9	10.3	8.8	75.4	15.8	**43**	**4**
	RP	**7**	**10**	**8**	**8**	**10**		
120mm	Value	65.2	10.4	8.9	75.1	16	**39**	**7**
	RP	**8**	**9**	**7**	**6**	**9**		
130mm	Value	67.3	10.6	8.3	75.4	16.3	**42**	**5**
	RP	**9**	**8**	**9**	**8**	**8**		
140mm	Value	68.4	10.7	8	75.6	16.4	**44**	**3**
	RP	**10**	**7**	**10**	**10**	**7**		
150mm	Value	70.7	10.8	7.5	75.7	16.9	**45**	**2**
	RP	**11**	**6**	**11**	**11**	**6**		
160mm	Value	73.1	10.9	7	75.8	17.2	**46**	**1**
	RP	**12**	**5**	**12**	**12**	**5**		
170mm	Value	75.2	11.1	6.6	75.5	17.9	**43**	**4**
	RP	**13**	**4**	**13**	**9**	**4**		
180mm	Value	76.3	11.4	6.4	74.6	19	**37**	**8**
	RP	**14**	**3**	**14**	**3**	**3**		
190mm	Value	78.6	11.7	6	73.7	20.3	**36**	**9**
	RP	**15**	**2**	**15**	**2**	**2**		
200mm	Value	80.6	14.4	5.8	70.8	23.3	**35**	**10**
	RP	**16**	**1**	**16**	**1**	**1**		

b) Analysis for east orientation

The rating and ranking value based on critical analysis for 16 different studied separation distance dimensions in east orientation are presented in the Table 4.8. The performances of the dimensions are compared for the metrics to assign them rating points.

In terms of mean DA percentages, 200mm separation distance with value 89.7% is assigned 11 rating points based on its performance (Figure 4.36). On the contrary, lowest mean DA% (88.1%) is observed for 60mm. Overall, the percentages seemed to increase with increase in separation distance.

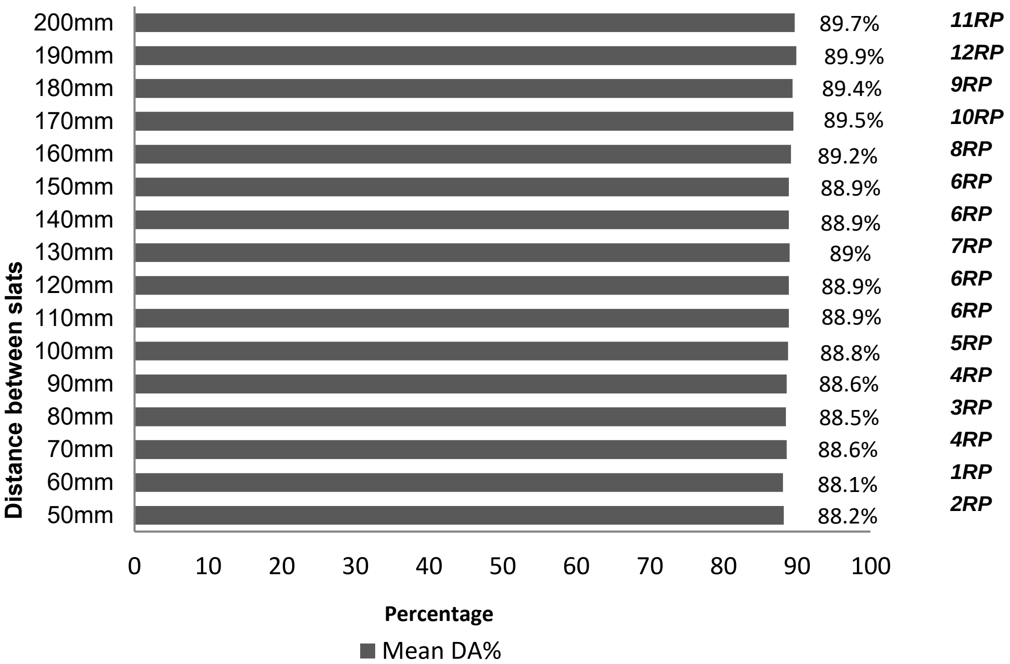


Figure 4.36: Mean DA% for distance between slats for east orientation with respective rating points (RP)

It is identified from Figure 4.37 that, the overall mean DA_{max} percentage difference between studied dimensions is only around 0.6% for east orientation. The lowest mean percentage (24.7%) is observed for 50mm, 60mm, 70mm, 80mm, 100mm and 110mm, whereas, it is highest (25.7%) for 180mm. The lowest rating point of 1 is assigned to separation distance of 180mm.

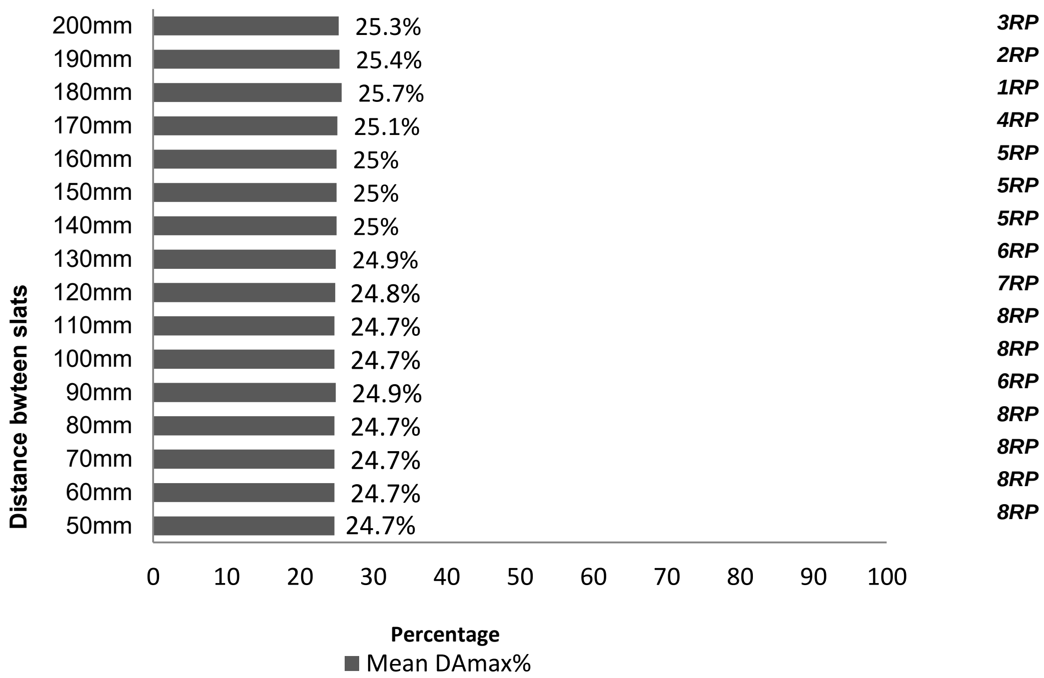


Figure 4.37: Mean DA_{max}% for distance between slats for east orientation with respective rating points (RP)

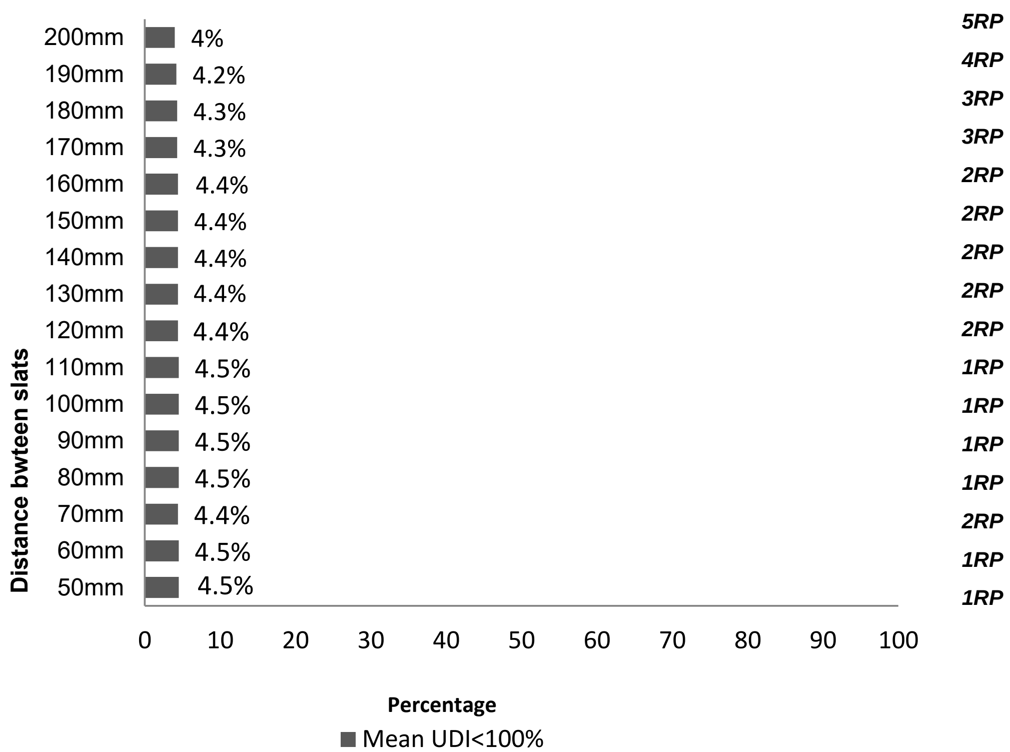


Figure 4.38: Mean $UDI_{<100}$ % for distance between slats for east orientation with respective rating points (RP)

On the other hand, the mean percentage for $UDI_{<100}$ showed that the number kept decreasing with increase in distance (Figure 4.38). The separation distance 200mm is rated 5 point with a mean $UDI_{<100}$ 4%. In comparison, highest percentage of 4.5% is observed for 50mm, 60mm, 80mm, 90mm, 100mm and 110mm.

In regards to mean $UDI_{100-2000}$ percentage, higher percentage indicates useful level of illuminance. The highest mean $UDI_{100-2000}$ percentage (61.7%) is observed for 50mm and 70mm (Figure 4.39), so rated highest rating point (9point). Rating point of 1 is assigned to 200mm for gaining lowest mean $UDI_{100-2000}$ percentage of 60.2%.

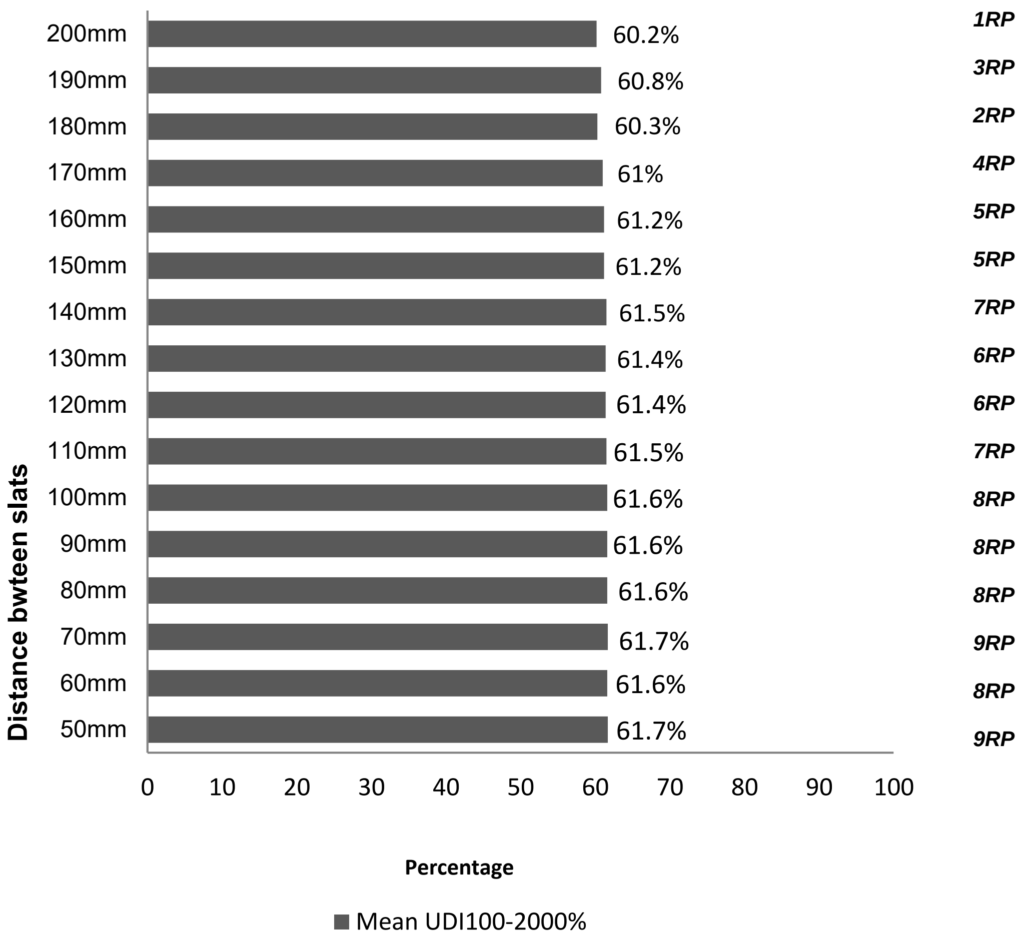


Figure 4.39: Mean $UDI_{100-2000}$% for distance between slats in east orientation with respective rating points (RP)

At last, mean percentage for $UDI_{>2000}$ showed that for separation distance 50mm, 60mm, 70mm, 80mm and 100mm, the value is lowest (33.9%) (Figure: 4.40). As a result, these options are assigned 9 points, whereas, lowest point of 1 is assigned to 200mm.

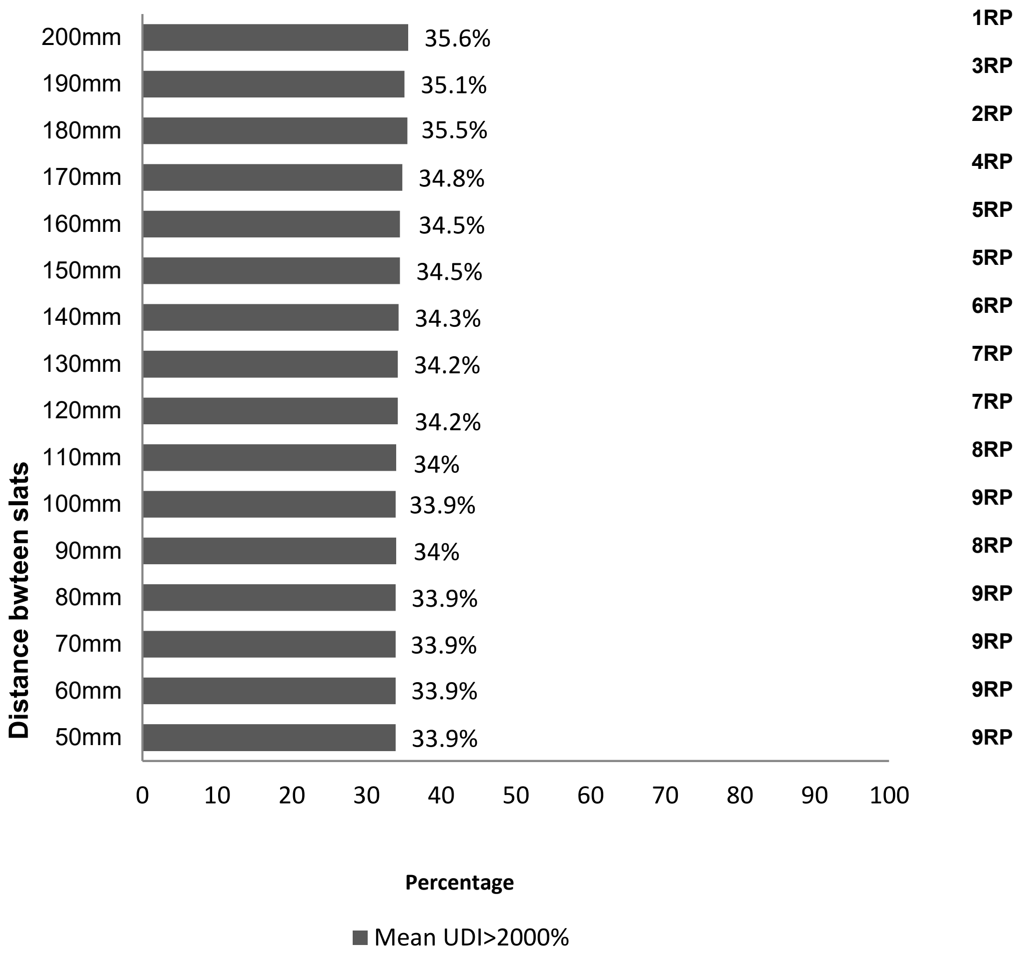


Figure 4.40: Mean $UDI_{>2000}$% for distance between slats in east orientation with respective rating points (RP)

It is shown in Table 4.8 that, in terms of total rating points 70mm scored highest points (32points) among the studied separation gaps. As a result, it is ranked first for showing good performance in terms of all the metrics. So, for east orientation, blind configurations with inverted V slat geometry at 45^0 vertex angle and having a separation distance of 70mm proved to be most feasible than any other studied parameters.

Table 4.8: Dynamic simulation output with rating points and ranking of distance between slats for East orientation

Distance between slats	***Value & Rating points (RP)***	***DA (%)***	***DA_{max} (%)***	***$UDI_{<100}$ (%)***	***$UDI_{100-2000}$ (%)***	***$UDI_{>2000}$ (%)***	***Total RP***	***Ranks***
50mm	Value	88.2	24.7	4.5	61.7	33.9	**29**	**4**
	RP	**2**	**8**	**1**	**9**	**9**		
60mm	Value	88.1	24.7	4.5	61.6	33.9	**27**	**6**
	RP	**1**	**8**	**1**	**8**	**9**		
70mm	Value	88.6	24.7	4.4	61.7	33.9	**32**	**1**
	RP	**4**	**8**	**2**	**9**	**9**		
80mm	Value	88.5	24.7	4.5	61.6	33.9	**29**	**4**
	RP	**3**	**8**	**1**	**8**	**9**		
90mm	Value	88.6	24.9	4.5	61.6	34	**27**	**6**
	RP	**4**	**6**	**1**	**8**	**8**		
100mm	Value	88.8	24.7	4.5	61.6	33.9	**31**	**2**
	RP	**5**	**8**	**1**	**8**	**9**		
110mm	Value	88.9	24.7	4.5	61.5	34	**30**	**3**
	RP	**6**	**8**	**1**	**7**	**8**		
120mm	Value	88.9	24.8	4.4	61.4	34.2	**28**	**5**
	RP	**6**	**7**	**2**	**6**	**7**		
130mm	Value	89	24.9	4.4	61.4	34.2	**28**	**5**
	RP	**7**	**6**	**2**	**6**	**7**		
140mm	Value	88.9	25	4.4	61.5	34.3	**26**	**7**
	RP	**6**	**5**	**2**	**7**	**6**		
150mm	Value	88.9	25	4.4	61.2	34.5	**23**	**10**
	RP	**6**	**5**	**2**	**5**	**5**		
160mm	Value	89.2	25	4.4	61.2	34.5	**25**	**8**
	RP	**8**	**5**	**2**	**5**	**5**		
170mm	Value	89.5	25.1	4.3	61	34.8	**25**	**8**
	RP	**10**	**4**	**3**	**4**	**4**		
180mm	Value	89.4	25.7	4.3	60.3	35.5	**17**	**12**
	RP	**9**	**1**	**3**	**2**	**2**		
190mm	Value	89.9	25.4	4.2	60.8	35.1	**24**	**9**
	RP	**12**	**2**	**4**	**3**	**3**		
200mm	Value	89.7	25.3	4	60.2	35.6	**21**	**11**
	RP	**11**	**3**	**5**	**1**	**1**		

c) Analysis for west orientation

The same procedure is followed for the rating and ranking of different separation distance dimensions for the west orientation and is tabulated in the Table 4.9.

In terms of mean DA% (Figure 4.41), the highest rating point is observed for separation distance of 200mm with a mean percentage of 89.8%. On the other hand, the lowest mean percentage (88.2%) is observed for 50mm and 60mm, so assigned 1 rating point. This indicates that separation gap of 200mm will ensure good day lighting performance.

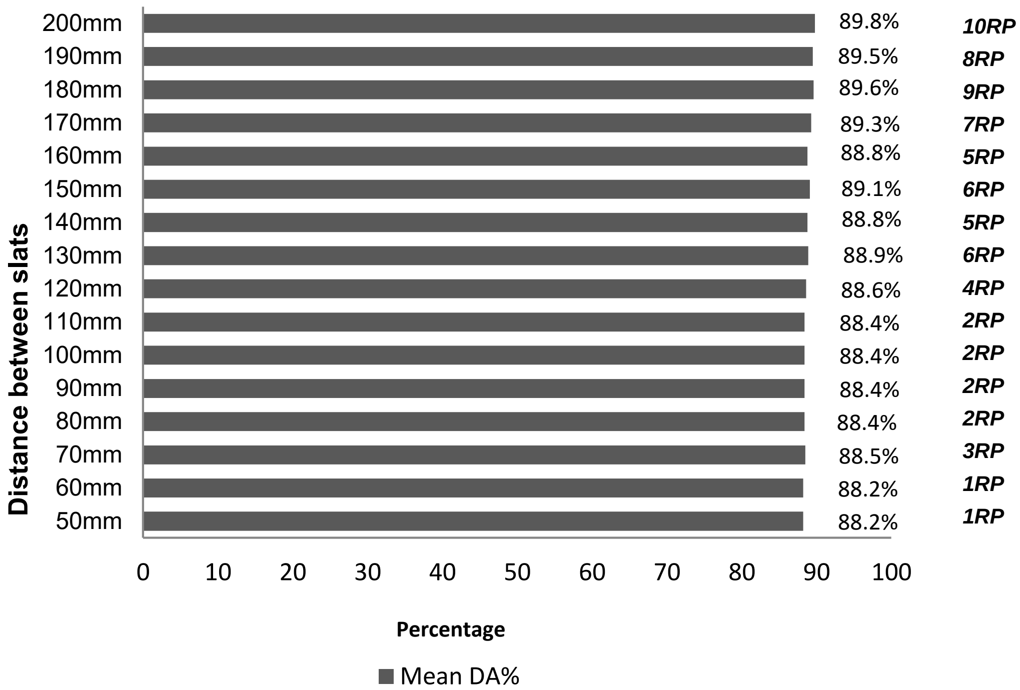


Figure 4.41: Mean DA% for distance between slats for west orientation with respective rating points (RP)

The mean DA_{max} percentage (Figure 4.42) showed that, the studied dimensions have little deviation of only 1.2%. The lowest percentage (23%) is observed for 70mm and 100mm and based on the DA_{max} performance; they are rated 10 points. Among the studied dimensions, the highest mean value of 24.5% is observed for separation distance of 180mm (Table 4.9).

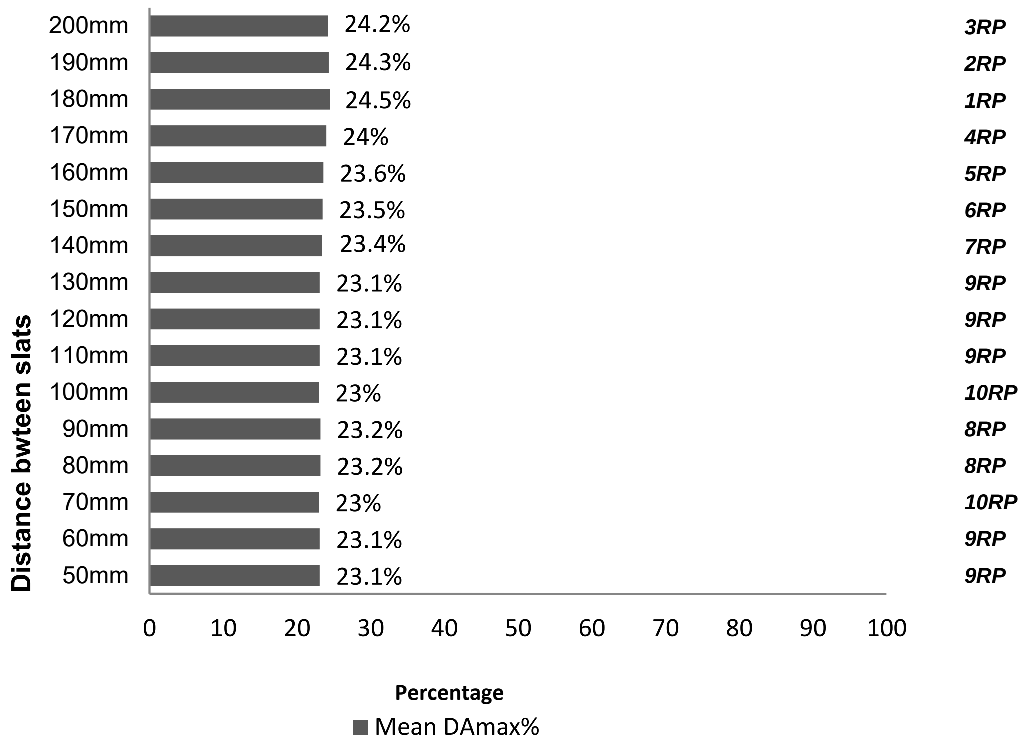


Figure 4.42: Mean DA_{max}% for distance between slats for west orientation with respective rating points (RP)

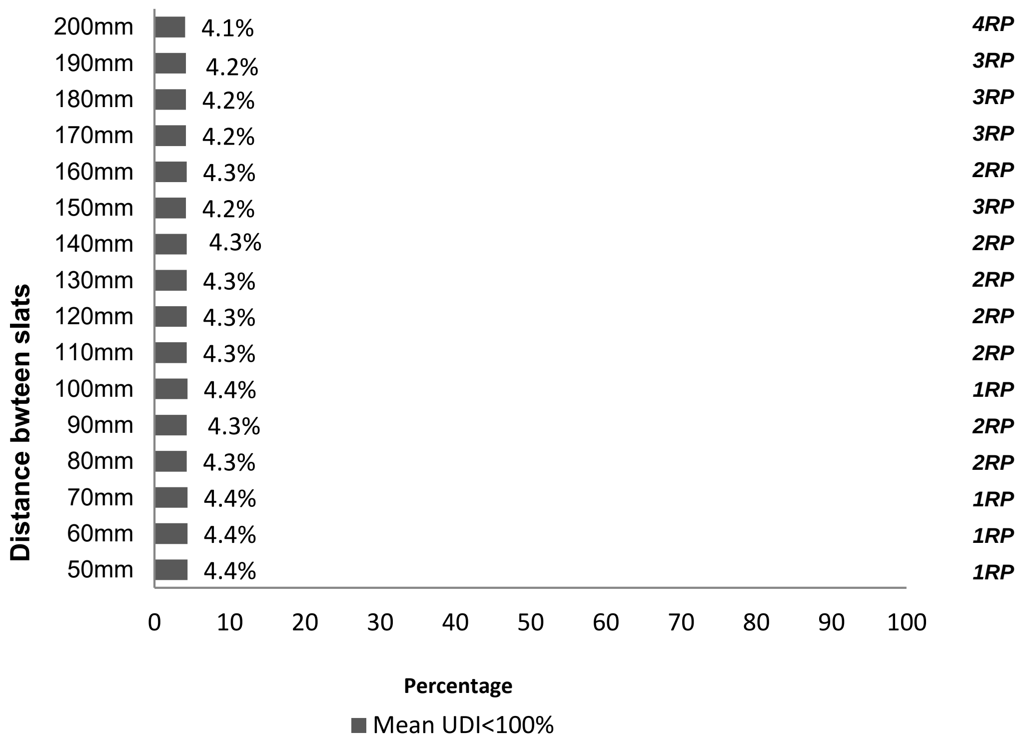


Figure 4.43: Mean $UDI_{<100}$% for distance between slats for west orientation with respective rating points (RP)

It is identified from Figure 4.43, that the mean percentage of $UDI_{<100}$ kept decreasing with the increase in separation distance. Highest rating point (4 point) is assigned to 200mm distance with a percentage of 4.1. On the contrary, highest mean $UDI_{<100}$ percentage of 4.4% is observed for 50mm, 60mm, 70mm and 100mm.

With regards to $UDI_{100-2000}$ which indicates useful daylight level identifies that, 200mm shows worst performance among the studied dimensions with a mean percentage of 59.9% (Figure 4.44). Two of the dimensions showed good performances which are 70mm and 100mm, with 11 rating points and a mean $UDI_{100-2000}$ percentage of 62.4.

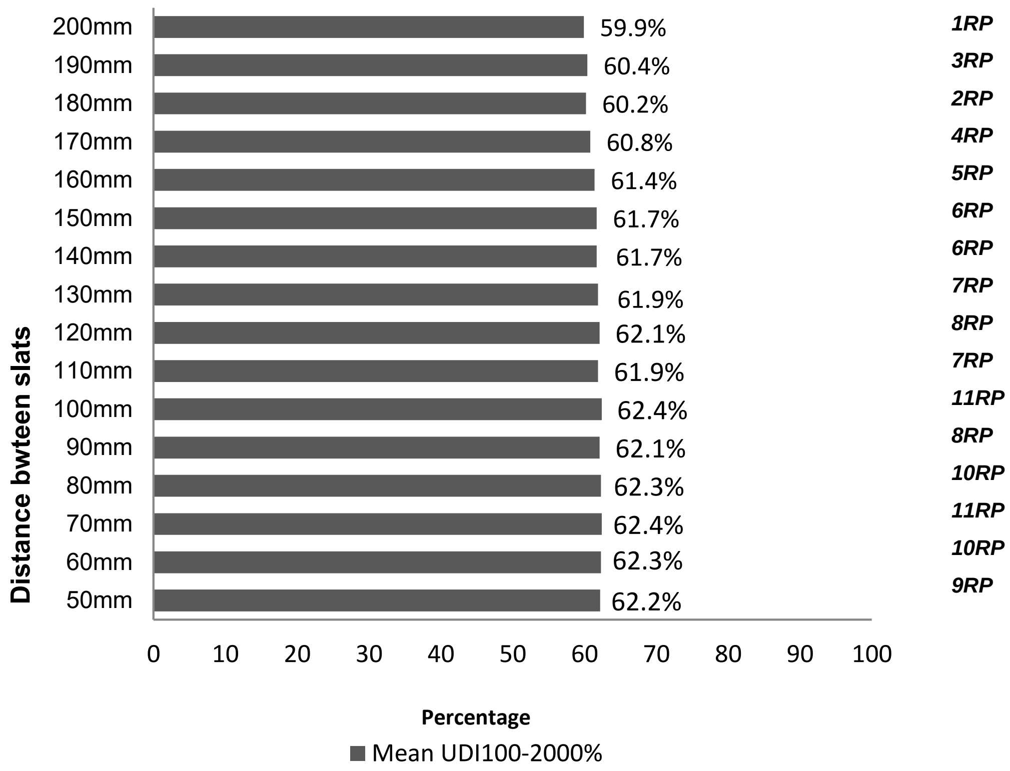


Figure 4.44: Mean $UDI_{100-2000}$% for distance between slats for west orientation with respective rating points (RP)

Finally, the last performance metrics $UDI_{>2000}$% showed a variation of around 2.8% among the studied dimensions. Highest mean percentage (36%) is observed for separation distance of 200mm, which indicates higher percentage of glare. So, it was assigned lowest rating points (1point) among all the studied options. On the other hand, highest rating point (13 point) is observed for 70mm and 100mm with mean percentages of 33.2% (Figure 4.45).

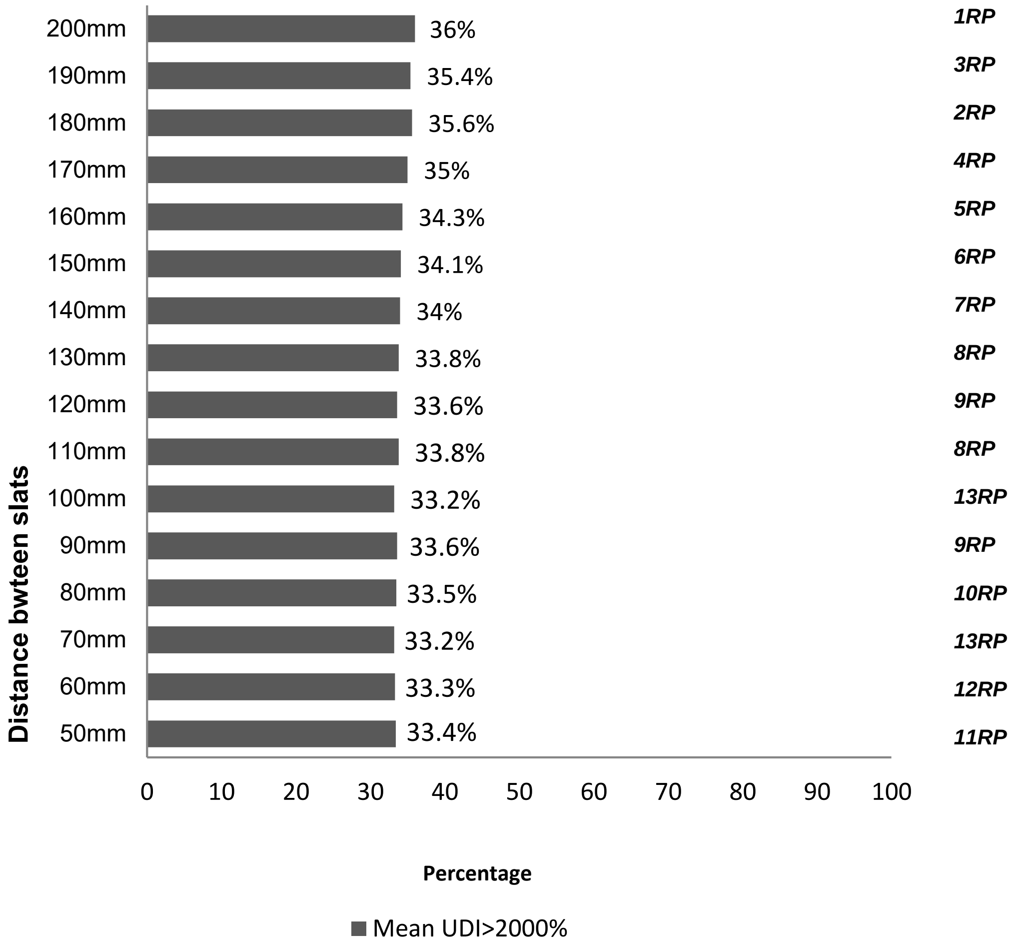


Figure 4.45: Mean UDI$_{>2000}$% for distance between slats for west orientation with respective rating points (RP)

The cumulative rating points of the performance metrics gives highest point of 38 to separation distance of 70mm (Table 4.9). Based on the rating point, 70mm distance is assigned 1st rank, followed by 100mm, 60mm and others. So, for west orientation, blind configurations with inverted V slat geometry having 45^{O} vertex angle and a separation distance of 70mm in between the Slats proved to be most feasible than any other studied parameters.

Table 4.9: Dynamic simulation output with rating points and ranking of distance between slats for west orientation

Distance between slats	***Value & Rating points (RP)***	***DA (%)***	***DA_{max} (%)***	***$UDI_{<100}$ (%)***	***$UDI_{100-2000}$ (%)***	***$UDI_{>2000}$ (%)***	***Total RP***	***Ranks***
50mm	Value	88.2	23.1	4.4	62.2	33.4	**31**	**5**
	RP	**1**	**9**	**1**	**9**	**11**		
60mm	Value	88.2	23.1	4.4	62.3	33.3	**33**	**3**
	RP	**1**	**9**	**1**	**10**	**12**		
70mm	Value	88.5	23	4.4	62.4	33.2	**38**	**1**
	RP	**3**	**10**	**1**	**11**	**13**		
80mm	Value	88.4	23.2	4.3	62.3	33.5	**32**	**4**
	RP	**2**	**8**	**2**	**10**	**10**		
90mm	Value	88.4	23.2	4.3	62.1	33.6	**29**	**6**
	RP	**2**	**8**	**2**	**8**	**9**		
100mm	Value	88.4	23	4.4	62.4	33.2	**37**	**2**
	RP	**2**	**10**	**1**	**11**	**13**		
110mm	Value	88.4	23.1	4.3	61.9	33.8	**28**	**7**
	RP	**2**	**9**	**2**	**7**	**8**		
120mm	Value	88.6	23.1	4.3	62.1	33.6	**32**	**4**
	RP	**4**	**9**	**2**	**8**	**9**		
130mm	Value	88.9	23.1	4.3	61.9	33.8	**32**	**4**
	RP	**6**	**9**	**2**	**7**	**8**		
140mm	Value	88.8	23.4	4.3	61.7	34	**27**	**8**
	RP	**5**	**7**	**2**	**6**	**7**		
150mm	Value	89.1	23.5	4.2	61.7	34.1	**27**	**8**
	RP	**6**	**6**	**3**	**6**	**6**		
160mm	Value	88.8	23.6	4.3	61.4	34.3	**22**	**9**
	RP	**5**	**5**	**2**	**5**	**5**		
170mm	Value	89.3	24	4.2	60.8	35	**22**	**9**
	RP	**7**	**4**	**3**	**4**	**4**		
180mm	Value	89.6	24.5	4.2	60.2	35.6	**17**	**11**
	RP	**9**	**1**	**3**	**2**	**2**		
190mm	Value	89.5	24.3	4.2	60.4	35.4	**19**	**10**
	RP	**8**	**2**	**3**	**3**	**3**		
200mm	Value	89.8	24.2	4.1	59.9	36	**19**	**10**
	RP	**10**	**3**	**4**	**1**	**1**		

The analysis and comparison of the vertex angles identified that internal venetian blind with inverted V slat geometry having 45^{O} vertex angle is feasible for south, east and west orientations. Separation distance of 160mm between slats in south orientation and a gap of 70mm in east and west orientations is needed for better daylight performance inside an office space.

4.4 Summary

This chapter identified feasible blind configurations by critical analysis and comparison of dynamic simulation outputs. The second and third objectives of this research have been achieved through this chapter. The second objective of this research was to select appropriate types of internal venetian blind inside glass faceted high-rise office building context of Dhaka.The second objective has been achieved in the simulation procedure where venetian blind slat geometry was evaluated. It was identified that inverted V slat geometry shape is the most feasible slat geometry inside office spaces in the context of Dhaka. Inverted V geometry is also identified as the most efficient geometries among seven different slat geometry options for three different orientations.

The third objective of this research was to identify the best parametric configuration of internal venetian blind for different orientations. This is achieved during the evaluation of slat geometric configurations and separation distance in between slats. The dynamic simulation output from evaluation of slat geometric configurations identified inverted V slat geometry with a vertex angle of 45^{O} as the most feasible option among 8 different studied angles for the three orientations. Along with that, the evaluation of distance in between slats identified 160mm separation distance as the best possible blind configuration for south orientation, whereas, 70mm is identified best for east and west orientations. The combination of these parametric configurations can be incorporated in high-rise commercial buildings with glazed envelopes to enable sustainable design. This Chapter leads to the presentation of the achievement of the research objectives in next Chapter 5 with recommendation and suggestion for future work.

CHAPTER: FIVE

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS AND RECOMMENDATIONS

5.1 Preamble

The framework of this research is arranged into five different chapters. The first chapter introduced the main hypothesis of this research, mentioned the objectives, followed by a detail literature synthesis, which formed the theoretical basis for this research. The second chapter identified importance of daylighting in office spaces, daylighting components, standard illumination level inside office spaces, importance of internal venetian blinds and blind characteristics and discussed the advantages of interior venetian blinds compared to other types of shading elements. The third chapter elaborated the detailed methodology that is followed in this study, along with field survey procedure. The dynamic simulation output for the studied parameters of venetian blind configuration is presented in Chapter Four. In addition to that, Chapter 4 also presents detailed analysis and comparison for blind configurations in various orientations. Rating points and ranking among the studied blind configurations are assigned for three of the orientations to identify the best possible blind configurations in the context of Dhaka. Finally, this chapter will conclude the research with achievement of the objectives which is mentioned in the first chapter and provide some recommendations for internal venetian blind configurations in commercial office spaces for various orientations and identify areas for further research.

5.2 Achievement of the objectives

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

5.2.1 Effectiveness of internal venetian blind

The first objective is to evaluate the effectiveness of internal venetian blinds as appropriate internal shading systems for office buildings in context of Dhaka. In order to achieve this particular objective, different types of internal and external shading systems are investigated through literature synthesis in Chapter 2. The characteristics and parameters of blind configurations are identified from published books and past studies. Literature studies showed that most of the office spaces in urban context of Dhaka have shifted in commercial buildings with deep plans and have little access to daylight. Commercial buildings with glazed facades in different orientations, allow excessive amount of daylight to penetrate which gives rise to heat, glare, thermal and visual discomfort. Internal venetian blinds have significant impact on incident light and have the ability to adjust their slats to ensure glare protection shown in Figure 5.1.

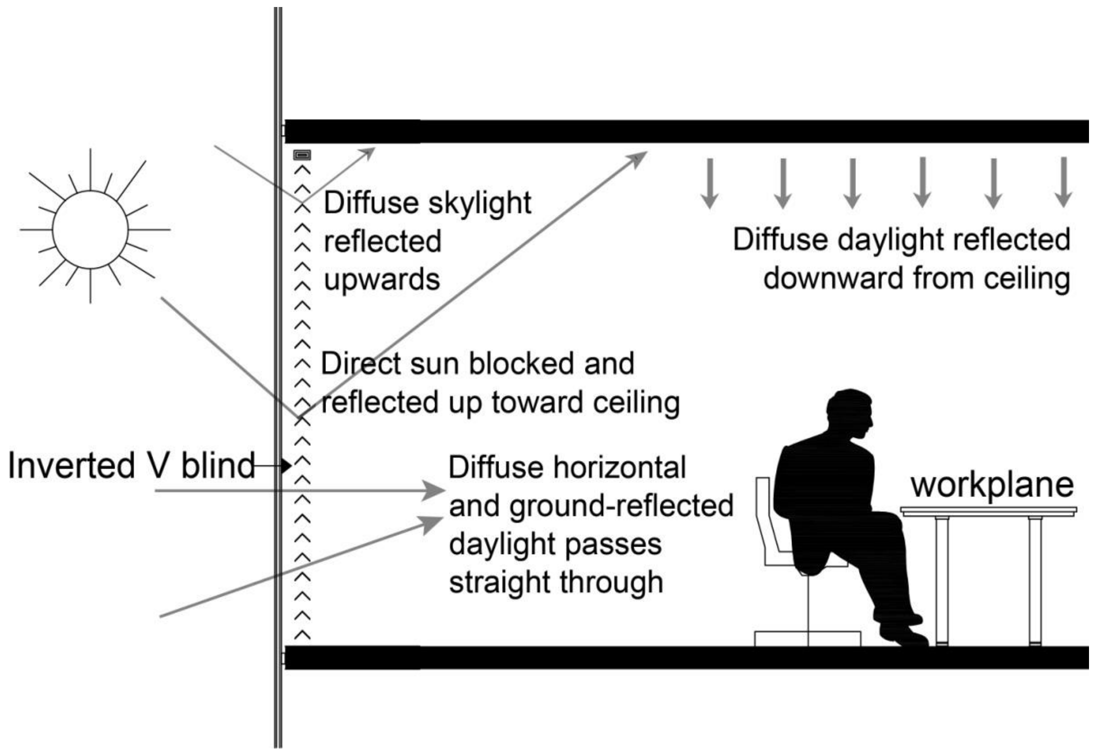


Figure 5.1: Mechanisms used by internal venetian blind in optimization of daylight.

It could be concluded from literature study that in comparison to vertical blind, venetian blind configuration is most feasible in optimization of daylight inside office spaces in the context of Dhaka. Internal venetian blinds take very little space and is cost efficient, which allows limitless possibilities of external façade for designers.

5.2.2 Appropriate type of internal venetian blind

The second objective was to identify the best possible slat geometry of internal venetian blind configurations for three different orientations inside office spaces in context of Dhaka. In order to achieve this objective detailed literature review was undertaken to find out common slat geometries and to understand characteristics of blind parameters. Climate based dynamic daylight simulation is conducted with seven different slat geometries for three orientations for the case office space, to identify the most feasible geometries from the performance metrics rating system (Figure 5.2). Simulation outputs for the studied geometries were also evaluated against the condition with no blinds. Inverted V slat geometry was found as the best possible configuration of internal venetian blind for all three orientations (East, West and South) for office spaces in the context of Dhaka considering the whole year.

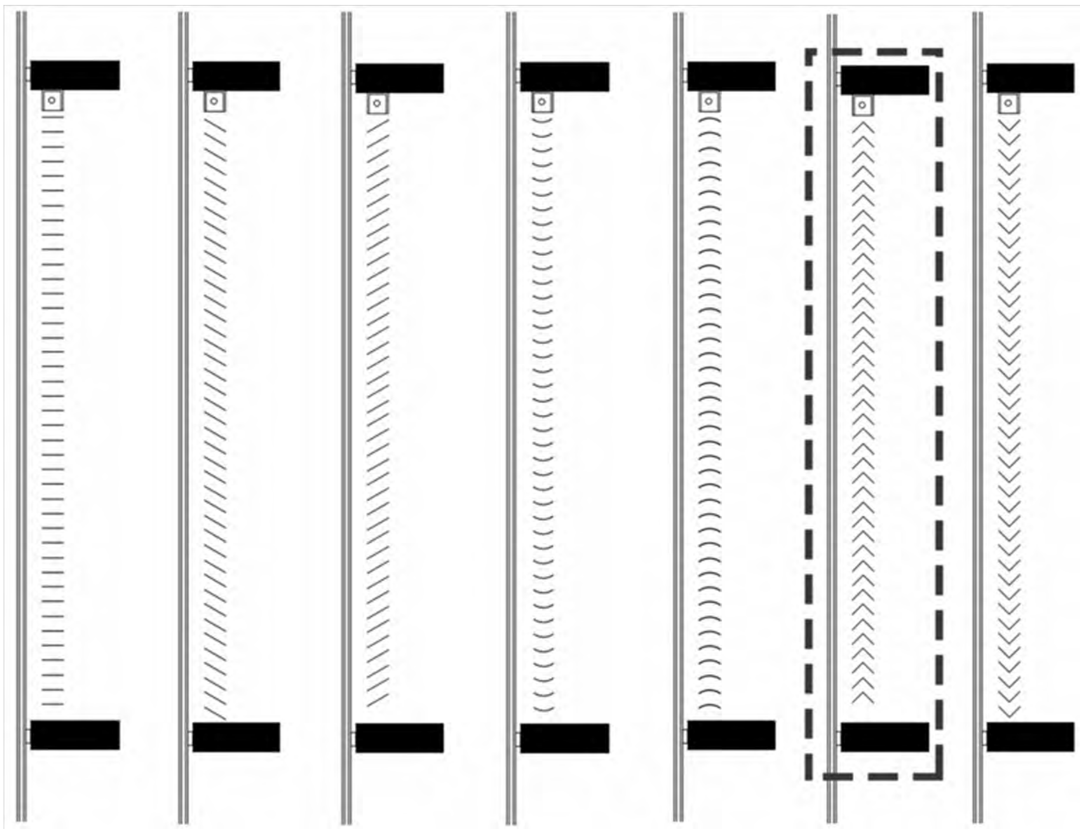


Figure 5.2: Inverted V slat geometry identified as the most feasible

5.2.3 Effective parametric configurations for internal venetian blind

The third objective of this research was to find out the best possible parameters for the blind slat geometry and blind configurations. To achieve this objective, simulation procedure was carried out in two stages.

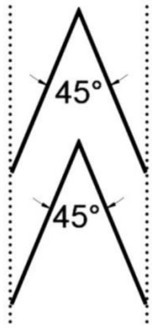


Figure 5.3: Inverted V geometry with 45^0 vertex identified as best possible configuration for three orientations

At first, the vertex angle of the identified slat geometry from the previous section was evaluated. In the next step, the distance in between the slats was varied in order to identify the best possible blind configurations for three orientations in the climatic context of Dhaka. With regards to vertex angle, eight different angles were evaluated and vertex angle of 45^0 was identified as the best possible parametric configuration for inverted V slat geometry among the studied options as shown in Figure 5.3.

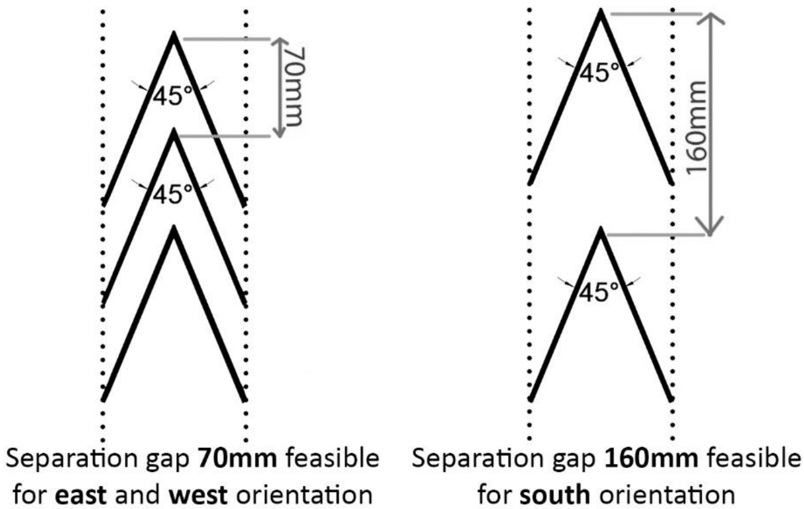


Figure 5.4: Feasible separation distances between slats for different orientations

The best parametric slat configuration was then evaluated varying the separation distance, where 16 different dimensions were studied. Among the studied options, 70mm separation gap was identified as the most feasible for east and west orientations, while 160mm was identified as the most feasible for south orientation as shown in Figure 5.4.

5.3 Recommendations

In order to design a sustainable office building and ensure appropriate illuminance level inside, it is necessary to maintain good daylight distribution. Only having a large window aperture or glazed envelope does not ensure proper distribution of daylight. In addition to that, selection of effective shading elements based on different orientations is fundamental.

From this research the following specific as well as some general recommendations have been drawn for active workspaces inside offices in Dhaka in order to improve the overall luminous environment by the installation of internal venetian blinds.

c) Installation of internal venetian blind provides better luminous environment inside office spaces compared to the condition with no blinds on the window.

d) Distance in between the slats has more impact on the overall daylight condition in the interior office space, in comparison to other tested blind parameters.

e) The office space will have illumination with in the recommended range for blind with inverted V slat geometry in south orientations, in comparison to other geometries.

f) Glare inside office space can be minimized by installing internal venetian blind with inverted V slat geometry on south, east and west orientations.

g) Internal venetian blind with 150^0 inclined slat geometry shows worst performance among all the geometries tested in terms of glare and illumination level for south, east and west orientations.

h) With gradual increase of inverted V slat vertex angle, the percentage of time providing recommended illumination level inside office space increases for south, east and west orientations. Recommended illumination level can be achieved most of the time throughout the year by installing inverted V slat with 120^0 vertex angle.
i) Maximum floor area stays dark (below recommended illumination level) with inverted V 15^0 vertex angle.
j) For south, east and west orientations, inverted V slat with 120^0 vertex angle shows worst performance inside office space in terms of ensuring good luminous environment.
k) The percentage of glare inside office space can be reduced by reducing the vertex angle of inverted V slat geometry, i.e., it is directly proportional.
l) The recommended illumination level can be achieved in most of the time by increasing the gap in between the slats for different orientations.
m) Optimization of daylighting and maintaining recommended illumination level only may not ensure effectiveness of blind configurations, other factors such as view to outside and human collaboration factors need to be within comfortable range as well.

5.4 Suggestion for future research

There are a few areas that need to be addressed in future studies with special reference to internal venetian blind configurations for commercial office buildings with glazed envelopes in context of Dhaka are as follows.

- Further research needs to be done to assess the effectiveness of blind configurations to understand the impact of solar heat gain, overall energy efficiency and cooling load on daylight inclusion.
- Investigation can be done on case buildings in a different context with peripheral shading, as daylight inclusion varies greatly due to peripheral shadings and surrounding buildings.

- Additional analysis can be done with different blind material with varying slat angles, width and other configurations of venetian blinds.
- The penetration of daylight depends on the type of glass on exterior façade, so future research can be done on the impact of blinds with different types of glazing.
- More analysis can be done to evaluate the impact of daylight inclusion on occupant's performance.
- A post occupancy evaluation can be done to evaluate the effectiveness of the studied blind configurations and find out whether the occupants are using them correctly or not.
- Further studies can be carried out with the recommended blind configurations in correspondence to view to the outside with suitable operating schedule/system.
- Study in consideration with human collaboration in real time setting need to be carried out to figure out user's level of satisfaction with the blind configurations.

Development in modern technologies have enabled to incorporate extensive glazed façade in high-rise office buildings. Daylight is essential inside office space to enhance comfortable visual environment and ensure sustainability. Appropriate shading systems help to re-direct and transmit daylight in interior space ensuring uniform illumination distribution. Shading system configurations need to be selected based on the orientation as the characteristics of daylighting are different for different directions. Internal shading devices are easy to incorporate and does not limit the aesthetics on exterior façade of a building. Internal venetian blinds are versatile, respond quickly to dynamic weather conditions. There are numerous blind parameters available and each one of them have different effect on incident sun rays. It is expected that the research can be used as a basis of further research to investigate other aspects as mentioned above for internal venetian blind configurations in office spaces in the context of Dhaka.

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APPENDICES

Appendix A

This presents summary of the Key findings of the research in relation to the objectives, methodologies and concerned chapter

Appendix B

This presents the Key terms and concepts related to this thesis

Appendix C

This presents the specification of tools and simulation software

Appendix D

This presents the detail daylight simulation results

Appendix A: Key findings

***Appendix 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 evaluate the effectiveness of internal venetian blind as shading system to ensure appropriate illuminance level inside deep plan office buildings.	Literature review	Chapter 2	Among available types of internal blinds, venetian blinds are one of the most suitable one to provide quality visual environment on annual basis. Internal venetian blind has great impact on the incident light which can protect the interior space from glare, at the same time allow sufficient amount of daylight inside and takes small amount of space.
Objective 2: To select appropriate types of internal venetian blind in context of Dhaka.	Simulation analysis	Chapter 4	Inverted V slat geometry is found as the best possible type of internal venetian blind configuration for three orientations (south, east and west) for office spaces from the performance metrics-based rating system among the studied configurations.
Objective 3: To identify the best parametric configuration of internal venetian blind for different orientations.	Simulation analysis	Chapter 4	Internal Venetian blind with inverted V slat geometry at 45^{O}vertex angle is feasible for south, east and west orientations. Along with a distance of 160mm between slats for south orientation and a gap of 70mm for east and west orientations provide the best performance among the studied options inside office spaces in the context of Dhaka throughout the year.

Appendix B: Key-terms

LIGHTING TERMINOLOGY

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

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

DAmax (Maximum Daylight Autonomy): is the percentage of the occupied hours when the daylight level is 10 times higher than design illumination; represents the likely appearance of glare.

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

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

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

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

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

LIGHTING METHODS

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

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

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

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

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

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

DAYSIM simulation: calculates the performance metrics considering the impact of local climate and generates a time series indoor annual illuminance profile at points of 137 interests in a building. DAYSIM requires two steps to calculate the annual amount of daylight in a building. Daylight coefficients are calculated first considering the available daylight surrounding the building. After that, the daylight coefficients are combined with the specified climate data of building site. Based on generated illumination profile, DAYSIM derives several dynamic, climate-based daylight performance matrices, such as Daylight Autonomy (DA), Useful Daylight Index (UDI), Continuous Daylight Autonomy (DAcon) and Maximum Daylight Autonomy (DAmax). More details on the simulation algorithm used by DAYSIM can be found under Reinhart (2006).

DAYSIM uses **Perez all weather sky luminance model**. Perez sky model was developed in early nineties by Richard Perez et al. (1990; 1993). To investigate the performance of a building under all possible sky conditions that may occur in a year, DAYSIM first imports hourly direct and diffuse irradiances from a climate file and if 138 required, a stochastic autocorrelation model is used to convert the time series down to five-minute time series of direct and diffuse irradiances from one hour. Then, these irradiances are converted into illuminance and a series of sky luminous distributions of the celestial hemisphere. The sky luminous distribution for a given sky condition varies with date, time, site and direct and diffuse irradiance values, and influence the relative intensity of light back-scattered from the earth surface, the width of the circumsolar region, the relative intensity of the circumsolar region, the luminance gradient near the horizon, and darkening or brightening of the horizon.

Daylight coefficients: calculate indoor lighting levels due to outdoor natural light levels under arbitrary sky conditions. Tregenza (1983) first proposed the concept of daylight coefficients. In this concept, the celestial hemisphere is theoretically divided into disjoint sky patches at the beginning. Then, total illuminance at a point in a building is calculated by summing the contribution of each sky patch individually. After, calculating a complete set of daylight coefficients on a sensor point for a building geometry, it is possible to couple the daylight coefficient with an arbitrary sky luminance distribution and calculate the total illuminance on the specified point by a simple linear superposition. So, using this simple algebraic equation, DAYSIM calculates daylight levels annually considering the short-time-step variances of the outdoor available natural light simultaneously with a time variation of minutes to hours. Reinhart and Herkel (2000) compared six different RADIANCE-based (backward raytracer) dynamic daylighting simulation concepts and found that daylight coefficient approaches is the most reliable and fastest methods to define the short-time step illuminance change in a building.

Appendix C: Specifications

C1: About ECOTECT software

ECOTECT v5.20

The ECOTECT software is developed by Dr. Andrew Marsh as part of his PhD thesis in the University of Western Australia. It is a very useful tool for architects to test the environmental impact on their design scheme even at an early design stage. Autodesk ECOTECT is very user-friendly software that could potentially integrate with the architectural design process. The 3D models are first generated in the ECOTECT, to study the distribution and uniformity of daylight within the interior space using the split-flux method

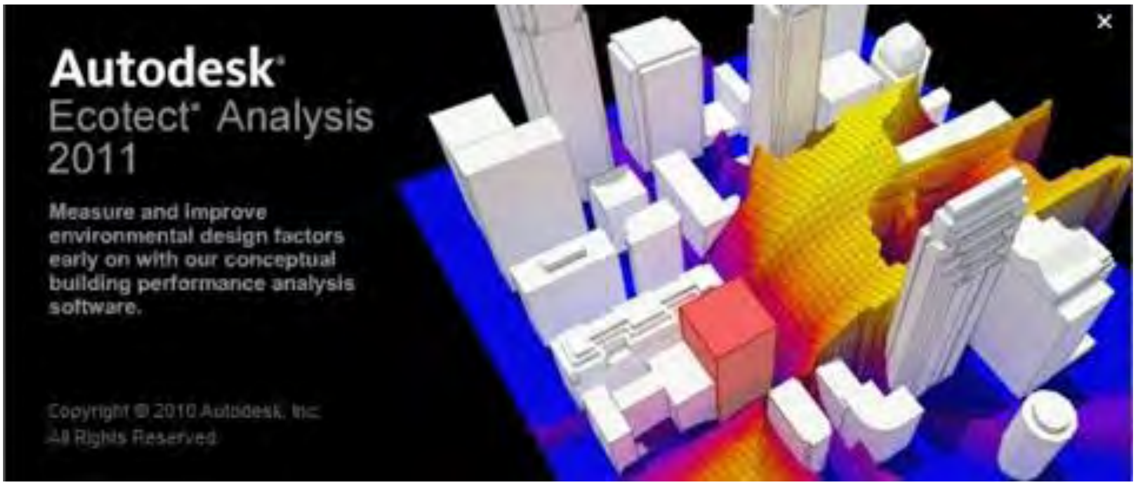

Figure A1: Detail Interface of ECOTECT simulation software

Thermal performance analysis in Autodesk ECOTECT is based on the Chartered Institution of Building Services Engineers (CIBSE) admittance method and thus inherits its limitations. Hence, the need to use more detailed thermal simulation tools during the final stage of a building design or research project. For daylighting performance analysis, ECOTECT software is used to obtain illuminance levels and daylight factor (DF) for glazing. It is an environmental assessment tool that allows simulating a model in terms of thermal, acoustic and lighting, having several detailed analysis functions with a visual and interactive display that presents test results directly within the context of the model of the building.

ECOTECT 5.6 tool offers a range of lighting analysis options. The main focus is on daylighting analysis. It implements the Building Research Establishments (BRE) split flux method for determining the natural light levels at points within a model. This is based on the Daylight Factor concept which is a ratio of the illuminance at a particular point within an enclosure to the simultaneous unobstructed outdoor illuminance. Figure presents the main screen of ECOTECT for daylighting calculation.

Currently, the new version of ECOTECT software is “Autodesk ECOTECT Analysis”. It is now sustainable design analysis software with a comprehensive concept-to-detail sustainable building design tool. ECOTECT Analysis offers a wide range of simulation and building energy analysis functionality that can improve performance of existing buildings and new building designs. This new version also allows simulation types shown in older versions (thermal performance, solar radiation and daylighting) whole building energy analysis; water usage and cost evaluation; shadows and reflections. For correct assessment of the values in daylighting simulations is required to produce the climate file from "epw" file (EnergyPlus) to “. wea” file in ECOTECT 5.6. According to the latitude of the location the outside illuminance is calculated. Although the exterior illuminance obtained by software ECOTECT present differences of the real situation, it is known that such values depend on the latitude of the location and do not affect the daylight factor obtained by computational simulation.

C2: About DAYSIM software

DAYSIM v2.1

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

To derive climate-based daylighting metrics

To calculate annual electric lighting use for different lighting controls based on available daylight

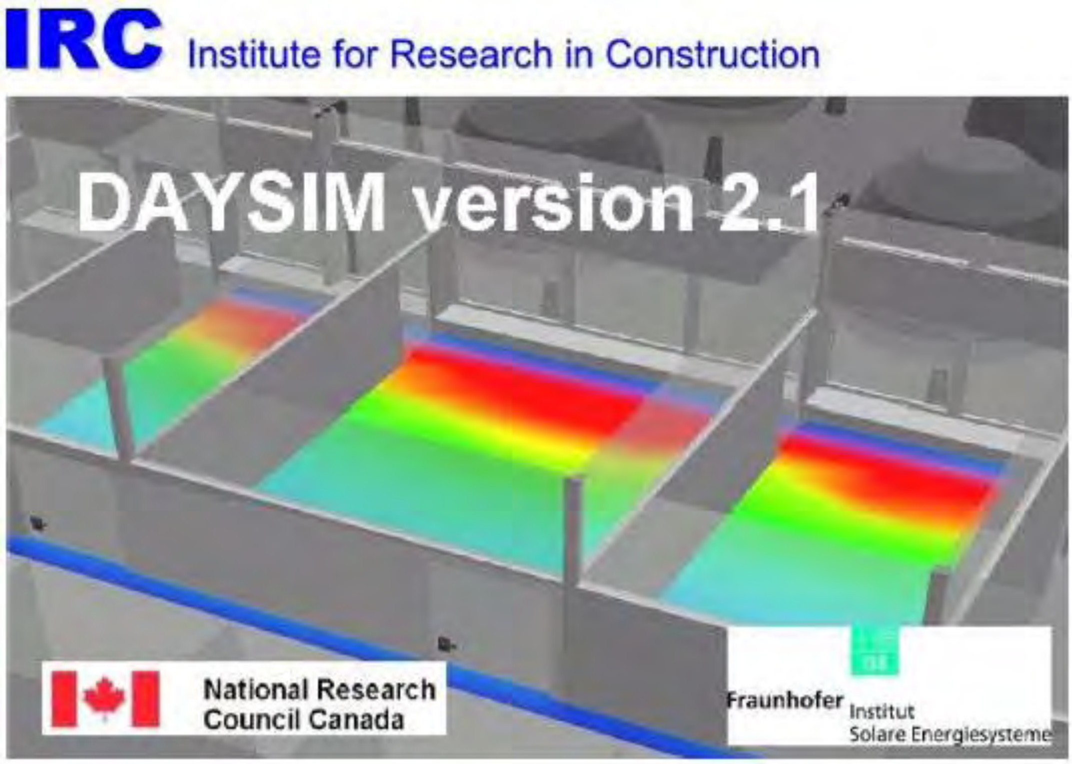

Figure A2: Detail Interface of DAYSIM simulation software.

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

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

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

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

Appendix D: Dynamic daylight simulation results

Appendix D1:
Dynamic simulation result for condition with no blind system

x	y	z	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
11.418	1.550	0.762	22.8	99	99	88	1	7	92	0	38980612
14.500	1.550	0.762	16.1	99	99	85	1	10	89	0	31135972
17.582	1.550	0.762	14.9	99	99	82	1	11	88	0	29189720
20.664	1.550	0.762	14.8	99	99	79	1	12	88	0	29064436
23.746	1.550	0.762	14.8	99	99	78	1	12	87	0	29186672
26.828	1.550	0.762	15.9	99	99	80	1	11	88	0	30529290
29.910	1.550	0.762	21.2	99	99	86	1	8	92	0	36778884
11.418	3.309	0.762	15.1	99	99	83	1	11	89	0	26804316
14.500	3.309	0.762	8.4	98	99	69	1	16	83	0	15899169
17.582	3.309	0.762	7.3	97	99	51	1	23	76	13	14114672
20.664	3.309	0.762	7.7	98	99	56	1	24	75	2	14859262
23.746	3.309	0.762	7.4	97	99	52	1	26	72	10	14256932
26.828	3.309	0.762	8.2	98	99	58	1	25	75	0	15629059
29.910	3.309	0.762	15.3	99	99	76	1	12	87	0	25748076
5.255	5.068	0.762	16.5	99	99	83	1	11	89	0	27282672
8.336	5.068	0.762	11.9	98	99	79	1	13	86	0	22328534
11.418	5.068	0.762	6.9	97	99	36	1	27	72	44	12231756
14.500	5.068	0.762	3.9	95	98	5	1	63	36	95	6147518
17.582	5.068	0.762	3.9	96	98	2	1	64	35	97	6108911
20.664	5.068	0.762	1.7	86	93	0	4	96	0	93	2846366
23.746	5.068	0.762	4.3	96	98	6	1	55	43	98	6621012
26.828	5.068	0.762	4.7	96	98	5	1	48	50	98	7088180
29.910	5.068	0.762	13.0	99	99	66	1	20	79	0	19822136
5.255	6.827	0.762	14.8	99	99	84	1	11	89	0	22083752
8.336	6.827	0.762	6.5	97	99	45	1	22	77	68	9745569
11.418	6.827	0.762	3.8	96	98	6	1	71	28	93	5991212
14.500	6.827	0.762	2.5	93	97	0	2	97	1	96	4032012
17.582	6.827	0.762	2.2	91	96	0	3	97	0	95	3597591
20.664	6.827	0.762	2.0	89	95	0	3	97	0	94	3253483
23.746	6.827	0.762	2.7	92	97	0	2	97	1	96	4304179
26.828	6.827	0.762	4.0	95	98	0	1	68	31	91	6434270
29.910	6.827	0.762	11.5	98	99	56	1	26	73	0	17947136
5.255	8.586	0.762	12.7	99	99	76	1	12	87	0	19572864
8.336	8.586	0.762	4.3	96	98	8	1	50	48	98	6827832
11.418	8.586	0.762	2.6	93	97	0	2	96	1	95	4102751
14.500	8.586	0.762	1.9	90	95	0	3	97	0	93	3001443
17.582	8.586	0.762	1.5	86	94	0	4	96	0	92	2446421
20.664	8.586	0.762	1.4	85	93	0	4	96	0	91	2326977
23.746	8.586	0.762	1.9	88	95	0	3	97	0	94	3173748
26.828	8.586	0.762	3.2	93	97	0	2	88	11	90	5383012
29.910	8.586	0.762	10.6	98	99	51	1	30	69	2	17054684
5.255	10.345	0.762	8.6	98	99	53	1	18	81	32	15020940
8.336	10.345	0.762	2.9	95	97	2	2	89	9	96	4754717
11.418	10.345	0.762	1.9	90	95	0	3	97	0	93	3025695
14.500	10.345	0.762	1.3	85	93	0	4	96	0	89	2117242
17.582	10.345	0.762	1.2	83	92	0	4	96	0	88	1967250
20.664	10.345	0.762	1.2	84	92	0	4	96	0	89	2056986
23.746	10.345	0.762	1.4	84	93	0	4	96	0	91	2405816
26.828	10.345	0.762	2.7	92	96	0	2	95	3	90	4703918
29.910	10.345	0.762	7.1	97	98	36	1	44	55	24	13370095
8.336	12.104	0.762	0.8	67	86	0	8	92	0	66	1350803
11.418	12.104	0.762	1.2	85	93	0	4	96	0	85	2028181
14.500	12.104	0.762	1.1	83	92	0	5	95	0	87	1862442
17.582	12.104	0.762	1.0	81	91	0	5	95	0	85	1712868
20.664	12.104	0.762	0.0	0	0	0	100	0	0	0	1964
23.746	12.104	0.762	0.9	73	89	0	6	94	0	84	1656086

Appendix D2

Dynamic simulation result for Inverted V slat geometry in South orientation

x	y	z	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
11.418	**1.550**	**0.762**	16.4	99	99	84	1	10	89	0	25420378
14.500	**1.550**	**0.762**	5.4	97	98	40	1	28	71	84	9186818
17.582	**1.550**	**0.762**	4.3	96	98	20	1	49	50	89	7220796
20.664	**1.550**	**0.762**	3.9	95	97	17	1	57	42	90	6690949
23.746	**1.550**	**0.762**	3.9	94	97	15	1	55	44	91	6688627
26.828	**1.550**	**0.762**	5.3	96	98	32	1	38	61	84	8660469
29.910	**1.550**	**0.762**	12.1	98	99	67	1	20	79	0	17168798
11.418	**3.309**	**0.762**	12.5	98	99	73	1	13	86	0	21003104
14.500	**3.309**	**0.762**	4.3	96	98	7	1	51	47	97	6836327
17.582	**3.309**	**0.762**	2.8	93	97	0	2	92	6	96	4351795
20.664	**3.309**	**0.762**	2.8	93	97	0	2	88	10	96	4437699
23.746	**3.309**	**0.762**	2.8	92	96	0	2	90	8	96	4441901
26.828	**3.309**	**0.762**	3.8	94	97	0	2	68	31	92	6087514
29.910	**3.309**	**0.762**	12.3	98	99	62	1	22	77	0	18929508
5.255	**5.068**	**0.762**	10.2	98	99	60	1	17	82	51	13560344
8.336	**5.068**	**0.762**	4.4	96	98	5	1	51	48	97	6593949
11.418	**5.068**	**0.762**	2.2	90	96	0	3	97	0	94	3506907
14.500	**5.068**	**0.762**	2.2	90	96	1	3	93	4	94	3566985
17.582	**5.068**	**0.762**	1.9	89	95	0	3	97	0	93	2946835
20.664	**5.068**	**0.762**	1.0	77	90	0	6	94	0	83	1659642
23.746	**5.068**	**0.762**	2.3	90	96	0	3	97	0	95	3576617
26.828	**5.068**	**0.762**	3.0	92	96	0	2	96	2	96	4520765
29.910	**5.068**	**0.762**	11.4	98	99	53	1	28	71	0	17644856
5.255	**6.827**	**0.762**	12.5	98	99	71	1	12	87	6	18736460
8.336	**6.827**	**0.762**	3.9	96	98	6	1	71	27	97	5858180
11.418	**6.827**	**0.762**	1.8	90	95	0	3	96	0	92	2946925
14.500	**6.827**	**0.762**	1.2	84	92	0	4	96	0	85	1949602
17.582	**6.827**	**0.762**	1.1	82	91	0	5	95	0	82	1749062
20.664	**6.827**	**0.762**	1.0	73	89	0	6	94	0	83	1598699
23.746	**6.827**	**0.762**	1.6	86	93	0	4	96	0	92	2581800
26.828	**6.827**	**0.762**	3.2	92	96	0	2	90	8	90	5147323
29.910	**6.827**	**0.762**	10.8	98	99	50	1	30	69	4	16933524
5.255	**8.586**	**0.762**	12.3	98	99	69	1	13	86	7	18761708
8.336	**8.586**	**0.762**	3.2	95	97	5	2	78	20	96	5185816
11.418	**8.586**	**0.762**	1.5	87	94	0	4	96	0	88	2342522
14.500	**8.586**	**0.762**	1.0	81	91	0	6	94	0	75	1567450
17.582	**8.586**	**0.762**	0.8	72	87	0	8	92	0	51	1252000
20.664	**8.586**	**0.762**	0.9	72	89	0	6	94	0	78	1494709
23.746	**8.586**	**0.762**	1.3	76	90	0	5	95	0	87	2157816
26.828	**8.586**	**0.762**	2.7	91	96	0	2	94	4	90	4633943
29.910	**8.586**	**0.762**	10.2	98	99	48	1	32	67	8	16379770
5.255	**10.345**	**0.762**	8.1	98	99	47	1	25	74	42	14202897
8.336	**10.345**	**0.762**	2.2	92	96	2	3	92	5	94	3673690
11.418	**10.345**	**0.762**	1.0	83	92	0	5	95	0	74	1742183
14.500	**10.345**	**0.762**	0.8	77	89	0	7	93	0	57	1342933
17.582	**10.345**	**0.762**	0.6	47	81	0	11	89	0	1	992636
20.664	**10.345**	**0.762**	0.7	57	83	0	10	90	0	37	1178246
23.746	**10.345**	**0.762**	1.0	70	88	0	7	93	0	80	1724341
26.828	**10.345**	**0.762**	2.3	90	96	0	3	97	1	90	4074271
29.910	**10.345**	**0.762**	6.7	96	98	33	1	48	51	28	12738950
8.336	**12.104**	**0.762**	0.5	2	65	0	16	84	0	0	724075
11.418	**12.104**	**0.762**	0.7	61	86	0	8	92	0	25	1141690
14.500	**12.104**	**0.762**	0.6	57	84	0	9	91	0	18	1056632
17.582	**12.104**	**0.762**	0.6	42	81	0	10	90	0	0	963621
20.664	**12.104**	**0.762**	0.0	0	0	0	100	0	0	0	3
23.746	**12.104**	**0.762**	0.6	40	77	0	12	88	0	7	1026090

Appendix D3:

Dynamic simulation result for Inverted V slat geometry in West orientation

x	y	z	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
11.418	1.550	0.762	12.5	99	99	78	1	13	86	0	24019468
14.500	1.550	0.762	14.7	99	99	80	1	12	88	0	29092960
17.582	1.550	0.762	14.6	99	99	78	1	12	87	0	28803556
20.664	1.550	0.762	14.7	99	99	79	1	12	87	0	28976408
23.746	1.550	0.762	14.8	99	99	78	1	12	87	0	29198304
26.828	1.550	0.762	15.8	99	99	80	1	11	88	0	30489824
29.910	1.550	0.762	21.2	99	99	86	1	8	92	0	36812076
11.418	3.309	0.762	7.2	97	99	57	1	21	78	19	13377879
14.500	3.309	0.762	7.1	97	99	49	1	25	74	16	13778844
17.582	3.309	0.762	7.0	97	99	47	1	28	71	17	13605438
20.664	3.309	0.762	7.7	98	99	55	1	25	74	2	14839737
23.746	3.309	0.762	7.5	97	99	52	1	27	72	9	14313628
26.828	3.309	0.762	8.2	98	99	58	1	25	74	0	15563777
29.910	3.309	0.762	15.3	99	99	76	1	12	87	0	25682600
5.255	5.068	0.762	10.6	98	99	72	1	17	82	0	20518188
8.336	5.068	0.762	10.7	98	99	71	1	15	84	0	20787924
11.418	5.068	0.762	6.4	97	98	30	1	35	64	51	11413949
14.500	5.068	0.762	3.5	94	97	1	2	73	25	97	5364857
17.582	5.068	0.762	3.6	95	97	1	2	71	27	97	5540833
20.664	5.068	0.762	1.7	85	93	0	4	96	0	93	2845466
23.746	5.068	0.762	4.0	96	98	2	1	61	38	98	6234118
26.828	5.068	0.762	4.8	96	98	6	1	47	52	98	7160554
29.910	5.068	0.762	12.8	99	99	65	1	21	78	0	19606942
5.255	6.827	0.762	6.2	97	98	43	1	25	74	83	9540809
8.336	6.827	0.762	5.0	96	98	20	1	40	58	88	7581999
11.418	6.827	0.762	3.3	95	97	4	2	79	19	94	5302428
14.500	6.827	0.762	2.3	91	96	0	3	97	0	95	3643534
17.582	6.827	0.762	2.0	89	95	0	3	97	0	94	3154580
20.664	6.827	0.762	1.9	88	95	0	3	97	0	94	3052069
23.746	6.827	0.762	2.7	92	96	0	2	97	1	96	4306439
26.828	6.827	0.762	3.9	95	97	1	1	67	32	90	6413526
29.910	6.827	0.762	11.4	98	99	56	1	26	73	0	17853432
5.255	8.586	0.762	4.7	96	98	12	1	43	56	98	7284412
8.336	8.586	0.762	3.0	94	97	1	2	86	13	96	4856725
11.418	8.586	0.762	2.1	90	96	0	3	97	0	94	3329608
14.500	8.586	0.762	1.5	87	94	0	4	96	0	92	2536923
17.582	8.586	0.762	1.4	84	93	0	4	96	0	91	2242400
20.664	8.586	0.762	1.5	85	93	0	4	96	0	92	2447991
23.746	8.586	0.762	1.9	88	94	0	3	97	0	94	3154909
26.828	8.586	0.762	3.2	92	97	0	2	86	12	90	5403427
29.910	8.586	0.762	10.6	98	99	51	1	30	69	2	17029156
5.255	10.345	0.762	3.1	95	97	1	2	87	11	96	4939470
8.336	10.345	0.762	2.0	91	96	1	3	95	2	94	3364559
11.418	10.345	0.762	1.4	86	93	0	4	96	0	90	2244630
14.500	10.345	0.762	1.2	82	92	0	4	96	0	88	1963861
17.582	10.345	0.762	1.1	81	91	0	5	95	0	88	1848750
20.664	10.345	0.762	1.1	80	91	0	5	95	0	88	1918176
23.746	10.345	0.762	1.3	83	92	0	4	96	0	91	2312185
26.828	10.345	0.762	2.6	91	96	0	2	94	4	90	4651580
29.910	10.345	0.762	7.1	97	98	36	1	43	55	24	13346884
8.336	12.104	0.762	0.7	59	82	0	10	90	0	44	1183704
11.418	12.104	0.762	1.0	81	91	0	5	95	0	83	1749549
14.500	12.104	0.762	1.0	76	90	0	5	95	0	84	1648082
17.582	12.104	0.762	0.9	75	90	0	6	94	0	82	1578955
20.664	12.104	0.762	0.0	0	0	0	100	0	0	0	357
23.746	12.104	0.762	0.9	70	88	0	6	94	0	82	1604452

Appendix D4:

Dynamic simulation result for Inverted V slat geometry in East orientation

x	y	z	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
11.418	**1.550**	**0.762**	22.8	99	99	88	1	7	92	0	38948248
14.500	**1.550**	**0.762**	16.0	99	99	85	1	10	89	0	31021330
17.582	**1.550**	**0.762**	14.7	99	99	82	1	11	88	0	29008164
20.664	**1.550**	**0.762**	14.6	99	99	78	1	12	87	0	28837372
23.746	**1.550**	**0.762**	14.5	99	99	78	1	12	87	0	28685782
26.828	**1.550**	**0.762**	14.9	99	99	79	1	12	87	0	29290788
29.910	**1.550**	**0.762**	15.5	99	99	80	1	11	88	0	30117580
11.418	**3.309**	**0.762**	15.1	99	99	83	1	11	89	0	26779148
14.500	**3.309**	**0.762**	8.3	98	99	68	1	17	82	0	15746063
17.582	**3.309**	**0.762**	7.1	97	99	48	1	24	75	17	13804204
20.664	**3.309**	**0.762**	7.7	98	99	55	1	24	75	3	14734054
23.746	**3.309**	**0.762**	7.0	97	99	47	1	28	71	19	13655876
26.828	**3.309**	**0.762**	7.4	97	99	51	1	26	73	5	14475130
29.910	**3.309**	**0.762**	8.2	98	99	60	1	24	75	0	14786271
5.255	**5.068**	**0.762**	16.4	99	99	82	1	11	89	0	27197996
8.336	**5.068**	**0.762**	12.1	98	99	80	1	13	86	0	22531846
11.418	**5.068**	**0.762**	6.7	97	98	34	1	29	70	48	11959294
14.500	**5.068**	**0.762**	3.9	96	98	5	1	63	36	95	6213211
17.582	**5.068**	**0.762**	3.8	95	98	1	1	67	32	97	5873354
20.664	**5.068**	**0.762**	1.6	85	93	0	4	96	0	92	2608125
23.746	**5.068**	**0.762**	3.7	95	98	1	2	68	30	97	5787861
26.828	**5.068**	**0.762**	3.6	95	98	0	2	73	26	97	5603630
29.910	**5.068**	**0.762**	5.2	96	98	20	1	44	55	91	8054549
5.255	**6.827**	**0.762**	14.5	99	99	83	1	11	88	0	21789376
8.336	**6.827**	**0.762**	6.5	97	99	44	1	22	77	69	9691209
11.418	**6.827**	**0.762**	3.8	96	98	7	1	71	28	93	6029903
14.500	**6.827**	**0.762**	2.4	93	96	0	2	97	0	96	3896615
17.582	**6.827**	**0.762**	2.1	91	96	0	3	97	0	94	3454746
20.664	**6.827**	**0.762**	1.8	88	95	0	3	97	0	93	2880245
23.746	**6.827**	**0.762**	2.2	90	96	0	3	97	0	95	3518450
26.828	**6.827**	**0.762**	2.5	92	96	0	2	98	0	94	4216941
29.910	**6.827**	**0.762**	3.8	94	97	1	1	69	30	93	6135734
5.255	**8.586**	**0.762**	12.9	99	99	76	1	12	87	0	19818148
8.336	**8.586**	**0.762**	4.4	96	98	8	1	48	50	98	6944193
11.418	**8.586**	**0.762**	2.5	93	97	0	2	97	1	95	4011134
14.500	**8.586**	**0.762**	1.8	89	95	0	3	97	0	93	2915832
17.582	**8.586**	**0.762**	1.4	86	93	0	4	96	0	91	2297780
20.664	**8.586**	**0.762**	1.4	86	93	0	4	96	0	91	2311981
23.746	**8.586**	**0.762**	1.4	85	93	0	4	96	0	91	2396823
26.828	**8.586**	**0.762**	1.9	88	95	0	3	97	0	93	3325301
29.910	**8.586**	**0.762**	3.3	93	97	0	2	83	16	93	5347076
5.255	**10.345**	**0.762**	8.5	98	99	52	1	19	80	32	14920496
8.336	**10.345**	**0.762**	2.8	94	97	2	2	90	9	96	4574775
11.418	**10.345**	**0.762**	1.8	90	95	0	3	97	0	93	3011232
14.500	**10.345**	**0.762**	1.3	85	93	0	4	96	0	89	2150688
17.582	**10.345**	**0.762**	1.1	81	91	0	5	95	0	86	1758131
20.664	**10.345**	**0.762**	1.1	83	92	0	5	95	0	88	1866624
23.746	**10.345**	**0.762**	1.0	74	89	0	6	94	0	85	1690987
26.828	**10.345**	**0.762**	1.6	87	94	0	4	96	0	92	2958750
29.910	**10.345**	**0.762**	2.2	89	95	0	3	97	0	94	3640022
8.336	**12.104**	**0.762**	0.8	65	85	0	9	91	0	57	1272021
11.418	**12.104**	**0.762**	1.2	85	93	0	4	96	0	86	2070303
14.500	**12.104**	**0.762**	1.1	83	92	0	5	95	0	85	1804904
17.582	**12.104**	**0.762**	0.9	78	90	0	5	95	0	83	1600689
20.664	**12.104**	**0.762**	0.0	0	0	0	100	0	0	0	2057
23.746	**12.104**	**0.762**	0.8	65	86	0	7	93	0	65	1362093

Appendix D5:

Dynamic simulation result for 45[0] vertex angle Inverted V slat geometry in South orientation

x	y	z	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
11.418	**1.550**	**0.762**	15.0	99	99	73	1	12	87	0	22808620
14.500	**1.550**	**0.762**	3.3	94	97	7	2	83	15	96	5160107
17.582	**1.550**	**0.762**	1.7	88	94	0	4	96	0	92	2601366
20.664	**1.550**	**0.762**	1.7	86	94	0	4	96	0	92	2523701
23.746	**1.550**	**0.762**	1.9	87	94	0	3	97	0	94	2889019
26.828	**1.550**	**0.762**	3.3	92	96	0	2	93	5	97	4747705
29.910	**1.550**	**0.762**	10.2	98	99	44	1	31	68	38	13514959
11.418	**3.309**	**0.762**	11.4	98	99	61	1	19	80	8	19222632
14.500	**3.309**	**0.762**	2.6	93	97	3	2	88	10	94	4040408
17.582	**3.309**	**0.762**	1.1	83	92	0	5	95	0	77	1771866
20.664	**3.309**	**0.762**	0.9	75	88	0	8	92	0	71	1421438
23.746	**3.309**	**0.762**	1.3	79	91	0	5	95	0	87	2069946
26.828	**3.309**	**0.762**	2.4	88	95	0	3	97	0	92	3768637
29.910	**3.309**	**0.762**	11.1	98	99	50	1	30	69	4	17023496
5.255	**5.068**	**0.762**	7.6	97	98	23	1	44	55	83	9757876
8.336	**5.068**	**0.762**	2.5	91	96	1	3	94	4	94	3500416
11.418	**5.068**	**0.762**	1.4	85	93	0	4	96	0	80	2104976
14.500	**5.068**	**0.762**	1.1	79	90	0	5	92	2	62	1791925
17.582	**5.068**	**0.762**	0.8	67	87	0	8	92	0	21	1177529
20.664	**5.068**	**0.762**	0.6	24	76	0	12	88	0	3	951606
23.746	**5.068**	**0.762**	1.1	71	88	0	7	93	0	77	1738163
26.828	**5.068**	**0.762**	2.2	87	94	0	4	96	0	94	3154883
29.910	**5.068**	**0.762**	11.1	98	99	50	1	30	68	4	17091804
5.255	**6.827**	**0.762**	10.1	98	99	50	1	22	77	38	15072285
8.336	**6.827**	**0.762**	2.4	92	96	2	3	89	8	93	3688785
11.418	**6.827**	**0.762**	1.1	78	90	0	5	94	0	58	1614648
14.500	**6.827**	**0.762**	0.6	42	81	0	10	90	0	7	994852
17.582	**6.827**	**0.762**	0.6	22	77	0	10	90	0	0	946799
20.664	**6.827**	**0.762**	0.6	25	76	0	12	88	0	2	922957
23.746	**6.827**	**0.762**	1.0	68	87	0	7	93	0	70	1644266
26.828	**6.827**	**0.762**	2.7	90	95	0	2	94	4	90	4396525
29.910	**6.827**	**0.762**	10.7	98	99	48	1	32	67	7	16540300
5.255	**8.586**	**0.762**	9.7	98	99	49	1	24	75	39	14886254
8.336	**8.586**	**0.762**	2.2	92	96	2	3	89	8	91	3572524
11.418	**8.586**	**0.762**	0.9	74	89	0	6	94	0	44	1450022
14.500	**8.586**	**0.762**	0.5	17	69	0	12	88	0	0	787219
17.582	**8.586**	**0.762**	0.4	0	59	0	16	84	0	0	686550
20.664	**8.586**	**0.762**	0.5	15	72	0	13	87	0	1	889537
23.746	**8.586**	**0.762**	0.9	60	84	0	8	92	0	55	1586076
26.828	**8.586**	**0.762**	2.5	89	95	0	3	95	2	90	4181137
29.910	**8.586**	**0.762**	9.9	98	99	45	1	35	64	10	15977770
5.255	**10.345**	**0.762**	6.4	97	98	31	1	44	55	53	11282555
8.336	**10.345**	**0.762**	1.6	88	94	1	4	93	3	82	2601759
11.418	**10.345**	**0.762**	0.7	47	82	0	9	91	0	12	1114343
14.500	**10.345**	**0.762**	0.4	2	58	0	15	85	0	0	642402
17.582	**10.345**	**0.762**	0.3	0	47	0	19	81	0	0	558293
20.664	**10.345**	**0.762**	0.4	5	60	0	17	83	0	0	754256
23.746	**10.345**	**0.762**	0.7	41	76	0	12	88	0	32	1246379
26.828	**10.345**	**0.762**	2.0	86	94	0	3	96	0	89	3506184
29.910	**10.345**	**0.762**	6.6	95	98	32	1	50	49	29	12435059
8.336	**12.104**	**0.762**	0.2	0	31	0	52	48	0	0	348902
11.418	**12.104**	**0.762**	0.4	11	62	0	14	86	0	0	720776
14.500	**12.104**	**0.762**	0.3	1	51	0	17	83	0	0	579318
17.582	**12.104**	**0.762**	0.3	0	40	0	25	75	0	0	474428
20.664	**12.104**	**0.762**	0.0	0	0	0	100	0	0	0	0
23.746	**12.104**	**0.762**	0.3	0	48	0	26	74	0	4	646485

Appendix D6:

Dynamic simulation result for 45^0 vertex angle Inverted V slat geometry in West orientation

x	y	z	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
11.418	**1.550**	**0.762**	11.2	98	99	64	1	22	77	0	22106136
14.500	**1.550**	**0.762**	14.6	99	99	77	1	13	87	0	28842132
17.582	**1.550**	**0.762**	14.5	99	99	78	1	12	87	0	28688398
20.664	**1.550**	**0.762**	14.4	99	99	78	1	12	87	0	28692002
23.746	**1.550**	**0.762**	14.8	99	99	78	1	12	87	0	29089336
26.828	**1.550**	**0.762**	15.9	99	99	80	1	11	88	0	30476290
29.910	**1.550**	**0.762**	21.2	99	99	86	1	8	92	0	36755896
11.418	**3.309**	**0.762**	5.9	97	98	32	1	37	62	46	11428416
14.500	**3.309**	**0.762**	6.9	97	98	45	1	30	69	18	13408233
17.582	**3.309**	**0.762**	6.9	97	99	45	1	29	70	19	13475931
20.664	**3.309**	**0.762**	7.7	98	99	54	1	25	74	4	14710383
23.746	**3.309**	**0.762**	7.2	97	99	50	1	27	72	12	14038067
26.828	**3.309**	**0.762**	8.1	98	99	58	1	25	74	0	15538009
29.910	**3.309**	**0.762**	15.4	99	99	76	1	12	87	0	25692948
5.255	**5.068**	**0.762**	9.2	98	99	54	1	27	72	0	18242576
8.336	**5.068**	**0.762**	10.3	98	99	67	1	19	80	0	20120248
11.418	**5.068**	**0.762**	6.0	97	98	25	1	40	59	53	10861689
14.500	**5.068**	**0.762**	3.3	93	97	0	2	76	22	97	5098217
17.582	**5.068**	**0.762**	3.5	94	97	1	2	72	26	97	5479574
20.664	**5.068**	**0.762**	1.7	84	93	0	4	96	0	93	2741981
23.746	**5.068**	**0.762**	4.1	96	98	4	1	58	40	98	6412276
26.828	**5.068**	**0.762**	4.7	96	98	6	1	48	51	98	7062119
29.910	**5.068**	**0.762**	12.5	98	99	64	1	21	78	0	19381630
5.255	**6.827**	**0.762**	4.1	94	97	13	1	66	32	92	6208559
8.336	**6.827**	**0.762**	4.3	95	98	13	1	62	36	93	6369152
11.418	**6.827**	**0.762**	3.2	95	97	4	2	81	17	94	5015851
14.500	**6.827**	**0.762**	2.0	89	95	0	3	97	0	94	3253370
17.582	**6.827**	**0.762**	2.0	89	95	0	3	97	0	94	3201661
20.664	**6.827**	**0.762**	1.9	88	95	0	3	97	0	94	3132701
23.746	**6.827**	**0.762**	2.6	91	96	0	2	97	1	96	4196965
26.828	**6.827**	**0.762**	4.0	95	98	1	1	66	33	90	6499186
29.910	**6.827**	**0.762**	11.4	98	99	56	1	26	73	0	17839856
5.255	**8.586**	**0.762**	2.5	91	96	0	2	97	1	96	3760274
8.336	**8.586**	**0.762**	2.2	89	95	0	3	96	1	94	3383853
11.418	**8.586**	**0.762**	1.9	89	95	0	3	97	0	94	3112828
14.500	**8.586**	**0.762**	1.5	86	94	0	4	96	0	92	2435224
17.582	**8.586**	**0.762**	1.4	83	92	0	4	96	0	91	2205877
20.664	**8.586**	**0.762**	1.5	86	93	0	4	96	0	92	2450163
23.746	**8.586**	**0.762**	1.9	88	94	0	3	97	0	94	3159367
26.828	**8.586**	**0.762**	3.2	92	97	0	2	86	12	90	5427876
29.910	**8.586**	**0.762**	10.6	98	99	51	1	30	69	2	16983666
5.255	**10.345**	**0.762**	1.7	86	94	0	4	96	0	93	2633172
8.336	**10.345**	**0.762**	1.3	82	92	0	5	95	0	89	2062777
11.418	**10.345**	**0.762**	1.3	83	92	0	4	96	0	88	2086537
14.500	**10.345**	**0.762**	1.0	74	90	0	5	95	0	84	1683828
17.582	**10.345**	**0.762**	1.1	77	90	0	5	95	0	86	1765340
20.664	**10.345**	**0.762**	1.1	76	90	0	5	95	0	88	1872776
23.746	**10.345**	**0.762**	1.4	84	92	0	4	96	0	91	2387620
26.828	**10.345**	**0.762**	2.8	92	96	0	2	92	6	90	4826641
29.910	**10.345**	**0.762**	7.1	97	98	36	1	44	55	24	13366134
8.336	**12.104**	**0.762**	0.7	53	80	0	11	89	0	37	1121704
11.418	**12.104**	**0.762**	0.8	69	87	0	7	93	0	66	1411527
14.500	**12.104**	**0.762**	0.9	70	88	0	7	93	0	75	1473085
17.582	**12.104**	**0.762**	0.9	71	88	0	6	94	0	77	1503371
20.664	**12.104**	**0.762**	0.0	0	0	0	100	0	0	0	1943
23.746	**12.104**	**0.762**	0.9	69	87	0	7	93	0	80	1565191

Appendix D7:

Dynamic simulation result for 45^0 vertex angle Inverted V slat geometry in East orientation

x	y	z	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
11.418	1.550	0.762	22.8	99	99	88	1	7	92	0	38907084
14.500	1.550	0.762	15.9	99	99	85	1	10	89	0	30901954
17.582	1.550	0.762	14.7	99	99	81	1	11	88	0	28982584
20.664	1.550	0.762	14.5	99	99	78	1	12	87	0	28700670
23.746	1.550	0.762	14.3	99	99	78	1	12	87	0	28420130
26.828	1.550	0.762	14.5	99	99	78	1	12	87	0	28643642
29.910	1.550	0.762	14.7	99	99	80	1	11	88	0	28688892
11.418	3.309	0.762	15.2	99	99	84	1	11	89	0	26860848
14.500	3.309	0.762	8.1	98	99	67	1	17	82	0	15469984
17.582	3.309	0.762	7.0	97	99	48	1	24	75	19	13715194
20.664	3.309	0.762	7.4	98	99	52	1	24	75	8	14380403
23.746	3.309	0.762	7.0	97	99	46	1	28	71	19	13600153
26.828	3.309	0.762	6.9	97	99	45	1	29	70	20	13413560
29.910	3.309	0.762	6.7	97	99	39	1	28	71	36	12263792
5.255	5.068	0.762	15.2	99	99	81	1	12	88	0	25634824
8.336	5.068	0.762	11.8	98	99	78	1	14	86	0	22102336
11.418	5.068	0.762	6.7	97	98	34	1	29	70	47	11983270
14.500	5.068	0.762	3.9	95	98	5	1	64	34	95	6125714
17.582	5.068	0.762	3.7	95	98	1	2	70	28	97	5664852
20.664	5.068	0.762	1.4	83	92	0	4	96	0	91	2340064
23.746	5.068	0.762	3.5	95	97	0	2	73	25	97	5420551
26.828	5.068	0.762	3.1	95	97	0	2	81	17	97	4797839
29.910	5.068	0.762	3.4	95	97	0	2	81	17	97	5102112
5.255	6.827	0.762	12.9	99	99	80	1	12	88	0	19267796
8.336	6.827	0.762	6.1	97	98	36	1	25	74	76	9061600
11.418	6.827	0.762	3.6	95	98	5	2	75	23	93	5731870
14.500	6.827	0.762	2.4	92	96	0	2	97	0	95	3771181
17.582	6.827	0.762	1.9	89	95	0	3	97	0	94	3105505
20.664	6.827	0.762	1.7	88	94	0	3	97	0	93	2790268
23.746	6.827	0.762	2.0	89	95	0	3	97	0	94	3169794
26.828	6.827	0.762	1.8	88	95	0	3	97	0	93	2771806
29.910	6.827	0.762	2.1	90	96	0	3	97	0	94	3190502
5.255	8.586	0.762	11.0	98	99	68	1	14	85	12	16980562
8.336	8.586	0.762	3.9	96	98	4	1	60	38	97	6190142
11.418	8.586	0.762	2.3	92	96	0	3	97	0	95	3730622
14.500	8.586	0.762	1.6	88	95	0	4	96	0	92	2641646
17.582	8.586	0.762	1.3	85	93	0	4	96	0	90	2161414
20.664	8.586	0.762	1.3	84	92	0	4	96	0	89	2086259
23.746	8.586	0.762	1.2	82	92	0	5	95	0	88	2079613
26.828	8.586	0.762	1.3	84	93	0	4	96	0	87	2068587
29.910	8.586	0.762	1.6	87	94	0	4	96	0	92	2412114
5.255	10.345	0.762	7.5	97	99	43	1	25	74	47	13068488
8.336	10.345	0.762	2.6	94	97	1	2	93	5	95	4272354
11.418	10.345	0.762	1.7	90	95	0	3	97	0	93	2815622
14.500	10.345	0.762	1.3	85	93	0	4	96	0	89	2061086
17.582	10.345	0.762	1.1	82	91	0	5	95	0	83	1734412
20.664	10.345	0.762	1.0	79	90	0	5	95	0	78	1587629
23.746	10.345	0.762	0.8	67	87	0	7	93	0	71	1426875
26.828	10.345	0.762	1.0	79	91	0	5	95	0	81	1670817
29.910	10.345	0.762	1.2	83	92	0	4	96	0	86	1880146
8.336	12.104	0.762	0.7	60	83	0	10	90	0	39	1139298
11.418	12.104	0.762	1.1	83	92	0	5	95	0	81	1838864
14.500	12.104	0.762	1.0	81	91	0	5	95	0	80	1674965
17.582	12.104	0.762	0.9	77	90	0	6	94	0	74	1505144
20.664	12.104	0.762	0.0	0	0	0	100	0	0	0	1049
23.746	12.104	0.762	0.7	62	85	0	8	92	0	50	1257594

Appendix D8:

Dynamic simulation result for 160mm separation distance in South orientation

x	y	z	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
11.418	**1.550**	**0.762**	15.3	99	99	76	1	11	88	0	23375600
14.500	**1.550**	**0.762**	3.9	96	98	8	1	67	32	97	6271858
17.582	**1.550**	**0.762**	2.3	90	96	0	3	97	0	95	3574530
20.664	**1.550**	**0.762**	2.2	89	95	0	3	97	0	95	3395330
23.746	**1.550**	**0.762**	2.3	90	95	0	3	97	0	95	3680034
26.828	**1.550**	**0.762**	3.9	94	97	0	2	71	28	98	5781616
29.910	**1.550**	**0.762**	10.6	98	99	51	1	28	71	25	14231631
11.418	**3.309**	**0.762**	11.7	98	99	64	1	16	83	4	19807802
14.500	**3.309**	**0.762**	3.1	95	97	4	2	81	17	96	4924551
17.582	**3.309**	**0.762**	1.5	87	94	0	4	96	0	90	2374955
20.664	**3.309**	**0.762**	1.6	87	94	0	4	96	0	92	2492118
23.746	**3.309**	**0.762**	1.9	88	94	0	3	97	0	94	3057829
26.828	**3.309**	**0.762**	3.1	92	96	0	2	93	5	92	4835636
29.910	**3.309**	**0.762**	11.4	98	99	53	1	28	71	0	17514022
5.255	**5.068**	**0.762**	8.2	97	99	31	1	30	69	79	10734263
8.336	**5.068**	**0.762**	2.9	93	97	1	2	94	4	96	4244679
11.418	**5.068**	**0.762**	1.6	87	94	0	4	96	0	88	2487594
14.500	**5.068**	**0.762**	1.4	85	93	1	4	93	2	89	2355165
17.582	**5.068**	**0.762**	1.1	82	91	0	5	95	0	78	1669468
20.664	**5.068**	**0.762**	0.7	49	80	0	11	89	0	18	1110031
23.746	**5.068**	**0.762**	1.7	86	94	0	4	96	0	93	2646183
26.828	**5.068**	**0.762**	2.6	91	96	0	3	97	0	95	3777146
29.910	**5.068**	**0.762**	11.3	98	99	51	1	29	70	1	17339822
5.255	**6.827**	**0.762**	10.2	98	99	53	1	21	78	37	15223558
8.336	**6.827**	**0.762**	2.7	93	97	3	2	88	9	95	4079924
11.418	**6.827**	**0.762**	1.3	85	93	0	4	96	0	81	2091739
14.500	**6.827**	**0.762**	0.8	76	89	0	7	93	0	48	1316497
17.582	**6.827**	**0.762**	0.8	75	88	0	7	93	0	55	1346665
20.664	**6.827**	**0.762**	0.8	67	87	0	8	92	0	59	1319443
23.746	**6.827**	**0.762**	1.2	73	89	0	7	93	0	82	1877525
26.828	**6.827**	**0.762**	2.9	91	96	0	2	93	5	90	4664200
29.910	**6.827**	**0.762**	10.7	98	99	49	1	31	68	6	16661561
5.255	**8.586**	**0.762**	10.0	98	99	53	1	22	77	36	15343231
8.336	**8.586**	**0.762**	2.5	93	97	2	2	88	9	94	3928870
11.418	**8.586**	**0.762**	1.1	83	92	0	5	95	0	70	1786683
14.500	**8.586**	**0.762**	0.6	43	81	0	10	90	0	1	960084
17.582	**8.586**	**0.762**	0.6	38	79	0	11	89	0	0	939205
20.664	**8.586**	**0.762**	0.7	54	82	0	10	90	0	19	1115713
23.746	**8.586**	**0.762**	1.1	72	89	0	6	94	0	79	1854576
26.828	**8.586**	**0.762**	2.5	89	95	0	2	96	1	90	4187082
29.910	**8.586**	**0.762**	10.1	98	99	46	1	34	65	10	16160375
5.255	**10.345**	**0.762**	6.4	97	98	31	1	42	57	53	11413940
8.336	**10.345**	**0.762**	1.7	90	95	1	3	93	4	88	2886719
11.418	**10.345**	**0.762**	0.8	70	88	0	7	93	0	33	1314249
14.500	**10.345**	**0.762**	0.6	28	79	0	10	90	0	0	899855
17.582	**10.345**	**0.762**	0.5	1	65	0	14	86	0	0	756615
20.664	**10.345**	**0.762**	0.6	28	75	0	12	88	0	3	945455
23.746	**10.345**	**0.762**	0.9	63	85	0	8	92	0	60	1554668
26.828	**10.345**	**0.762**	2.1	88	95	0	3	97	0	89	3745308
29.910	**10.345**	**0.762**	6.6	96	98	32	1	49	50	29	12514730
8.336	**12.104**	**0.762**	0.3	0	44	0	23	77	0	0	498777
11.418	**12.104**	**0.762**	0.5	15	70	0	12	88	0	0	811781
14.500	**12.104**	**0.762**	0.4	1	63	0	14	86	0	0	700613
17.582	**12.104**	**0.762**	0.4	1	61	0	14	86	0	0	718383
20.664	**12.104**	**0.762**	0.0	0	0	0	100	0	0	0	0
23.746	**12.104**	**0.762**	0.5	20	70	0	14	86	0	5	905530

Appendix D9:

Dynamic simulation result for 70mm separation distance in West orientation

x	y	z	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
11.418	**1.550**	**0.762**	11.2	98	99	62	1	23	76	0	22018412
14.500	**1.550**	**0.762**	14.6	99	99	77	1	13	86	0	28763520
17.582	**1.550**	**0.762**	14.4	99	99	77	1	13	87	0	28559980
20.664	**1.550**	**0.762**	14.6	99	99	78	1	12	87	0	28807516
23.746	**1.550**	**0.762**	14.8	99	99	78	1	12	87	0	29132116
26.828	**1.550**	**0.762**	15.8	99	99	79	1	11	88	0	30402038
29.910	**1.550**	**0.762**	21.0	99	99	86	1	8	92	0	36637288
11.418	**3.309**	**0.762**	5.8	97	98	32	1	40	59	43	11358299
14.500	**3.309**	**0.762**	6.7	97	99	43	1	31	68	19	13188127
17.582	**3.309**	**0.762**	7.0	97	99	46	1	29	70	17	13572228
20.664	**3.309**	**0.762**	7.7	98	99	55	1	25	74	3	14716314
23.746	**3.309**	**0.762**	7.2	97	99	50	1	28	71	12	14041581
26.828	**3.309**	**0.762**	8.2	98	99	58	1	25	74	0	15546432
29.910	**3.309**	**0.762**	15.3	99	99	76	1	12	87	0	25724444
5.255	**5.068**	**0.762**	9.0	98	99	52	1	28	71	0	17904930
8.336	**5.068**	**0.762**	10.3	98	99	67	1	20	80	0	20090248
11.418	**5.068**	**0.762**	5.9	97	98	25	1	42	57	54	10731599
14.500	**5.068**	**0.762**	3.3	93	97	0	2	76	23	97	5084492
17.582	**5.068**	**0.762**	3.5	94	97	1	2	73	26	97	5383386
20.664	**5.068**	**0.762**	1.6	84	92	0	5	95	0	92	2665825
23.746	**5.068**	**0.762**	3.9	96	98	2	1	61	37	98	6188173
26.828	**5.068**	**0.762**	4.7	96	98	5	1	49	50	98	7056483
29.910	**5.068**	**0.762**	12.7	99	99	65	1	21	79	0	19532386
5.255	**6.827**	**0.762**	3.8	94	97	11	1	70	28	92	5840788
8.336	**6.827**	**0.762**	4.4	95	98	14	1	59	40	92	6501400
11.418	**6.827**	**0.762**	3.1	94	97	4	2	82	16	94	4850692
14.500	**6.827**	**0.762**	2.2	90	96	0	3	97	0	95	3455237
17.582	**6.827**	**0.762**	2.0	88	95	0	3	97	0	94	3142749
20.664	**6.827**	**0.762**	1.9	88	95	0	3	97	0	94	3076359
23.746	**6.827**	**0.762**	2.6	91	96	0	2	97	0	96	4096222
26.828	**6.827**	**0.762**	4.0	95	98	1	1	66	33	90	6482035
29.910	**6.827**	**0.762**	11.5	98	99	57	1	25	74	0	17903908
5.255	**8.586**	**0.762**	2.3	90	95	0	3	97	1	95	3484049
8.336	**8.586**	**0.762**	2.3	90	95	0	3	96	2	95	3506033
11.418	**8.586**	**0.762**	1.8	88	95	0	3	97	0	93	2842996
14.500	**8.586**	**0.762**	1.4	86	93	0	4	96	0	91	2387909
17.582	**8.586**	**0.762**	1.4	84	93	0	4	96	0	91	2257112
20.664	**8.586**	**0.762**	1.4	84	92	0	4	96	0	91	2302823
23.746	**8.586**	**0.762**	1.9	88	94	0	3	97	0	94	3145673
26.828	**8.586**	**0.762**	3.3	92	97	0	2	85	13	90	5475634
29.910	**8.586**	**0.762**	10.5	98	99	51	1	30	70	3	16931700
5.255	**10.345**	**0.762**	1.6	85	93	0	4	96	0	92	2458545
8.336	**10.345**	**0.762**	1.4	84	92	0	4	96	0	91	2213924
11.418	**10.345**	**0.762**	1.3	82	92	0	4	96	0	89	2047014
14.500	**10.345**	**0.762**	1.1	80	91	0	5	95	0	87	1868559
17.582	**10.345**	**0.762**	1.0	76	90	0	5	95	0	86	1722291
20.664	**10.345**	**0.762**	1.1	75	90	0	5	95	0	88	1868476
23.746	**10.345**	**0.762**	1.4	83	92	0	4	96	0	91	2334702
26.828	**10.345**	**0.762**	2.7	91	96	0	2	94	4	90	4712477
29.910	**10.345**	**0.762**	7.0	96	98	36	1	44	55	25	13231845
8.336	**12.104**	**0.762**	0.7	58	82	0	10	90	0	45	1185703
11.418	**12.104**	**0.762**	0.9	71	88	0	7	93	0	75	1494233
14.500	**12.104**	**0.762**	0.9	70	87	0	7	93	0	74	1459066
17.582	**12.104**	**0.762**	0.9	70	87	0	7	93	0	79	1503978
20.664	**12.104**	**0.762**	0.0	0	0	0	100	0	0	0	1285
23.746	**12.104**	**0.762**	0.9	70	88	0	6	94	0	81	1574331

Appendix D10:

Dynamic simulation result for 70mm separation distance in East orientation

x	y	z	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
11.418	**1.550**	**0.762**	22.8	99	99	88	1	7	92	0	38913236
14.500	**1.550**	**0.762**	15.8	99	99	85	1	10	89	0	30838996
17.582	**1.550**	**0.762**	14.7	99	99	81	1	11	88	0	29019536
20.664	**1.550**	**0.762**	14.5	99	99	78	1	12	87	0	28701900
23.746	**1.550**	**0.762**	14.3	99	99	78	1	12	87	0	28452670
26.828	**1.550**	**0.762**	14.4	99	99	78	1	12	87	0	28607040
29.910	**1.550**	**0.762**	14.5	99	99	79	1	12	88	0	28482694
11.418	**3.309**	**0.762**	15.1	99	99	83	1	11	89	0	26883024
14.500	**3.309**	**0.762**	8.2	98	99	67	1	17	82	0	15540761
17.582	**3.309**	**0.762**	7.1	97	99	49	1	25	74	16	13840967
20.664	**3.309**	**0.762**	7.5	98	99	53	1	24	75	7	14451755
23.746	**3.309**	**0.762**	6.8	97	99	45	1	29	70	21	13317058
26.828	**3.309**	**0.762**	6.7	97	99	43	1	29	70	22	13244169
29.910	**3.309**	**0.762**	6.4	97	99	34	1	30	69	38	11862008
5.255	**5.068**	**0.762**	15.1	99	99	81	1	12	87	0	25466252
8.336	**5.068**	**0.762**	11.6	98	99	78	1	14	86	0	21885460
11.418	**5.068**	**0.762**	6.8	97	99	34	1	29	70	46	11986284
14.500	**5.068**	**0.762**	3.9	95	98	5	1	63	36	95	6169212
17.582	**5.068**	**0.762**	3.7	95	98	1	1	70	29	97	5733709
20.664	**5.068**	**0.762**	1.4	82	92	0	5	95	0	91	2303619
23.746	**5.068**	**0.762**	3.5	95	97	1	2	74	24	97	5387399
26.828	**5.068**	**0.762**	3.1	94	97	0	2	82	16	97	4767724
29.910	**5.068**	**0.762**	3.1	94	97	0	2	86	13	97	4692764
5.255	**6.827**	**0.762**	12.7	99	99	80	1	12	88	0	19032198
8.336	**6.827**	**0.762**	6.2	97	99	39	1	24	75	74	9226859
11.418	**6.827**	**0.762**	3.7	95	98	5	1	75	24	93	5749189
14.500	**6.827**	**0.762**	2.3	92	96	0	2	97	0	95	3768451
17.582	**6.827**	**0.762**	2.1	90	96	0	3	97	0	94	3348495
20.664	**6.827**	**0.762**	1.7	87	94	0	3	97	0	93	2737594
23.746	**6.827**	**0.762**	2.0	89	95	0	3	97	0	94	3108464
26.828	**6.827**	**0.762**	1.7	88	95	0	3	97	0	93	2751309
29.910	**6.827**	**0.762**	1.8	88	95	0	3	97	0	93	2768596
5.255	**8.586**	**0.762**	11.1	98	99	68	1	14	86	11	17054826
8.336	**8.586**	**0.762**	3.9	96	98	4	1	60	39	97	6204782
11.418	**8.586**	**0.762**	2.4	93	97	0	2	97	1	95	3877190
14.500	**8.586**	**0.762**	1.7	89	95	0	3	97	0	93	2784069
17.582	**8.586**	**0.762**	1.5	87	94	0	4	96	0	92	2434135
20.664	**8.586**	**0.762**	1.3	84	93	0	4	96	0	90	2130231
23.746	**8.586**	**0.762**	1.3	84	92	0	4	96	0	90	2110843
26.828	**8.586**	**0.762**	1.1	81	91	0	5	95	0	82	1830580
29.910	**8.586**	**0.762**	1.4	85	93	0	4	96	0	88	2102923
5.255	**10.345**	**0.762**	7.4	98	99	43	1	26	73	48	12892034
8.336	**10.345**	**0.762**	2.8	94	97	2	2	91	7	96	4471160
11.418	**10.345**	**0.762**	1.6	88	95	0	4	96	0	92	2604974
14.500	**10.345**	**0.762**	1.3	85	93	0	4	96	0	88	2083952
17.582	**10.345**	**0.762**	1.1	82	91	0	5	95	0	81	1735886
20.664	**10.345**	**0.762**	0.9	76	90	0	6	94	0	77	1561358
23.746	**10.345**	**0.762**	0.8	70	88	0	7	93	0	68	1390399
26.828	**10.345**	**0.762**	1.0	78	90	0	5	95	0	77	1616599
29.910	**10.345**	**0.762**	1.0	80	91	0	5	95	0	80	1641670
8.336	**12.104**	**0.762**	0.7	58	82	0	11	89	0	34	1093197
11.418	**12.104**	**0.762**	1.1	82	92	0	5	95	0	81	1818197
14.500	**12.104**	**0.762**	1.0	80	91	0	5	95	0	79	1620057
17.582	**12.104**	**0.762**	0.9	75	90	0	6	94	0	72	1473520
20.664	**12.104**	**0.762**	0.0	0	0	0	100	0	0	0	625
23.746	**12.104**	**0.762**	0.7	61	84	0	9	91	0	42	1156885