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A Numerical Assessment of Daylight Performance of Office Buildings in Dhaka, Bangladesh: Introducing Light Shelves to Enhance Daylighting Quality

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Abstract

Daylighting is one of the significant factors affecting the working environment in an office which is recognized as a vital source of energy savings. Occupants require proper daylight for desk jobs in their working spaces which largely depends on a set of internal and external aspects. This paper aims at analyzing the natural daylighting performance of the office buildings in Dhaka and providing a few design options concerning light shelves in order to enhance interior daylighting performance. A total of eleven commercial office buildings were selected in the survey based on a set of building parameters that has significant effects on daylighting. Among those selected buildings, one typical office building was further analyzed and simulated for a more detailed assessment of daylighting performance. Daylighting performance is assessed in terms of illuminance value concerning useful daylighting illuminance. The resultant data shows the inner office region lags in terms of illuminance value and is not very suitable for office works. Hence, light shelves were introduced as architectural design elements which were then simulated at different heights and angles to find out the optimum solution for daylighting enhancement which will save electrical lighting energy consumption.

Keywords: Daylighting; Useful Daylighting Illuminance; Light Shelves; Office Buildings; Tropical Climate.

1. Introduction

Daylighting is the supervised admission of natural light, direct or diffused sunlight into a building in order to reduce the use of electric lighting and saving the consumption of energy.

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Daylight can also create a pleasant visual environment for the occupants and is considered the best source of light. The main sources of entering daylight into a building are windows, as well as other transparent channels and reflective surfaces which perform a dual purpose not only to create a healthy indoor environment but also to allow its occupants to maintain visible contact with the outside environment. A daylighting system is not just creating daylight apertures, such as windows or skylight, but it is to create a daylight-responsive lighting control system to reduce the use of artificial lighting. Artificial lighting is one of the major electricity-consuming items in many non-domestic buildings, accounting for about 20–30% of the total building energy load [1]. As low energy consumption is an important concern nowadays, it is necessary to incorporate daylight performance into architecture and to create a more suitable and comfortable environment by reducing energy demand in non-domestic buildings by utilizing daylight more effectively. Dhaka city is an overly populated country, so for being an economic growth center, there's a rapid growth of urbanization. As result multistory buildings were built more rapidly in recent years. So, there's a growing concern about energy consumption facing by local building designers, engineers, and architects. Artificial lights are one of the main sources of total energy consumption of a building. So, management of daylight performance through the building interior is an important part that not only reduces energy consumption but also helps to create a healthy work environment.

2. Literature Review

The energy demand has been rising continuously and is likely to continue in the future. British Petroleum published a report on the current status of energy in the world, which shows an increase of 2.3% in the global primary energy consumption [2]. Direct sunlight can be characterized with very high intensity. The illuminance produced on the surface of the earth may sometimes exceed 100000 lux [3]. The luminosity of direct sunlight varies by season, sky conditions, location, and time of day. For tropical climates like Bangladesh, architectural design is required with careful regulation for allowance of proper daylight, also consideration about diffusing, shading and reflecting light. Daylight that penetrates the building is a combination of direct sunlight, diffused sunlight, and light reflected from the ground surface and the surrounding elements. Daylighting design needs to consider the built area and orientation of a building as well as the site location, facade treatment, type and placement of window openings, glass type, and shading devices. Spaces that are designed with good daylighting can ensure adequate sunlight during the daytime. The daylight factor at any point in space is the ratio of the (internal) illuminance at that point to the unobstructed (external) horizontal illuminance under the CIE standard overcast sky [4]. The recommended level mentioned in Bangladesh National Building Code for general office work is 300 lux [5]. If the deeper parts of the office interior are supplied with the recommended illumination level by supplementary light, the points that have values higher than 900 lux will create glare, as these levels exceed three times the recommended values. There have been studies that show the importance of analyzing the daylighting performance of 35 office buildings in subtropical Hong Kong. D. H. W. Li and E. K. W. Tsang used Radiance software to evaluate further information about the daylight factor to distance from the window of two buildings to understand the distribution of daylight on different floors. Based on their stimulated results, around 25% and 20% of total electric lighting energy is possible to save for Buildings 30 and 20, respectively with considered glare issues. So, this paper suggested that the building facade designs are conducive to daylighting and proper daylight linked lighting controls have potential for significant energy savings [6] . Another study shows the effects of light shelves that can enhance the daylighting quality in the deeper floor area in office

buildings in Dhaka city. A. R. Joarder, Z. N. Ahmed, A. Price, and M. Mourshed used Ecotect to analyze daylight illuminance at different grid points and Radiance for daylight contour distribution of the same spaces at work plane level for the different heights of light shelves to evaluate the optimized condition. This paper also conclude that light shelf can be an effective element to enhance the quality of daylight in tropical buildings. But as they simulate light shelves at different heights but didn't consider the angle of light shelves for further optimizing solutions [7].

2.1 Light shelves and shading

In architectural design shading devices are used as part of the exterior facade. Light shelves, fins, overhangs, shade screens, Venetian blinds, are commonly used as shading devices. One downside of using shading devices is that it can reduce daylight level because it can reduce the view of the sky, which is an essential source of daylight. Shading devices can increase energy consumption as it often requires artificial light use to ensure adequate illuminance at the interior spaces. But using light shelves can minimize the effect as light shelves reflect sunlight into the interior spaces to penetrate sunlight into the deeper spaces and distribute the light more evenly throughout the interior spaces. Light shelves are horizontal solid fixtures positioned to either the outside or the inside of a window (or both) and the upper surface of the shelf is coated with a white or reflective covering [8]. This coat permits both direct and diffuse sunlight falling on the upper surface to be reflected into the spaces. However, light shelves provide shading near the window area. Light shelves are placed just above eye level so that daylight can reflect into the interior ceiling and by using the ceiling as a light reflector for penetrating the light into the deeper parts of the room. To understand a clearer idea about the impact of light shelves, daylight simulation was performed and analyzed in this study for custom light shelves with different height levels.

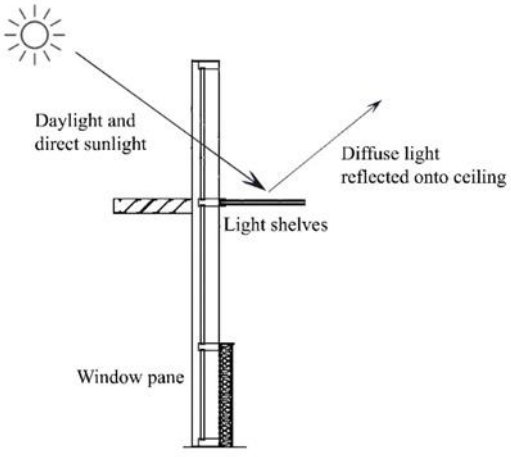


Figure 01: Light Shelf

3. Research Methodology

This study is conducted in two phases. Firstly, several buildings are selected for surveying their lighting aspects, and then detailed computer simulation is conducted for a precise result in order to find out an optimum design

solution.

3.1 Building Selection Parameters

Daylight performance of urban office buildings in Dhaka is investigated through a survey of eleven office buildings completed in different years. A set of building selection criteria is determined in order to rule out the unsuitable office buildings so that proper daylight performance measurement can be done. The selection of office buildings is the result of the following criteria:

- The building should be representative within the territory in case of scale and volume.
- The Year of completion of the building should cover the past forty years (i.e., 1980–2020).
- Office buildings must be at least 20 storied.
- The sample office building should possess common glazing window types, i.e., clear, tinted, or reflective glasses on the window.
- The office space should have an open floor plan so that there can be provision for daylight inclusion and distribution of daylight.
- All the office buildings must be air-conditioned.

3.2 Computer Simulation to Assess Daylighting Performance

Among the eleven buildings, an optimum case is selected according to its daylighting behavior which is further analyzed for a more detailed investigation of daylight performance. Ecotect Analysis 2011 and Radiance are the two software that are used for this study. The simulation is conducted in two different phases. At first, the present daylighting condition is tested numerically which will show whether the office space is suitable for desk jobs or not. If the resultant data shows the incapability of the space for working in the case of natural lighting, only then, the effect of light shelves to enhance daylighting performance will be simulated. Ecotect Analysis 2011 and Radiance software will be used in both cases.

The following flowchart represents the whole simulation process:

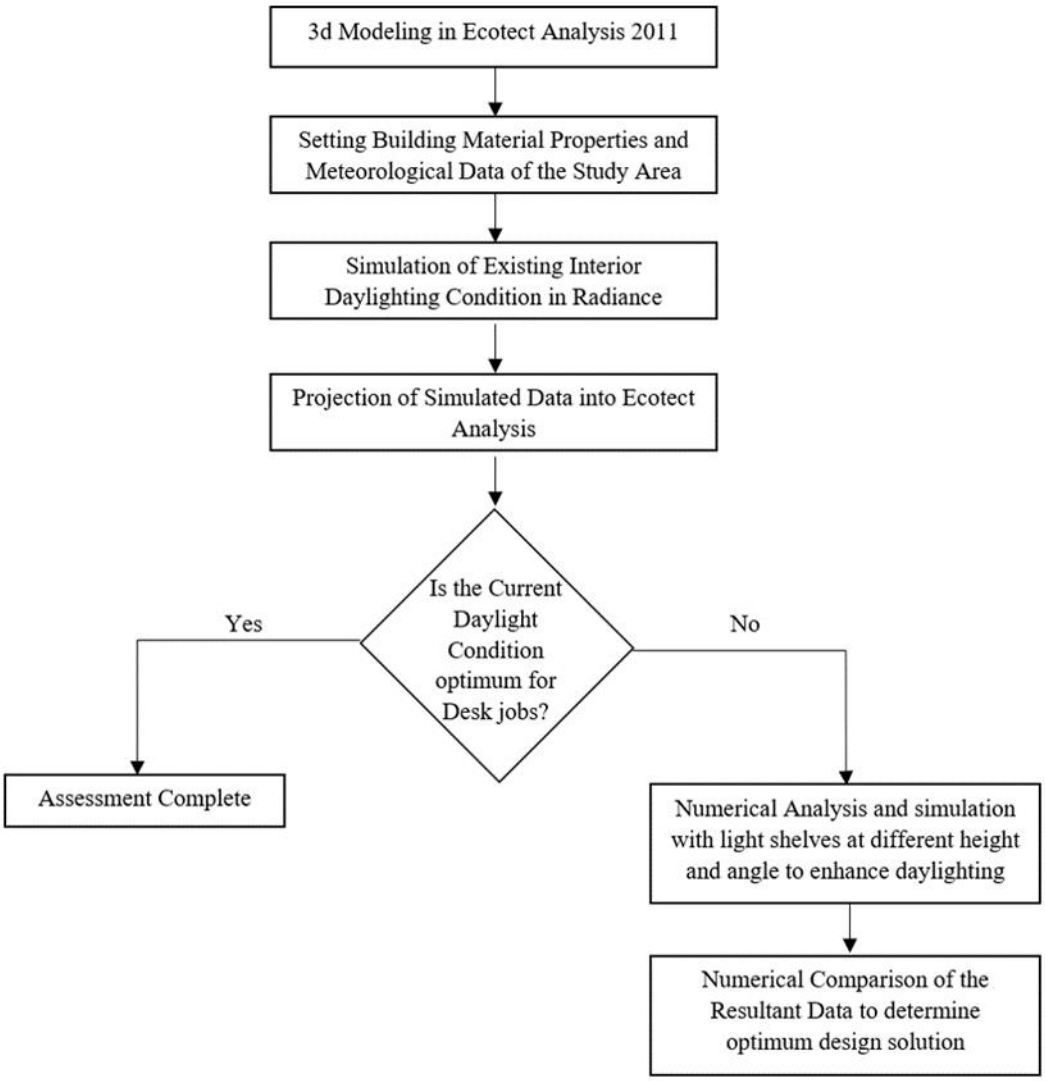


Figure 02: Computer Simulation Flowchart for Assessing Daylighting Performance of Office Buildings in Dhaka

4. Study Area

According to the considered parameters for selecting buildings, Dhaka, the capital of Bangladesh is selected as the study area. After studying the sky condition of Dhaka city, 11 office buildings were selected which are completed in different years to analyze their daylighting performance.

4.1 Building survey and parameters affecting daylighting performance

All the data about building envelop and plans were collected from original design documents and site surveys. The 11 office buildings selected are located in the main business hub of Dhaka city. The buildings are within 20 to 37 floors. Building 01 has a total of 37 floors and the tallest building in Bangladesh. More than half of the buildings were completed during 2005 till date, the flourishing period of Bangladesh in the economy as well as

the local building industry. All the surveyed buildings are selected from defined parameters so that it can give us a better indication of the general daylighting conditions of the office buildings of Dhaka city. In the following sections, four key factors to understand the daylighting performance including building area and orientation, glass & window type, shading, and external obstruction are briefly described.

4.1.1 Building area and orientation

Daylight performance is often calculated by daylight factor (DF) which is defined as the ratio of the indoor daylight illuminance at a point within the enclosure to the outdoor illuminance at that point under the same unobstructed overcast sky[9]. And also, by the daylight illuminance (UDI) which is a daylight availability metric measured by the fraction of time across a daylighting study period where the illuminance at a point lies between the selected minimum and maximum levels (typically 100 and 3,000 lux) [10]. The average DF and illuminance depend on the window area as well as the floor area and orientation. The bigger the floor surface area and depth from a window the smaller will be the average value of DF and illuminance. Small floor surface areas tend to have a higher average of DF and illuminance value. Table 1 shows a summary of the building envelope information for the 11 selected office buildings of Dhaka. The gross floor area (GFA) per floor varies from 361 sqm to 2831 sqm and the number of stories is from 20 to 37. 10 of the 11 buildings have approximately square or rectangular plan layout and one has a circular plan layout with a rectangular core. Every building has a symmetrical layout which represents typical office buildings of Dhaka city. Occupants expect good natural light in their working spaces and likely to be located near the window area to ensure enough light and a good outside view.

4.1.2 Shading

Shading devices are used to shade the window from direct sunlight and to allow a diffused light to improve visual comfort and avoid glare. As for the typical multistorey office buildings of Dhaka use of exterior shading devices is rare. Interior shading devices such as curtain blinds and Venetian blinds are used to avoid solar heat. According to table 1, only two of the eleven buildings are designed with recessed windows that were completed in 1985 and the extended floor plan is working as an overhang shading device. But the other nine buildings have no exterior shading devices.

Table 01: Summary of daylight parameter for surveyed buildings

Building no	Building name	Total area per Floor (sqm)	No. of story	Year built	External reflectance	Mean obstructed angle	Glazing type	Shading Coefficient	Visible transmittance	Shading type
01	City Center	1480	37	2012	Light	57	Single glazing tinted glass	0.65	0.51	nil
02	Bangladesh Bank Building	2831	31	1985	Light	52	Single glazing clear glass	0.9	0.88	Recessed window
03	BSC Tower	361	28	2017	Light	53	Single glazing reflective glass	0.4	0.26	nil
04	Peoples Insurance Bhaban	938	22	2005	Light	61	Single glazing tinted glass	0.65	0.51	nil
05	Confidence Tower	630	25	2013	Medium	47	Single glazing tinted glass	0.65	0.51	nil
06	Sena kallyan Bhaban	1446	22	1985	Light	55	Single glazing tinted glass	0.65	0.51	nil
07	The Pearl Trade Center	882	21	2015	Light	65	Single glazing reflective glass	0.4	0.26	nil
08	Sanmar Tower 2	522	20	2018	Light	58	Single glazing reflective glass	0.4	0.26	nil
09	Unique trade center	2794	20	2002	Medium	53	Single glazing tinted glass	0.65	0.51	nil
10	Brack center	495	20	1995	Light	62	Single glazing tinted glass	0.65	0.51	nil
11	Janata Bank tower	576	24	1985	Light	56	Single glazing tinted glass	0.65	0.51	Recessed window

4.1.3 Glass and window type

Glass and window type governs the amount of daylight entering into the building interior in terms of light transmittance value. In Dhaka city, most of the multistoried office buildings are designed with full-height glass

windows. From table 1 we find that only two of the eleven buildings were designed with a recessed window that is fixed inside a recess within a wall and the other nine buildings were designed with full height fixed windows. To calculate daylight performance light transmittance is directly proportional to the daylight factor. From table 1 it can be observed that all the buildings used single glazing. Three types of single glazing glass types are found i.e., clear, tinted, and reflected. Clear glass type has high transmission of daylight with visible transmittance (VT) of .88 but also has a high shading coefficient of .09 which allows a great amount of solar heat into the building. Tinted glass has a comparatively lower shading coefficient of .65 but it also reduced the VT to .51. Reflective glass on the other hand has a lower shading coefficient value of .4 but also has a very low VT value of .26. From the table 1, it can be seen that one of the eleven buildings used clear glass window that was completed in 1985 and two buildings used reflective glass window that was built in recent years. Most of the buildings used tinted glass windows with moderate shading coefficient and VT value.

4.1.4 External obstruction

External obstruction can affect the daylight performance of any buildings which depends on two aspects. First is the sky condition, obstructed or unobstructed. Second is the color finish of the exterior surface of the obstructed buildings, which can be considered as reflected luminance. The colors can be grouped as light or medium and depend on the choice of the architects and clients. Light color exterior surface finish can give higher reflected luminance but can also create glare. From table 1 it can be found that buildings 05 and 09 have medium external reflectance and other buildings have light external reflectance. External obstruction can also be evaluated by vertical obstruction angle (θ). It depends on the height of the neighboring building and the setback between the buildings. For the present study, θ is measured from the lowest office floor level of the surveyed building to the highest level of its surrounding buildings [6]. The mean obstruction angle is the average value of the four primary surfaces of a given building. In Dhaka, city buildings are often built in close proximity that creates high obstruction angle. From table 1, it can be seen that 47 and 65 are the lowest and highest obstruction angles for the surveyed buildings. Most of the buildings in Dhaka city have a high obstruction angle value as a result of urban hub building location, high land value, and economic demand.

4.2 Selection of building for simulation

In order to have a better understanding of the daylight performance and daylight illuminance at an office space, building 01 is selected to simulate the current daylight situation and analysis the data to find an optimum solution for a better working environment. Ecotect analysis 2011 and Radiance daylight simulation tool was used for the simulation.

4.2.1 Building Description

Building 01 is a high-rise office block with 37 floors and currently, the tallest building in Bangladesh that was completed in 2012. It has a rectangular plan with a symmetrical layout. It has a central core with eight lifts and fire stairs, a storeroom, service rooms, and the toilet was placed beside the lobby. Figure 03 shows that it has a 1480 sqm floor area with an interior depth of about 12 m and two office spaces are located on two sides of the

core. Building 01 has no exterior shading devices, with full height fixed windows that used single glazing tinted glass with a visible transmittance value of 0.51. The building is located in front of a 37m wide highway and surrounded by multistory buildings on the east and north side. the value of vertical obstruction angle x for the south, east, west and north are 64, 77, 15, 72, respectively.

4.2.2 Simulation Parameters

The qualitative assessments for the design strategies to analyze daylight simulation were based on the following parameters:

Location: Dhaka, Bangladesh. (90.40 E, 23.80 N) [11]

Time: 1 October, 12.00 pm

Calculation Settings: Full Daylight Analysis

Precision: High

Local Terrain: Urban

Window (dirt on glass): Average

Sky Illumination Model: CIE Overcast (considering the worst-case scenario in terms of sky condition)

Design sky Illuminance: 9204 lux according to Tregenza Formula [12]

4.2.3 Study space

The seventh office floor of the building was chosen for the simulation study as it is the lowest office floor of the building. The Ecotect model was created by assuming the unshaded peripheral wall and the interior space was also modeled as empty, free from any furniture or obstruction to avoid any effect of surfaces that can both block or reflect daylight to ensure precise data. The other parameters of the Ecotect model for the interior space, which were incorporated from values found in a physical survey, are as follows.

Total floor area: 1480 sqm

Usable office space: 1053 sqm (263 sqm per office zone)

Service area: 428 sqm

Simulation area: 263 sqm

Clear height of office space: 3m

Work Plane height: 0.75m

The following parameters of existing internal finish materials (as found in the field survey) were used in the model for simulations.

Ceiling/ Roof of 7th floor: White painted plaster (reflectance: 0.7).

Internal wall: White painted plasterwork (reflectance: 0.7).

Floor: White ceramic tiles finishes (reflectance: 0.6).

Glazing: Single pane of glass with aluminum frame

(reflectance: 0.92, U value: 6 W/m^2K).

The upper and lower floors of the simulation space were hidden during simulation, as these floors had no contribution to the simulation output but only extend the simulation processing time unnecessarily.

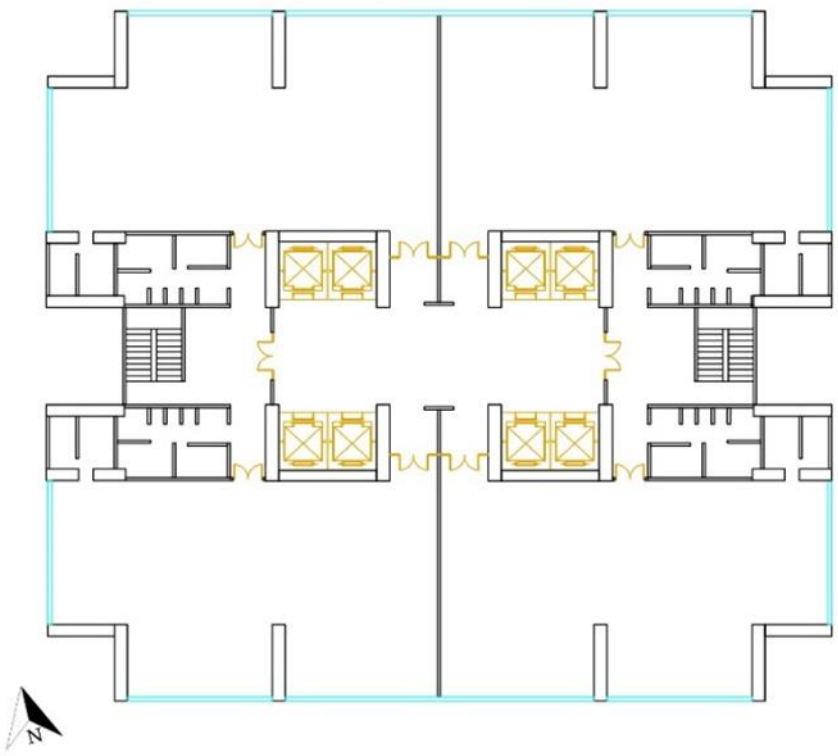


Figure 03: Typical Office Plan of Building 01 (City Center, Dhaka)

5. Result and Discussion

A Typical office floor plan of the City Center in Dhaka is divided symmetrically into four separate office zones.

Among them, one zone is taken into consideration for a more detailed understanding of the indoor daylighting condition which is modeled in Ecotect Analysis 2011 for further simulation.

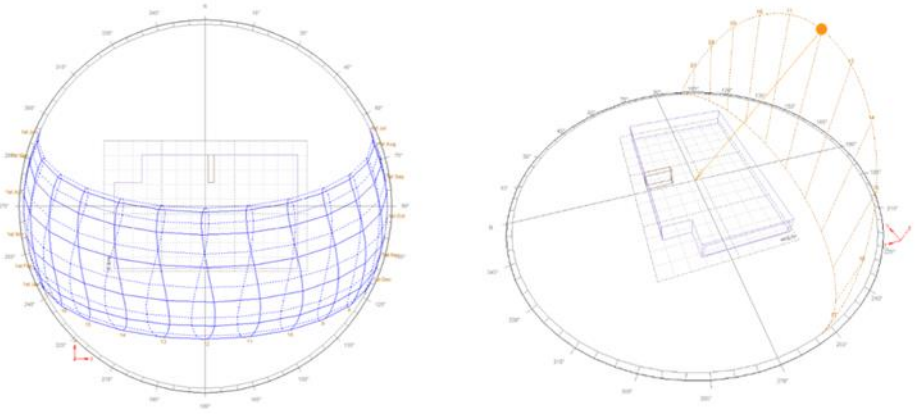
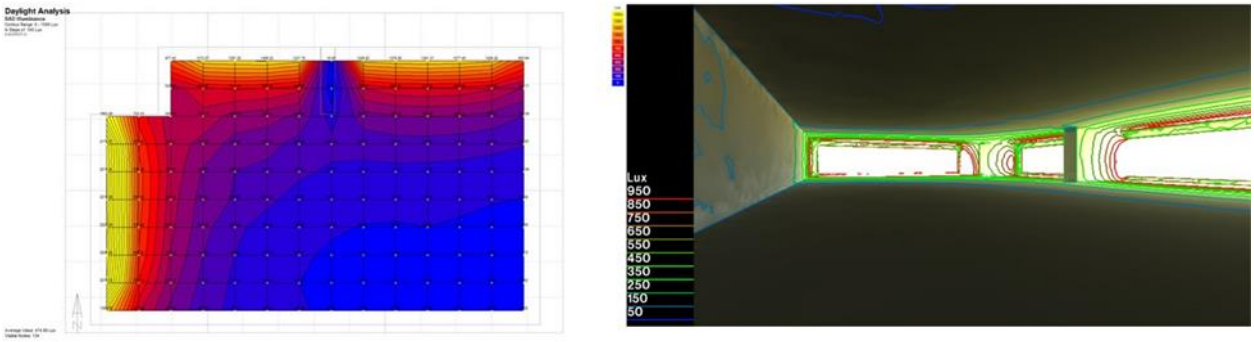


Figure 04: Annual Solar data of selected office zone

From the meteorological data of Dhaka, the annual sun path diagram is extracted which shows that the mean average sun position for the site area is during October. Hence, 12:00 pm on October 1st, 2020 is selected as the reference time of solar data concerning which simulation is undertaken.

5.1 Assessment of Existing Daylighting Condition



Grid Analysis for Existing Illuminance Level

Contour Lines for Existing Illuminance Level

Figure 05: Existing daylight performance of the selected Office Zone.

The existing daylighting condition of the office zone is simulated in Radiance software and the resultant projected data on Ecotect Analysis 2011 is analyzed based on 134 grid points. The maximum illuminance value inside the office zone is tested as 2221.54 lux where the minimum value is 48.62 lux. The average illuminance value is 474.98 lux. Among the 134 points, only 43 points are within the useful daylight illuminance (UDI) range where 73 points fall behind the minimum illuminance range for desk jobs i.e., 300 lux. A whopping number of 31 points gets less than 100 lux which is the minimum range for useful light. Total 18 points get light which is more than 900 lux that cause glare.

5.2 Effects of light shelves in enhancing daylight

The resultant data shows that the existing daylighting performance of the city center office building is not very suitable for desk jobs as most of the grid points possess an illuminance value of less than 300 lux. Hence, multiple design options have to be tested in order to enhance the natural lighting condition. In this study, light shelves are introduced as a design option at four different heights ranging from 1.5m to 2.25m with a regular interval of 0.25m between them. As the work plane is considered to be at a height of 0.75m from the floor, the eye level of the occupants remains at 1.5m level. [7] Hence, light shelves are considered starting from 1.5m levels in order to avoid glare at eye level.

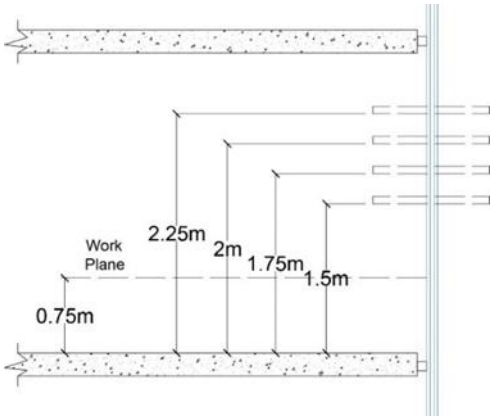


Figure 6: light shelves heights for simulation

Each option is modeled separately in Ecotect Analysis 2011 for further simulation in Radiance software. The resultant data is as follows

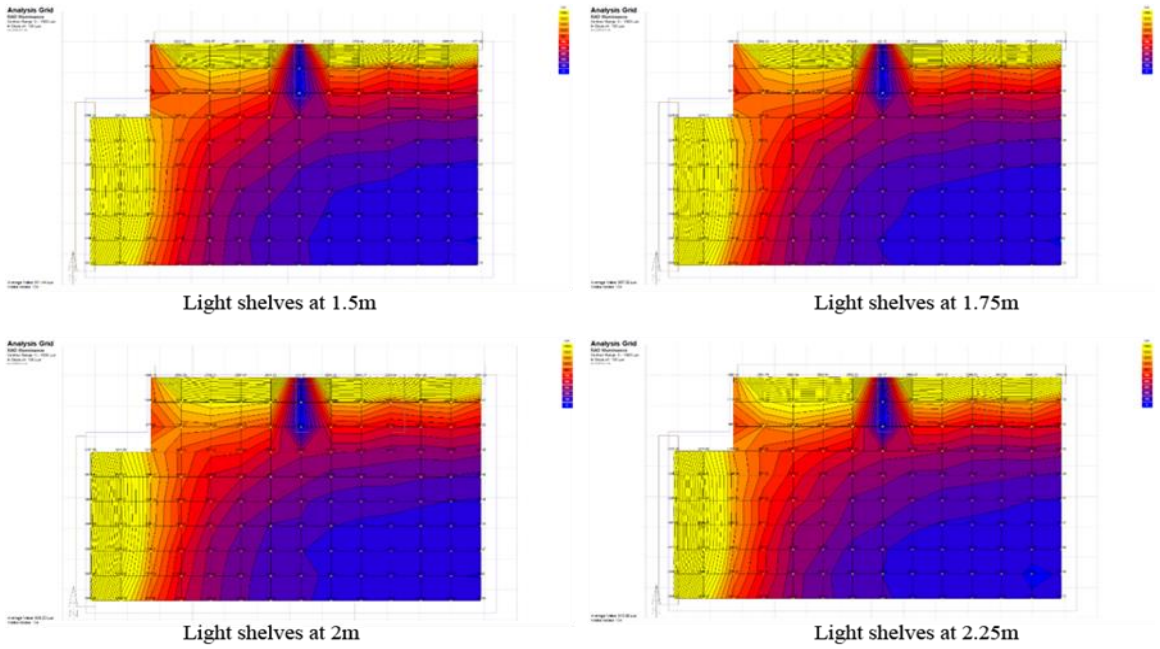


Figure 07: Daylight performance with light shelves at different heights

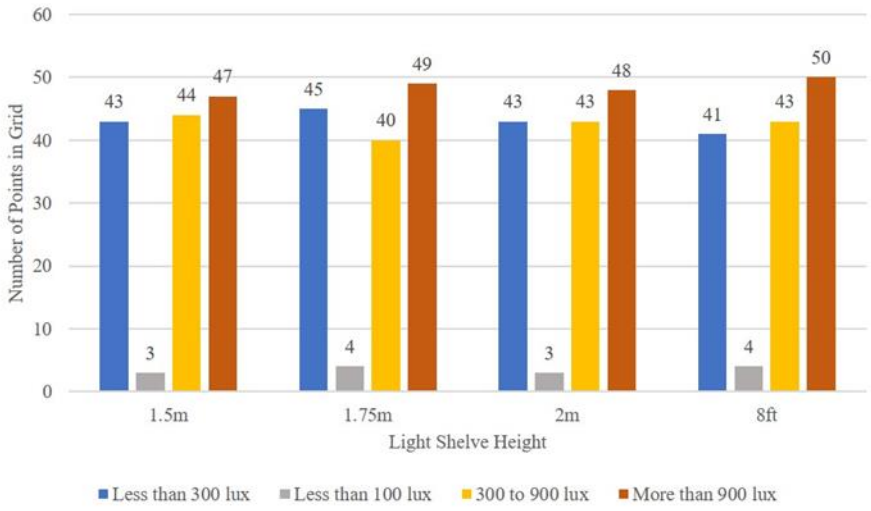


Figure 8: Light Shelves Comparison in Terms of Illuminance Value in grid

Simulated data with light shelves at different levels show changes in daylighting quality of the office space. The minimum and maximum illuminance values for light shelves being at different heights vary significantly from the existing situation. The maximum illuminance values for light shelves at 1.5m, 1.75m, 2m, and 2.25m are 3283.6 lux, 3315.58 lux, 3354.8 lux, and 3390.5 lux respectively where the minimum values are 98.32 lux, 98.42 lux, 99.22 lux, and 93.56 lux respectively. This data shows that light shelves at 7ft height eradicate the interior less illuminated spaces better than the other options. An analysis grid containing 134 points is analyzed numerically to compare several aspects. The comparison chart shows that light shelves at 1.75m level have the least effect of achieving UDI level where light shelves at 8ft level have the most significant effect. Light shelves at 1.5ft and 2m levels have moderate effects. Light shelves at 1.75m and 2.25m level results in producing the most points that are unusable for any kind of work as they possess an illuminance value of less than 100 lux. Hence, these two options should be avoided. Light shelves at 1.5m and 2m levels have better effects in this case. Light shelves at 1.75m have the most adverse effect as it allows the least number of points having an illuminance value that is between 300 to 900 lux. Light shelves at 1.5m level allow the most number of points that are within the range from 300 to 900 lux. Light shelves at 2m and 2.25m level have moderate effects as they both allow 43 points to be illuminated at a recommended value of 300 to 900 lux which is optimum for office works in Bangladesh according to Bangladesh National Building Code. Illuminance value of more than 900 lux created glare and it creates a disturbance for the desk jobs. The simulation shows that light shelves at 2.25m level create the most glare in the office zone which is problematic for the occupants. Light shelves at 1.5m and 2m perform moderately in this case. Hence, light shelves at 8ft level should be avoided. Light shelves at 1.5m and 2.25m levels have a higher average illuminance value which represents the increased glare in the office zone. Here light shelves at 6ft height have the least average value of 907.02 lux. Light shelves at 2m level have a moderate illuminance average value of 909.23 that represents the even distribution of daylight inside the office zone. All the other aspects mentioned above also reflect the suitability of light shelves height at 2m from the floor for optimum daylighting condition possible at that particular urban setting at overcast sky condition. Hence, a light shelf at 7ft height is considered as the optimum value for further analysis. A more detailed analysis is conducted on light shelves angle for enhancing daylight performance within the office zone.

Simulation is conducted considering light shelves angle of 0 degrees, 15 degrees, and 30 degrees. Results for light shelves at zero degrees have been mentioned above.

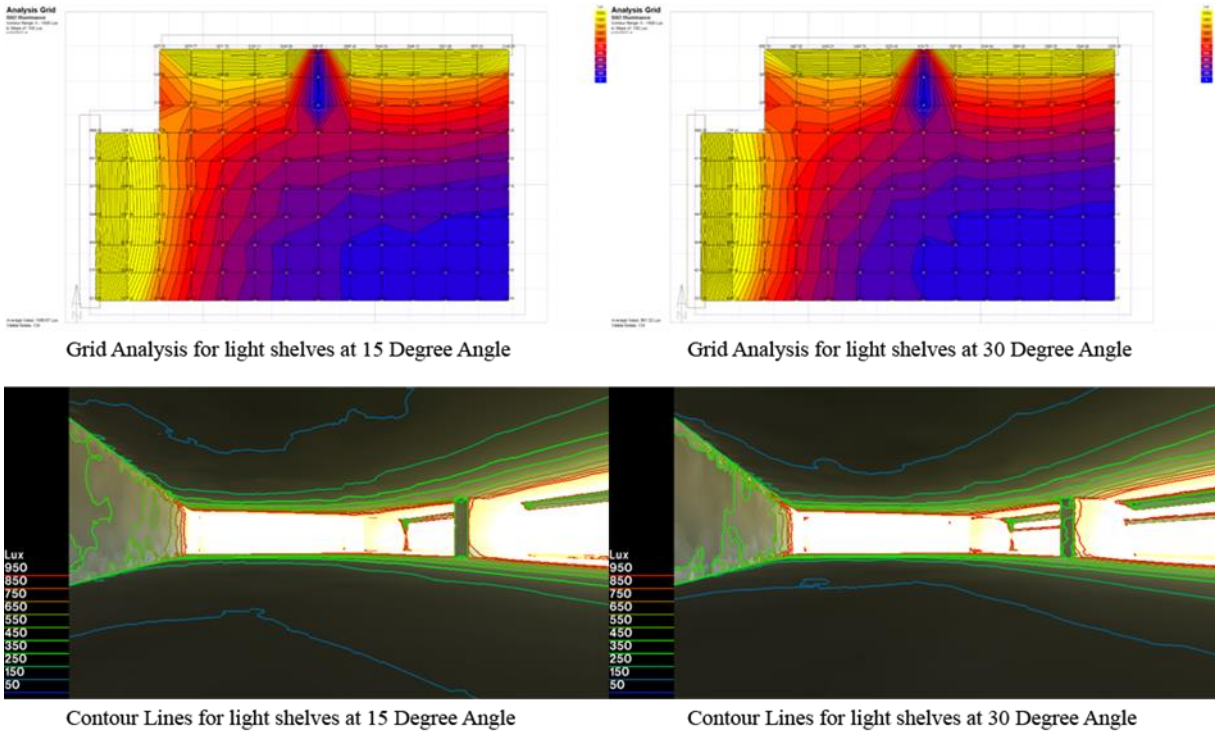


Figure 9: Daylight performance with light shelves at 2m height at an angle of 15 degree

Light shelves angle has a significant impact on illuminance inside the office zone. Both cases are modeled in Ecotect Analysis 2011 and then simulated in Radiance software for a more accurate result.

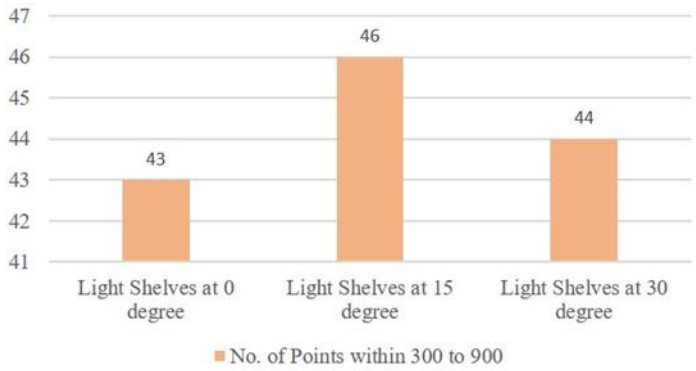


Figure 10: Number of points getting illuminance value within the range from 300 to 900 lux at different angles

The resultant data shows that 43, 46, and 44 points are illuminated with a value ranging from 300 to 900 lux for light shelves being at 2m height from the floor at an angle of 0,15 and 30 degrees respectively. Light shelves with 15 degrees angle at 2m height from the floor level enhance the interior daylight performance of office buildings in Dhaka the most compared to the other design options. Hence, this option is the most suitable for

desk jobs in Dhaka.

5.3 Limitations of the study

All the resultant data are extracted from computer aided simulation which may differ slightly from real-life measurement. The simulation is conducted considering an overcast sky condition. Other sky conditions may require further consideration in case of choosing light shelves.

6. Conclusion

According to the 2010 report of the International Energy Agency (IEA), the consumption of lighting energy in the building sector is 18% of the total energy consumption in this sector [13]. Another study shows that almost one-third of the electricity consumed in commercial office buildings is represented by lighting appliances [14]. Hence, a reduction in artificial lighting consumption will result in a large deduction in building energy cost and improve its energy rating. In this paper, the natural daylighting quality of a commercial office building is analyzed to determine a suitable design solution that will enable a proper working environment for desk jobs. The current working environment of the office building in an urban setting of Dhaka is not very suitable in terms of daylight performance. Only the perimeter zone of an office gets the recommended value of illuminance for desk jobs. The inner region does not get proper illuminance due to deep floor plans. It causes visual discomfort for the occupants. Light shelves can be a suitable solution concerning this problem. Light shelves allow daylight to enter into the inner region and enhances interior daylighting quality. This study finds that light shelves at 2m height with an angle of 15 degree works the best for office buildings in a tropical climatic zone. Findings from this study will help architects and civil engineers to design contemporary office buildings with better lighting performance and reduce their energy consumption.

7. Conflict of Interest

The authors declare that they have no conflicts of interest.

8. Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article. All data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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