Parametric control of multiple blinds to enhance daylighting performance in the dome building: Case study of a mosque building in Saudi Arabia

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Abstract

Clerestory windows encircling the dome are a common feature in mosque architecture. They serve the purpose of allowing daylight to penetrate the spacious interior from all directions through smaller windows compared to side-lit windows. However, maintaining the required uniform daylighting coverage throughout the day in buildings with different directions remains a challenge. The integration of advanced daylighting systems with dome geometry, coupled with parametric control, can significantly enhance daylighting performance. In this research, a novel approach and simplified integrated method for parametrically controlling a multiple blinds system with incremental slat angle in a mosque dome's drum are developed, whereby the blinds in each direction respond independently and parametrically to the sun's movement. Parametrically controlled blinds are installed on the windows around the mosque's dome to maximize the utilization of daylight while preventing direct penetration of solar radiation. Then, the daylighting performance of parametrically controlled multiple blinds was compared to that of conventional blinds and unshaded windows in a typical Mosque in Saudi Arabia during the noon prayer time. The study found that the parametrically controlled blinds can dramatically enhance the daylight coverage inside the mosque from around 38% to 88% for an illuminance range of 150–500 lux, while protecting users from direct sunlight. Promisingly, the system revealed that it can protect worshippers from direct sunlight, minimize potential glare and provide visual comfort.

Keywords
Daylighting, parametric design, multiple blinds system, visual comfort, dome building, mosque.

1. Introduction

Building interiors can significantly benefit from natural light, which is one of the most important environmental aspects to consider [1]. Energy-saving and visual comfort can be achieved if the sunlight that enters the interior spaces is efficiently adjusted [2]. Daylight plays a crucial role in influencing the well-being of occupants within a building, impacting both visual comfort and energy consumption [3]. According to the record, between 2010 and 2020, Saudi Arabia's energy consumption increased by 33% [4]. The mosque buildings in Saudi Arabia are considered the most energy-intensive buildings. In addition, it was found that energy consumption in mosques is more than that of public hospitals [5]. One of the main reasons for high consumption in mosques is the demand for artificial lighting to compensate the poor lighting quality due to a lack of natural daylight. Electrical lighting is considered the second most significant energy usage in mosques 22% after air conditioning 73% of total energy used [6]. The use of shading devices as daylighting systems can efficiently enhance the light performance of buildings’ interiors and minimize their electricity consumption [7, 8].

Simultaneously, shading devices can protect buildings from excessive sunlight [9, 10] and prevent the penetration of direct solar radiation during the summer [11]. According to previous studies, shading devices can significantly reduce cooling loads and save energy up to 40% [12, 13]. On the other hand, providing uniform daylight can potentially reduce energy consumption compared to a nonuniform daylight distribution [14]. Thus, the more precise control over shading devices, the better visual comfort and energy saving [15].

In most common design of mosques, the top windows that surround the dome's drum are the main source of daylight for the prayer hall. However, due to the drum's geometric shape, these windows face all directions, allowing direct sunlight to penetrate the prayer hall throughout the day. The intensity of the light permanently changes according to the position of the sun, which leads to a severe contrast of the illuminance levels in the prayer hall with a much brighter pattern in some areas and a darker pattern in other areas which dramatically causes worshippers' visual discomfort. However, controlled shading devices could help to mitigate light penetration and reduce the daylight contrast. Consequently, improved visual comfort could be regarded as a significant indicator of worshipper satisfaction, as this factor enhances the quality of prayer and the reading performance of the Quran [16, 17].

Recently, different kinds of daylighting systems were evaluated to be used such as; adaptive fluid lenses [18], Fresnel lenses [19], and compound parabolic concentrators [20, 21] as collector systems to redirect sunlight under large-span roofs. Other systems used more complex control methods to distribute the daylight [22-24], which also adjusted to respond to the sun movement and redirected the light beams into the deep-plan floor. However, such systems were limited due to the complexity of their mechanical components and the maintenance high cost. On the other hand, some systems used reflector tools, such as the automated blinds system, which likewise reacted to the sun path by adjusting the slats' rotation angles and redirecting solar beams to particular targets over the ceiling, then the ceiling works as a source of light to the room [25, 26]. Although the daylighting optimization algorithms in these systems were successful and proven to be highly efficient in illuminance performance and visual comfort in buildings with flat roofs [27-29], however, these studies were limited to south-oriented side windows.

Meanwhile, studies related to domes using daylighting are limited, the majority of these studies either just tested the acoustical impact [30] or daylighting analysis [31] regardless of any controlling methods for daylighting performance improvement using advanced daylighting systems. It is worth mentioning that the majority of mosques in Saudi Arabia were built in a traditional style with a dome structure based on a drum at the center of the mosque. On these drums, clerestory windows are mainly used to provide daylighting for deep spaces. In mosques with long dimensions, for instance, side windows might not be efficient for providing sufficient light in deep areas, leaving the prayer hall poor in daylight. Therefore, top light such as the dome drum windows is considered essential to providing the mosque with natural light [32]. However, the clerestory windows in many mosques, particularly in Saudi Arabia, are not adapted to protect worshippers from direct sunlight during the summer, leading to blocking or coating of these windows. Consequently, the use of electrical lights has been increased to compensate the limited daylight availability under the dome, depriving worshippers of the benefits of natural light. To address this issue, advanced shading devices may help distribute and improve the daylight performance in the prayer hall.

This study, therefore, will investigate the capability of providing the prayer hall with homogeneous and uniform daylight via using the mosque's dome windows through a novel method to control a multiple blinds system parametrically, which can be changed independently in different directions at the same time. This study develops a model based on an algorithmic system for the perimeter of the dome's drum that can control daylight penetration through windows in all directions, simultaneously.

An advanced daylight system known as “multiple blinds system” has been applied for the dome windows to control light penetration. A parametric software tool was utilized in this study to control the rotation of those blinds to achieve more uniform daylight distribution in the prayer room, as illustrated in Figure 1. The slats’ angles of each window were adjusted to redirect sunlight upwards, considering the window's orientation. Specifically, the bottom slats were rotated to reflect sunlight towards the base of the dome, while the top slats were adjusted to direct sunlight towards the highest point of the dome. The remaining slats' angles were incrementally (parametrically) adjusted to ensure an equal distribution of the reflected light between these two target areas. The simplified parametric control method of the multiple blinds system is used in this study to achieve better daylighting performance and lower illuminance contrast.

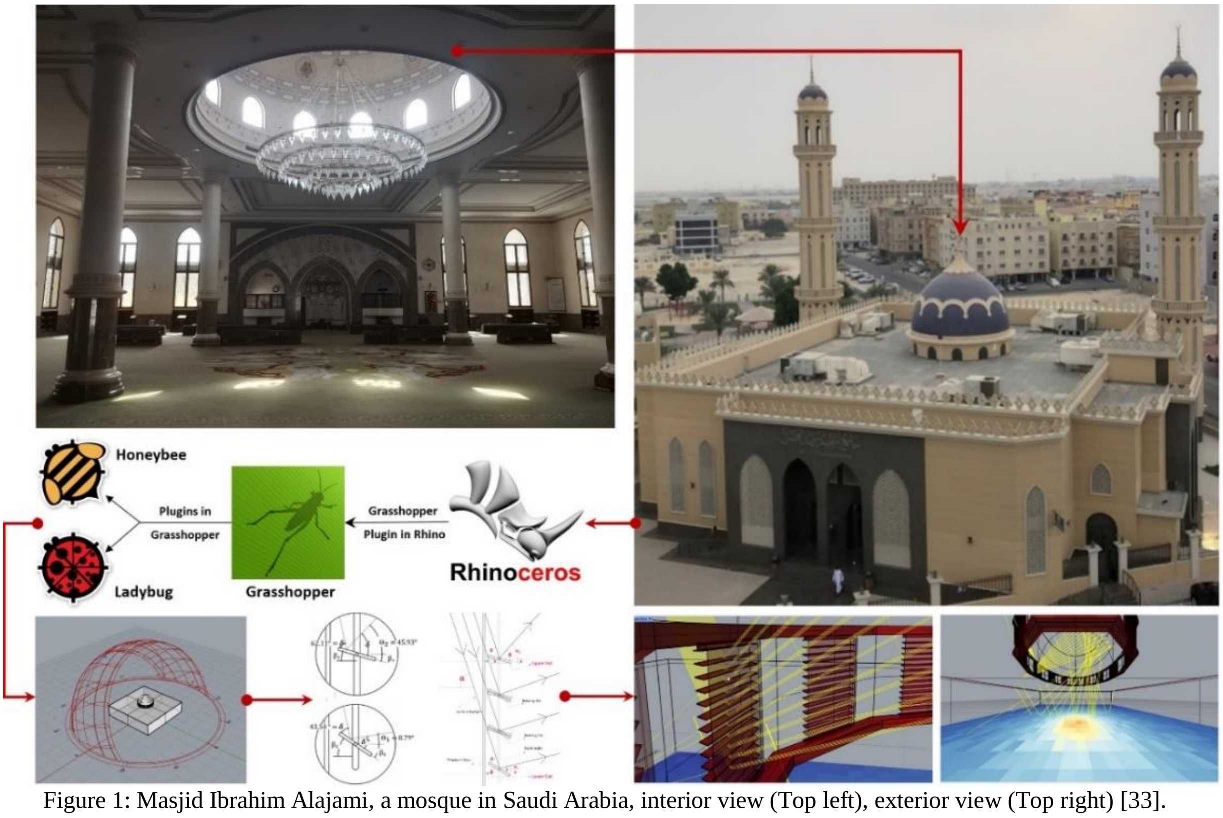

Figure 1: Masjid Ibrahim Alajami, a mosque in Saudi Arabia, interior view (Top left), exterior view (Top right) [33]. Mosque modelling in “Rhinoceros 3D”, daylighting simulation process in “Grasshopper” (Bottom).

2. Methodology

The proposed design uses rotating slats that can respond to the sun movement to increase daylight exploitation [34]. The curved ceiling of the dome helps to distribute and diffuse the reflected sunlight. The daylighting performance was evaluated at different window directions under a mosque dome in Dammam city, Saudi Arabia, as seen in Figure 1. The occupancy time period was selected between 10:30 am & 13:30 pm every day (Dhuhr Prayer time in the Islamic calendar in Saudi Arabia) [35, 36]. The prayers usually start to go to pray during this time before the announcement, then the mosque reaches its peak of occupancy at noon time, and then they start to leave again within one hour after the prayer time. Therefore, the analysis was conducted at nine different times throughout the year (at 10:30 am, 12:00 pm, and 13:30 pm) during the noon prayer time on June 21st, September 21st, and December 21st. These dates represent the highest, moderate, and lowest tendency of solar altitudes throughout the year.

2.1. Rhinoceros 3D & Grasshopper software

Grasshopper software offers designers an outstanding graphical algorithm editor, empowering them to create intricate parametric designs. Grasshopper has been developed as a plugin for Rhinoceros 3D that serves as an intuitive interface for parametric design, allowing manipulation of various parameters using mathematical formulas to generate the model [37]. These formulas are displayed as canvas that can be easily modified and controlled parametrically via their own graphical interface [38], see Figure 2.

Radiance and EnergyPlus in Grasshopper are utilised to evaluate the daylight performance of shading systems, run via “Honeybee and Ladybug” environmental software plugins for Grasshopper [39]. Radiance calculates the light transmission by utilizing the front transmission data from the assigned BSDF file of the shading system [40]. The parametric multiple blinds were evaluated using the three-phase method [41].

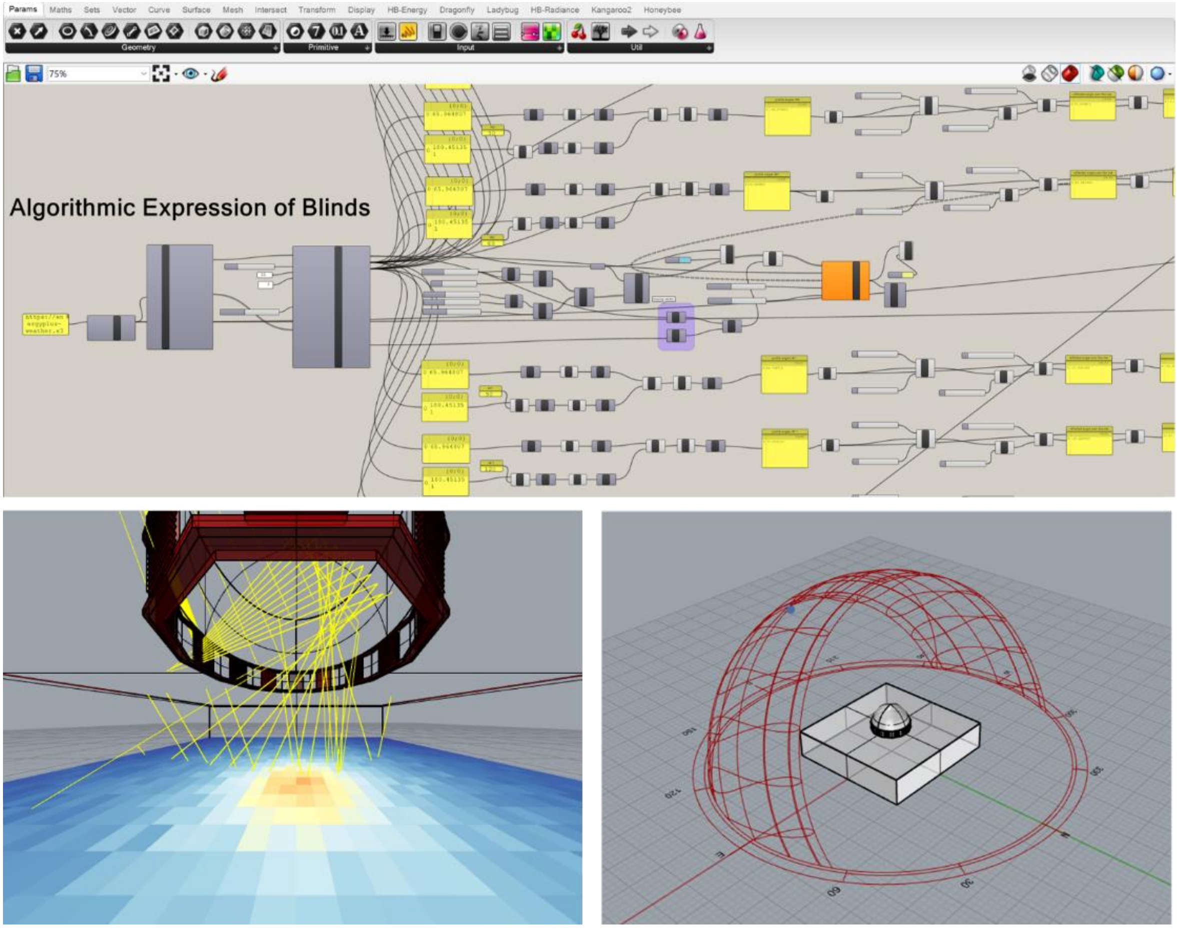

Figure 2: The cables and components from the Grasshopper interface and the 3D model and daylighting simulation result in Rhino viewport

2.2. Location of the case study

Weather files are used in simulations to get weather data for any specific location. The city of Dammam, Saudi Arabia, was selected for this study due to its dominant clear sky condition throughout the year [42].

2.3. The model of the reference dome mosque

2.3.1 The model dimensions and materials

Typical mosques in Saudi Arabia usually range between 401 and 1015 m^2 [43]. In our study, the mosque's indoor area is 400 m^2 with a square shape. The mosque's dimensions are 20 m length, 20 m width and 5 m height excluding the dome. The dome is 3 m height and 6 m diameter based on dodecagon drum (a 12-sided polygon) surrounded by 12 windows with 80 cm width and 1 m height. The dome is white painted with 80% reflectance, while the walls are white painted with 30% reflectance, with a clear glass window transmittance of 88%. The floor is carpeted in a matt light green colour with 20% reflectivity. The windows are mounted with aluminium slats with 85% reflectance that used as a shading device system.

2.3.2 The test points settings

The grid size of the test points was set to 50 cm, and these points were deployed within the examined area at a level suitable for reading position level at 35 cm (sitting on the ground while reading Quran) to determine the illuminance level for a daylighting simulation and analysis. Each individual point calculates the illuminance value in lux above the mosque's ground floor, as seen in Figure 3, within the highlighted zone aiming to focus on the dome's surrounding area. Despite having large, shaded side windows with a height of 3.2 m on the western side of this model, they are ineffective in providing adequate daylighting to the deep area of the mosque because they exceed the generally accepted 2.5 H to 3.6 H rule of thumb for employing an appropriate shading design to achieve effective daylighting [44].To emphasize the effect of the blinds system's reflected light, the side windows in the walls are closed. The simulation results reveal the illuminance values at each individual point under the dome. The values ranged between 150 and 500 lux, representing the illuminance level of reading position and praying requirements [45].

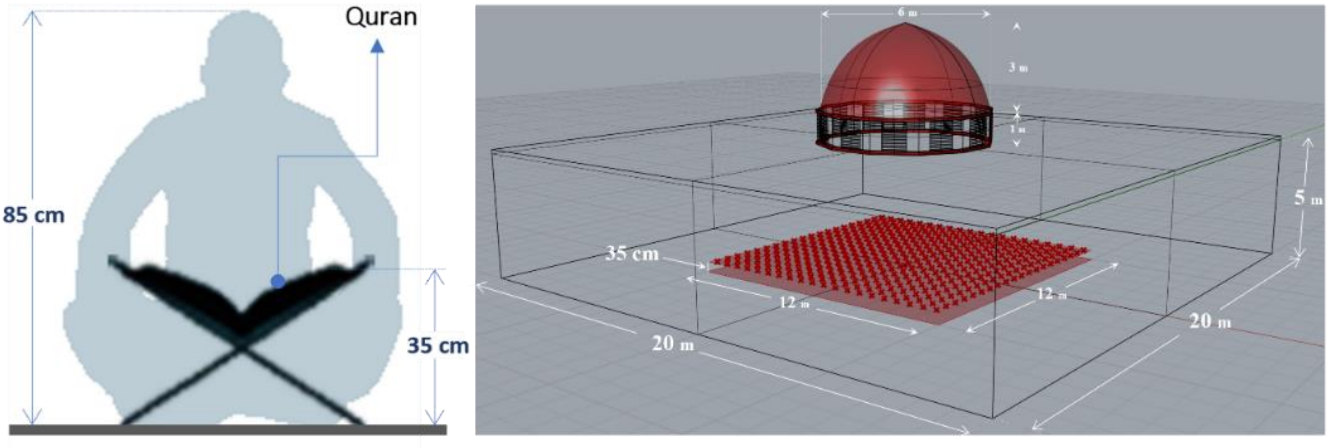

Figure 3: Reading position level (left), and the test points included in the base model configuration (right).

2.4 Daylighting system operation

The reflective surfaces' shape can improve the daylighting performance by diffusing light into the room [46, 47]. With the curved ceiling (dome) case, the surface can distribute the reflected light in a variety of directions based on two primary factors: the angle of incidence of the light and the centre of the curve [48], as seen in Figure 4. Therefore, the curved ceiling can increase daylighting efficiency by diffusing the reflected light coming from the slats.

The aluminium blinds were adopted in this study as a commercially available product [49]. Figure 5 shows a detailed cross-section with characteristics and the dimensions of the proposed system, which consists of 13 rotated slats, each single slat is 50 mm wide and 4 mm thick.

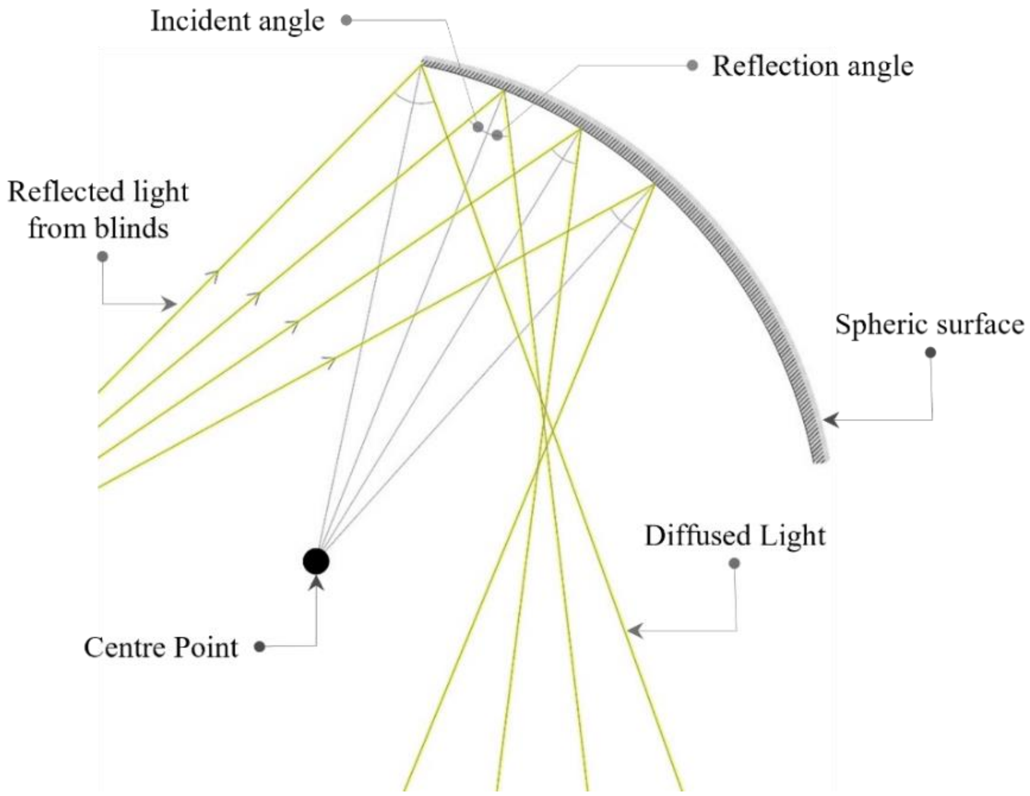

Figure 4: Law of reflection on a curved dome ceiling.

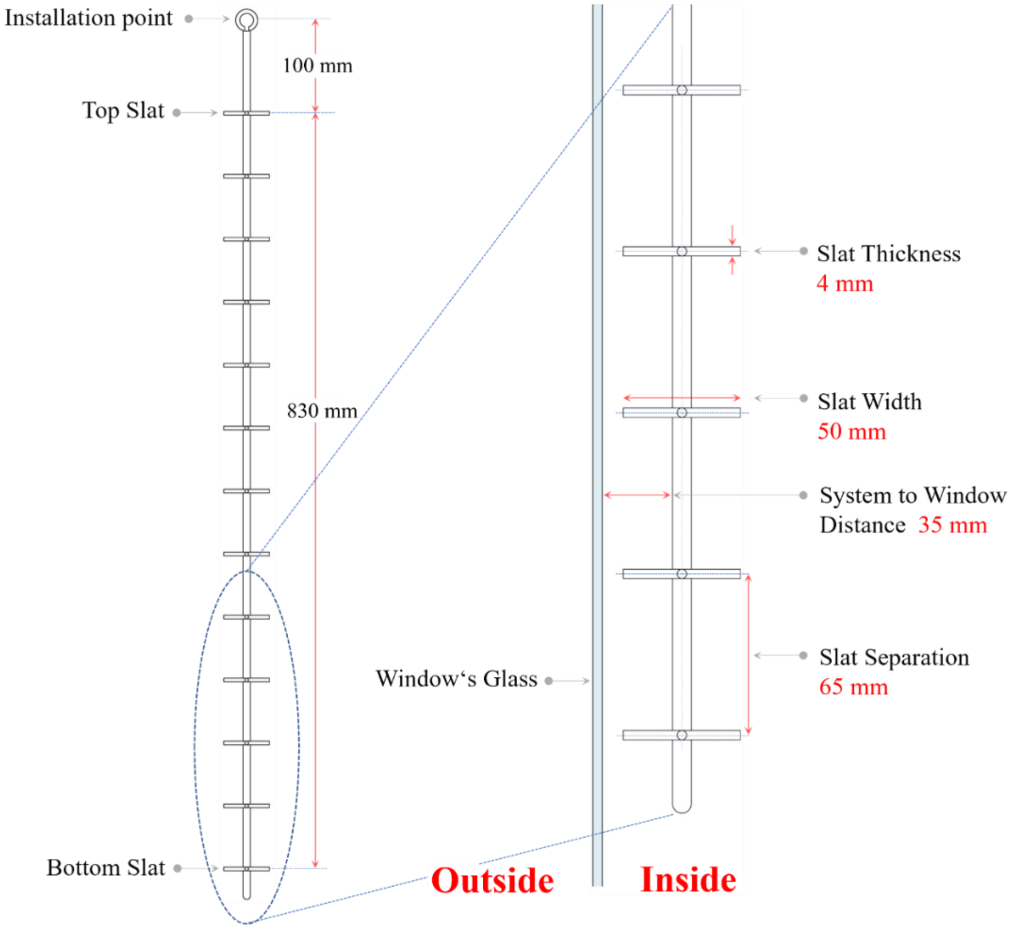

Figure 5: A detailed cross-section of venetian blinds system.

Discomfort glare in mosques usually comes from direct sunlight, which can be significantly mitigated by automated reflective slats which can redirect it into the dome and provide better distribution of daylight in the prayer zone. Automated reflective slats adjust their rotations in response to sun movement via particular tilt angle. Using the solar profile angle, which is a perpendicular plane aligned with the sunray and the direction of the windows, the slat angle is calculated [50]. To calculate the profile and slat tilt angle, it is required to know both solar altitude and azimuth, which are the two primary variables in the basic profile angle formula (1) [51].

The solar profile angle (Ω) can be given according to the formula illustrated in Figure 6:

$$tan\,(\Omega) = \frac{\mathrm{R}\sin(\alpha)}{\mathrm{r}\cos(\alpha)\ \cos(\Phi+\gamma)} \text{ i.e., } tan\,(\Omega) = \frac{tan(\alpha)}{cos(\ \Phi+\gamma)}$$

Therefore, the solar profile angle can be calculated by:

$$\Omega = \tan^{-1}\ \frac{\sin(\alpha)}{\cos(\Phi+\gamma)} \quad (1)$$

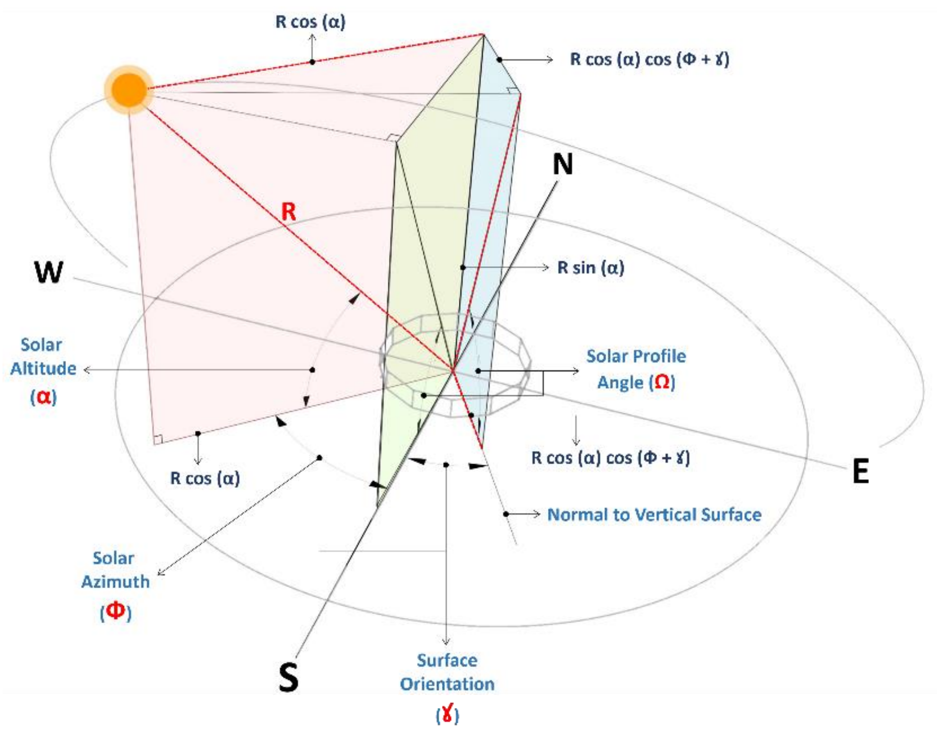

Figure 6: Concept of the solar profile angle and relation with solar azimuth and altitude.

Where, α is solar altitude angle, Φ is solar azimuth angle, ɣ is windows direction.

2.4.1 Parametric design for multiple automated blinds

In order to improve daylighting performance in the mosque, the drum windows are covered by multiple automated reflective slats to control daylight penetration. The reflective slat mechanism can automatically rotate in response to the sun movement at different times during the daytime to collect and distribute sun rays toward the curved ceiling. Each individual slat has a specific rotation angle to redirect sunlight to a fixed target over the dome to maintain the required illuminance level and provide uniformly diffused light to the prayer hall, where the reflected light on the dome surface acts as source of light for the mosque, as shown in Figure 2. This method is parametrically controlled in Grasshopper using algorithmic equations.

In this study, there are three main angles to consider: **ϴ**, **δ** and **β**. "**ϴ"** is the angle formed by the reflected light from the slats' surface and the dome's surface, as illustrated in Figure 7. "**δ"** represents the two opposite angles above the slat, where the first angle represents the angle between direct sunlight and the slat's surface and the second one is the angle between the slat and the reflected light, as shown in Figure 8. This system requires both angles constant regardless of the sun position. The angle **β** plays an important role in maintaining that the opposing two angles **δ** and **δ'** are identical above the slat surface. On the other hand, it is a required parameter to achieve the cut-off angle, which is a critical angle to block the direct sunlight passing through the slats, and it is the most common automatic blind control angle known as the "cut-off angle" that reflects incident sunlight toward the target area in a curved ceiling. In conventional blind control [52], the slat tilt angle **β** is determined in formulas (2 and 3) as follows [53].

B: Top Slat

$\Theta_2 = tan^{-1} (\frac{T+R}{u})$

$\delta_2 = 90 - (0.5(180 - \Omega - \Theta_2))$

$\boldsymbol{\beta_2 = \Omega - \delta_2}$ (2)

D: Bottom Slat

$\Theta_1 = tan^{-1} (\frac{S+R}{V_1+V_2})$

$\delta_1 = 90 - (0.5(180 - \Omega - \Theta_1))$

$\boldsymbol{\beta_1 = \Omega - \delta_1}$

(3)

Where, **Ω** is the angle of the solar profile. (S) indicates the distance between the lower slat's centre (D) and the upper slat's centre (B). (V_1) and (V_2) are the distances between point (A), which is the system's installation point in the top portion of the window, and the first target point (F) also is the base of the diameter of the dome. (R) is the distance between the upper slat's centre (B) to the top portion of the window (A). (T) is the height of the dome.

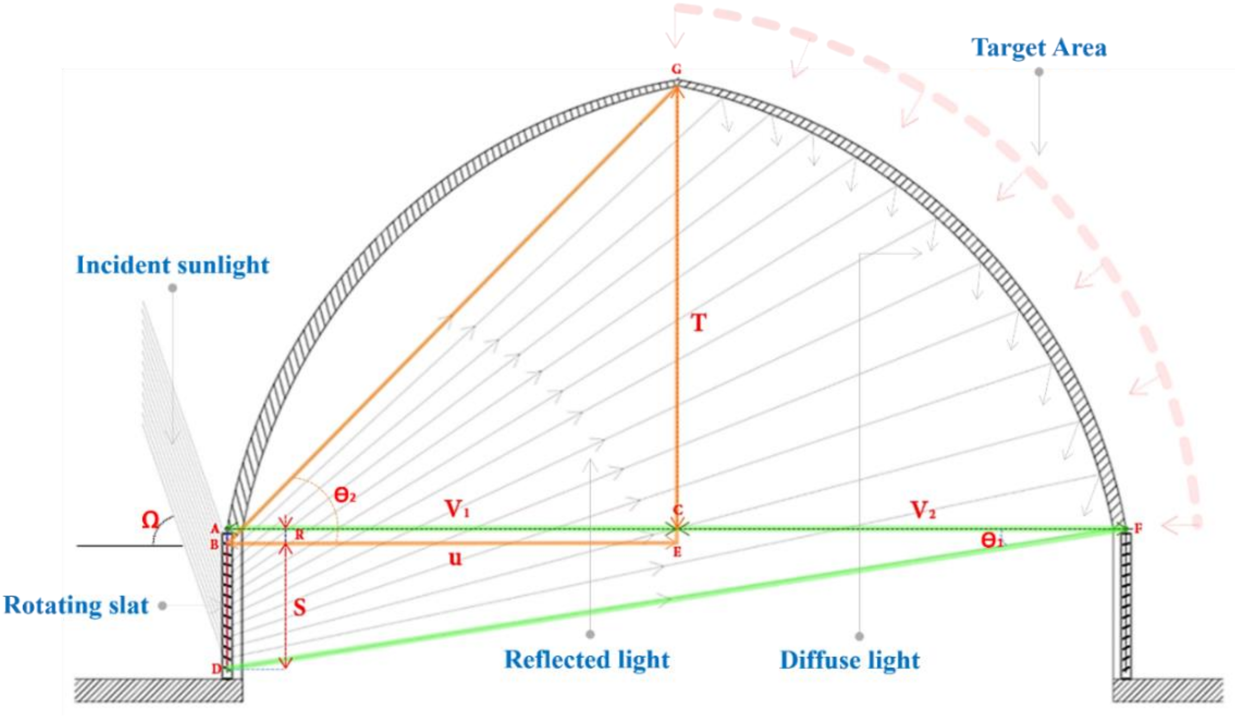

Figure 7: A cross-sectional illustration of the reflection of incident sunlight by the rotating slats onto the curved ceiling.

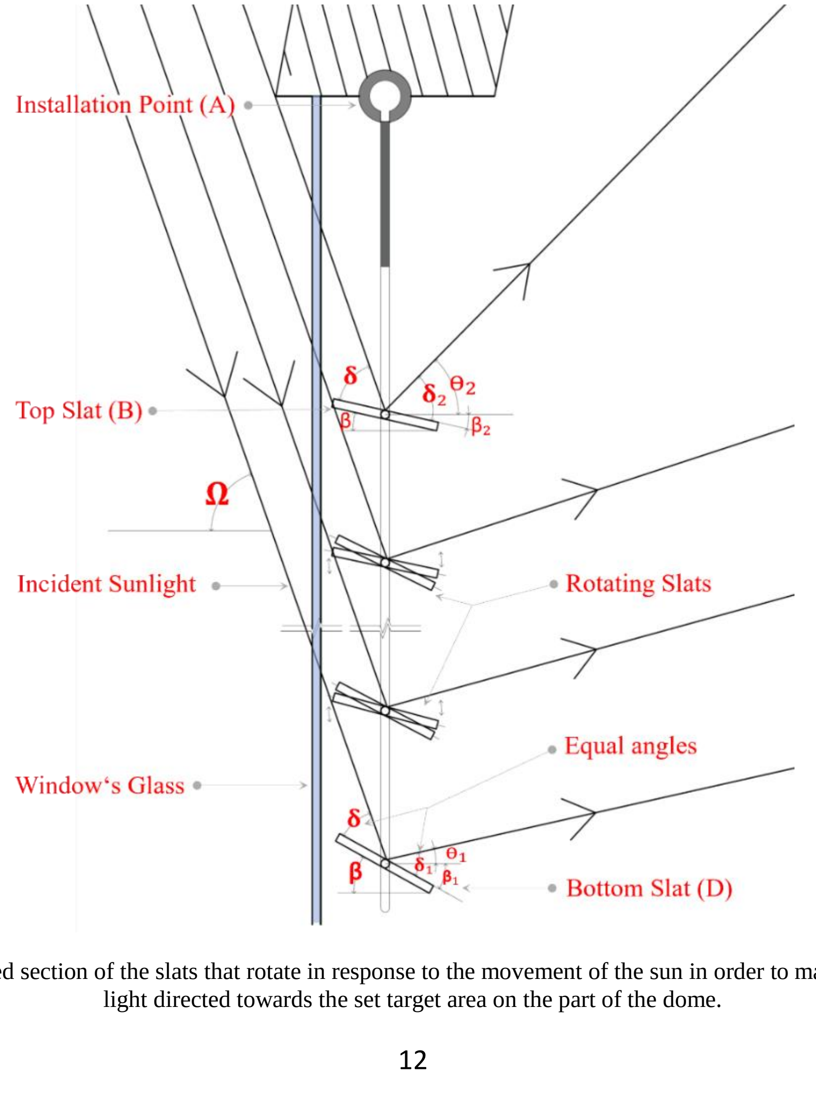

Figure 8: A detailed section of the slats that rotate in response to the movement of the sun in order to maintain the reflected light directed towards the set target area on the part of the dome.

The parametric control method is based on predetermining the rotation angle for the top slat, which is adjusted to target the highest point of the dome, and the bottom slat is adjusted to target the base of the dome, parametrically. Accordingly, the angle differences between the slat and the other were determined by deriving a simple equation to calculate the incremental slat angle **ω**, which relates only to the dome's geometry and depends on the number of slats [54]. Whereas the remaining slats will rotate accordingly to distribute the reflected light equally between the two targets and maintain an equally illuminated dome ceiling for uniform distribution, as shown in Figure 9. Accordingly, each slat should have its own rotation angle for individual control since each slat has its own target over the dome's curving ceiling. However, for simplified control, the whole slats must rotate with the same angle **ω** at each movement, which is determined using an algorithmic formula (4).

$$\omega = \frac{(\beta_2 - \beta_1)}{\text{number of slats} - 1} \quad \text{i.e.,} \quad \omega = \frac{(\Omega - \delta_2) - (\Omega - \delta_1)}{\text{number of slats} - 1} \quad \text{i.e.,}$$

$$\omega = \frac{-(90 - (0.5(180 - \Omega - \theta_2))) + (90 - (0.5(180 - \Omega - \theta_1)))}{\text{number of slats} - 1}$$

$$\omega = \frac{\frac{tan^{-1}\left(\frac{T+R}{u}\right)}{2} - \frac{tan^{-1}\left(\frac{S+R}{V_1+V_2}\right)}{2}}{\text{number of slats} - 1} \tag{4}$$

Where, $\boldsymbol{\beta_2}$ the tilt angle of the top slat of the system, $\boldsymbol{\beta_1}$ the tilt angle of the bottom slat.

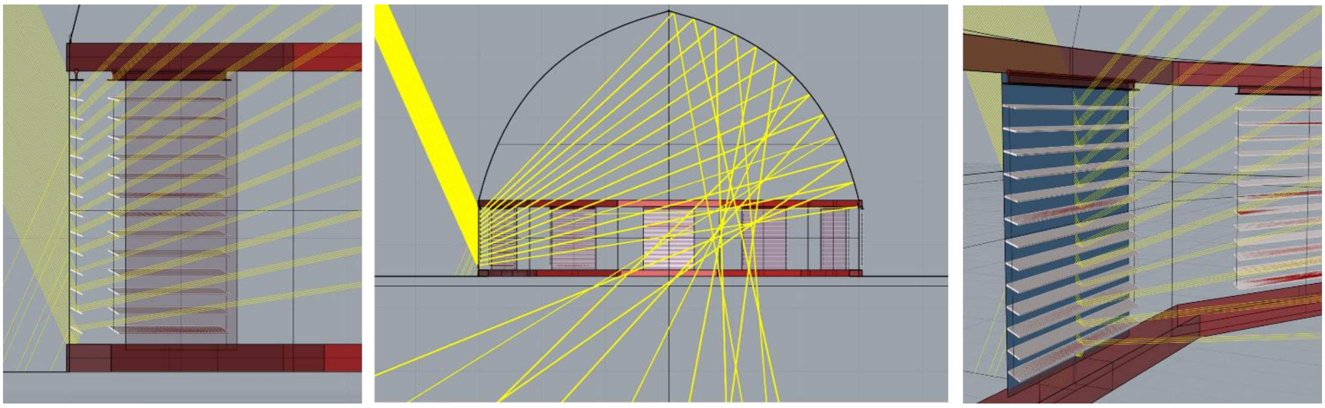

Figure 9: Side and perspective views of the ray-tracing study show the equal distribution of the reversed light on the dome.

2.4.2 The Simplified parametric Control approach for multiple blinds

In this case, the daylight performance in the prayer hall was evaluated in twelve different directions, as shown in Figure 10. Therefore, solar azimuth angle should be considered, which has a significant influence on the daylight penetrating to the prayer zone. Multiple blinds should be independently controlled based on changing solar azimuth angles and window direction. Therefore, all the slats of the blinds would be parametrically altered to different positions to redirect sunlight into the dome ceiling. The system responds to sun movement and redirects the light beam according to the profile angles that face the window surfaces. While the tilt angle β of other blinds is adjusted and fixed at 0°. This method considers the occupants' preferences on daylight distribution, where the redirected light can be distributed to a deep area of the prayer zone by the dome and reflective slats can be controlled to protect the zone from direct sunlight at the same time. The daylighting performance was evaluated at the same time on June 21st, September 21st, and December 21st in different directions during the noon prayer time, from 10:30 am to 1:35 pm, using solar profile angle and compared with other different cases.

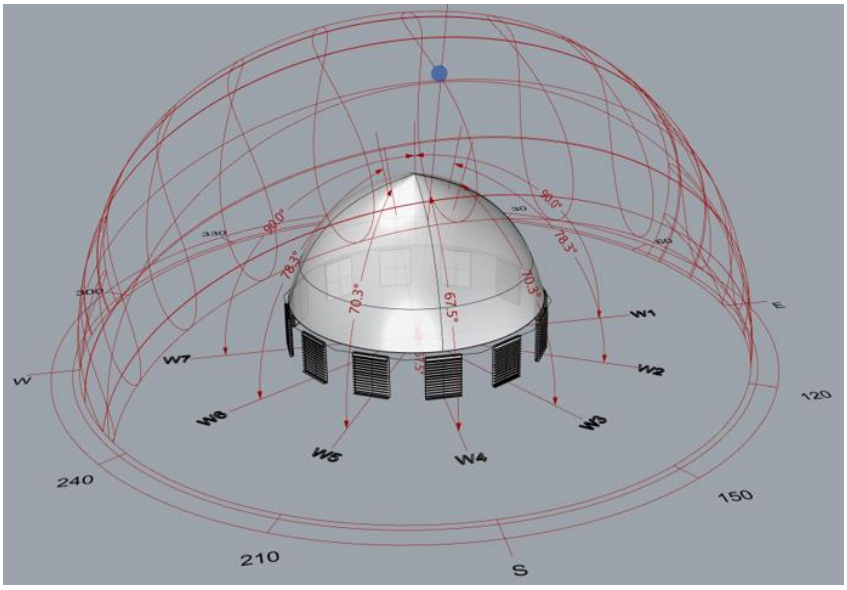

Figure 10: Perspective view of the dome shows the windows' orientation, solar azimuths, and profile angle at 12:00 pm on the 21st of September.

The parametric control technique of the system depends on each individual slat having a particular tilt angle. Meanwhile, the adjacent slats rotate, and the slats' rotation increases by one rotational angle **ω** sequentially. For example, as seen in Figure 10, if the sun profile angles differ between 70.3° to 78.3° ($W_{3,5}$ and $W_{2,6}$), all slats will adjust in response to the incident sunlight with an 8° magnitude. To illustrate this process, an evaluation study was conducted of the efficiency of using the simplified parametric control method for five blinds facing direct sunlight with variations in incidence sunlight of three different solar profile angles at 12:00 pm on September 21st in different window directions: W_2, W_3, W_4, W_5, and W_6. In this test, it was found that the difference between the rotation angles of one slat and the adjacent slat is always 1.547°, as calculated by the formula (4). Therefore, in response to the different angles of the sunlight, the slats of multiple blinds should rotate in their tracks within a limited range of -3.93° to 38.63°. This simplified approach could better cope with the different parameters while requiring fewer control segmentation settings. Therefore, the controlling method of the multiple-blind systems was defined by a sequence of equal angles starting from the upper slat angle β_2 , to the lowest slat angle β_1 as seen in Figure 11. As a result, the incremental slat parametric angles are considered as the primary component to control other slats in all windows except the north-facing window. Thus, given these variables, formula (5) could be used to calculate the rotation slat angle position.

The rotation slat angle: $\mathbf{n\,(\omega)+\beta_2}$ (5)

Where **n** represents the slat number from the up to lowest up slat.

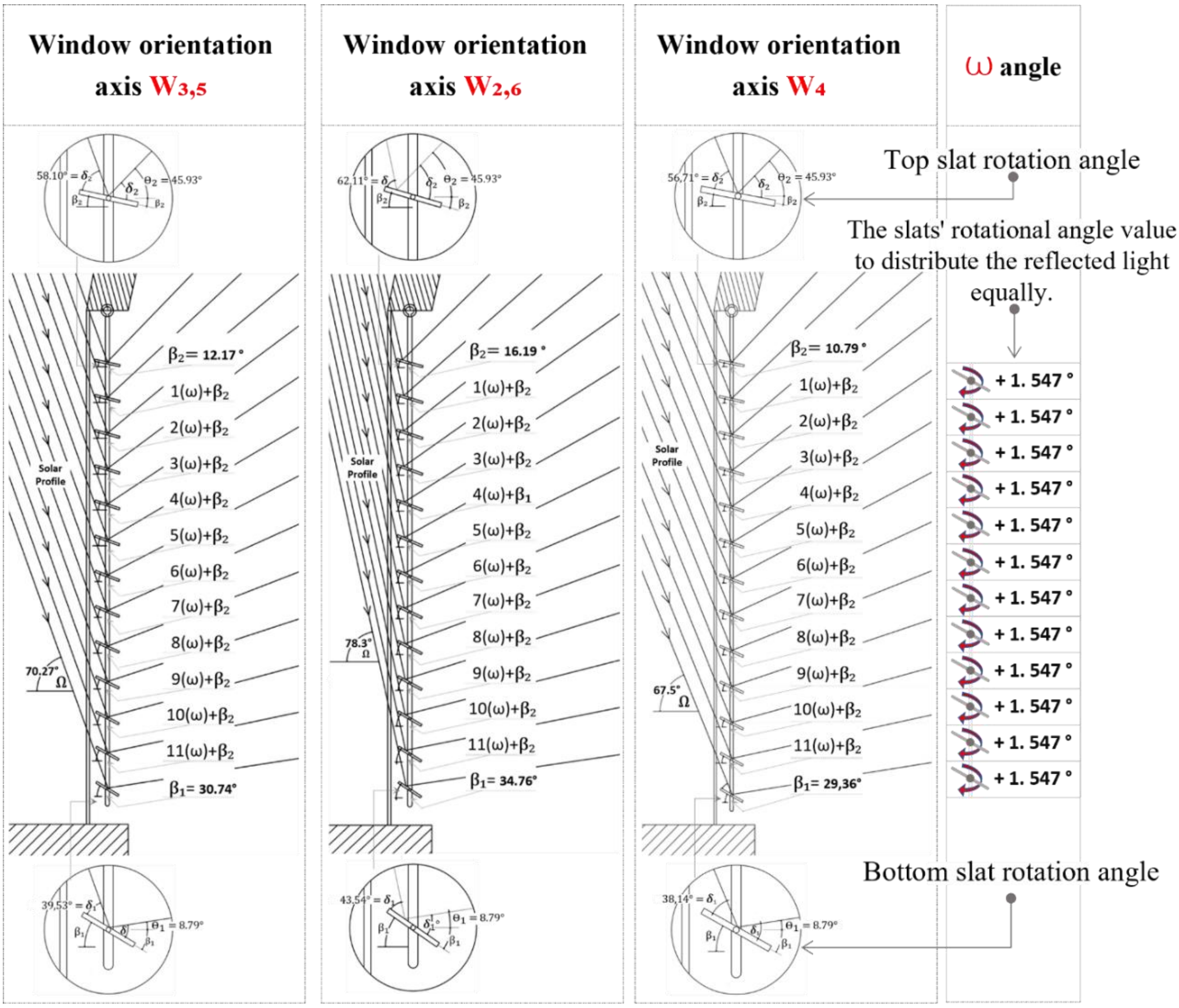

Figure 11: Controlling method of the multiple-blind systems (an example of the slat's positions at a specific date, demonstrating the system controls for different window orientations, at 12 pm on September 21st).

3. Cases and scenarios of modelling

The comparison of the daylight coverage analysis's results was performed through three different cases to improve the distribution of daylight during the occupancy time in the mosque from 10:30 am to 13:30 pm on June 21st, September 21st, and December 21st. In the first case, clear glazing windows were used to analyse the sun movement and coverage percentage area under the dome before using shading devices. Then, in the second scenario, conventional blinds were added to the windows and adjusted horizontally, i.e., 0° tilt angle. In the third case, the multi-blinds system was set parametrically to adapt in response to the sun movement (i.e., the solar profile angle) as the primary parameter to calculate the cut-off angle and determine the slats' rotation angles. This method was controlled parametrically in Grasshopper using an algorithm equation that was previously demonstrated.

The performance of these cases in terms of the average daylight distribution levels was evaluated using cross-sections through the middle area of the mosque. Then the average illuminance level of the test point results was collected into 11 points in each cross-section at a 1 m interval at reading position level based on the required range of 150-500 lux on the three selected dates. Finally, the Daylight Glare Probability (DGP) index was calculated for each case to evaluate the visual comfort inside the prayer hall.

For the first case, simulation results were obtained for windows with clear glazing using the two-phase method. In the second and third cases, a Radiance three-phase method simulation was conducted, employing the BSDF generated from both the fixed conventional blinds and the multi-automated blinds system.

4. Study Comparisons and Results

4.1. Comparative daylighting analysis for prayer time on June 21st

The daylighting analysis was conducted between 10:30 am and 13:30 pm on June 21st during the noon pray time. The results are summarized in Figure 12 and Figure 13, which illustrate the illuminance map at the reading position level and the illuminance level percentages in the three cases, respectively.

In the first case, as shown in Figure 12 the daylighting performance and coverage percentage at the reading position level rate are 50% and 47% at 10:30 am and 13:30 pm, respectively. While, at 12:00 pm, the daylighting level that exceeded 1000 lux is above 91% at the range of 150-500 lux. The reason for this excessive illuminance is the use of clear glazing window and the direct solar radiation.

In the second case, by using the horizontal static blinds, there is a notable improvement in illuminance near walls, with coverage ranging between 62 % at 10:30 am and 64% at 13:30 pm. However, the central part of the prayer area under the dome is directly struck by sunlight, which therefore the illuminance level exceeded 1000 lux.

In the third case, by using automated blinds, the illuminance maps show a significant improvement in the average daylighting performance and coverage percentage by 40% for the average of the three selected times within the range of 150-500 lux as compared to the previous case, which provided the best performance with uniform distribution by reaching an illuminance coverage range between 81% and 89%.

On the other hand, the cross-section in Figure 13 shows the different levels of daylight illuminance along the space; the illuminance levels of conventional window glazing, and horizontal static blinds were much higher than those of automatic blinds, which exceed the acceptable range by over than 1300 lux at the central prayer hall. Whereas the parametric system helped to mitigate the high illuminance level to achieve the required range of 150-500 lux, with the exception of the central area, which stayed high at 647 lux due to the intensity of solar radiation.

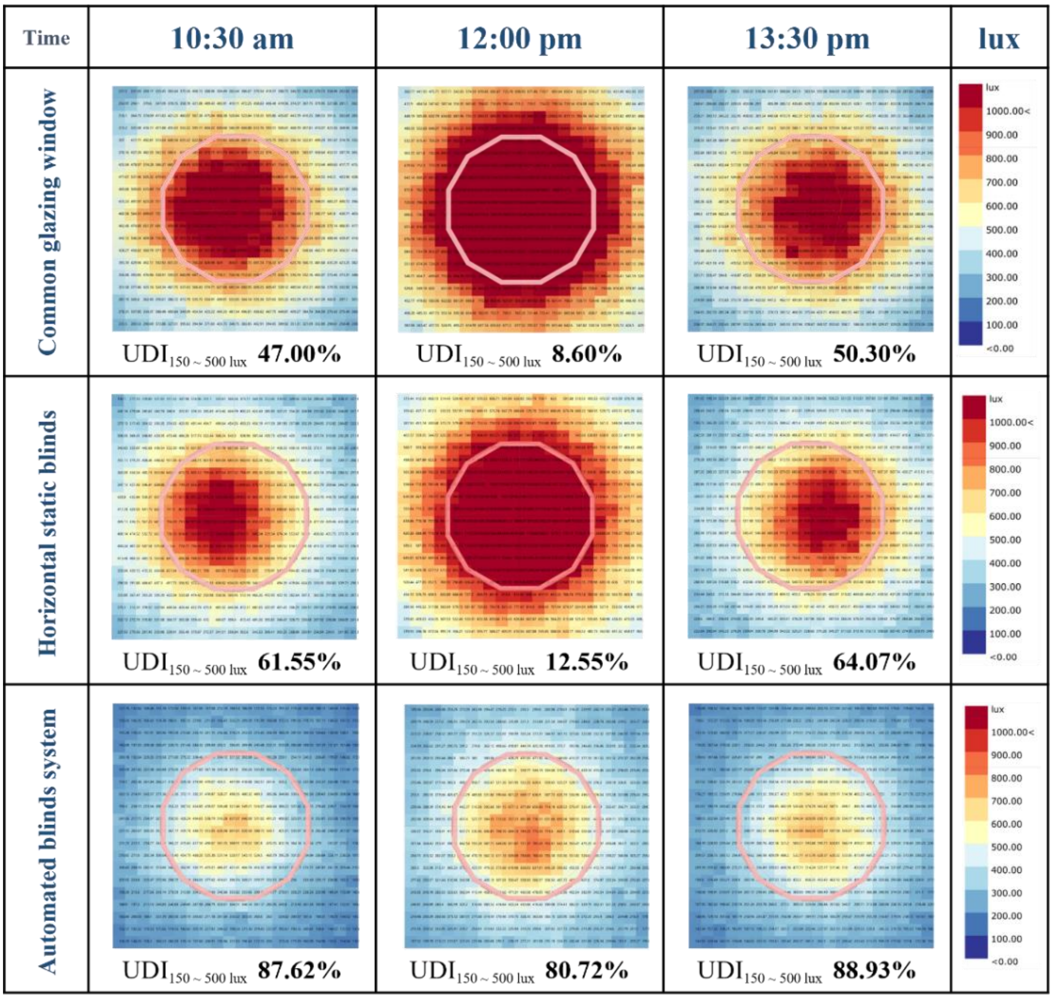

Figure 12: Comparison of daylighting distribution and percentage level of useful daylight illuminance within 150-500 lux on June 21st during the noon prayer time.

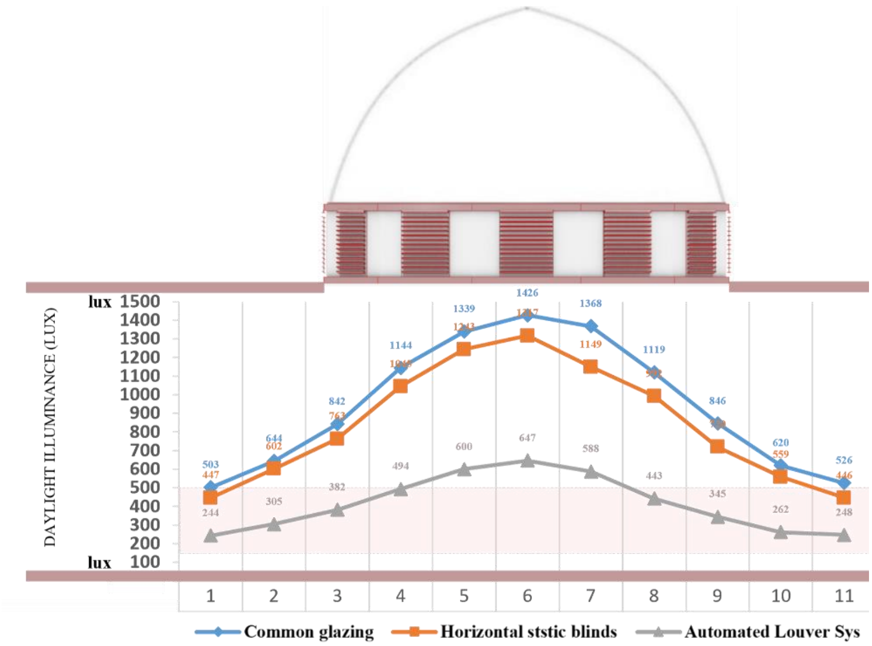

Figure 13: The cross-section shows the daylight illuminance distribution level across the dome area during the noon prayer time on June 21st.

4.2. Comparative daylighting analysis for prayer time on September 21st and December 21st

The distribution of daylighting and percentage level of illuminance for the three cases were conducted between the remaining two dates on September 21st and December 21st during the three selected noon times.

It can be seen in Figure 14 that the typical glazing window and conventional blinds cases on September 21st had almost 31% to 85% of the prayer hall exceeding the acceptable illuminance range, where the illuminance level exceeded 950 lux in both cases, see Figure 15. This excessive illuminance caused due to the low inclination of the direct light in addition to multiple reflections from the bottom side of the slats [55]. However, this penetration was successfully controlled by the automated parametric system by achieving 88% – 90% of acceptable range coverage in December, see Figure 16.

On the other hand, the system provided consistent distribution of daylight throughout all 11 points under the dome, although there was a slight contrast in daylight distribution with a much brighter circle under the dome surrounded by an area of lower illuminance, with 620 lux in the centre and 244 lux near the wall in September, as it was in June with a slight increase, as seen in Figure 15 and Figure 17. The reason behind this contrast in illuminance levels could be due to the flat shape of the slats, which tends to reflect sunlight beams concentrated in one direction rather than scattering the light (in further study, this issue will be deeply investigated). However, a previous study [56] claimed the range of illuminance levels between 100 - 2000 was considered an acceptable range for occupants. Overall, multiple automated blinds based on the simplified parametric control method succeeded in optimising daylight performance. In addition to protecting worshippers from direct sunlight, the diffused light that was conducted from the dome surface provided uniform daylight distribution under the dome within the range of 150–500 lux.

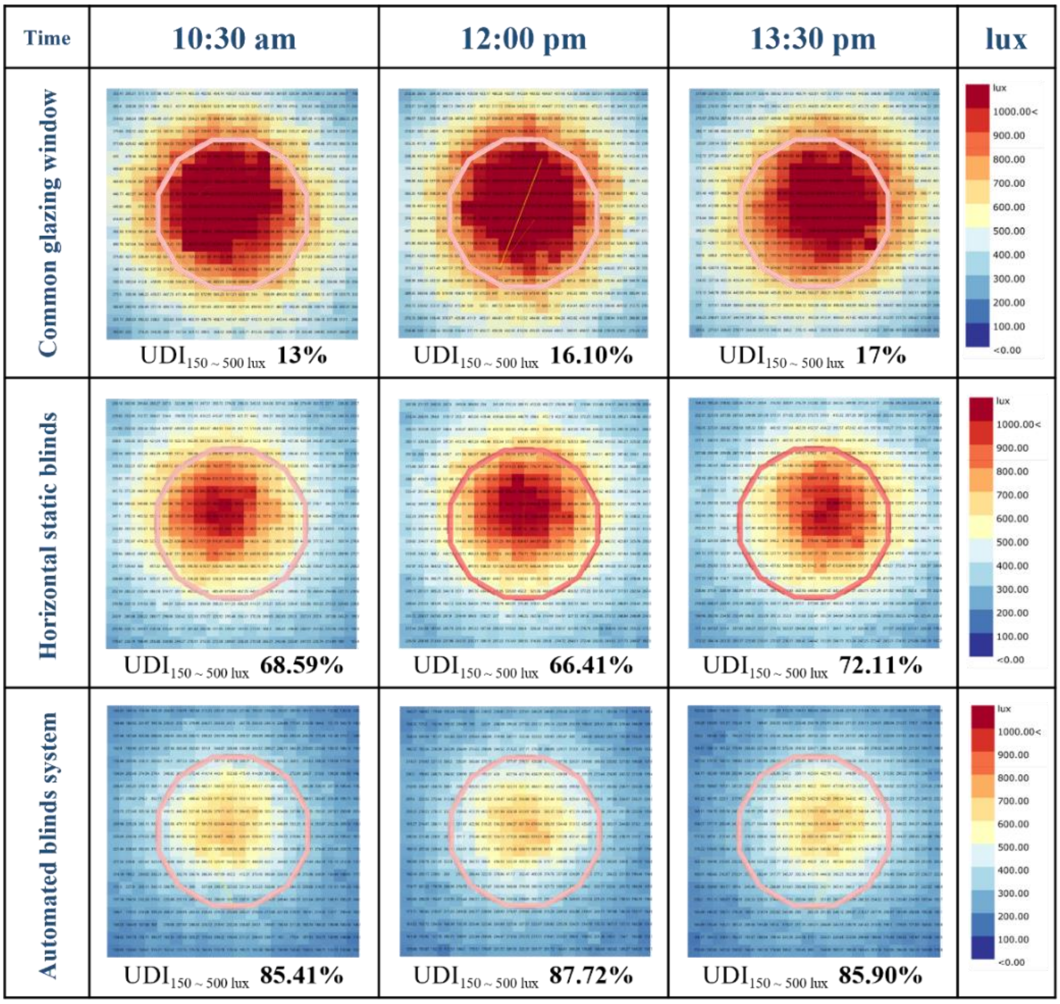

Figure 14: Comparison of daylighting distribution and percentage level of useful daylight illuminance within 150 - 500 lux on September 21st during the noon prayer time.

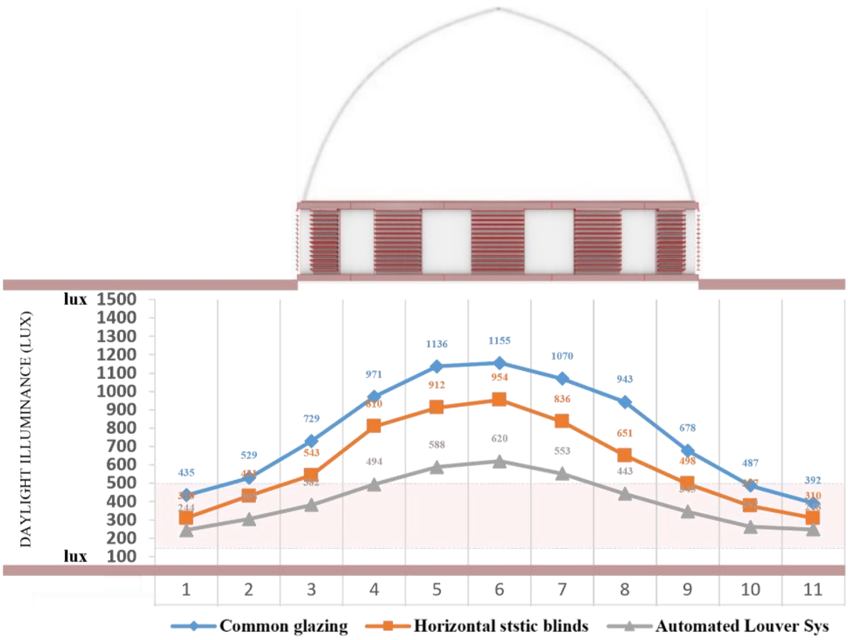

Figure 15: The cross-section shows the daylight illuminance distribution level across the dome area during the noon prayer time on September 21st.

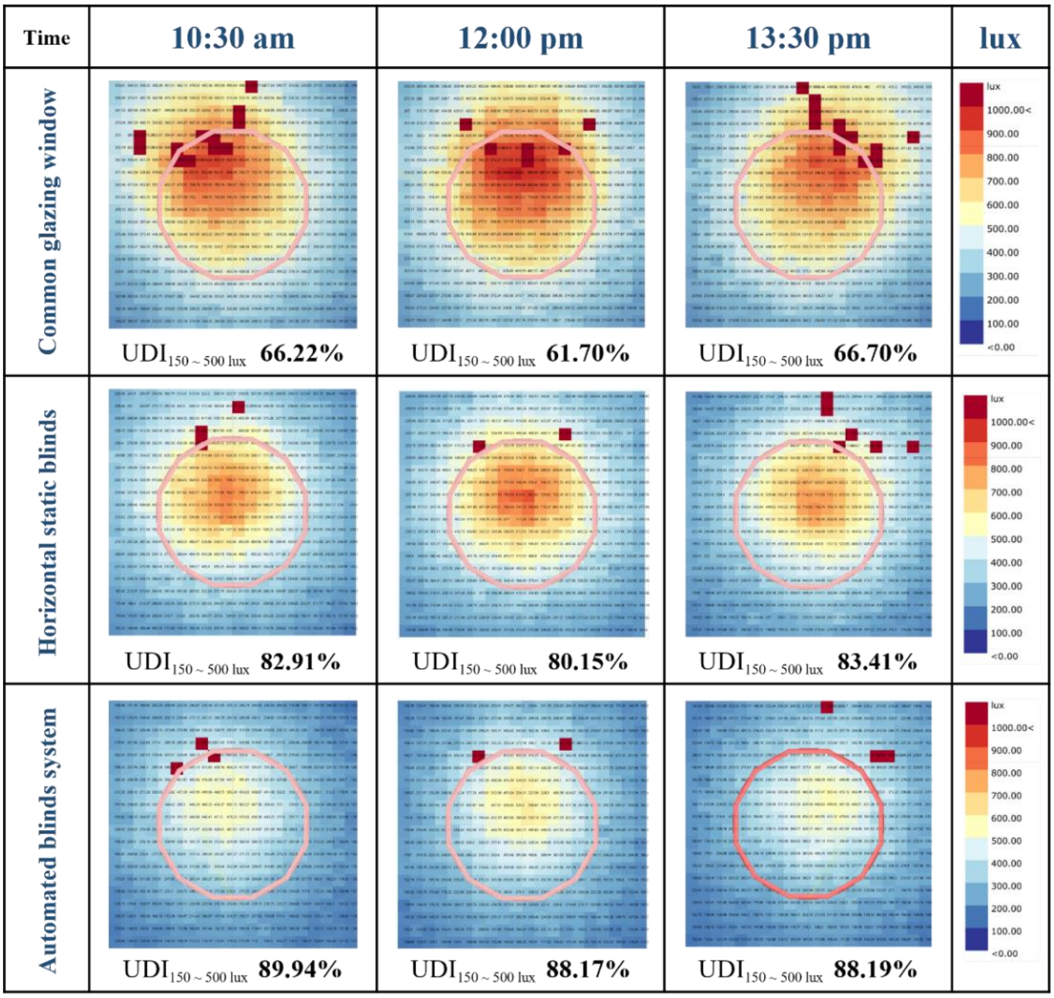

Figure 16: Comparison of daylighting distribution and percentage level of useful daylight illuminance within 150 - 500 lux on December 21st during the noon prayer time.

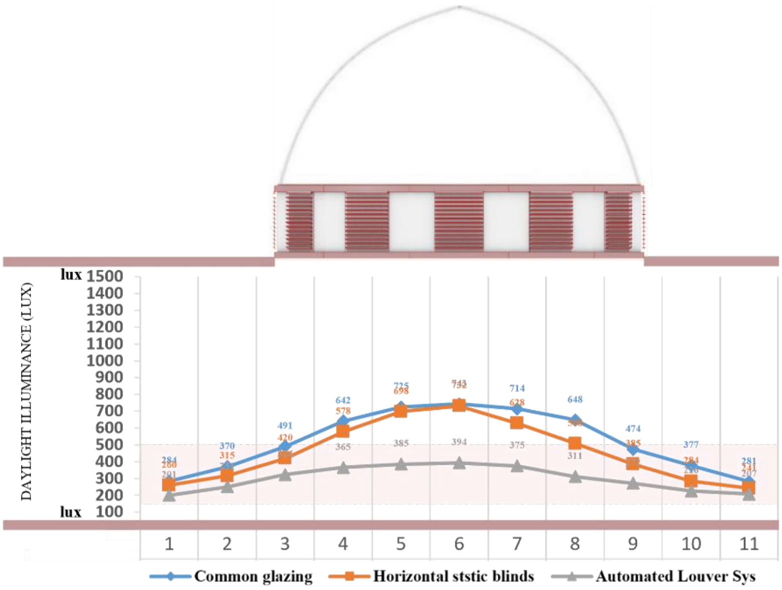

Figure 17: The cross-section shows the daylight illuminance distribution level across the dome area during the noon prayer time on December 21st.

4.3. Daylight glare probability (DGP) analysis

Intensive glare affects worshipers' visual comfort inside mosques [57]. For this purpose, Daylight Glare Probability (DGP) values were calculated to evaluate the influence of multiple automated blinds system to enhance the visual comfort within the dome building and compared between clear-glazing windows and horizontal conventional blinds. The DGP values were categorised into four comfort ranges: imperceptible glare if (DGP < 0.35), perceptible glare if (0.4 > DGP > = 0.35), disturbing glare if (0.45 > DGP > = 0.4), and intolerable glare if (DGP > = 0.45) [58]. The study measured the DGP by considering the position of the eye level, which was situated 4 m from the centre of the prayer hall and 6 m from the southern wall. Radiance plugin for Grasshopper was utilised to simulate the DGP maps for the three selected dates and periods depicted in Figure 18 and Figure 19. Generally, the DGP values at the reading position level for all three selected dates and cases were within the accepted level of less than 0.35, which is considered imperceptible glare. It can be observed from these figures that even though clear-glazed windows were the most permeable, their DGP index value was always noticeably lower than that of conventional horizontal blinds, where the values of glare index ranged in both cases between 0.11 and 0.14 to 0.22 and 0.25, respectively, at all times. The reason behind the increased value of the DGP in the conventional case was the multi-reflections on both sides of the slats, where specular slats create higher glare probabilities [59]. However, this issue was resolved by using automated blind systems, which decreased secondary reflections between the slats. The DGP index decreased to reach its optimum value on December 21st in a range of 0.05 and 0.01. While the value of the DGP index on September 21st ranged between 0.13 and 0.17, the value of the DGP index reached its highest level on June 21st at 0.16 – 0.2. However, the values remain within an acceptable range which is considered an imperceptible glare.

This research primarily focused on daylighting performance within a specific climate condition. However, an upcoming study will extend this investigation by exploring the efficiency of multiple automated blinds in diverse regions and environments. It will assess their applicability to different designs of the drum's dome and various ceiling geometries.

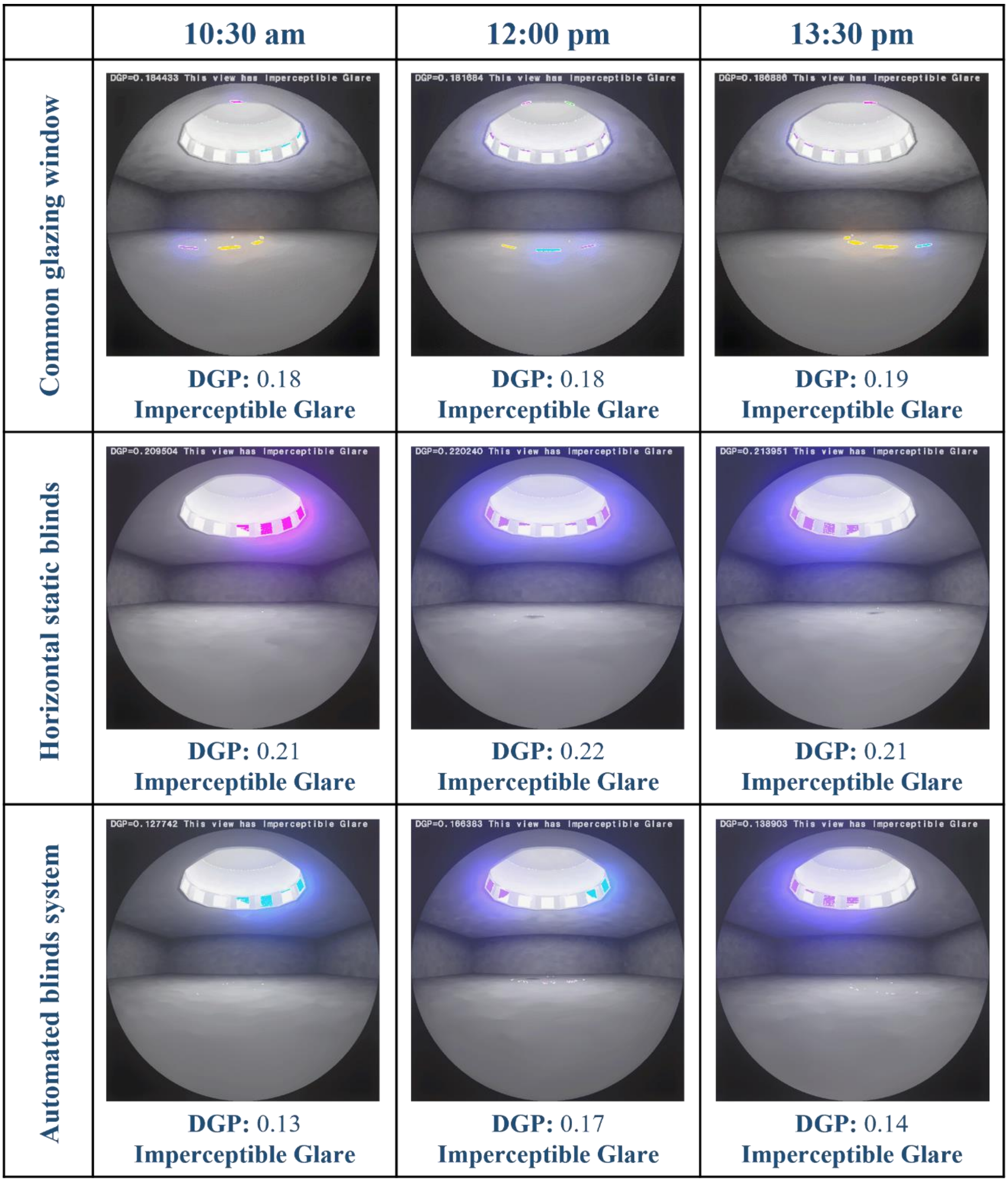

Figure 18: Comparison of the daylight glare probability analysis maps in September for the three cases.

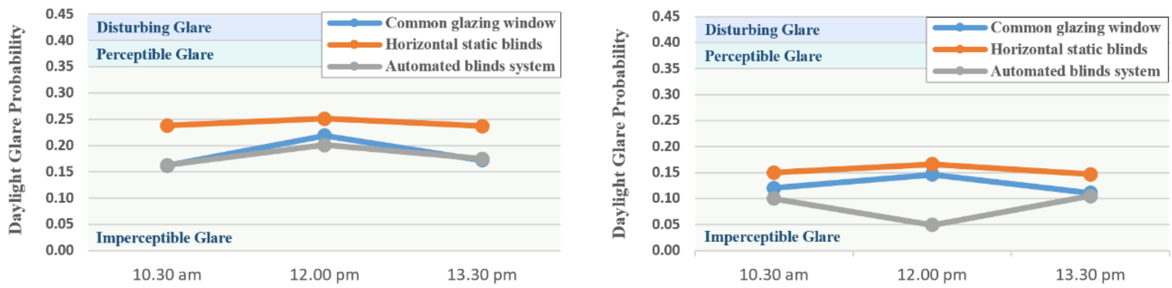

Figure 19: Comparison of the daylight glare probability in June (Left), in December (Right) for the three cases.

5. Conclusion

The controlling methods of shading devices to maintain the required illuminance level at buildings are influenced by a variety of parameters, such as directions, building geometry, and facade shapes. However, a significant parameter, such as solar azimuth angle, that controls the tilt angle of the slat in facades in various directions.

In flat facades, control methods of shading systems are focused on minimizing the negative impacts of direct daylight on buildings in only one direction, in which the solar azimuth must be between 90˚ and 270˚ to strike the slats [60]. Therefore, with curved building cases that exceed the façade 's boundaries by 180 degrees, an innovative approach is needed. For this purpose, the current study provided a new parametric control method for multiple automated blinds controlled automatically in response to the sun movement by using an incremental slat angle as a simplified parametric component. The control method of the system was defined by a sequence of equal rotation angles starting from the top slat angle to the bottom slat angle according to both solar azimuth and profile angle. Then the system's suitability was examined for installation on windows with different directions to maximize the benefits of daylight while preventing direct sunlight. The proposed system was conducted by using parametric simulation software known as the Grasshopper plugin for Rhinoceros 3D software through a particular algorithm, at Dammam, Saudi Arabia, on June 21st, September 21st, and December 21st under clear sky conditions.

The results revealed that the parametric system gives better daylight distribution inside the prayer hall, with an average of 87% area coverage for the daylight illuminance range of 150–500 lux at the noon prayer period throughout the year. This is higher by about 21% to 48% compared to conventional blinds and clear-glazed windows, respectively. Additionally, the proposed system ensures optimal visual comfort for worshippers at the reading position level.

As mentioned earlier regarding the contrast in daylight distribution, future work is needed to investigate the feasibility of this system by testing various slat configurations and shapes in order to achieve better daylighting performance. Therefore, these advanced modifications will be evaluated over longer periods throughout the day and year in different climatic regions to obtain more reliable and improved results.

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Declaration of interests

☑The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: