Highlights:

- Proposing an Automated Louver system based on parametrically angled reflective slats as a daylighting system.
- Using Grasshopper as a control method within its environmental plugins.
- Provide uniform and steady daylight inside the room and save energy.
- Modifying the slats' size and shape for better performance and more feasibility.
- Further, improve the daylight distribution and reduce glare probability.

A novel automated louver with parametrically-angled reflective slats; design evaluation for better practicality and daylighting uniformity

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Abstract

Daylighting harvest systems have been improved in recent decades. They have been dramatically used in green buildings to achieve a more sustainable living environment. However, their cost, sizes, shapes, materials, accuracy and control methods are considered as critical aspects towards their feasibility and practicality. The optimal integration between these aspects can achieve more reliable and practical daylight harvest systems. Grasshopper, as a parametric control method, can be exploited in such systems to optimise the use of each aspect. Parametric approach is considered as the most convenient way to control and manipulate different parameters simultaneously, with respond to the sun movement. This study investigates a parametrically controlled daylighting louver system, which can respond to the sun movement to collect as much daylight as possible inside the deep room, via using parametrically-angled reflective slats. To consider our main purpose of feasibility and performance, the study will evaluate the performance of the proposed system by changing its slats' size and shape to achieve optimum balance between practicality and performance. The study found that reducing the louver size and modifying the slat's curvature, can significantly increase the daylight coverage percentage inside the deep room from 93% to 98% within the illuminance standard range 300 ~ 500 lx, in addition to reducing the glare probability to an imperceptible level, besides achieving lighter weight and better strength-limber shape.

Keywords

Daylight performance; Parametric design; Automated reflective louver; Feasibility; Daylight Glare Probability; Visual comfort.

1 Introduction

Advanced daylighting systems are used to optimise the utilization of daylight, and protect occupants from glare, to achieve visual comfort and energy saving [1]. Moreover, manipulating with building geometry, fenestration size and shading shape can dramatically influence the daylighting performance and visual comfort through optimized design options [2, 3]. However, cost, size, efficiency and maintenance are still crucial challenges for such systems [4]. Therefore, practicality and feasibility aspects should be taken into account to promote the application of these systems [5]. Indeed, practicality leads to feasibility, to be practical for easy handling rather than being a theoretical application. For instance, light-shelves [6] and SunCentral [7] can optimise the use of daylight, however, their size can be a potential obstacle against market spreading [8].

Several studies in the recent years investigated integrated daylighting systems [9, 10], automated systems [11, 12] and responsive systems [13, 14] to optimize the use of daylight and save energy regardless their practicality [4]. A study was conducted in Indonesia using light-shelf to optimise daylight in an open-plan room by using Grasshopper as a parametric design [15]. Grasshopper has been employed to manipulate with the external and internal overhang of the light-shelf and its tilt angle. The study resulted an increase of daylight inside the room, however, the distribution of daylight was not equally uniform, in addition to the huge size of the overhang which extended to 1.20 meter outside the window [14].

On the other hand, a study investigated the possibility to reduce the size of daylight redirecting micro-prism system while retaining its optical performance [16], aiming to achieve better practical use. Similarly, a study used three-dimensional textile to improve daylight performance via manipulating with the shape and using small size apertures [17].

Potentially, controlling the fenestration size can enhance the daylight penetration inside the room, due to the Penumbra effect [18] that plays an important role in such cases, which efficiently occurred when reducing the apertures' size of any fenestration system [18]. This phenomenon mitigates the intensity of the light, reduces potential glare and provides diffuse light. In addition to the daylight performance, consideration of thermal comfort inside the building may influence the practicality of a daylighting system [19, 20], accordingly, it is important to find a compromise between both daylight performance and thermal comfort [21, 22].

Parametric design in the current study plays an important role in controlling several parameters simultaneously [14] without affecting their primary performance, aiming to increase their feasibility and practicality. This study uses Grasshopper software as a control method of an automated daylighting louver system, which can respond to the sun movement via using rotating slats that can reflect the sun light to specific targets over the ceiling, then the ceiling works as a source of diffuse light to the room [23]. The concept of using parametrically-angled reflective slats is to improve the daylighting uniformity and increase its stability [24], to achieve human visual comfort and save electrical energy [25]. Further to our previous study [26], this study evaluates the use of slim and curved slats for easy installation in practice, better robustness and promisingly, greater illuminance performance with lower glare probability. The study examined reducing the slat size of the of the automated louver system on seven intervals (from 25 cm to 2.5 cm) for a flat, concave and convex slat, respectively, on the 22nd of March, hourly during the daytime, in a sunny hot territory such as Egypt, to find the optimum slat size and shape with the best performance. The study revealed that the convex 2.5 cm slat (slim slat) is the optimum choice. Thereafter, the chosen slim slat (flat, concave and convex) has been evaluated at different dates during the year, on June, September and December for more performance affirmation. In this study, the analysis has been made hourly from 9 a.m. to 5 p.m., however, the analysis has been presented only at noon time due to its convenient altitude and azimuth for more obvious clarification for the reader.

2 Methodology

The research follows an empirical approach, by using computer simulation to assess different daylight harvest strategies. The aim is to compare different settings of automated daylight harvest systems in terms of system's performance as well as feasibility. The research conceptual framework is shown in Figure 1.

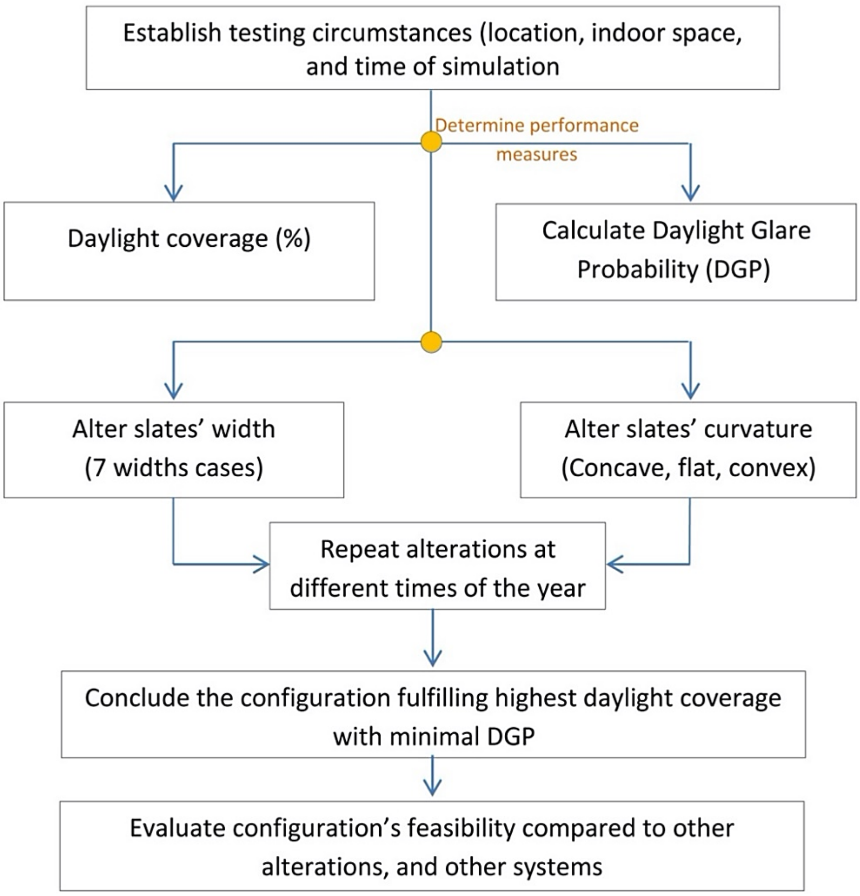


Figure 1: Research conceptual framework

The research starts by determining the simulation environment and circumstances. The simulation is run in an example south oriented office room with 8m depth and 12m width in new Cairo in Egypt at the location latitude and longitude (30.1128° N, 31.3998° E).

Egypt is one of the countries that receives huge amount of solar irradiance, see Figure 2. Therefore, either green rated or non-rated buildings in Egypt must harvest daylight to allow for better human comfort, and to maximize energy savings as well. However, maximizing daylight harvest in such climate leads to the challenge of overcoming glare. Therefore, the current study investigates a strategy to maximising the use of daylight while, minimising the potential glare. It should bear in mind that the original parametric louver system with 10 cm slat width has been investigated and validated in previous researches at different times and orientations during the whole year [23, 25-27]. However, this paper investigates the practicality and feasibility of the parametric louver by achieving the optimum slat size/shape with the best performance.

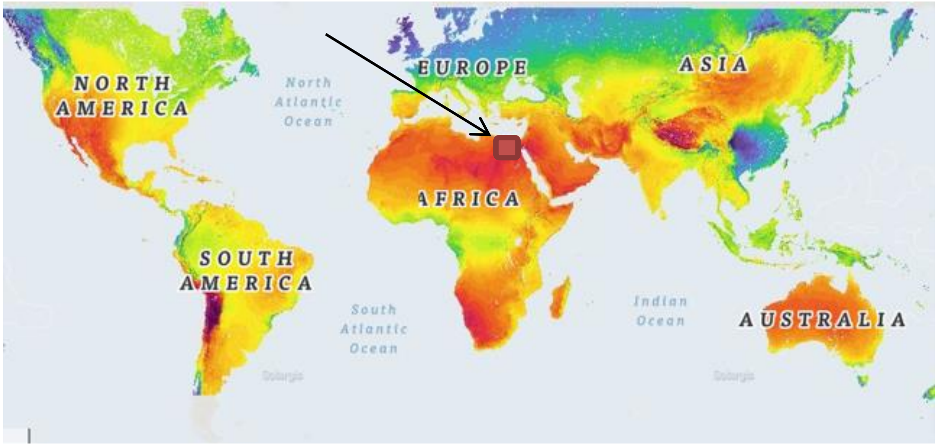


Figure 2: Solar availability map. Retrieved from [The world bank group, "Global Solar Atlas," 2016. [Online]. Available: https://globalsolaratlas.info/?c=9.275622,23.90625,2. [Accessed: 06-May-2019].].

This region is chosen as it receives high solar irradiance amount, which is ideal for evaluating system's performance in terms of glare. The simulation tools used are Rhinoceros 3D (version 5) for the room geometry, Grasshopper (for Rhino 5) for simulating the parametric louver, which rotate based on the provided sun path, and "Ladybug (0.0.68) & Honeybee (0.0.65)" for evaluating daylight performance. Daylight performance is evaluated in terms of two measures: daylight coverage (based on illuminance analysis) and Daylight Glare Probability (DGP). The daylight coverage in this study represents using a spread of test points at the desktop level 0.75 m above the floor, with a range 0.5*0.5 m analysis grid. Each single point measures the daylight illuminance level in lux. The accepted illuminance level for offices area should be within 300~500 lux, according to CIE standards [28, 29] and "The Lighting Handbook" [30]. The average sum of these points represents the daylight coverage percentage of this area, whereas the percentage number represents the sum of figures within 300~500 lx. For instance, if we have 4 test points in a room, and each point measured 350, 370, 440 and 560 lx, so the daylight coverage percentage for this room should be 75%, because we have three points within the accepted range 300~500 lx and one point (560 lx) will be omitted which is over the accepted limit.

For more clarification, Figure 3 is a sample image for a daylight simulation analysis for an example office room, where the blue colour represents a low illuminance level and the red colour is a high illuminance level, while the light blue colour represents the recommended illuminance level range which should be between 300 and 500 lx.

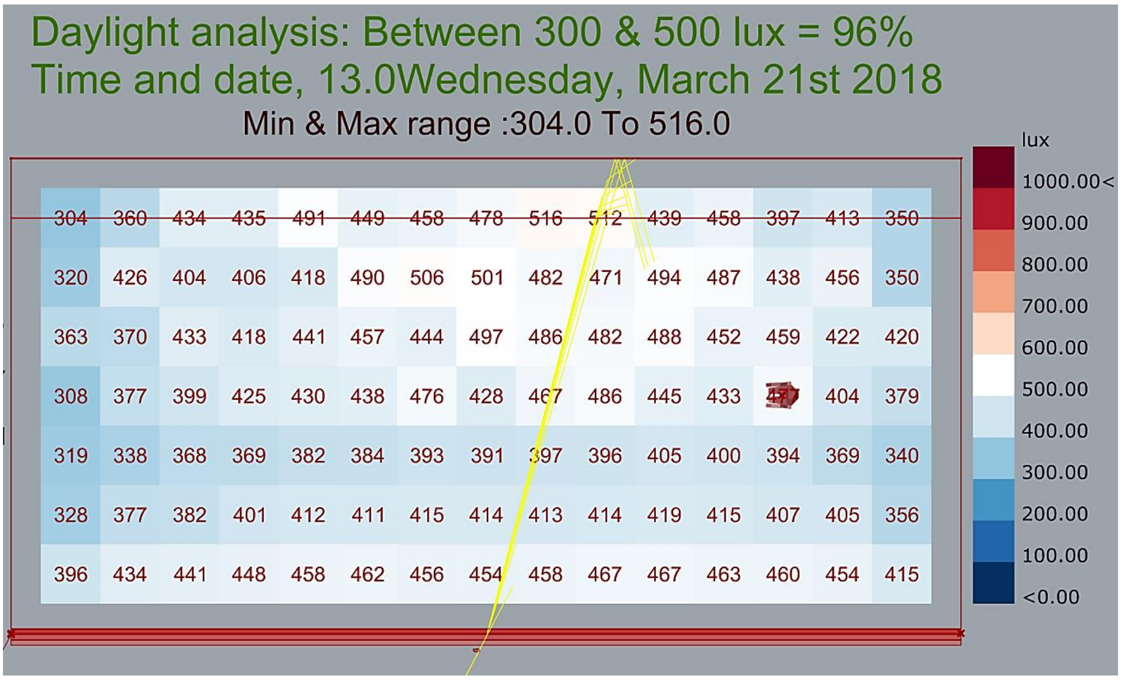


Figure 3: Sample daylight simulation analysis for an example office room

Under the circumstances that the louver is dynamic, computational power available is not capable of running metrics like daylight annual autonomy, hence, three representative times were selected to conduct the simulation; daytime from 9 a.m. to 5 p.m. on three days: 21st of June, 23rd of September and 21st of December. Finally, the louver system with the least DGP, maximum daylight coverage, and most feasibility (lowest size, lighter weight, and limber shape) was determined.

A novel automated louver with parametrically-angled reflective slats installed at the upper part of the window at 2.5 m from the floor in a 4 m height room. The upper window was assigned as a thermochromic-glazing [31] which used to control the intensity of the reflected sunlight [24]. The lower part of the window was assigned as an electrochromic window [32] to control the daylight transmittance at the area near to the window, see Figure 4. (The electrochromic window properties and control were discussed in details in this article [33]).

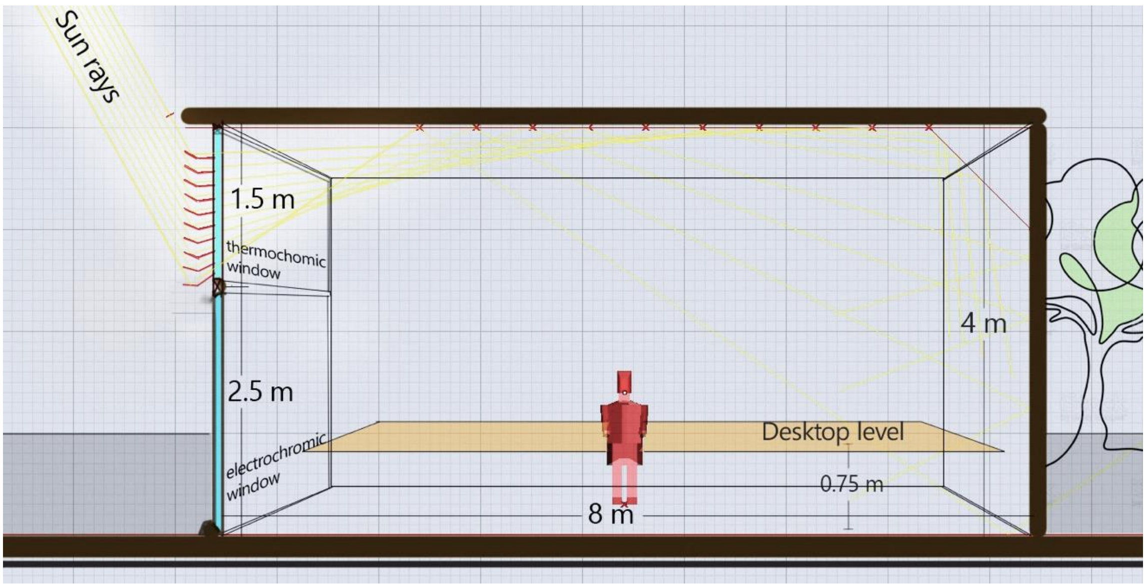


Figure 4: Cross-section through the example office room

The louver can reflect sunlight to fixed targets on a ceiling, which then acts as a source of diffuse light to provide more uniform and steadier illumination. For the light raytracing, four ambient bounces (AB) were set in the Radiance file to give better accuracy in the simulation. The walls and ceiling were assigned as white matt material with 80% reflectivity, the louver was assigned as aluminium slats with 90% reflectivity, and the floor was assigned as a dark matt carpet [33]. The reason of using fixed targets on the ceiling is to keep the reflected beams horizontally constant, parallel to the window and moving in a straight line in one path according to sun azimuth as shown in Figure 6. Number of targets is varying based on number of slats, meanwhile, the distance between the targets is equidistant, whereas, the first target is 240 cm away from the window and the last target is 50 cm away from the wall, that is to keep the illuminated area equally distribute [23, 26]. Each single slat has a specific rotation angle, with one rotation angle at each movement for all slats, see Figure 5. For instance, if the sun altitude changed from 30° to 50°, all slats will rotate accordingly with respond to the sun movement with one magnitude 20°, meanwhile, each single slat has a different rotation angle compared to the other slats.

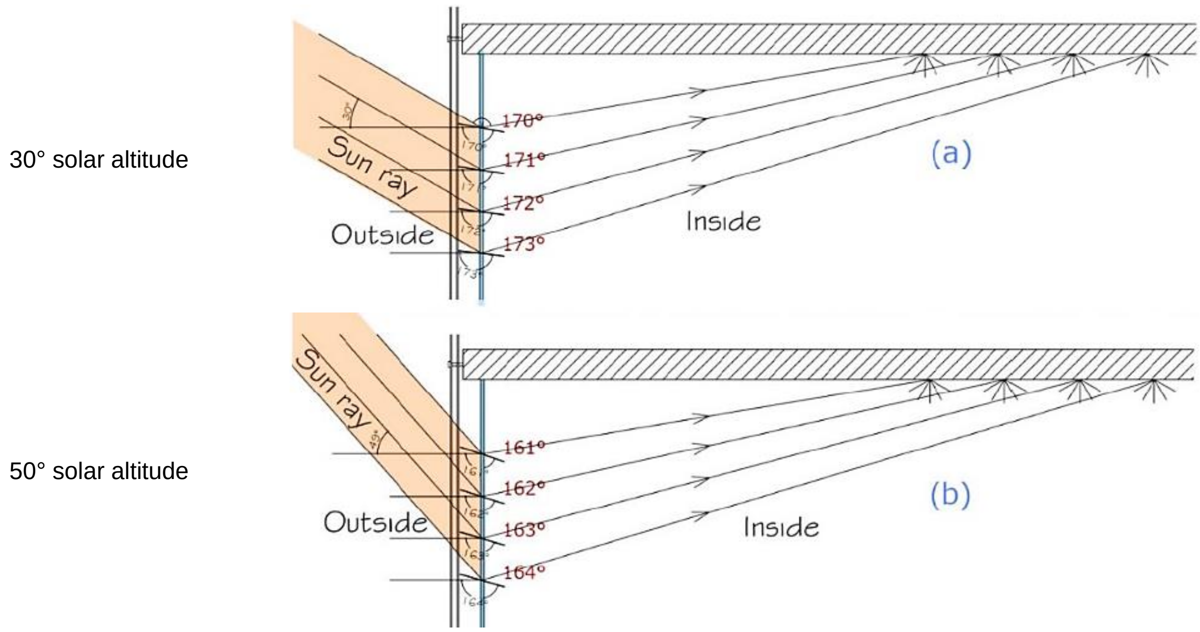


Figure 5: One rotation angle at each movement for the whole slats


Figure 6: Radiance maps inside the room showing the parallel reflection on the ceiling during the daytime from 9 a.m.: 5 p.m.

Two different slats' shapes were used in our evaluation; the concave shape and the convex shape, see *FIGURE 7*. Modifying the slat's shape can generate thinner slat that is more likely to achieve more limber characteristic and feasible material.

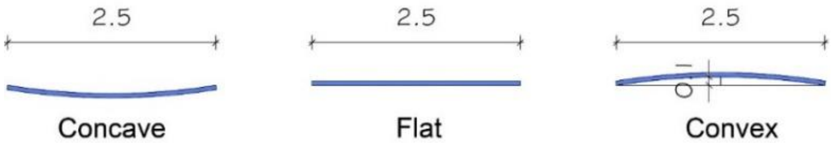


Figure 7: Various slat shapes (width in centimetre), curvature height is 0.1 cm.

The concave slat behaviour is similar to the “parabolic trough”, where sunlight is collected and focused to a specific focal point at a specific distance then distributed again until reaching the ceiling as seen in Figure 8 *(LEFT)*. The reflected light is slightly concentrated near to the window then distributed in patches, then overlapped at the end of the room. On the contrary, the convex slat tends to distribute the reflected lights in wide patches where the lights are overlapped on the ceiling.

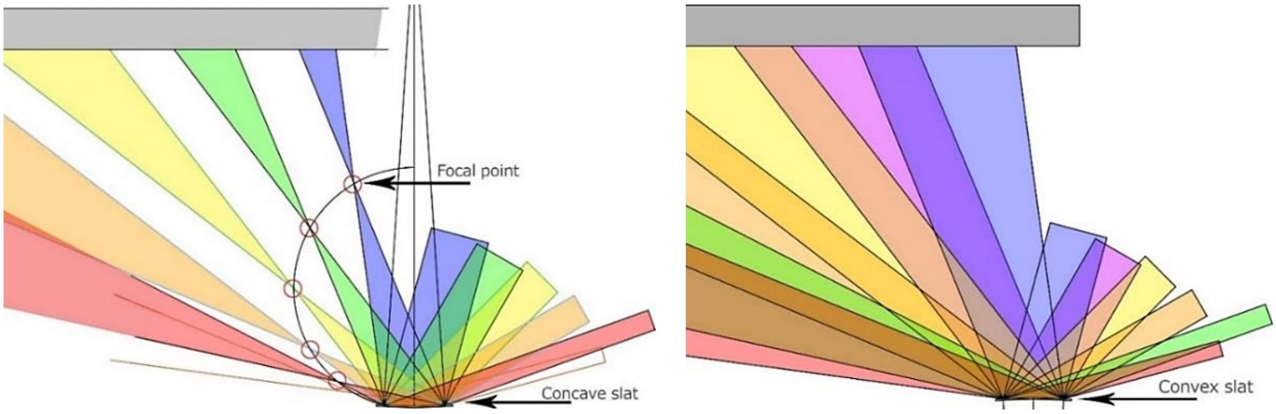
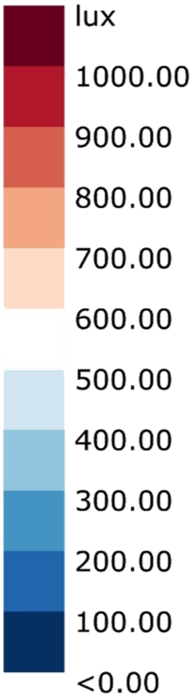
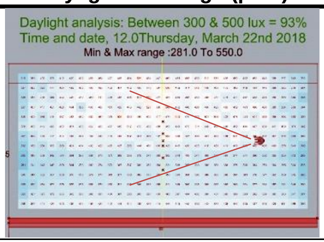
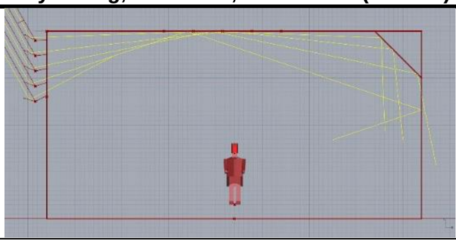
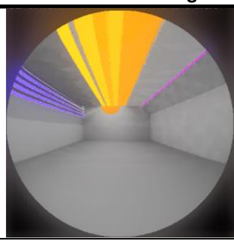


Figure 8: Side view showing the shape of the reflected light with a 5 cm concave slat (left) and convex slat (right) at different inclinations

The parametric control method has been evaluated in our previous studies [26], based on installing a wide louver system outside the building envelope, however, the use of slimmer slats may present wider applicability of this concept as being suitable for installation inside a façade or in between a double-glazing window. Therefore, a compromise control will be performed between the slat width and the number of slats to retain the daylighting performance of the louver system at an acceptable illuminance level [23].

In the current study, “daylight distribution” and “Glare check image (using HDR image)” were simulated, and the “Daylight Glare Probability (DGP) index” for each case were calculated for the example office room with a virtual installation of the proposed louver, with a slat width 25 cm descending to 2.5 cm at seven intervals. Daylight Glare Probability influences occupants’ visual comfort inside the office room [34] and considered the most recent index to evaluate glare from daylight [35, 36]. In our case, DGP index was measured at one point at the “eye level” of a red mannequin sitting at the desk level facing side wall, see Figure 9, case (1) “plan” (the mannequin’s eye view angle for the Glare check image). The eye level of the mannequin was set at 1.1 m from the floor. Daylight analysis has been calculated in lux at the desk level 0.75 m using test points over the whole room for each case, meanwhile, the illuminance coverage percentage has been considered within the illuminance level 300~500 lx (the white and light blue colours in the light scale in Figure 9).

Using the same approach, the width of the concave and convex slats was changed at seven intervals, as shown in Figure 10 and Figure 11, respectively. The simulation consists of; daylight coverage percentage analysis (plan) at the desk level, left view of the room (section) with light raytracing, and DGP map (mannequin view). For convenience in descriptions, the automated louver with a slat width 2.5 cm will be denoted as (Slim Flat-louver or SF-louver), (Slim Concave-louver or SCC-louver) and (Slim Convex-louver or SCV-louver), respectively.

<table>
<tr><th>Light scale</th><th></th><th>Daylight Coverage (plan)</th><th>Raytracing, slat width, no. of slats (section)</th><th>Glare check image</th></tr>
<tr><td rowspan="14">
</td><td rowspan="2">Case (1)</td><td>
</td><td></td><td></td></tr>
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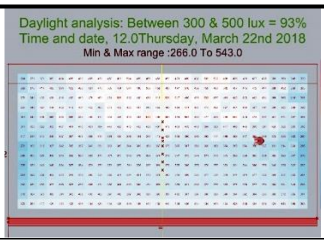
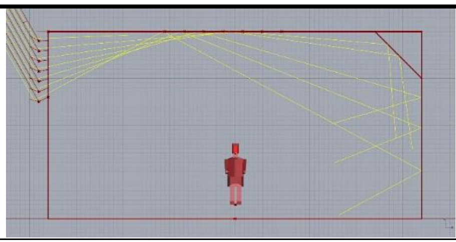
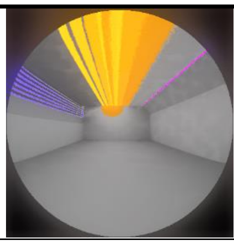
<tr><td rowspan="2">Case (2)</td><td>
</td><td></td><td></td></tr>
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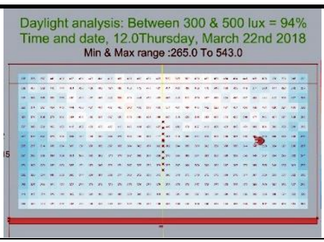
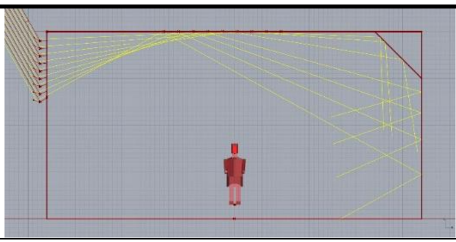
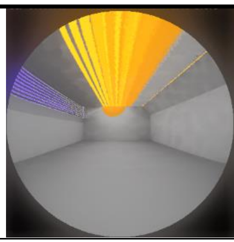
<tr><td rowspan="2">Case (3)</td><td>
</td><td></td><td></td></tr>
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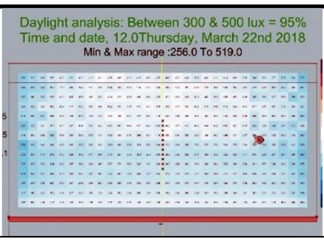
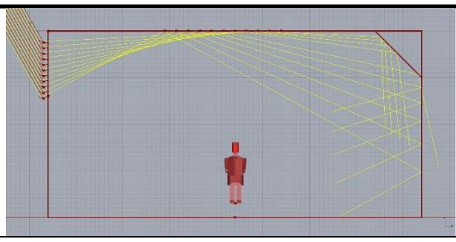
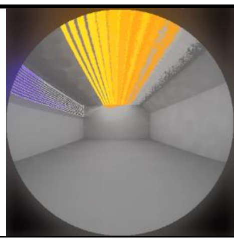
<tr><td rowspan="2">Case (4)</td><td>
</td><td></td><td></td></tr>
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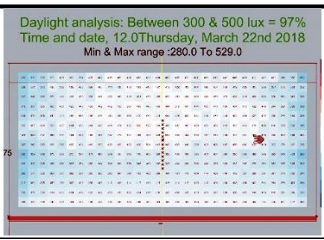
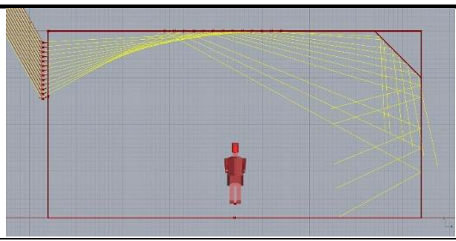
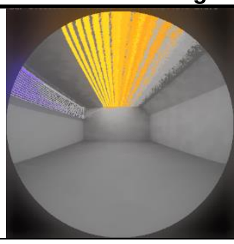
<tr><td rowspan="2">Case (5)</td><td>
</td><td></td><td></td></tr>
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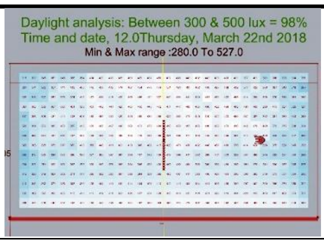
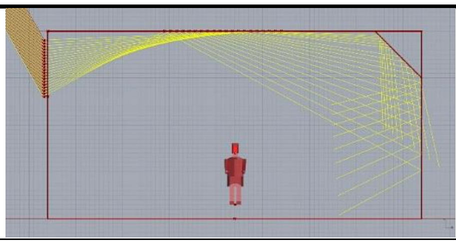
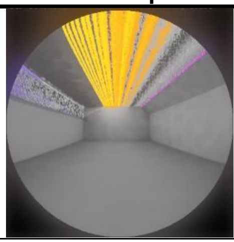
<tr><td rowspan="2">Case (6)</td><td>
</td><td></td><td></td></tr>
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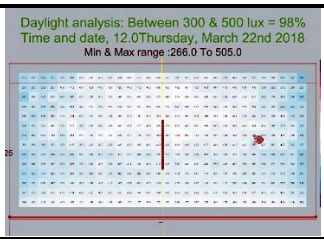
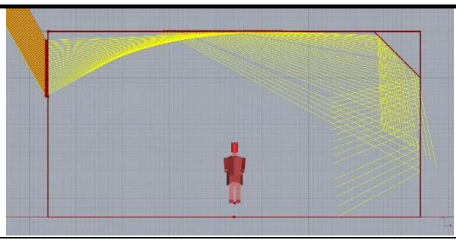
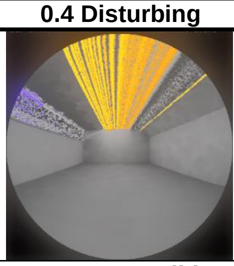
<tr><td rowspan="2">Case (7)</td><td>
</td><td></td><td></td></tr>
<tr><td>98%</td><td>2.5 cm – 38 slats</td><td>0.38 Perceptible</td></tr>
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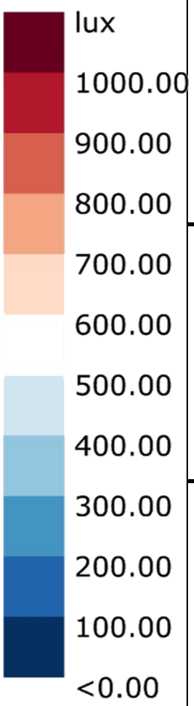
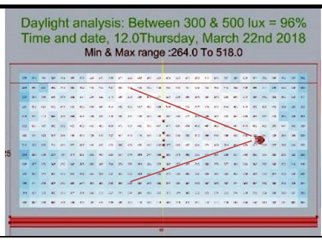
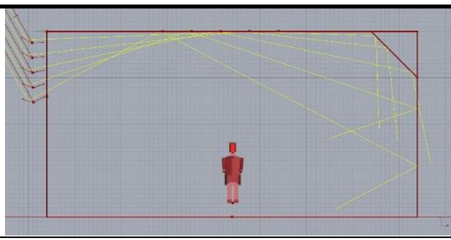
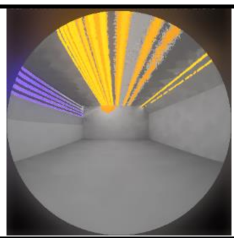
*Figure 9: Flat louver shape applied in an example office room 8*12 m in New Cairo on the 22nd of March at noontime, showing; top view for daylight analysis (left), side view for raytracing study (middle) and DGP map (right).*

Light scale		Daylight Coverage (plan)	Raytracing, slat width, no. of slats (section)	Glare check image
	Case (1)			
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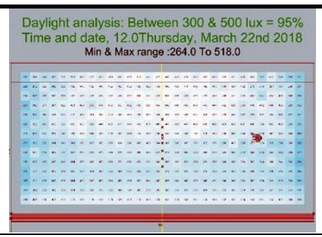
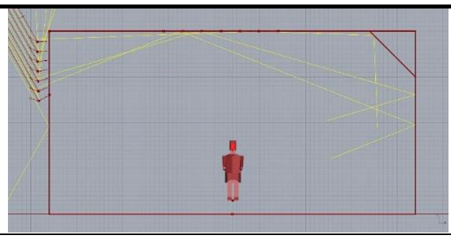
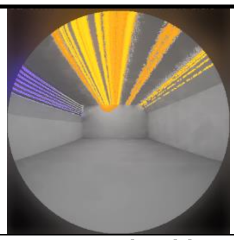
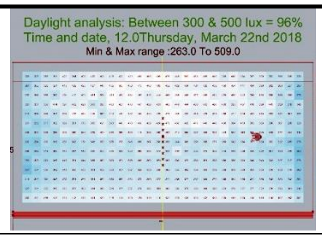
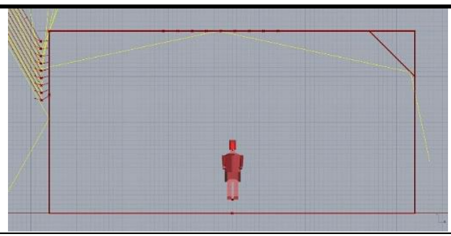
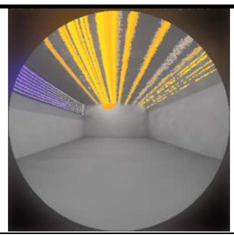
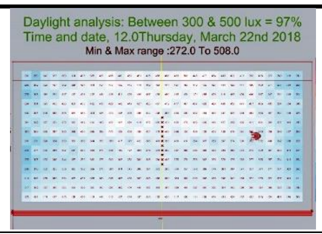
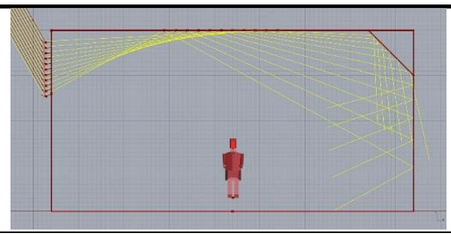
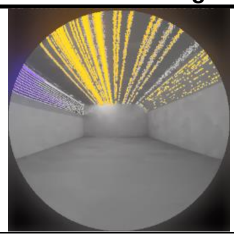
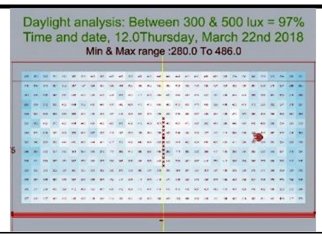
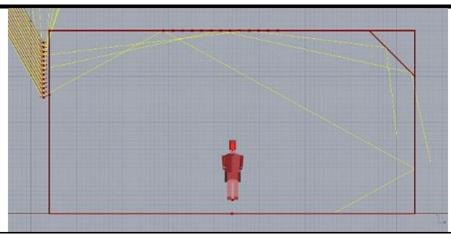
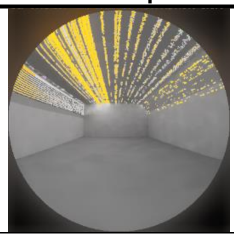
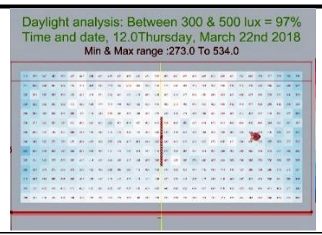
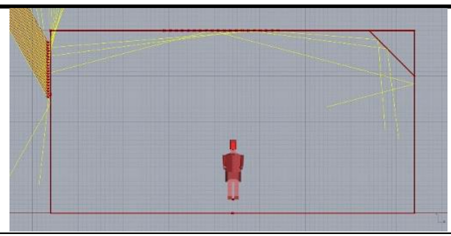
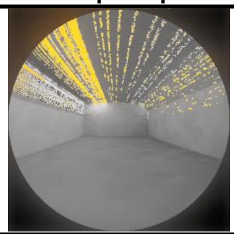
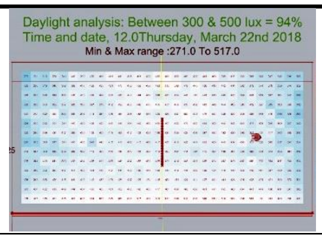
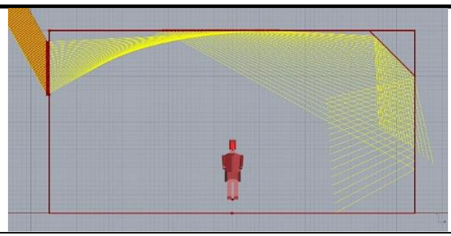
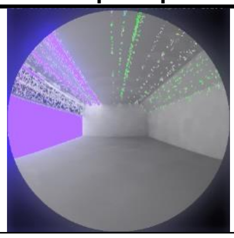
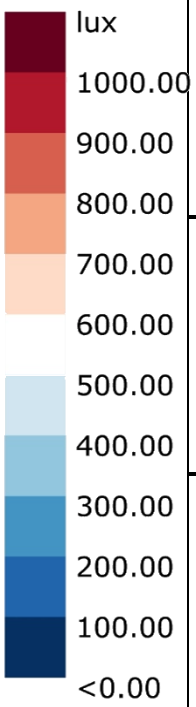
	Case (2)			
		95%	20 cm – 7 slats	0.46 Intolerable
	Case (3)			
		96%	15 cm – 9 slats	0.44 Disturbing
	Case (4)			
		97%	10 cm – 11 slats	0.37 Perceptible
	Case (5)			
		97%	7.5 cm – 13 slats	0.32 Imperceptible
	Case (6)			
		97%	5 cm – 20 slats	0.31 Imperceptible
	Case (7)			
		94%	2.5 cm – 38 slats	0.34 Imperceptible

Figure 10: Concave slats shape – applied in an example office room in New Cairo on 22nd of March at noontime, showing; top view – daylight analysis percentage(left), side view – raytracing study (middle) and DGP map (right), respectively.



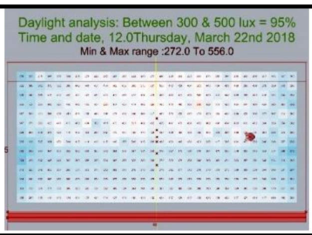
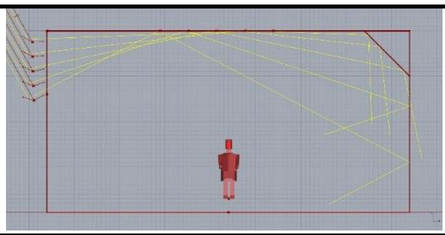
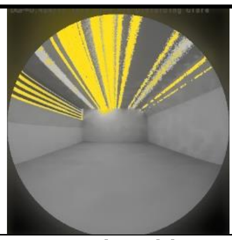
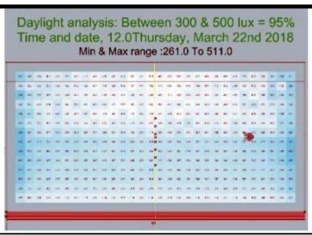
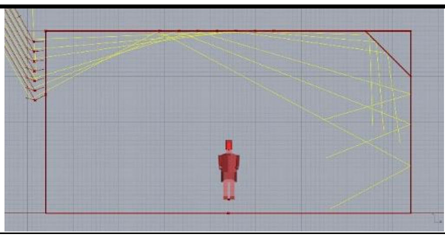
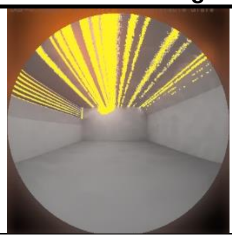
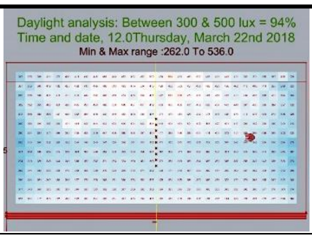
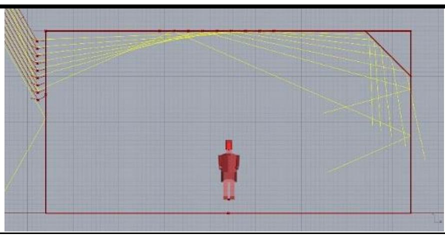
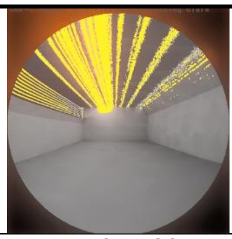
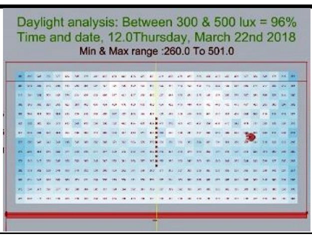
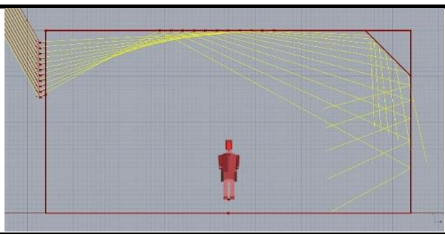
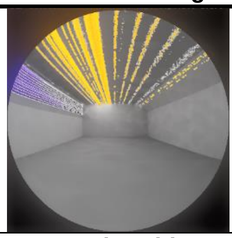
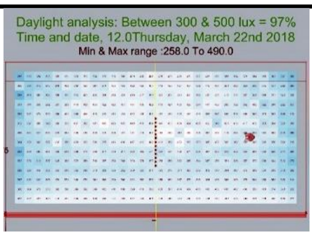
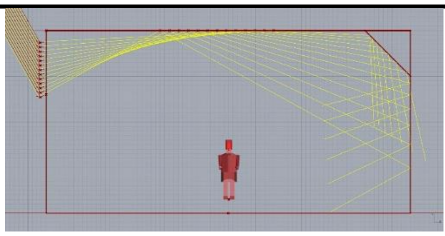
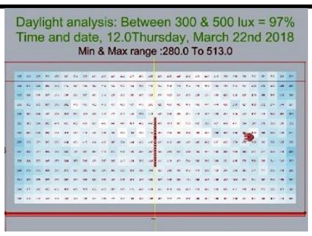
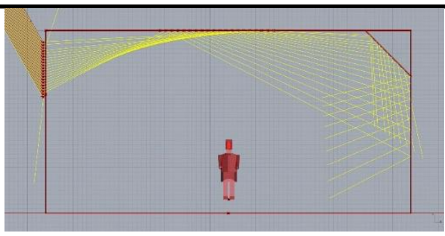
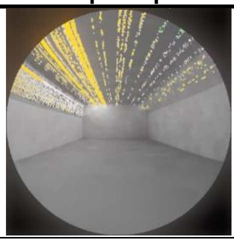
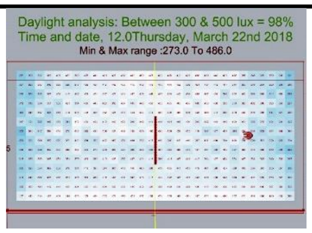
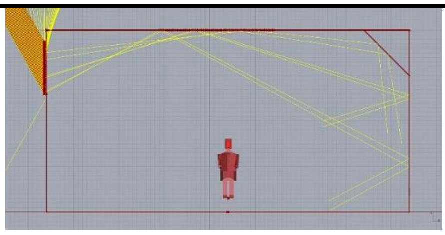
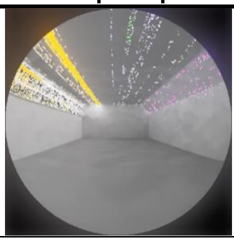
Light scale		Daylight Coverage (plan)	Raytracing, slat width no. of slats (section)	Glare check image
	Case (1)			
		95%	**25 cm – 5 slats**	**0.43 Disturbing**
	Case (2)			
		95%	**20 cm – 7 slats**	**0.45 Intolerable**
	Case (3)			
		94%	**15 cm – 9 slats**	**0.43 Disturbing**
	Case (4)			
		96%	**10 cm – 11 slats**	**0.43 Disturbing**
	Case (5)			
		97%	**7.5 cm – 13 slats**	**0.3 Imperceptible**
	Case (6)			
		97%	**5 cm – 20 slats**	**0.29 Imperceptible**
	Case (7)			
		98%	**2.5 cm – 38 slats**	**0.25 Imperceptible**

Figure 11: Convex louver shape – applied in an example office room in New Cairo on 22nd of March at noontime, showing; top view – daylight analysis percentage (left), side view – raytracing study (middle) and DGP map (right), respectively.

3 Results

3.1 *Reducing the slat width of the (flat, concave and convex) automated louvre*

The numerical results in Figure 9, Figure 10 and Figure 11 have been summarized in Figure 12 and Figure 13 for more clarification. It can be observed in Figure 12 that daylight coverage percentage has been slightly improved from 93% to 98% when the slat width is gradually reduced. This change becomes negligible when the slat width is lower than 7.5 cm. In addition to this aspect, DGP values were also decreased gradually to a Perceptible level, which is considered acceptable for visual comfort [37, 38] as shown in Figure *13* (accepted level highlighted in green). Note that "Glare check images" in Figure 9, Figure 10 and Figure 11 are based on fisheye camera of the mannequin view. The yellow colour stripes on the ceiling represents only the luminance distribution. For the DGP index, if the measured value is larger than (0.45) I will be considered as "Intolerable glare" and if a value is smaller than (0.35) it will be considered as "Imperceptible glare".

Based on the results in Figure 12, it can be concluded that daylight coverage is slightly better by using the CC- louver and CV-louver compared to the F-louver. Moreover, it can be seen in Figure 13 that DGP is slightly decreased with the CC-louver compared to the F-louver. Overall, there is an obvious improvement in the performance of the daylight coverage and lower glare probability when using the CV-louver shape. Daylight coverage percentage in Case (7) achieved 98% corresponding to an apparent drop in DGP at 0.25, which is considered "Imperceptible" glare at that level compared to other cases. Among all other shapes, the "2.5 cm" CV-shape in Case (7) achieved the best performance of daylight coverage and lowest glare, as shown in Figure 12 and Figure 13, respectively. Additionally, the caustics (luminance intensity level) on the ceiling has almost disappeared as shown in Figure 11 "Case (7), DGP map". Although the 5 cm slat showing promising results likewise the 2.5 cm, however, the 2.5 cm slim slat should be more practical if we consider a louver system between a double-glazing window.

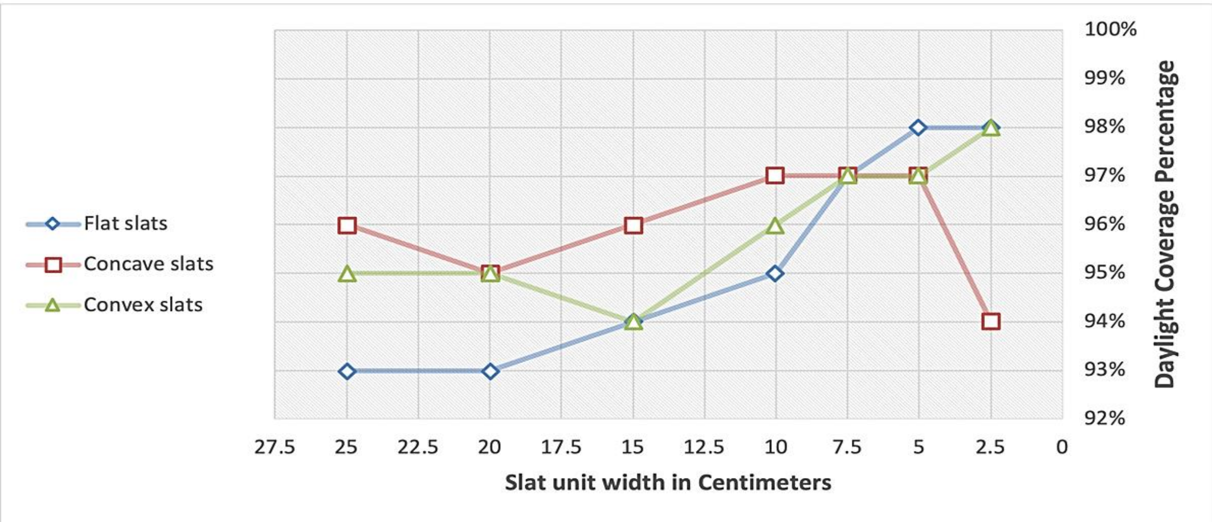


Figure 12: Comparison of Daylight coverage percentage of the three shapes on the 22nd of March at noontime.

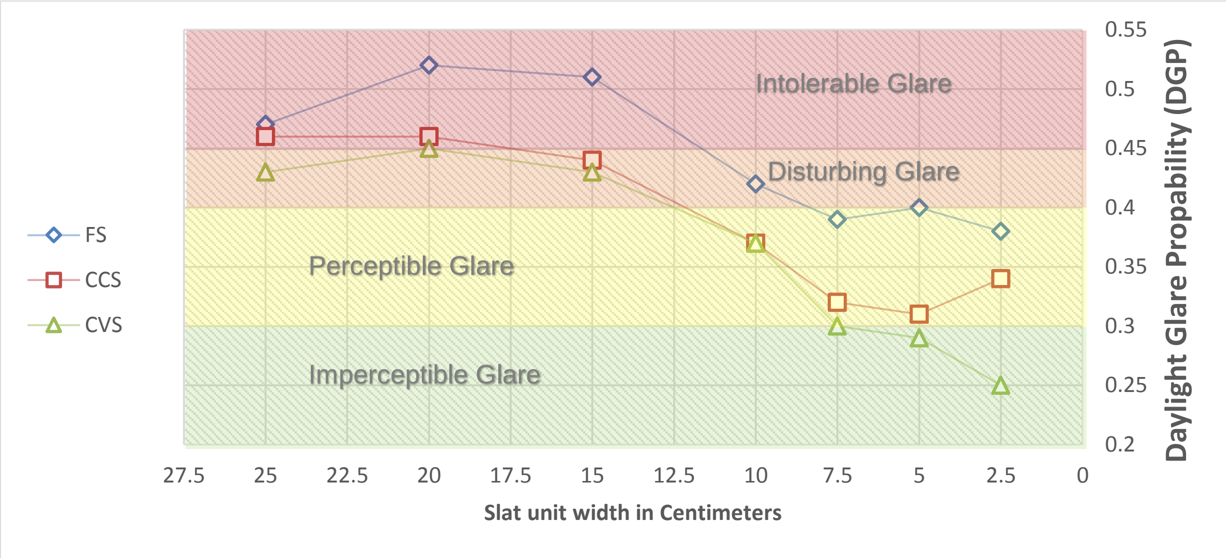


Figure 13: Daylight Glare Probability comparison results of the reduced slats' size of the FS, SCC, and SCV-louver on the 22nd of March at Noontime.

3.2 *Examining the slim slats with different curvatures at different dates*

It is apparent from the previous tests that modifying the slat size and shape achieved better performance compared to its initial size and its flat shape. Accordingly, these new applied modifications will be examined in different seasons at different times for performance substantiation.

A comparison was conducted between SF-louver, SCC-louver and SCV–louver during daytime from 9 a.m. to 5 p.m. on the 21st of June, 23rd of September and 21st of December to examine the performance of daylight coverage percentage analysis as well as DGP for each shape individually, via using DAYSIM based on Ladybug as a plugin in Grasshopper, see Figure 14, Figure 15 and Figure 16 for daylight analysis, and Figure 17, Figure 18 and Figure 19 for DGP indices (using the same mannequin's eye direction). The test was performed under a clear sky condition with direct sunlight in an example south oriented office room in the New Cairo location by using the EPW weather file. The comparison here is only for the slim slat of 2.5 cm wide.

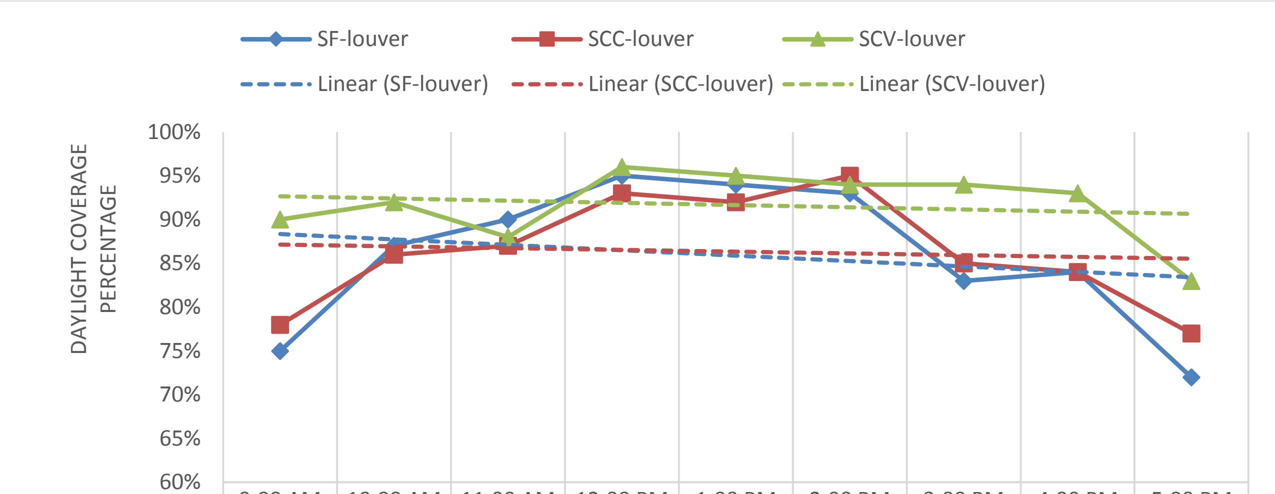
On the 21st of June, among all slats' shapes, the SCV-louver reveals the best performance of daylight during the working hours, especially at early and late hours as shown in *FIGURE 14*. This is due to the scattering effect of the convex shape, which is more likely to diffuse the received light rather than the flat shape which tends to reflect the same amount of any received light, and even the concave shape which tends to focus the received light as shown in Figure 8.

Moreover, the SCV-louver plays a vital role with the light received from the skydome, regardless of the direct sunlight. For instance, at 4 p.m. and 5 p.m. on the 21st of June, the azimuth inclination of the sunbeam is not striking the south window, which means that the received daylight only depends on the light coming from the skydome. Accordingly, this steepness of incident light can be a rational reason for the lack of daylight availability in the SF and SCC cases.

It can be seen in Figure 15, on the 23rd of September that the performance of all shapes is almost similar during the daytime, wheres, the illuminance coverage percentage ranges between 77% - 96%, which should be sufficient to meet the occupants' visual comfort and save energy. Accordingly, the

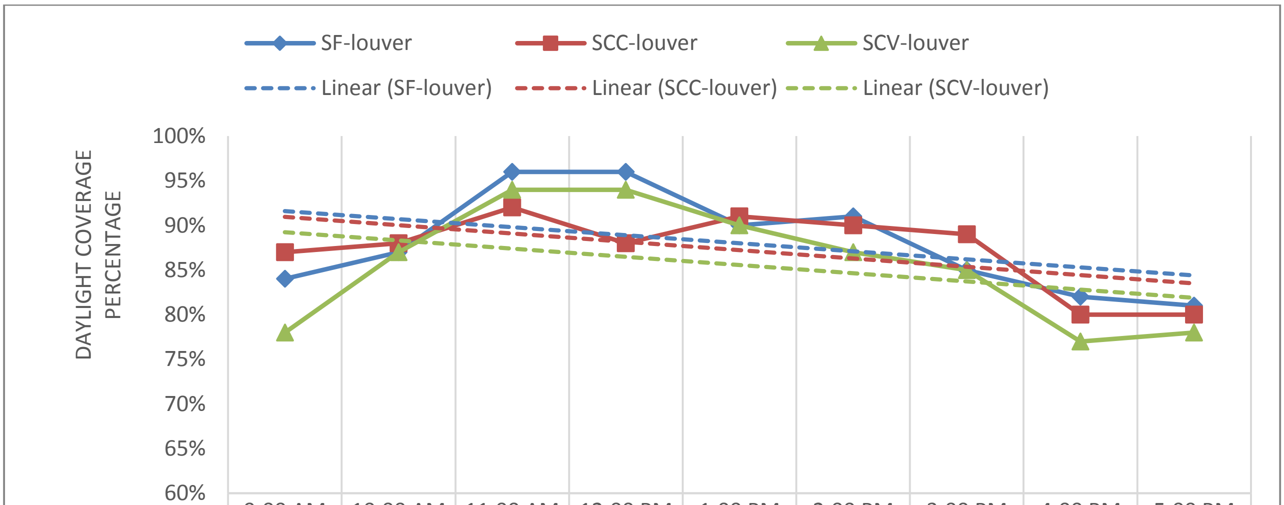
SCC and SCV-louver can be considered as efficient shapes likewise the FS shape. On the 21st of December, the performance all shapes are almost similar as well, with a slight difference at the morning hours, see *Figure 16*. Due to solar weakness and short daytime, the daylight coverage gradually decreased from 80% at 3 p.m. to 0% at 5 p.m. Meanwhile, daylight coverage performance during the other hours is almost steady of around 85% except at 9 am, which is relatively low.

Interestingly, DGP indices are showing similar performance for all shapes in June and September at values below 0.25 which considered “Imperceptible Glare”, see Figure 17 and Figure 18. However, on December, the DGP indices were increased from “Imperceptible Glare” to an “Intolerable Glare” at a value of ~0.59, due to the low inclination of the sun altitudes especially at the late hours which directly strikes the mannequin’s eye, as shown in Figure 19.



	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM
SF-louver	75%	87%	90%	95%	94%	93%	83%	84%	72%
SCC-louver	78%	86%	87%	93%	92%	95%	85%	84%	77%
SCV-louver	90%	92%	88%	96%	95%	94%	94%	93%	83%

Figure 14: Daylight coverage percentage on the21st of June for the SF, SCC and SCV-louver from 9 a.m. to 5 p.m.



	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM
SF-louver	84%	87%	96%	96%	90%	91%	85%	82%	81%
SCC-louver	87%	88%	92%	88%	91%	90%	89%	80%	80%
SCV-louver	78%	87%	94%	94%	90%	87%	85%	77%	78%

Figure 15: Daylight coverage percentage on the 23rd of September for the SF, SCC and SCV-louver from 9 a.m. to 5 p.m.

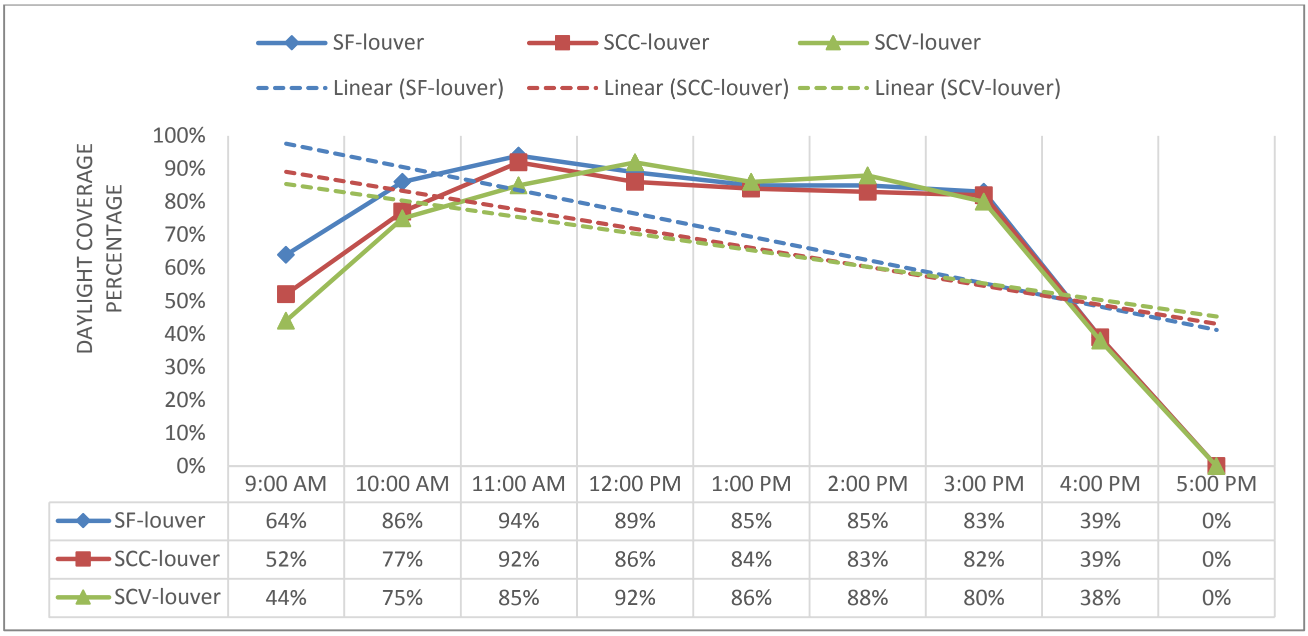
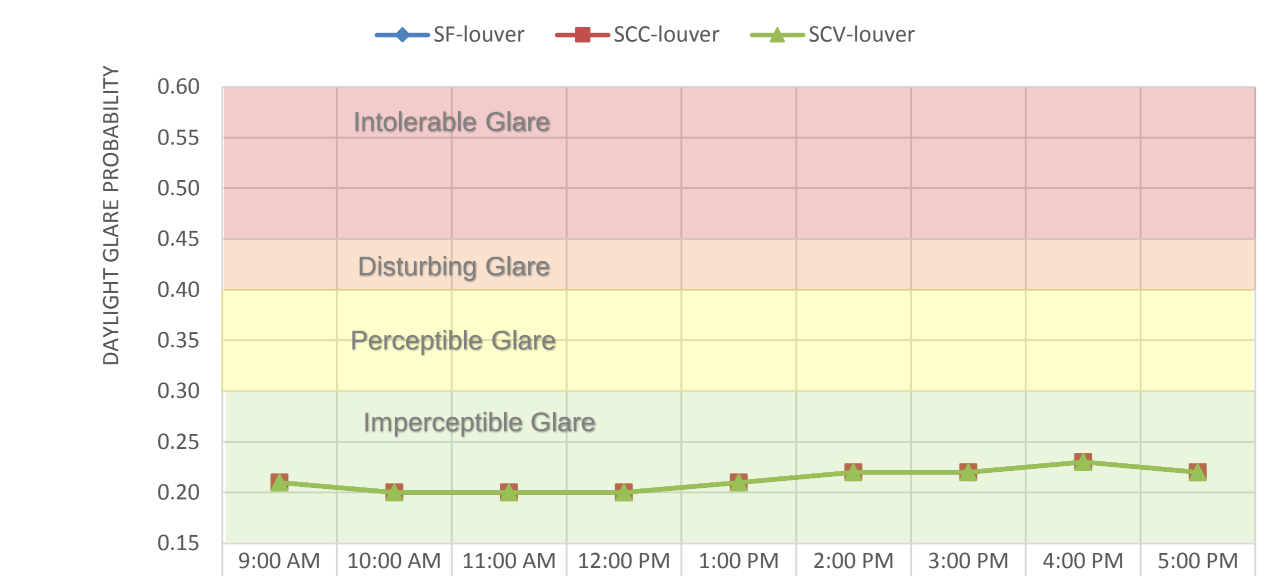


Figure 16: Daylight coverage percentage on the 21st of December for the SF, SCC and SCV-louver from 9 a.m. to 5 p.m.

Table 1: Mean Daylight coverage and Standard Deviation for all shapes in June, September and December.

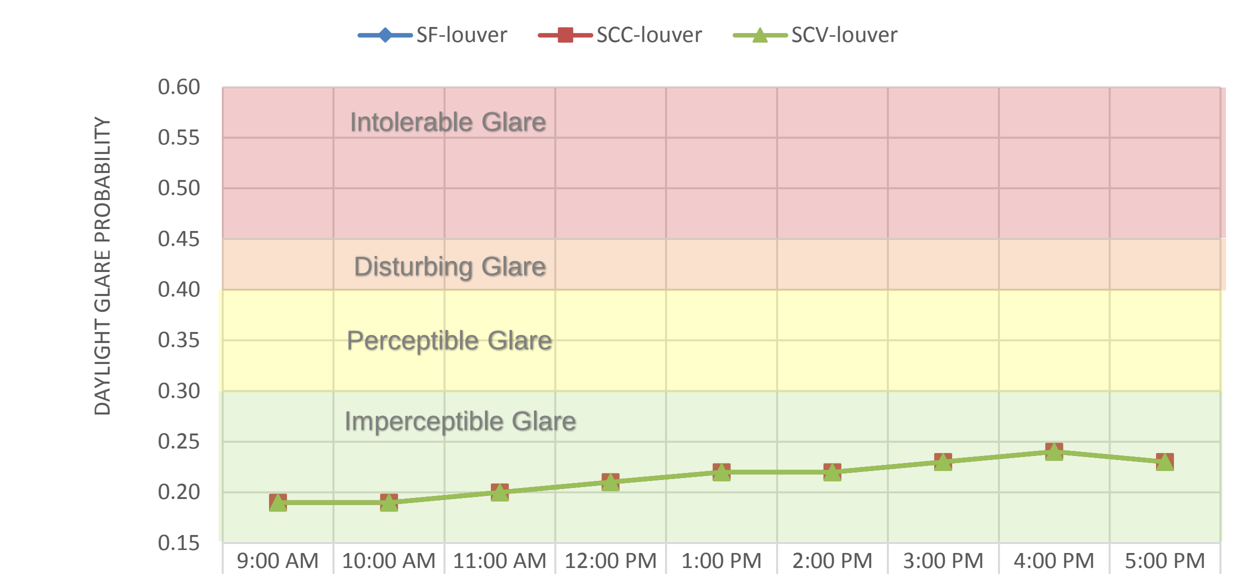
Mean Daylight coverage	June 21st	Sept 23rd	Dec 21st		Standard Deviation	June 21st	Sept 23rd	Dec 21st
SF-louver	86%	88%	69%		**SF-louver**	8%	6%	31%
SCC-louver	86%	87%	66%		**SCC-louver**	6%	4%	30%
SCV-louver	92%	86%	65%		**SCV-louver**	4%	7%	31%

It can be noticed in Figure 14, Figure 15 and Figure 16 that each of the three louver shapes has its own daylight coverage behaviour along the day in June, September, and December. To conclude the best performing louver, the mean daylight coverage was derived and fitted to Figure 14, Figure 15 and Figure 16. The daily mean value for each louver was calculated as shown in Table 1. From this table it may be inferred that the daylight coverage of the SCV-louver is significantly higher than the SF and SCC louvers during June, while they all have approximately the same performance in September and December.



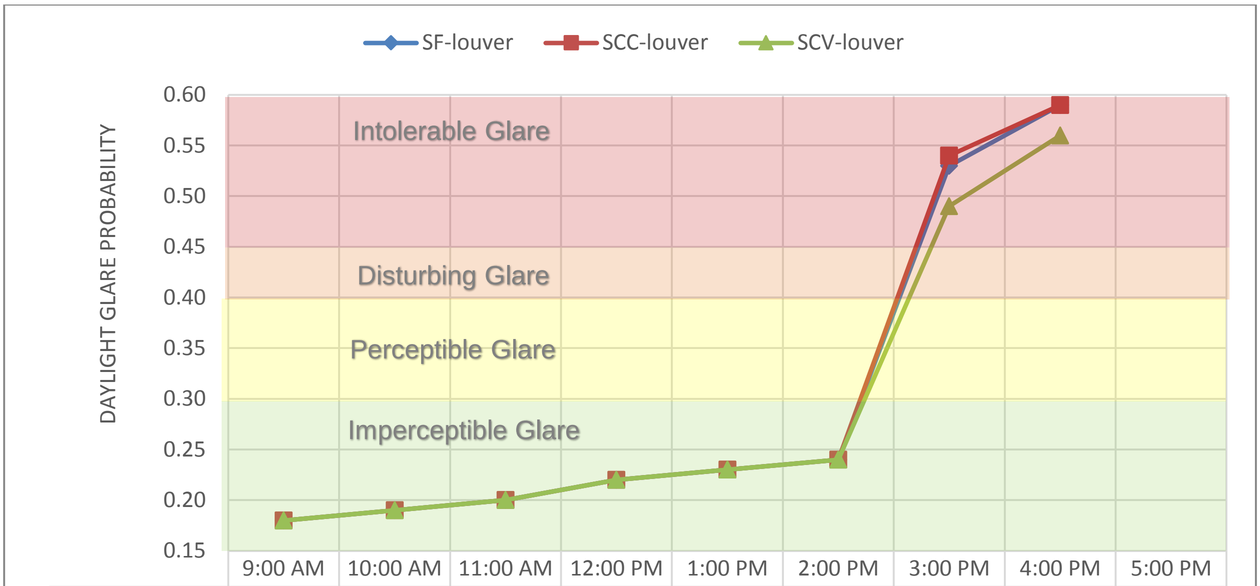
	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM
SF-louver	0.21	0.20	0.20	0.20	0.21	0.22	0.22	0.23	0.22
SCC-louver	0.21	0.20	0.20	0.20	0.21	0.22	0.22	0.23	0.22
SCV-louver	0.21	0.20	0.20	0.20	0.21	0.22	0.22	0.23	0.22

Figure 17: Daylight Glare Probability on the 21st of June for the SF, SCC and SCV-louver from 9 a.m. to 5 p.m.



	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM
SF-louver	0.19	0.19	0.20	0.21	0.22	0.22	0.23	0.24	0.23
SCC-louver	0.19	0.19	0.20	0.21	0.22	0.22	0.23	0.24	0.23
SCV-louver	0.19	0.19	0.20	0.21	0.22	0.22	0.23	0.24	0.23

Figure 18: Daylight Glare Probability on the 23rd of September for the SF, SCC and SCV-louver from 9 a.m. to 5 p.m.



	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM
SF-louver	0.18	0.19	0.20	0.22	0.23	0.24	0.53	0.59	
SCC-louver	0.18	0.19	0.20	0.22	0.23	0.24	0.54	0.59	
SCV-louver	0.18	0.19	0.20	0.22	0.23	0.24	0.49	0.56	

Figure 19: Daylight Glare Probability on the 21st of December for the SF, SCC and SCV-louver from 9 a.m. to 5 p.m.

Despite the significant variations in altitudes due to solar solstices [39]; parametric design is still capable to control the slats' rotations in response to these solar fluctuations, and accordingly facilitates the manipulation with the target locations over the ceiling [23], which eliminates dim spots inside the deep room.

4 Discussion

The focal points in the concave case may have a potential risk of heat concentration in the interior space, which can be a potential drawback of such a system, see Figure 8 *(LEFT)*. While the convex shape tends to disperse light over the whole ceiling, as shown in Figure 8 *(RIGHT)*, which is considered as an advantage for better light distribution.

Considering the previous point, it can be seen in the false-colour maps in Figure 20 the distribution of the bright stripes on the ceiling has a noticeable impact on the daylight uniformity in the room. The size and intensity of these bright stripes on the ceiling influence the illuminance fluctuations within +/-150 lx. For instance, in Figure 9, Figure 10 and Figure 11 if we check the daylight coverage in Case (1), we can find that the illuminance variation between the area near to the window and the area in the deep room is +/-150 lx (i.e. 320~470 lx, respectively). On the other hand, in Case (7), the illuminance difference is promisingly reduced to +/-50 lx (i.e. 420~470 lx) which means better uniformity.

Thanks to the slim slats, which dramatically reduce the contrast between the bright stripes that gradually blended as shown in Cases (7), which accordingly yield better daylight uniformity. Moreover, the false-colour maps in Figure 20 reveal caustic patches in Case (1) and Case (4); however, these patches are slightly diminished in Case (7), which are homogeneously distributed with no contrast. This distribution effect is based on a phenomenon known as Penumbra effect [18], which can disperse the light between a tiny aperture similar to the effect of light passing through a “tree” or “Mashrabia”. Mashrabia is a semi-transparent screen can be assembled from different materials to create geometrical shapes of systematic apertures based on a specific design. These kinds of screens can allow limited penetration of incident sunlight due to its small orifices [40].

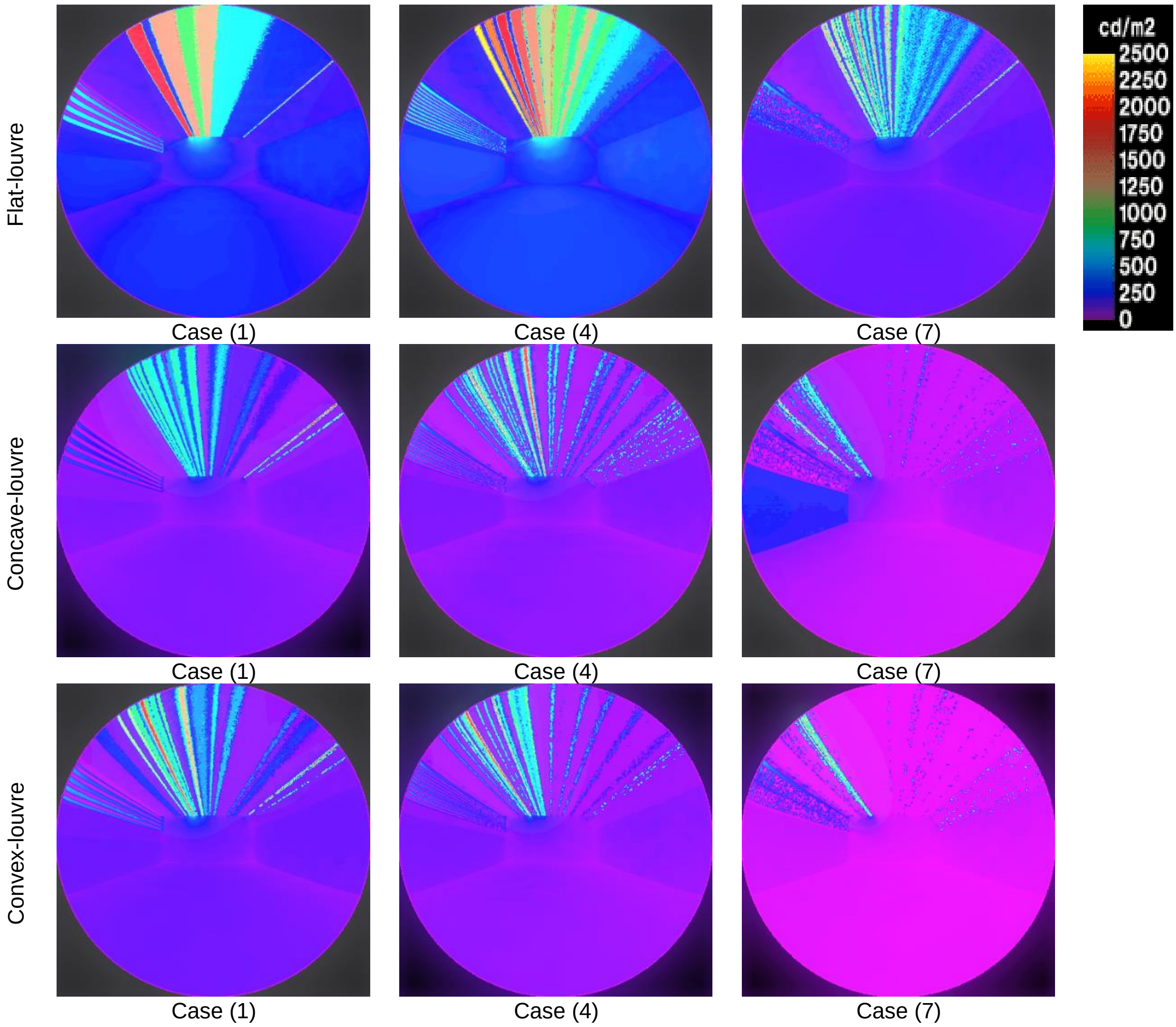


Figure 20: HDRI false colour maps for the cases (1), (4) and (7) of the Flat, Concave and Convex louver, respectively, on the 22nd of March at noontime.

Besides, we can notice tangible improvement among the SF, SCC and SCV-louvre in Case (7), respectively, where the SCV-louvre is the brightest case and the lowest in glare. Generally, we can conclude that reducing the slat width can have a positive influence on daylighting performance, better illuminance distribution and glare reduction, in addition to the benefits of decreasing the system’s weight for more accessibility and increasing the slats’ strength. Accordingly, such a system can be reduced to the size of a home shutter instead of a large louver, whilst achieving the same purpose. For a hot territory such as Egypt, diffused light together with lower caustics (concentration of light) can dramatically reduce potential heat gain, which accordingly can improve thermal comfort [20].

5 Conclusion

Practical and feasible aspects are essential to promote innovative daylighting systems. The proposed automated louver system has been investigated previously as a daylighting system, which was initially designated to be installed outdoor over a building's façade. This study investigated using more reliable and practical automated louver system by reducing the slats' width and changing the slats' shape, this can accordingly reduce their weight, which reflects on reducing cost as well, and increase their strength and achieve a graceful shape. The performance of the automated louver has been examined after reducing its slats' width gradually from 25 cm to 2.5 cm. The examination occurred on flat, concave and convex shapes by analysing their daylight coverage percentage within an illuminance level 300~500 lx and daylight glare probability (which ranging between 0.25~0.55) for each shape. The results revealed that the reduced slats at 2.5 cm could achieve better performance in both daylighting coverage and DGP, compared to the bigger ones. Especially, the concave and the convex shapes were resulting in much lower glare than the flat shape.

It is important to mention the balance between the daylight performance and thermal comfort inside the building. The reflected light from a slim slat plays an important role in this study, resulting the so-called Penumbra effect. This effect can dramatically reduce the heat gain from solar radiation thanks to the dispersed light, which simultaneously decrease the potential glare. Moreover, the slim size louver can fit between a double-glazing system, which also works as an insulation layer to reduce the heat gain inside the building. On the other hand, bigger slats can produce larger luminance strips that create caustics over the ceiling, which means potential heat gain and potential glare.

The slim shapes (Slim-flat, Slim-concave and Slim-convex louver) have been examined in a specific climate with a dominant sunny territory such as Egypt, at different dates during the daytime, in June, September and December for more diverse results. The results revealed that all shapes almost had similar performance; however, the Slim-convex louvre among other shapes can be considered as the most promising shape, due to its consistent performance, especially in June, in addition to its lowest glare probability. Even in a climate like Egypt, with high solar irradiance, the automated louver proved to provide sufficient daylight and minimize DGP to acceptable levels, without compromising visual quality, as the louver is installed at 2.5 meters above the glazing, hence, it does not block views to the outdoors. Indeed, a four-meter office room hight means more cubic meters of indoor space-of-air needed to cool for such a hot climate like Egypt. For a daylighting system which can dramatically block any direct solar radiation which can strike the interior, heat gain still a critical factor that should be considered in such a study.

In conclusion, Slim-convex louver can be recommended as a promising daylighting system in arid climate, while it has slim size, lightweight, strength, graceful shape, and simultaneously can provide better daylight performance with lower glare. Such a system can be installed at the upper part of the window inside the room for more handy control and even can be attached between double glazing due to its slim size. This study focused on daylighting performance with a limited climate condition;

however, a future study will extend the investigation of the daylight performance in different territories considering the heat gain in conjunction with thermal comfort.

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