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Using integrated parametric control to achieve better daylighting uniformity in an office room: A multi-Step comparison study

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ABSTRACT

In addition to windows, louvers are the most common architectural elements widely used in office buildings to protect them from excessive daylight and improve daylight penetration as well. Advanced glazing, window blinds, other fenestration systems and their automation can further improve daylighting performance. However, the stability and uniformity of daylight distribution throughout a day inside a building remain a challenge. To explore a solution for this issue, this paper proposes an advanced integrated lighting system combining different architectural elements, which can be controlled parametrically. The suitable design of such integrated system is identified through a multi-step comparison study employing parametric design approach. The criteria is to keep a relatively uniform daylight distribution in the range of 300–500 lx over 90% of the whole desktop area in a 7-m-deep office room. An office building in New Cairo was chosen for a case study, where it is south oriented with a prevailing condition of clear sky. Hourly results on the 21st of several chosen months are given to show the suitability of the proposed design throughout a year, aiming to explore the maximum use of daylight and hence reduce the energy consumption of electrical lighting. The comparison indicates that the combined use of the integrated system can achieve a satisfactory relatively uniform distribution of daylight over about 90% of the desktop area, within illuminance range of 300–500 lx for most of the working hours throughout a year.

1. Introduction

Daylight plays an important role in our life [1], and it has vital influence on humans' health, and substantial effect on buildings' energy consumption. Therefore, curtain wall is used in abundance in office buildings as a pathway for daylight. Meanwhile, shading devices are used to protect the buildings from excessive direct sunlight [2] and to reduce solar heat gain in the summer [3].

A study revealed that 80–90% of respondents believed that common window blinds are used as a shading device to protect from excessive light more than thermal comfort and energy saving [4]. However, advanced blinds and other types of shading devices are controlled automatically[5] to maximize the benefits of daylight [6], save energy[7,8], provide visual comfort and improve the occupants' efficiency [1,9]. They can also be in different shapes and mechanisms according to facades' orientations and buildings' needs. It has been found that using automated blinds can reduce the users' behaviour of turning on the electric light, which can save electrical energy by up to 30% due to the utilization of daylight [9].

In order to improve daylight penetration; reflective shelves [10,11] and optical louver systems (OLS) [12] have been used as reflectors to redirect sunlight into the deep interior of a building. Likewise, electrochromic (EC) glass; an advanced type of smart-glass [13], which also known as switchable glass. This type of glass is used in buildings' facades to protect from glare and heat gain inside a room [14], and sometimes it is used in interiors for a privacy sake. EC glass has the significant property to tune from transparent to translucent state instantly using the application of applied voltage, which can be controlled using movement sensors [15]. Therefore, EC glass in our study can be used as a source of amended diffuse light via controlling the penetration of solar radiation inside the building [16], which can then help to improve the performance of daylight inside the building. A study by A. Freewan investigated the combination of ceiling shapes and light shelves to enhance daylight distribution inside a deep room [17]. Meanwhile, recently developed parametric software such as Grasshopper offers an efficient tool with a link to the popular software RADIANCNE and DAYSIM [18] and therefore be able to control and optimize daylighting systems [19]. Overall, we can find that recent technologies of several architectural elements have clear influence on daylighting performance, while they are using different keys to achieving the goal of saving energy.

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0378-7788/

Fig. 1. (Top left) Location of the office building at the 90th street in New Cairo, Egypt [25], exported form Google Earth. (Top right) The image of the office building, Union National Bank UNB in Egypt [26]. (Bottom left) Sunlight directions, exported form Grasshopper. (Bottom right) Close view to the office room.

Although daylight penetration has been improved to various extents with those reported daylighting designs, the desired uniform distribution of daylight inside a room remains a challenge. Our study therefore endeavours to find an integrated compromise between the typical architectural elements such as reflective blinds, windows and ceiling based on parametric control, aiming to maximize the use of daylight, and achieving satisfactory uniformity of daylight distribution within the required range of 300–500 lx. The proposed methodology for the daylight elements will be introduced in Section 2. While, the combinations of these elements will be studied in five phases, each phase will be investigated individually, and then upgraded gradually through improving the properties of each phase to identifying the most suitable combination to reach the desired daylight distribution. The performance of each element will be clarified in a comparison in Section 3 at specified dates, and then throughout some selected months. This will be followed by a discussion of the results.

2. Methodology

The methodology depends on the purpose of optimising daylight distribution at the desktop level inside an office space by using the parametric tool Grasshopper and its plugins; Honeybee and Ladybug [20]. Grasshopper itself is an algorithmic software used as a scripting language within Rhinoceros 3D computer graphics and computer aided design (CAD) [21], and it can deal with different parameters using specific formulas in order to define the model. These formulae appears as canvas connections which can be amended and controlled parametrically at a convenient graphical interface [22].

The case study will be evolved through five phases by using reflective blinds as a common factor, starting with conventional static blinds, and ending with parametric integrated system. The blinds in the model were used to prevent direct sunlight, and simultaneously redirect sunlight onto the ceiling [10] in order to provide sufficient daylight [23].

2.1. The case study

The selected case study is a south oriented office building at the 90th street, New Cairo, Egypt, as shown in Fig. 1. The reason for using this location is that New Cairo is located in a hot territory [24], which has a dominating clear sky condition for most of the year. The southern façade of the building is a curtain wall, with no outdoor shading devices.

2.2. Model description

The model is for an office room in the chosen building in New Cairo, built in Grasshopper based on Rhinoceros 3D. The office room is south oriented with 4 m height finish to finish, 7 m depth and 18 m length. The slats were set on the upper portion of the window and between 2.2 and 4 m high from the floor. Mirrored surface was added to the slats form the upper side with 70% reflectivity, while the bottom side of the slats is a black matt painted with reflectivity 0% to absorb any specular light coming from the mirrored side of the following slat, and decrease the potential diffuse light [11,27]. Walls were set to white matt with 80% reflectivity, while, the floor was set to dark matt with 0% reflectivity to absorb any potential reflections.

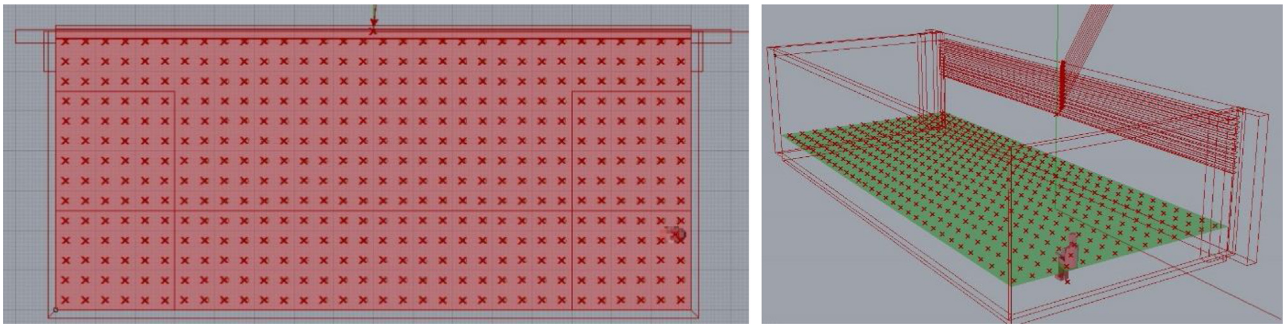
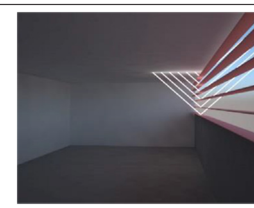
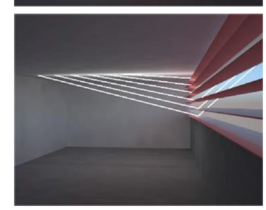
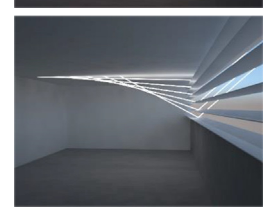
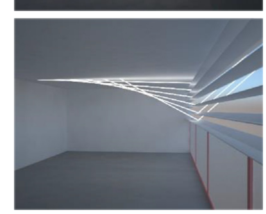
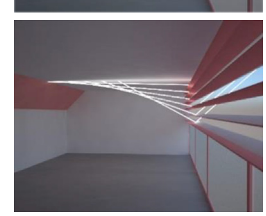


Fig. 2. Test points distribution, exported from Rhinoceros 3D. (Left) top view, (right) perspective view.

Table 1
List of modelling phases (the changes between the phases appear in red italic).

Phase number	Slats type	Protrusion to the slats	Glazing type on the lower portion of window	Ceiling type	Rendered image, exported from V-ray (3D Max)
Phase 1	*Conventional* slats	No protrusion	No glazing	Flat ceiling	
Phase 2	*Parametric* normal slats	*Protrusion added*	No glazing	Flat ceiling	
Phase 3	Parametric *reversed* slats	Protrusion added	No glazing	Flat ceiling	
Phase 4	Automated reversed slats	Protrusion added	*Electrochromic* glazing	Flat ceiling	
Phase 5	Automated reversed slats	Protrusion added	Electrochromic glazing	*Chamfered ceiling*	

Daylight illuminance will be measured using test points created in Honeybee as a [28,29] plugin in Grasshopper, which used as an engine to stimulate RADIANCE and DAYSIM simulations. RADIANCE is used to create the illuminance maps for a specified space, while DAYSIM is used to produce the values at the test points for detailed daylight analysis for a specific area. The test points were set at a desktop level 70 cm high from the floor [30] to measure the illuminance value at this level. The grid size of test points was set to 0.5 m, i.e. four points each square meter, as shown in Fig. 2.

The results of test points will display the illuminance value of each point, and be used to determine the percentage average for the whole area for the daylight illuminance range between 300 and 500 lx. The available EnergyPlus Weather file (EPW) for Cairo Airport was used as it is the closest location to the New Cairo. The EPW weather file was imported to Grasshopper using Ladybug plugin [23] which can visualize sun path, control time, date and sun movement parametrically.

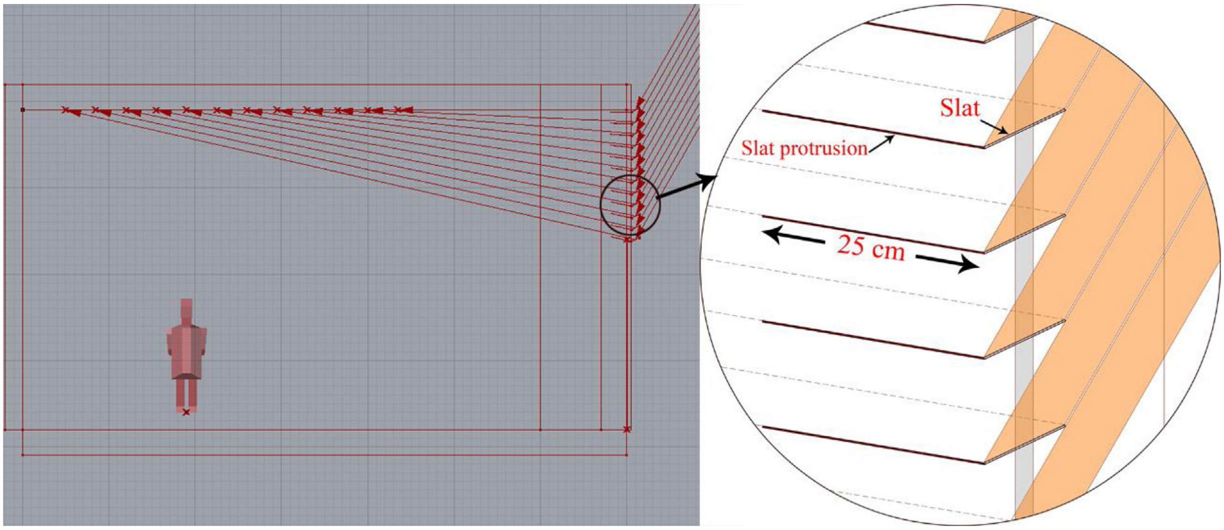


Fig. 3. Detailed cross section for the protrusion.

Fig. 4. Side view for the reversed targeting sequence.

2.3. Phases of modelling

As mentioned before, modelling of the office room will evolve through five phases via changing parameters and adding elements, aiming to achieve better daylight distribution, see Table 1. At the first stage, the comparison will use a fixed time and date, at 12:00 pm on September 21st, in order to demonstrate the modelling methodology and to understand the designs from a suitable ray tracing results [23]. Where it is an equinox time and sun ray gives a moderate tendency, meanwhile, the number of slats was determined to be 12 according to the sun altitude.

At the following stage, time and date will be changed, in order to reveal the suitability and efficiency of the system at different times and dates throughout the year. It would be also seen that the number of slats will be adjusted for different months.

2.3.1. Phase 1

In Phase 1, the 10 cm width blinds were set to 0° tilt angle in their conventional shape, which is considered the best state of utilizing daylight [31] putting in consideration the influence of specular and diffuse light coming from slats and sky dome [27]. The slats are not controlled parametrically, so the light reflected by them would not go to any specified points as expected in the other modelling phases. In another word, the slats in this phase are static and not responding to the sun movement, therefore, as long as the sun moves; the light will be reflected to different points on the ceiling, unlike the fixed target points for the parametrically controlled slats in the other modelling phases. The lower portion under the slats was closed in Phase 1, 2 & 3 in order to demonstrate particularly the effect of the reflected light produced by the slats.

2.3.2. Phase 2

The blinds in Phase 2 were set parametrically to respond to the sun movement, where reflected light is redirected to some specific targets on the ceiling wherever the sun moves (this parameter was demonstrated in details in a previous research [23]). In this phase, a protrusion was added to the slats in a parallel direction with the reflected beams as shown in Fig. 3, in order to decrease the potential diffuse light coming from sky dome. The protrusion length was set to 25 cm and it has the same characteristic as the bottom side of the slats; black matt painted with 0% reflectivity, where the aim is to focus on the influence of the redirected light, excluding scattered light.

Sunlight in Phase 2 were re-directed by the slats to the ceiling in a normal sequence, that is, the uppermost slat reflects light to the closest point from the window, and the second slat reflects light to the next target further from window, et cetera, see Fig. 3. The targets were specified parametrically in Grasshopper at some fixed points on the ceiling. This means as long as the sun moves the slats will respond to its movement in a Heliotropic response [32], to reflect sunlight to the fixed targets. The distance between targets are equidistant, while the first target is 240 cm away from the window and the last target is 50 cm away from the wall.

2.3.3. Phase 3

The settings in this phase are similar to Phase 2, except for the slats' targeting sequence which were reversed parametrically, that

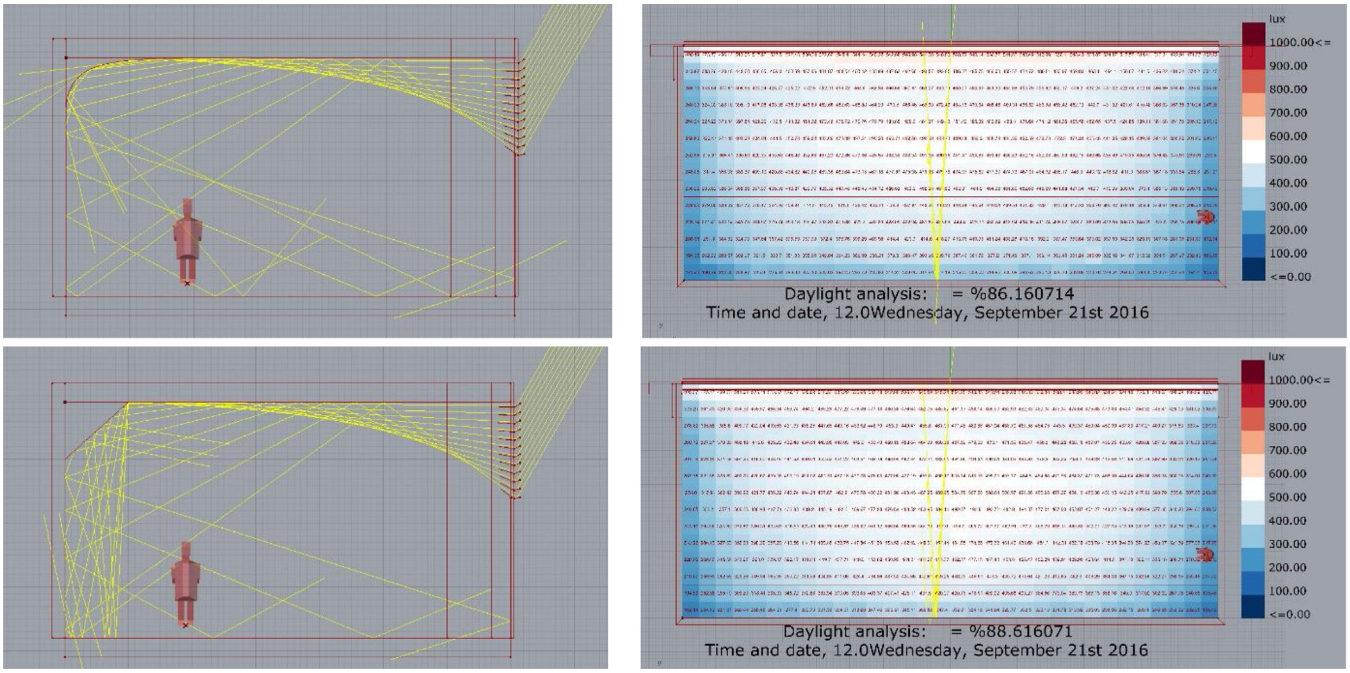


Fig. 5. Comparison between curved and chamfered ceiling, using raytracing and test points. (Top) curved ceiling results 86% area between 300~500 lx, (Bottom) chamfered ceiling results 88.6% between 300~500 lx.

is, the uppermost slat reflects light towards the farthest point from window (the closest point to wall) and the lowermost slat reflects light to the target point closest to the window, et cetera, see Fig. 4 and Table 1.

2.3.4. Phase 4

In addition to the previous phase, an electrochromic window was added to the lower portion of the wall below the slats to form Phase 4, as shown in Table 1. This part of the window will work as a source of diffuse light to lit the nearest area to the window within 2 m depth [33]. Electrochromic (EC) window was chosen for this study because of its significant function of light transmission control [13,15,16]. The amount of diffuse light provided by electrochromic window is controlled parametrically [14] based on the amount of needed illumination, which was assigned between 300 and 500 lx and adapted by using the test points.

As mentioned previously, EC window can transfer from transparent to translucent state, and this property can be specified in Grasshopper using Honeybee (HB) Translucent Material [34]. This HB material has several parameters such as reflectivity, specularity, diffuse transmission and roughness. While other parameters were set to a fixed value, the diffuse transmission would be amended parametrically, where this parameter is responsible for the translucency function.

Diffuse transmission of the translucent material can be set from 0.01 (almost opaque) to 1 (clear) and any in-between value specifies the amount of transmitted diffuse light. To control daylight penetration in response to solar intensity, a formula was created in Grasshopper to represent a relation between diffuse transmission and solar radiation intensity. Following many trials, the diffuse transmission of translucent material was determined to be 0.01–0.07 (as a translucency level). Which responding gradually to the solar intensity, in order to control the daylight illuminance within 300–500 lx in the area near to the window, under the prevailing clear sky condition in new Cairo. For instance, if solar radiation is 790 W/m^2; the diffuse transmission will be automatically set to 0.01, so the daylight penetration can be reduced from 20,000 lx to 400 lx.

2.3.5. Phase 5

In this phase, the integrated system was completed after adding a new element to the previous phase, revealed in a chamfered section added at the farthest end of the ceiling, as shown in Fig. 5 **(Bottom)**. A previous study [17] proved that adding curved shape to the ceiling at the end of the room can improve light distribution by about 10%. In our study, the results show that chamfered ceiling is giving better distribution by approximately 3% comparing with curved ceiling, as shown in Fig. 5, furthermore, the chamfered ceiling is more practical in installation. The chamfered ceiling was installed at the end of the room at a 45° angle with the ceiling.

3. Comparison study

3.1. Comparison study results for september 21st at 12pm

A comparison study is illustrated in Fig. 6 with two kinds of results, raytracing analysis (Left) and illuminance map at the desktop level (Right), aiming to determine the percentage area coverage for the required daylight illumination between 300 and 500 lx. It is worth to mention that the ray paths in the raytracing analysis is for the purpose of illustration, and do not mean that the ceiling or wall are specular reflective.

It can be observed in Fig. 6 Phase 1 that almost 100% desktop area has the daylight level exceeding 1000 lx at the chosen date and time. The reason for this excessive amount of light is the high intensity of solar radiation which increases the scattered light, and then produces an excessive illumination. Therefore, the slats should be set to 45° tilt angle to shade off sunlight completely and allow skylight penetration only, see Fig. 7. However even so, this leads to a noticeable contrast in daylight distribution with a much brighter pattern near the window, as seen in Fig. 7 (Right). Although all rays were blocked, daylight analysis revealed irregular distribution, starting form 1000 lx near to the window and ending with 200 lx near to the wall.

In Phase 2, daylight illuminance distribution gives an acceptable value of 46.6% area coverage for the daylight illuminance range of 300–500 lx, due to the added protrusion to the slats which helped to

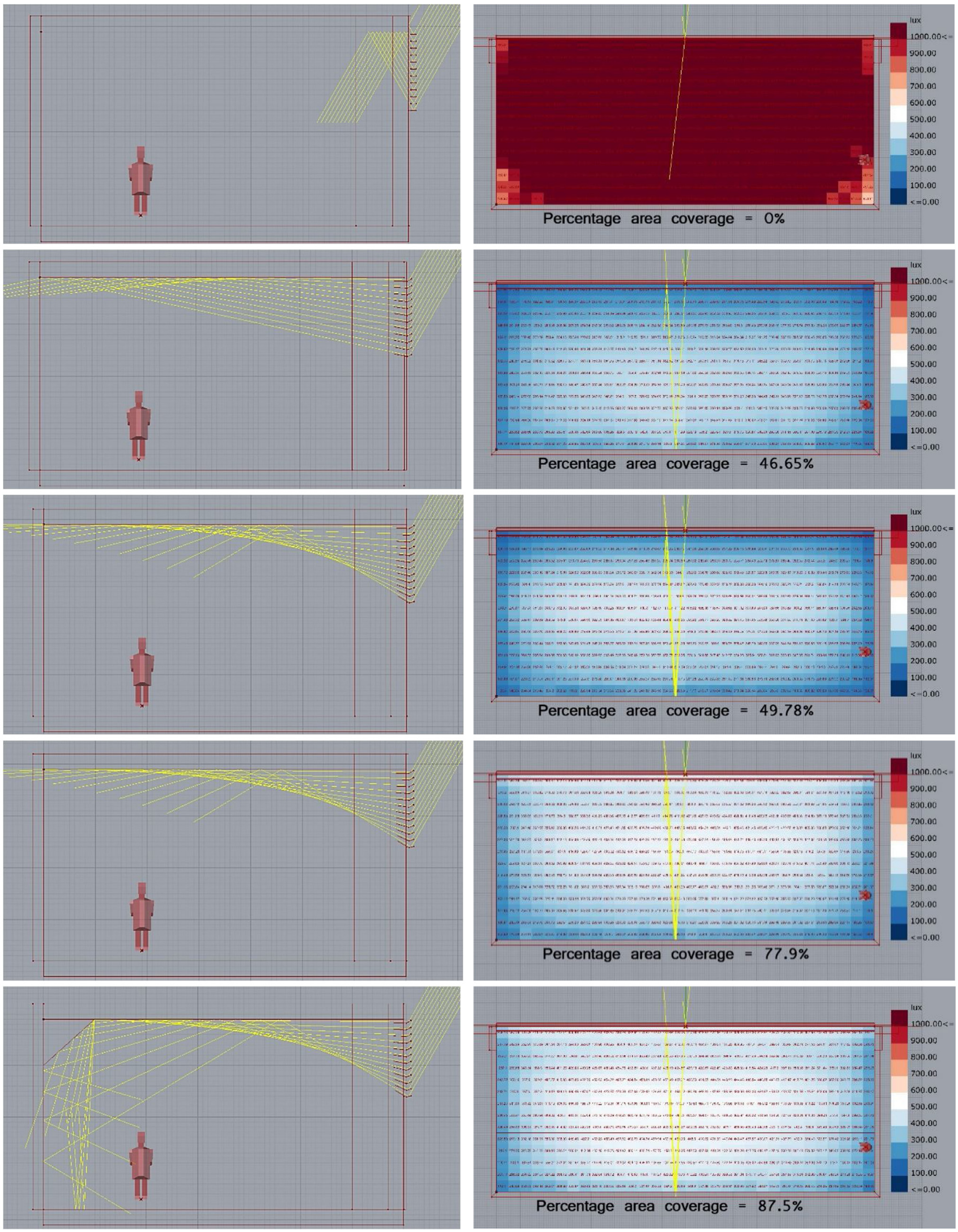


Fig. 6. (Left) side view, illustrating raytracing study; starting from top with conventional slats, and ending with automated sequence-reversed slats with EC window and chamfered ceiling, respectively. (Right) illuminance maps at the desktop level and the percentage area coverage for the daylight illuminance range between 300 and 500 lx.

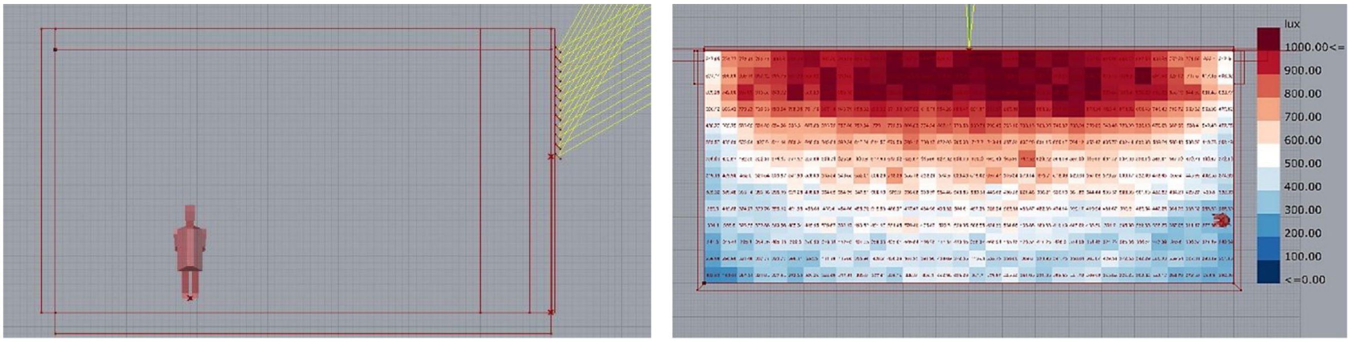


Fig. 7. Conventional slats with 45° tilt angle (Left) side view, (Right) top view.

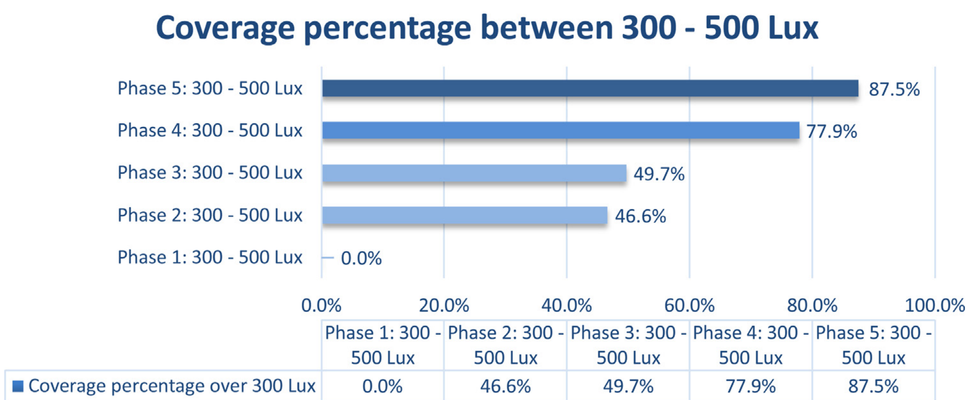


Fig. 8. Bar graph showing the coverage percentage between 300–500 lx for the five phases on September 21st at 12pm.

shade the skylight for the area near the window. The results of better daylight distribution were achieved mainly from the reflected light.

In Phase 3, a fundamental change can be observed in the ray-tracing due to the reversed targeting sequence, in addition to the difference in daylighting coverage which increases from 46.6% to 49.7%, which shows a relative improvement in daylight distribution for the given range 300–500 lx, see Fig. 8.

In Phase 4, 28% enhancement was achieved after adding the EC window which influenced on the coverage area near to the window, via providing sufficient amount of daylight at this area. Consequently, daylight coverage area increased in this phase to 77.9% which considered a significant improvement comparing to the previous one as shown in Fig. 8.

In Phase 5, a full distribution is covering the whole area after adding the chamfered ceiling, which achieved 87.5% area coverage for the daylight illuminance range of 300–500 lx. The chamfered ceiling in this phase has a clear impact on the illumination in the deep area of the room by 10% improvement comparing to Phase 4, as shown in Fig. 6.

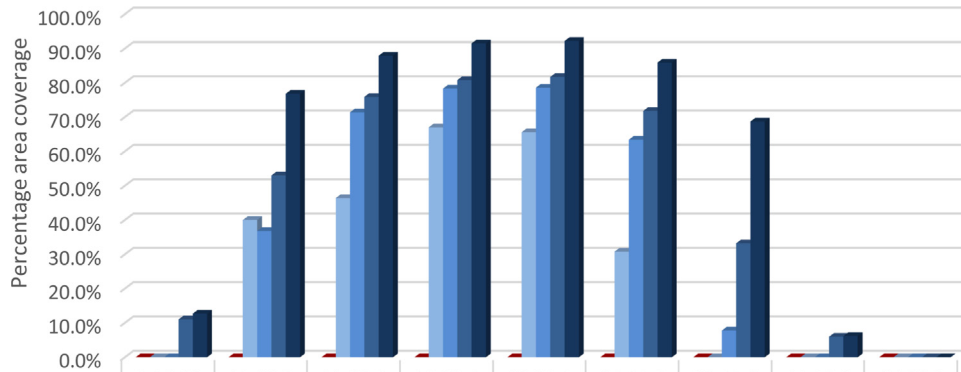
3.2. Comparison study results for the working hours on 21st from june to december

Some further comparisons were made for these five phases on the 21st of each month from June to December respectively, during the normal working hours. In these comparisons; the number of slats and their tilt angle were changed parametrically, according to the changes of solar trajectories in different seasons. In Winter, sun altitude is lower than other seasons, and solar radiation is relatively weak. Therefore, number of slats should be increased in order to prevent the penetration of sun light due to its low inclination at this time, and simultaneously reflect larger amount of daylight to compensate the weakness of solar radiation [35]. For the latitude of new Cairo, the sun altitude reaches 83° at the zenith time in June [24]. As well, the first target point on the ceiling needs to be changed parametrically to 0.4 m away from the window in November and December in order to compensate solar radiation weakness in the deep area of the room, while the transmittance of the electrochromic window was increased to allow more daylight transmission [23].

Generally, one can see that the electrochromic window and chamfered ceiling playing a crucial role in improving daylight distribution during the working hours especially in the first and last hours. For instance, at 9am or 3pm on September 21st, there is almost no direct sunlight shining on the south-facing window and the automated blinds deliver limited daylight at the time, so this lack of direct sunlight can be compensated by diffuse skylight through the electrochromic window.

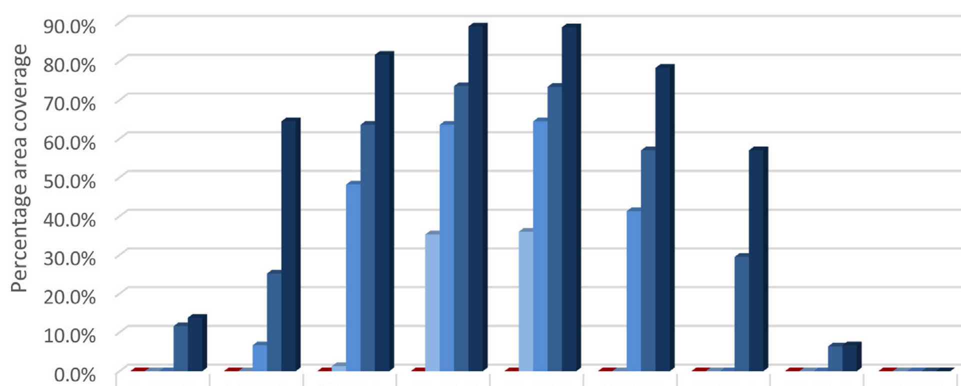
During the working hours, the design of Phase 5 is providing relatively constant distribution from 10am to 3pm with a percentage area coverage of 70~80%, then this coverage is strongly stoop till reaching 0% at 5pm. At 9am; for around 40% of the desktop area, electrical light can be used to compensate the weakness of natural daylight, and the electrical light should be then gradually swished off till approaching 10am. On the contrast, at 4pm we may use the electrical light for about 50% desktop area to compensate the diminishing of daylight availability, then this backup should gradually increase to 100% at 5pm when it is becoming dark. Therefore, we can deduce that electrical light should be used partially only in the first and last two hours of the day for the location of Cairo. Accordingly, using the proposed integrated design can save the lighting electricity consumption by more than 80% during the working hours.

It can be seen from Fig. 9 that the influence of the reflective slats is relatively clearer in June, when the sun altitude is almost



	9:00:00	10:00:00	11:00:00	12:00:00	13:00:00	14:00:00	15:00:00	16:00:00	17:00:00
Phase 1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Phase 2	0.0%	40.0%	46.4%	67.0%	65.6%	30.8%	0.0%	0.0%	0.0%
Phase 3	0.0%	36.8%	71.4%	78.3%	78.6%	63.4%	7.8%	0.0%	0.0%
Phase 4	11.0%	53.0%	75.9%	80.8%	81.7%	71.8%	33.2%	6.0%	0.0%
Phase 5	12.7%	76.8%	87.9%	91.5%	92.2%	85.9%	68.7%	6.2%	0.0%

Fig. 9. Percentage area coverage for the daylight illuminance range of 300–500 lx during working hours on June 21st for the five phases.



	9:00:00	10:00:00	11:00:00	12:00:00	13:00:00	14:00:00	15:00:00	16:00:00	17:00:00
Phase 1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Phase 2	0.0%	0.0%	1.3%	35.3%	36.0%	0.0%	0.0%	0.0%	0.0%
Phase 3	0.0%	6.7%	48.2%	63.6%	64.5%	41.3%	0.0%	0.0%	0.0%
Phase 4	11.6%	25.2%	63.6%	73.6%	73.4%	57.0%	29.5%	6.4%	0.0%
Phase 5	13.8%	64.5%	81.7%	89.0%	88.8%	78.3%	57.0%	6.7%	0.0%

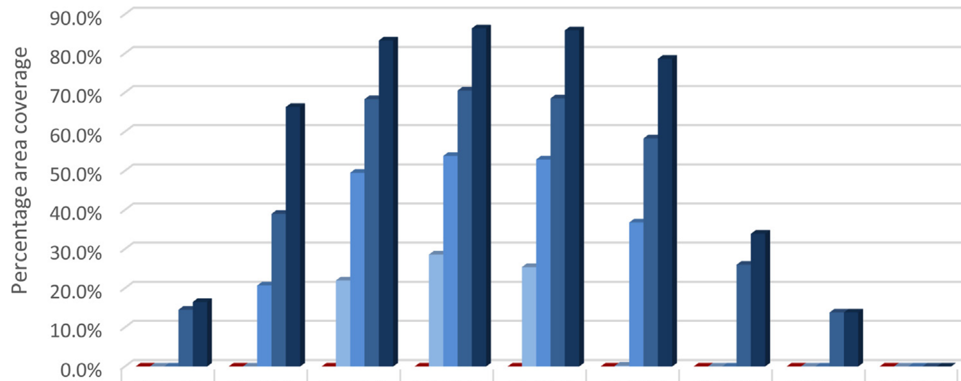
Fig. 10. Percentage area coverage for the daylight illuminance range of 300–500 lx during working hours on July 21st for the five phases, at each hour separately.

at the zenith, therefore, the slats is playing a big role in order to collect more sunlight, as revealed in Phase 3 in Fig. 9, which is giving higher values comparing to the following months Figs. 10–12. On the other hand, in October, November and December, the design of Phase 5 is more relied on the use of the electrochromic window and chamfered ceiling as shown in Figs. 13–15, when the sun altitude is low and solar radiation gives lower values at those times such as around 9am and 4pm.

4. Discussions

It can be observed in Fig. 16 that light distribution in Phase 2 of the design is more uniform than Phase 3 for the first impression, however, light distribution on the ceiling is not our target. The study focuses on more uniform daylight distribution over the desktop level, where, the results of the test points shown previously in Fig. 6 reveals better performance in Phase 3 comparing to Phase 2. In addition to that, we can observe in Fig. 16 a blue area on the wall in Phase 2, which means that the reflected light on the ceiling is more redirected to the top of the wall in the second bounce, instead of the working area. Whilst, the blue area on the wall in Phase 3 is relatively weak and fade, which means that the reflected light is distributed more onto the desktop area, as shown in Fig. 6 (Phase 3).

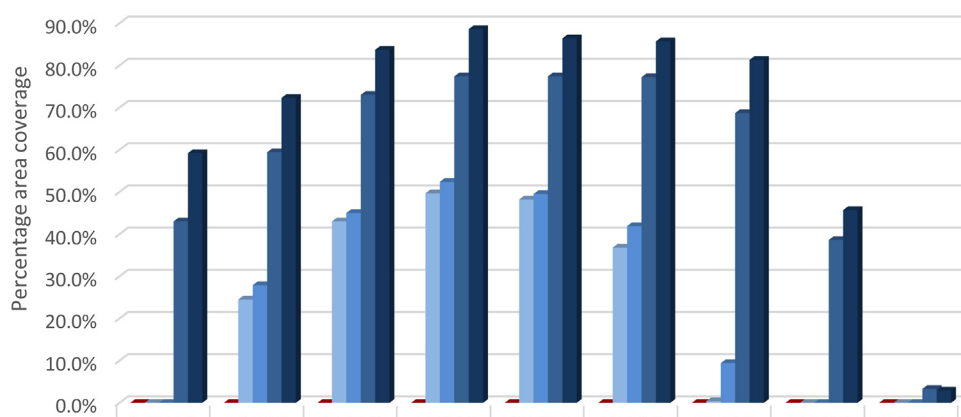
In the design of automatic blinds for illuminating a deep room, the reflection from the lowermost slat in Phase 2 of this comparison study may have a risk of being blocked by any obstacles in the room while it is the closest slat to the occupants, see Table 1. However, in



	9:00:00	10:00:00	11:00:00	12:00:00	13:00:00	14:00:00	15:00:00	16:00:00	17:00:00
Phase 1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Phase 2	0.0%	0.0%	22.0%	28.6%	25.4%	0.2%	0.0%	0.0%	0.0%
Phase 3	0.0%	20.7%	49.5%	53.8%	52.9%	36.8%	0.0%	0.0%	0.0%
Phase 4	14.5%	39.0%	68.3%	70.5%	68.5%	58.3%	26.0%	13.8%	0.0%
Phase 5	16.5%	66.3%	83.3%	86.4%	85.9%	78.6%	33.9%	13.8%	0.0%

Phase 1 Phase 2 Phase 3 Phase 4 Phase 5

Fig. 11. Percentage area coverage for the daylight illuminance range of 300–500 lx during working hours on August 21st for the five phases, at each hour separately.



	9:00:00	10:00:00	11:00:00	12:00:00	13:00:00	14:00:00	15:00:00	16:00:00	17:00:00
Phase 1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Phase 2	0.0%	24.5%	43.0%	49.7%	48.2%	36.8%	0.4%	0.0%	0.0%
Phase 3	0.0%	27.9%	45.0%	52.4%	49.5%	41.9%	9.4%	0.0%	0.0%
Phase 4	43.0%	59.4%	73.0%	77.4%	77.4%	77.2%	68.7%	38.6%	3.3%
Phase 5	59.2%	72.3%	83.7%	88.6%	86.4%	85.7%	81.3%	45.7%	2.9%

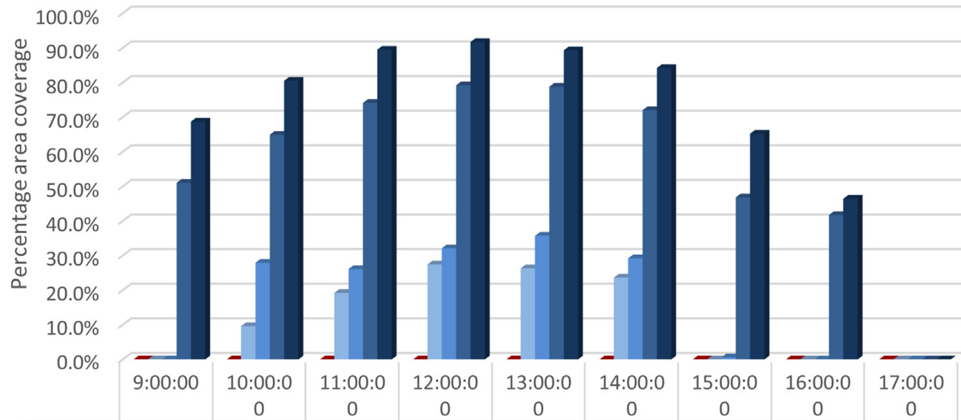
Phase 1 Phase 2 Phase 3 Phase 4 Phase 5

Fig. 12. Percentage area coverage for the daylight illuminance range of 300–500 lx during working hours on September 21st for the five phases, at each hour separately.

Phase 3 this issue was solved by reversing the targeting sequence parametrically, which means that the uppermost slat will reflect light to the farthest target point on the ceiling with little risk of blocking, and likewise for the next slats respectively.

In addition to the previous point, illumination distribution issue in Phase 2 is likely solved in Phase 3 by reversing the targeting sequence, which contributed to improve the daylight performance. From the raytracing point of view, the reflected light striking the ceiling surface shows a somewhat concentrated effect in Phase 3 comparing to Phase 2. Moreover, the chamfered ceiling added in Phase 5, acts as a second diffuse reflector and accordingly contributed better distribution in the deep room.

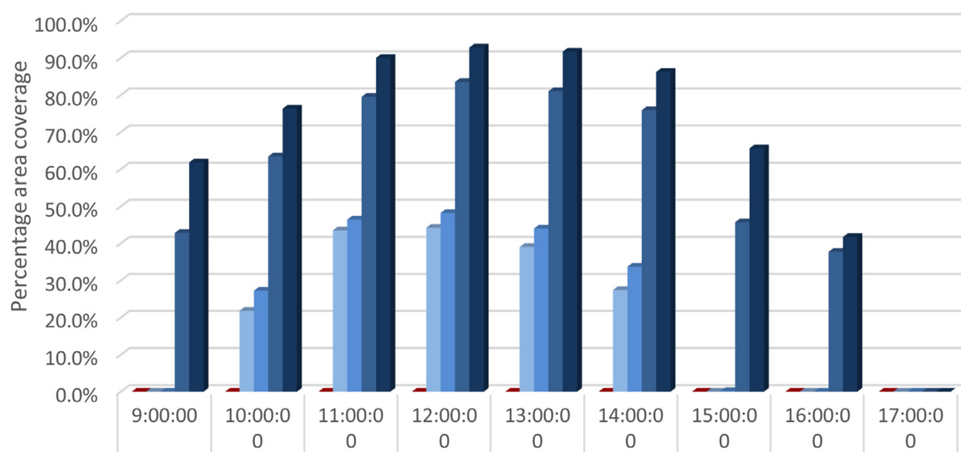
Excluding Phase 1 of the design, we can observe that the edges and corners in the room are relatively dim, due to the blockage or interception of light by the walls, and the so-called penumbra effect [38] may somewhat also influence on this issue. These small edge areas can be ignored according to the design standards of the offices and the general pattern of workspace [39], which is usually about half of a meter away from the walls. Accordingly, if the edges and corners which is around 12% of the total floor area were ignored in daylighting evaluation, the percentage area coverage for the daylight illuminance range of 300–500 lx would reach 100% for even more number of working hours. Therefore, it is reasonable to neglect those edge areas in daylighting evaluation in order to give a more practical result for the office room.



	9:00:00	10:00:00	11:00:00	12:00:00	13:00:00	14:00:00	15:00:00	16:00:00	17:00:00
Phase 1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Phase 2	0.0%	9.6%	19.2%	27.4%	26.3%	23.6%	0.0%	0.0%	0.0%
Phase 3	0.0%	27.9%	26.1%	32.1%	35.7%	29.2%	0.6%	0.0%	0.0%
Phase 4	51.0%	64.9%	74.1%	79.2%	78.8%	72.0%	46.8%	41.7%	0.0%
Phase 5	68.7%	80.5%	89.5%	91.7%	89.3%	84.2%	65.2%	46.4%	0.0%

Phase 1 Phase 2 Phase 3 Phase 4 Phase 5

Fig. 13. Percentage area coverage for the daylight illuminance range of 300–500 lx during working hours on October 21st for the five phases, at each hour separately.



	9:00:00	10:00:00	11:00:00	12:00:00	13:00:00	14:00:00	15:00:00	16:00:00	17:00:00
Phase 1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Phase 2	0.0%	21.8%	43.5%	44.2%	39.0%	27.4%	0.0%	0.0%	0.0%
Phase 3	0.0%	27.2%	46.4%	48.2%	44.0%	33.7%	0.2%	0.0%	0.0%
Phase 4	42.8%	63.4%	79.5%	83.5%	81.0%	75.9%	45.7%	37.7%	0.0%
Phase 5	61.8%	76.3%	90.0%	92.8%	91.7%	86.2%	65.6%	41.7%	0.0%

Phase 1 Phase 2 Phase 3 Phase 4 Phase 5

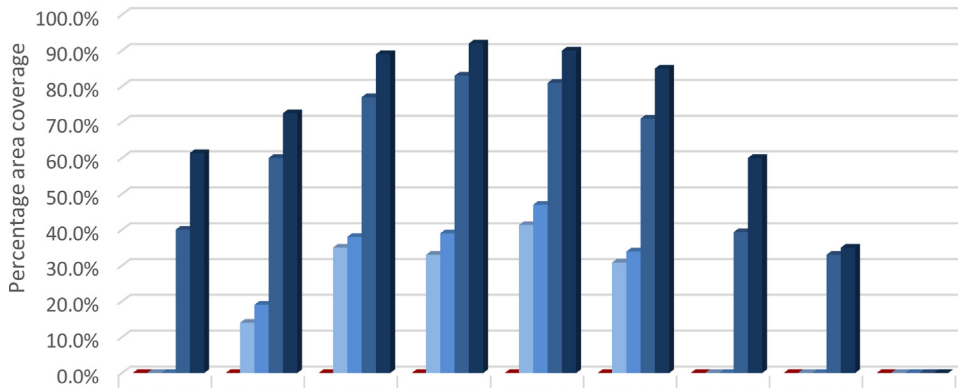
Fig. 14. Percentage area coverage for the daylight illuminance range of 300–500 lx during working hours on November 21st for the five phases, at each hour separately.

Overall, as mentioned earlier, each element in this integrated daylighting system has a special utility for a specific time and season. The significant utility of each element can be higher sometimes, which may compensate the weakness of the other elements at the same time, and vice versa. Therefore, the combination between different utilities contributes to achieving a better distribution of daylight, as revealed in the presented integrated parametric daylighting system.

5. Conclusions

This study has investigated the combinations between different architectural elements parametrically, in order to achieve more uniform daylight distribution inside an office room, with New Cairo chosen as a location for the case study.

The proposed design has been identified through a multi-step comparison study employing parametric design approach, aiming to improve the daylight distribution within the usable range of 300–500 lx. Starting with the fixed blinds in Phase 1, the daylighting system was then upgraded to the automated blinds in Phase 2, then the slats targeting sequence was reversed in Phase 3, which has slightly improved daylight distribution. In Phase 4, an electrochromic (EC) window was added to the lower portion of the façade and its translucency can be controlled parametrically, resulting in a noticeable improvement in this phase. Finally, a chamfered ceiling was added in the interior design to complete the integrated



	9:00:00	10:00:00	11:00:00	12:00:00	13:00:00	14:00:00	15:00:00	16:00:00	17:00:00
Phase 1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Phase 2	0.0%	14.0%	35.0%	33.0%	41.3%	30.8%	0.0%	0.0%	0.0%
Phase 3	0.0%	19.0%	38.0%	39.0%	47.0%	33.9%	0.0%	0.0%	0.0%
Phase 4	40.0%	60.0%	77.0%	83.0%	81.0%	71.0%	39.3%	33.0%	0.0%
Phase 5	61.4%	72.5%	89.0%	92.0%	90.0%	85.0%	60.0%	35.0%	0.0%

Fig. 15. Percentage area coverage for the daylight illuminance range of 300–500 lx during working hours on December 21st for the five phases, at each hour separately.

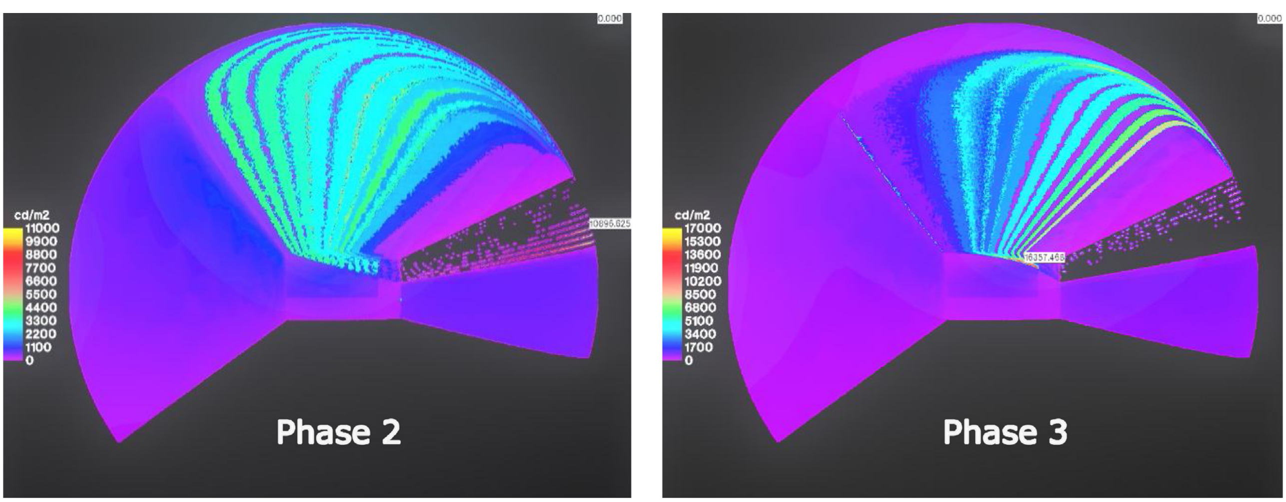


Fig. 16. High dynamic illuminance map exported from Honeybee plugin; showing the reflected light distribution on the ceiling. (Left) Phase 2, (Right) Phase 3.

system in Phase 5. The whole system was integrally connected and controlled parametrically using Grasshopper as a parametric software based on Rhinoceros 3D.

The first part of this study covers the detailed designs for 5 phases at a specific time and date, in order to compare the designs from the raytracing results and daylighting analysis clearly; then the following part reveals some summarised results for the 21st day of seven months from June to December to give a more comprehensive comparison.

The integrated designs in Phase 4 and 5 have succeeded to improve daylight distribution inside the room by achieving an average 80% area coverage for the daylight illuminance range of 300–500 lx for most of the working hours throughout a year, as exemplified with the data on the 21st of every month from June to December. By neglecting the edges and corners of the room while they are not usually used; the percentage area coverage for the required daylight range can be even higher by additional 10%. Accordingly, this integrated system based on parametric control is expected to save about 80% of electrical lighting energy consumption.

This study has been focused on improving the daylight distribution in a south oriented deep room in new Cairo. To evaluate the overall energy saving potential, the effect of design on the cooling and heating energy consumption will be investigated in a future study. In addition, the future study will also investigate the integrated system performance for different orientations and locations of buildings.

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