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Daylighting performance improvements using of split louver with parametrically incremental slat angle control

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ABSTRACT

Different shading device systems and control strategies can be employed in different parts of a window system to perform different functions, particularly for fully glazed façades. A split louver with various improvements was proposed in this study as an innovative daylighting device to improve daylighting distribution and uniformity. An 8 m deep office room in Jordan was chosen for a case study, where it is south-oriented with a high window-to-wall ratio (WWR: 95%). The split louver system features two sections with different functions that can affect the quality and quantity of daylighting performance in the deep room space. Four types of parametrically controlled reflective slats, i.e., unanimous, incremental, fully parametric, and parametrically incremental, were investigated for the upper section of the split louver. While the daylighting performance of the four systems is extremely similar in terms of illuminance level but different in distribution, the parametrically incremental control is the preferred one attributed to its practicality and distribution performance. The upper section of the split louver includes blind integration, and different slat surface materials (diffuse, semi-mirrored, and mirrored) were evolved through various improvement phases. Simultaneously, the lower section of the split louver was investigated in order to adjust the overall illuminance level. The proposal of scheduled angles of split louver in both sections presented the most optimal combinations to achieve balanced daylighting levels in both the front and back of the space. This resulted in a free-glare indoor with accepted daylight uniformity levels of up to 0.60 and high percentage coverage within $UDI_{150\sim750\ lx}$ for most of the working hours throughout the year are realized (between 90% and 100% at noontime and no less than 50% along the rest of the working hours).

1. Introduction

Window systems impact air quality and provide thermal, lighting, and visual comfort, which will consequently affect the energy consumption needed for lighting, cooling, or heating. The lighting requirements include suitable illuminance, glare protection, and visual connection with the outdoors. As part of a window system, the shading device helps to meet these requirements by providing protection from direct sunlight and overheating in the summer, reducing cooling loads, avoiding glare, and providing privacy or even a view of the outside [1–4]. In most cases, conventional shades are adjusted manually by occupants based on their preferences, which may not meet the lighting or visual requirements [1,5,6]. Therefore, conventional shading systems are considered impractical [4,7].

Shading techniques that do not incorporate light redirection or light transmission solutions to improve the daylighting inside the space are considered a waste of free natural resources [4,8]. However, such new systems are developed and improved, and light redirection into spaces is one of the key topics under investigation in the field of daylighting. Two fundamental functions of light-redirecting systems are (1) preventing light penetration inside the space to reduce overheating and glare and (2) redirecting light into the space to improve illumination inside the deep room [9,10]. Reflectors [11], prismatic panels [10,12,13], mirrored blinds [14], and light shelves [15] are some of the options available.

Multiple shading control strategies should be used in various parts of a window system to perform different functions [7,16] through implementing a complicated window system with a simple control method [17]. To meet the lighting requirements for

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glare-free workspaces and to optimize light distribution in the deep room, the glazed façade should be divided into different sections. Previous studies dealt with different forms of split shading devices in terms of the type of shading and splitting segments. A novel split blind system was proposed with two main parts, where the lower part of the blinds is set to block direct sunlight and the upper part is utilized to redirect sunlight into the deep space [18,19]. Different studies considered split shading façade with three sections: a top section that represents the upper daylighting part, a middle viewing part, and a bottom part to control heat [3,17,20,21]. A study on two sectional split blinds operated manually revealed that they required an automated control system to improve their efficiency [22]. In most cases, the slat tilt angle of a louver system parametrically responds to the solar angle to achieve a more uniform light distribution [14,23,24]. The common automatically controlled shades have the same tilt angle for all slats along the window.

In addition to daylighting, taking the view into account when designing transparent building surfaces is crucial [25]. The tilt angle of the louver influences view quality. As a result, the visual quality generally improves with increased slat openness [26]. Split louvers' improved functional efficiency would enhance daylighting performance; however, if the lower section were closed, it would still obstruct views of the outside. Controlling both sections of the split louver would fundamentally decrease the negative effects of direct sunlight while also maintaining a view of the outside.

A balance between different parameters, such as solar intensity, solar direction, orientation, and space design, should be considered by using a multi-functional shading system. Moreover, a few studies have been conducted on annual daylighting performance to highlight both functions of solar shading and daylight redirecting systems with adaptable parametric control. The key contribution of this study is to explore both quality and quantity of daylighting performance via the combinations of the upper and lower sections of the proposed improved split louver throughout the year. Parametric software was employed in this study to control a split louver system with two parts to meet the daylighting requirements, including achieving maximum uniform coverage inside the space. This can be achieved by modifying the slats of each section parametrically depending on their functions. The upper section slats reflect sunlight to the ceiling in a consistent manner to illuminate the deep area of the room. Responding to sun exposure, the upper section slats are processed through different parametric systems: unanimous, incremental, fully parametric, and parametrically incremental (combined system). On the other hand, the lower section is utilized as a shading device, protecting the occupants from direct sunlight and heat gain. The lower section slats were also regulated parametrically by responding to variations in solar angle. With various modifications in controls and standards, a parametrically controlled split louver in both sections achieved better overall daylighting performance and is regarded as practical and easy to implement in a real-world setting.

2. Methodology

In the present work, the daylighting performance of the split louver system with different slat angles was examined using the parametric software "Grasshopper" and its plugins "Ladybug & Honeybee". The study introduced the performance of each slat angle control as a preliminary phase to continue with the rest of the split louver improvements. The study compared different modifications in the split louver system. These modifications were evolved through gradual improvement phases: (1) common blind integration, (2) reflective slat materials, (3) lower section slat angles selections, and (4) scheduled slat angles for both upper and lower sections. The detailed gradual improvements of the split louver are illustrated in Fig. 1.

The simulations considered site location and local time, window orientation, and slat material properties. Indoor daylight spatial distribution uniformity, useful daylight illuminances (UDI) and annual daylight analysis were all part of the daylight simulation. The range of visual comfort should be defined based on visual tasks and room design/function. The suggested minimum ratio of uniformity is 0.4, which is determined by the minimum illuminance divided by the average illuminance [27] from the daylight study points. According to several studies, the maximum illuminance limit should be 2000 lx, while the lower limit should be 100 lx [28–30]. According to some reports, light illuminance should be 300 lx in public spaces, 150 lx in working spaces where visual tasks are only performed on occasion, 750 lx for medium contrast or small size visual tasks, and 3000 lx for low contrast and very small size visual tasks over a long period [31–33]. The visual comfort is ensured completely by daylight without any artificial lighting. The range between 750 lx (no excessive daylighting and no possibility of glare) and 150 lx (sufficient daylighting and no artificial illumination) was assumed [34]. In this study, the targeted indoor illuminance values are within $UDI_{150\sim750\ lx}$. These values, however, might vary based on the design requirements, the building's actual use, and the visual task.

2.1. Model description and software

Based on Rhinoceros 3D, Grasshopper is a visual algorithmic programming language for parametric modelling that can be used as a scripting language to deal with various parameters [35,36], and was used to build the model in this work. The dimensions of the proposed model are 4 m in clear height, 8 m in depth, and 12 m in length, with a glazed south window (6 mm common single glazing with a visual transmittance of 88%). The guidelines for using an appropriate shading design to achieve effective daylighting in contemporary high-rise open-plan offices can be within the generally accepted 2.5H to 3.6H rule of thumb (2.5 to 3.6 times the height of the window). Contemporary office buildings frequently have a highly glazed façade. The office room's 8 m depth and 95% window-to-wall ratio were consequently chosen [37]. The split louver system is mounted on the fully glazed southern façade of the office room model in a clear sky sunny territory. Grasshopper was employed to parametrically regulate the split louver system using a built-in formula. This formula defines the model parameters and is adjusted to react to sun movement by using CIE clear sky with direct sunlight according to the dominant clear sky conditions in the studied location (Amman, Jordan) [38]. The external global horizontal illuminance (a combination of direct and diffuse horizontal illuminance) in the working hours on three typical dates is represented in Fig. 2. It is worth noting that the Grasshopper itself calculates the illuminance received by the tilted split louver. The daylighting performance simulation was performed using Grasshopper's plugins: Ladybug & Honeybee [39,40]. Ladybug plugin implements Daysim and EnergyPlus, which obtains weather data and sun-path for any specified location using EPW weather-file [40]. Meanwhile, Radiance, a lighting simulation analysis software, is run using Honeybee plugin based on a backward ray-tracing approach for sun irradiation and grid-based daylight analysis [41]. For all daylighting performance simulations, the work plane height inside the room is 0.80 m with 50 cm test points grid. See Fig. 3 for the base model details. To achieve accurate results and include the effects of the slats' material reflections, it is necessary to specify the radiation ambient parameters for the daylight simulation, which requires the following ambient settings: "-aa 0.15, -ab 2, -ad 2048, -ar 128, -as 256, -dr 3, -dp 512, -lw 0.002,-lr 8,-st 0.15" [39,42], as shown in Table 1.

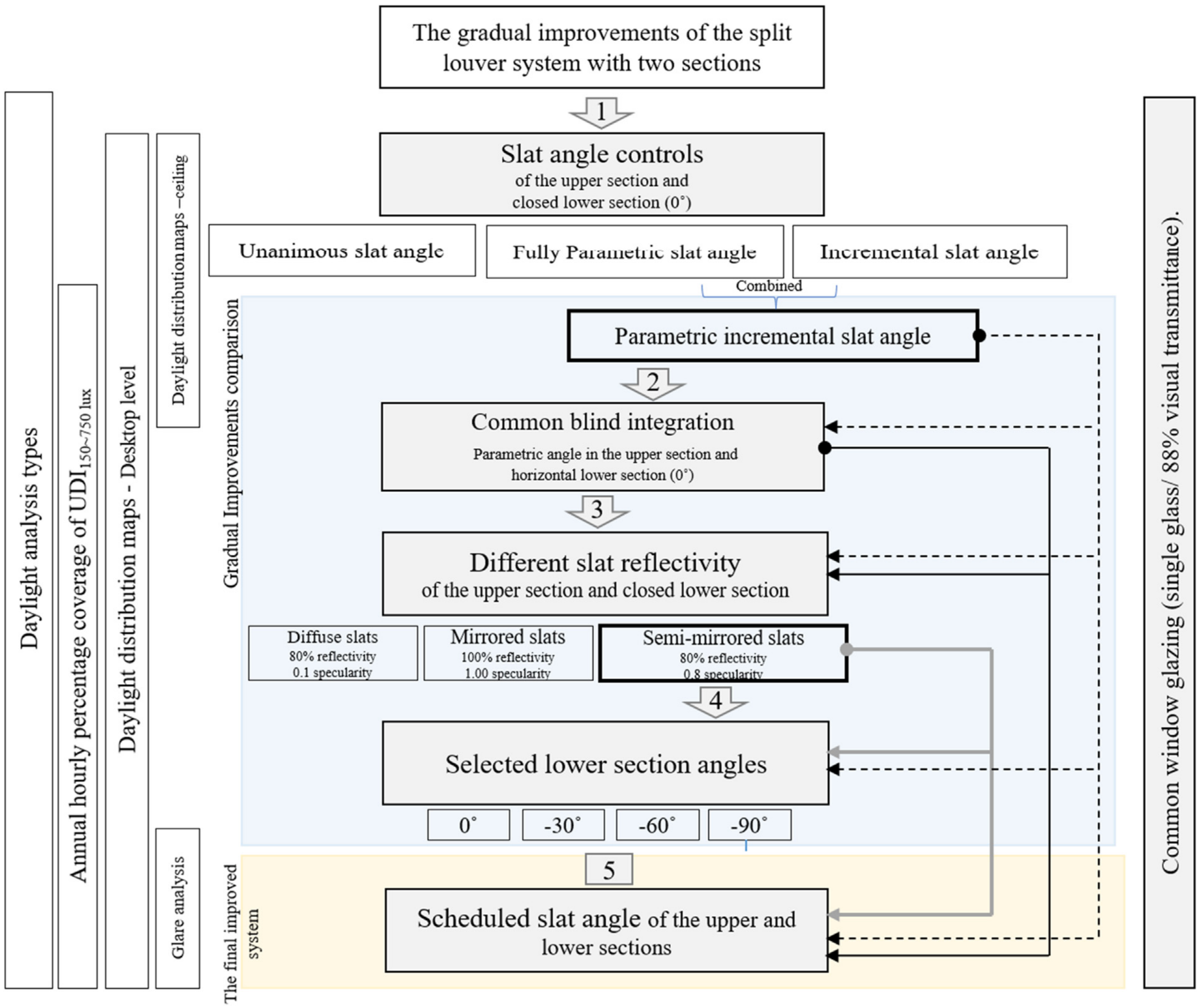
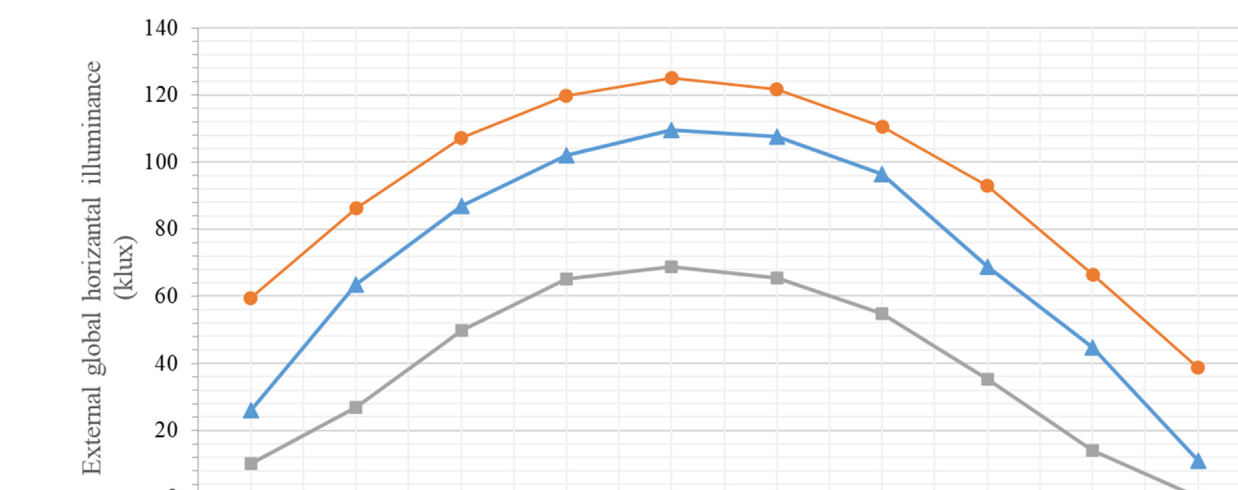


Fig. 1. The gradual improvement phases of the split louver in the study.



	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
March 21st	26.0	63.5	86.9	101.9	109.5	107.5	96.5	68.7	44.7	11.0
June 21st	59.6	86.3	107.3	119.8	125.1	121.7	110.7	93.1	66.5	38.8
December 21st	10.3	26.9	49.8	65.3	68.9	65.4	54.8	35.4	14.2	0.0

Fig. 2. External global horizontal illuminance (klux) for the working hours on the three typical dates.

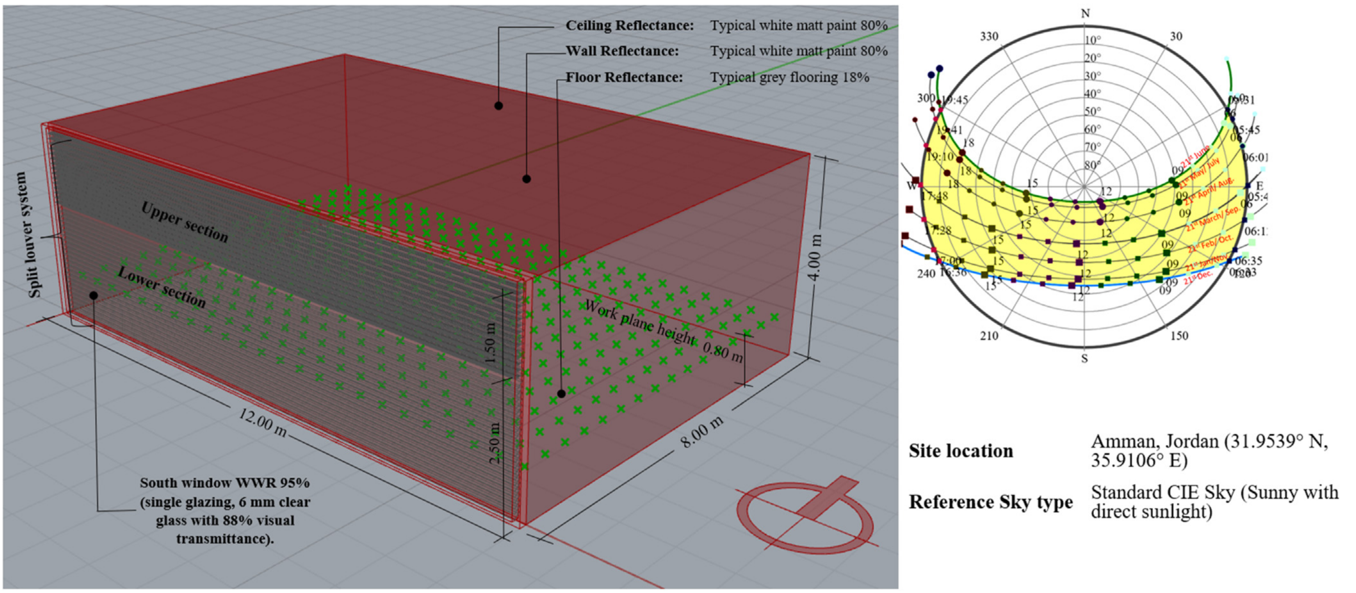


Fig. 3. Base model configuration of a virtual office room.

Table 1
The Radiance settings used in the simulation.

Radiance parameter	Description	Value
-aa	Ambient accuracy	0.15
-ab	Ambient bounces	2
-ad	Ambient divisions	512
-ar	Ambient resolution	128
-as	Ambient super-samples	256
-dr	Direct relays	3
-dp	Direct pretest density	512
-lw	Limit weight	0.002
-lr	Limit reflection	8
-st	Specular threshold	0.15

2.2. Description of the automated split louver system design

The study focuses on designing a practical daylighting system that includes a split louver with two sections that automatically respond to the sun's movement. The practical design aims to regulate the slat rotation in response to sun movement parametrically throughout the day while maintaining a rigid and efficient split louver system using a simplified parametric control. The split louver should achieve two simultaneous functions: redirecting the incident sunlight to the ceiling through the upper section and preventing direct sunlight from reaching the workstation through the lower section. The input settings for the split louver are shown in Fig. 4. The four-meter-high window was divided into two sections, 1.5 m for the upper section with 15 slats and 2.5 m for the lower section with 23 slats. In both sections, a slat unit is 1 mm thick, 12 cm wide, and 10 cm spaced apart. The slats in the upper section rotate toward the interior with a parametric slat angle (β_1), and the slats in the lower section rotate toward the exterior with a parametric slat angle (β_2). The slat rotation angle is the one between a horizontal plane and the slat plane. It is worth mentioning that if the slats are horizontal, the angle is adjusted to 0°. The slat rotation angle is a negative value if the slats are inclined anti-clockwise downward to the exterior, and vice-versa.

Four parametric methods to control the split louver in the upper section were explored in this study, namely, the unanimous, incremental, fully parametric, and parametrically incremental (note that the parametrically incremental one is a combination of the fully parametric control and incremental control). Recent research revealed that using pre-determined angles for all slats to achieve a simplified parametric control with incremental slat angles could be implemented at any time [43]. It was successfully discovered that the angle differences between every-two adjacent slats are exactly the same on all typical days.

The slat angle in the upper section is calculated by [43]:

$$\beta = \frac{\Omega - \tan^{-1}(U/V)}{2} \tag{1}$$

where Ω is the solar profile angle, °; U is the vertical distance between a slat and the ceiling, cm; and V is the horizontal distance between a slat and a point on the ceiling, cm.

In all scenarios of angle control, the lowest slat is set to target the nearest point from the deep corner.

(a) In the unanimous control, one single target point is assigned to the lowest slat in the upper section (40 cm away from the deep corner), and all slats are rotated at the same angle during each movement. The reflected sunlight is parallel with no angle increment, as shown in Fig. 5 (a).
(b) In the incremental control, as shown in Fig. 5 (b), the incremental slat angle control is calculated from the lowest slat to the highest slat in fixed increments, while the target point of the highest slat is ¾ of the ceiling width away from the deep corner.
(c) In the fully parametric control, as shown in Fig. 5 (c), the slats are parametrically and individually tilted. Each slat rotates and reflects incident sunlight at various angles to specific target points on the ceiling.
(d) In the parametrically incremental control, the change in the slats angle relies on a prefixed series and one variable angle, which is the lowest slat angle, as shown in Fig. 5 (d).

2.3. Different slat angle controls of split louver

A comparison study is conducted among the proposed four types of split louver controls for the upper section, with the lower section slats being closed. The spring equinox (March 21st) is selected for the case study as sun rays give moderate sunlight exposure on this day. The distribution quality of reflected sunlight

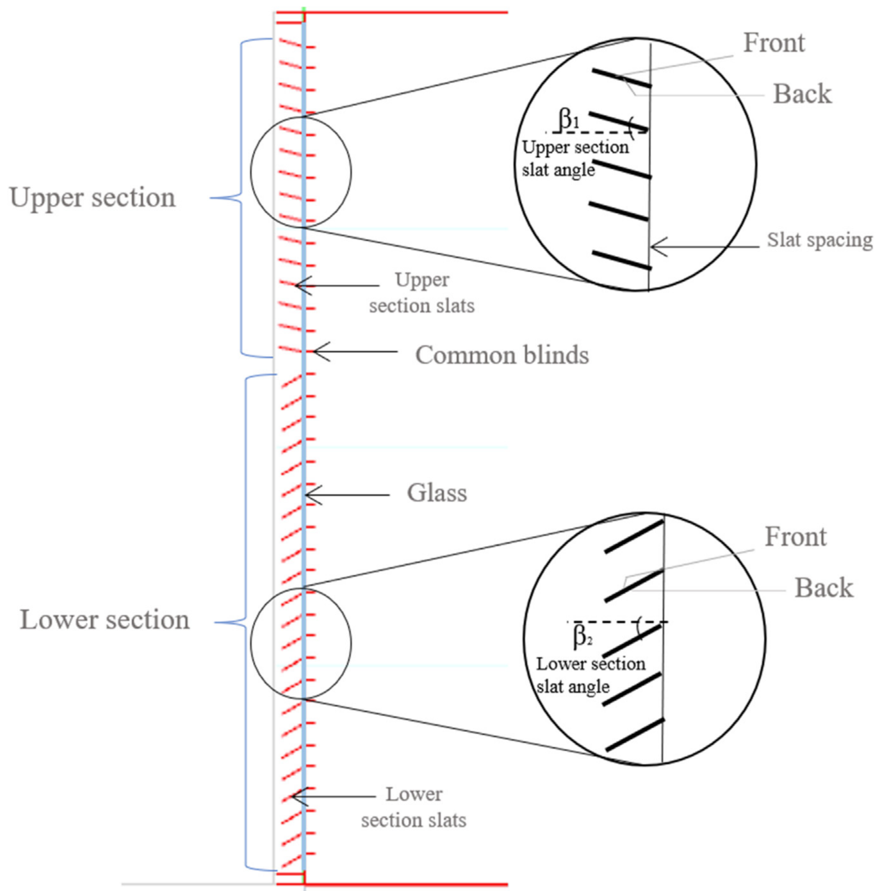


Fig. 4. Split louver design description.

on the ceiling using mirrored slat is the emphasis of this first step of comparison, regardless of the illuminance levels, which will be analyzed thoroughly later in this research. However, sunlight distribution on the ceiling is not the main purpose. Fig. 6 shows the daylighting performance of the split louver with different slat angle controls in the upper section on March 21st at 12:00 pm using "false-colour fisheye maps" exported from Honeybee plugin, ceiling illuminance maps, and cross-sectional distribution.

The density of the bright patches on the ceiling was investigated. The illuminance distribution of the unanimous control case is more concentrated in the front area near the window than in the middle and deep areas. Moreover, the light stripes reflected on the ceiling are segregated. However, in the incremental control case, the contrasts between the bright patches are more blended and concentrated in the deep areas of the ceiling. Accordingly, this increases the illumination in the deep area. Furthermore, a blue area on the wall can be seen in this control, indicating that the wall absorbs the diffuse light from the ceiling as a second bounce rather than distributes it to the workstation. In the fully parametric control case, the maps reveal regular light patches on the ceiling, i.e., better balanced illuminance. The performance of the parametrically incremental control indicates that the reflected sunlight striking the ceiling is almost similar to that in the fully parametric control. However, using the parametrically incremental control is simpler and more practical, with only one target and one variable component in the automation process.

Overall, the performance of the daylight distribution for the slat angle control in the upper section should be considered in conjunction with the lower section. Therefore, unanimous control may not help since both sections will affect the front space, resulting in non-uniform daylight distribution and excessive lighting near the window. Although the incremental control shows reflection toward a deeper area, the distribution of the reflected sunlight is limited to the corner, and some of the lights bounce directly onto the wall. The reflected sunlight is dominated in the center and deep areas of the space in the fully parametric and the parametrically incremental controls; therefore, the lower section is expected to operate efficiently in these cases. A summary of the initial comparison of the different controls depending on design, automation, and daylighting performance is shown in Table 2.

2.4. Scheduled slat angles of the split louver

The split louver sections should work simultaneously to achieve a compromise between the daylighting levels and the daylight distribution in the whole space. The lower section collaborates with the upper section to address any issues that may occur because of the variable intensity of the sun. Considering solar altitudes, the adjusted tilt angles of the slats in the upper section should be addressed while mapping the light distribution inside the space to provide a comfortable glare-free workspace. The parametric tilt angle of the lowest slat in the upper section of the parametrically incremental control was calculated using Grasshopper for different typical days from 8:00 am to 17:00 pm, see Fig. 7.

To achieve acceptable illuminance values and uniform daylighting distribution throughout the year, the angle variations of the slat in the lower section should also respond to the sun movement. Therefore, the analysis below is used to determine a scheduled angle for this section. The slats are tilted downwards to the exte-

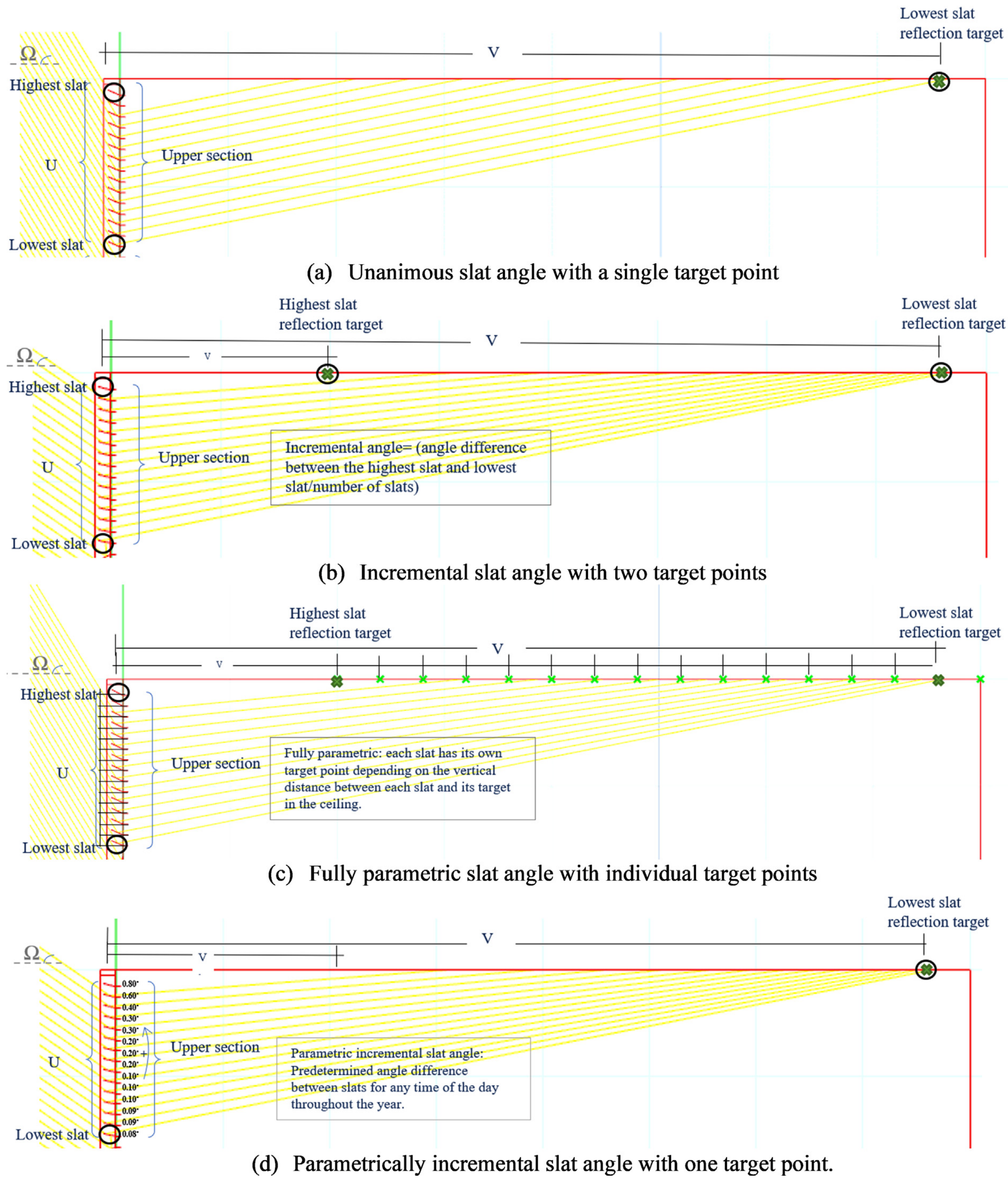
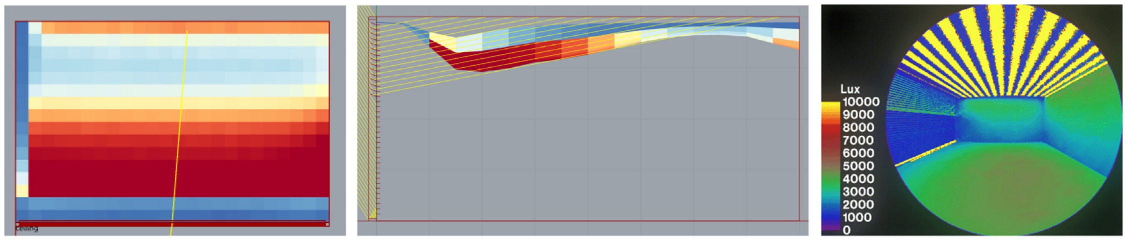
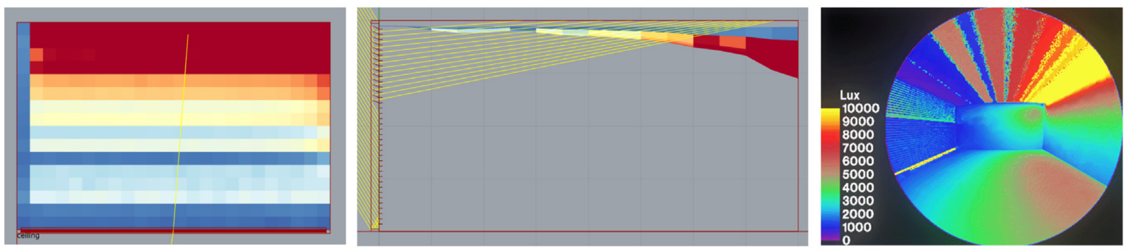


Fig. 5. Different slat angle systems for the upper section of the split louver.

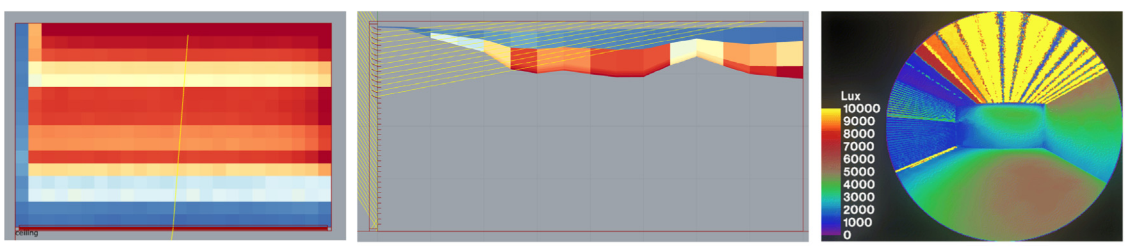
rior at different angles based on the sun's movement. Due to lower altitudes in the winter, the slats are excessively rotated toward the outside to prevent sunlight penetration. Multiple assessments were performed for different typical days to evaluate the daylighting performance and determine an automation control strategy. The allowable angle for the lower section of the split louver is designed to enhance the daylighting performance and maintain a visual connection to the outside. Therefore, it is tuned to be in the range between fully open slats (0^{o}) and half-open slats (-45^{o}) to both avoid any possible glare in the workstation and maintain the view quality in the space. The scheduled slat angle of the lower section is set to respond to the variation in solar profile angle, as shown in Fig. 8. The higher solar profile angle on June 21st is 127^{o} at noontime, meaning that the workstation receives less sunlight. Therefore, the lower section angle is set to be horizontal (the maximum allowance for the lower section that provides a direct view to the outside) on June 21st in the late afternoon and at -45^{o} in the late afternoon on December 21st. Consequently, the lower section angle at any other time will be calculated based on the mathematical formula (2), varying between 0^{o} and -45^{o} (see Fig. 9). The ratio between the highest and lowest profile angle is calculated to meet the suitable angle of the lower slats angle range



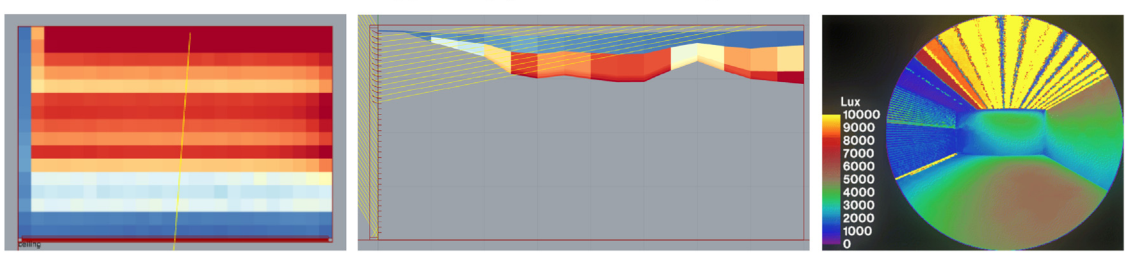
(a) Unanimous slat angle control



(b) Incremental slat angle control



(c) Fully parametric slat angle control



(d) Parametrically incremental slat angle control

Fig. 6. Comparison of daylighting performance of split louver with different slat angle controls in the upper section and closed lower section on March 21st at 12:00 pm: (a) unanimous, (b) incremental, (c) fully parametric, and (d) parametrically incremental slat angle control.

Table 2
The main differences between the four slat angles controls in terms of design, automation, and daylighting performance.

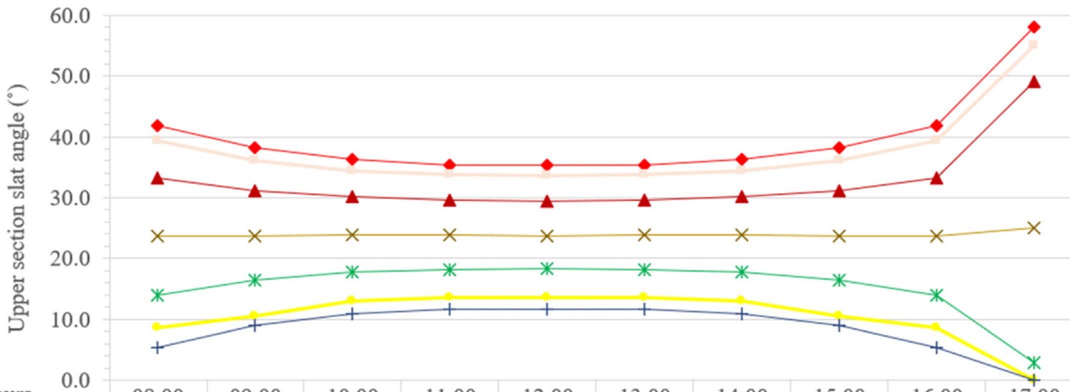
Slat angle control	Number of targets	The variable component in the automation	Slat angle differences (increment from the lowest to the highest slat)	Room depth coverage	Daylight distribution and location
Unanimous	One	The lowest slat	No difference	Along the ceiling width.	Area near the window
Incremental	Two	The lowest and highest slats	Fixed number	¾ of the ceiling width away from the deep corner.	Area near the deep wall
Fully parametric	Multiple	All slats	Variable	¾ of the ceiling width away from the deep corner.	Middle and deep areas.
Parametrically incremental	One	The lowest slat	Fixed series	¾ of the ceiling width away from the deep corner.	Middle and deep areas.

(0° to 45°) and is confirmed as 0.353. The negative value is functioned to convert the direction of the slats from inward to outward.

$$\beta_2 = -(127^\circ - \Omega) * 0.353 \quad (2)$$

3. Comparison study

In this comparison study, the original design of the split louver system mentioned in section 2.2 (with the parametrically incre-



Working hours	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
June 21st	41.9	38.2	36.2	35.4	35.3	35.4	36.2	38.2	41.9	58.0
May and July 21st	39.3	36.1	34.4	33.7	33.7	33.7	34.4	36.1	39.3	55.0
April and August 21st	33.3	31.1	30.2	29.6	29.5	29.6	30.2	31.1	33.3	49.0
March and September 21st	23.7	23.7	23.9	23.9	23.7	23.9	23.9	23.7	23.7	25.0
February and October 21st	14.0	16.4	17.8	18.1	18.3	18.1	17.8	16.4	14.0	3.0
January and November 21st	8.7	10.6	12.9	13.5	13.6	13.5	12.9	10.6	8.7	0.0
December 21st	5.5	9.0	10.9	11.7	11.7	11.7	10.9	9.0	5.5	0.0

Fig. 7. Parametric tilt angle of the lowest slat in the upper section of the split louver (parametrically incremental control).

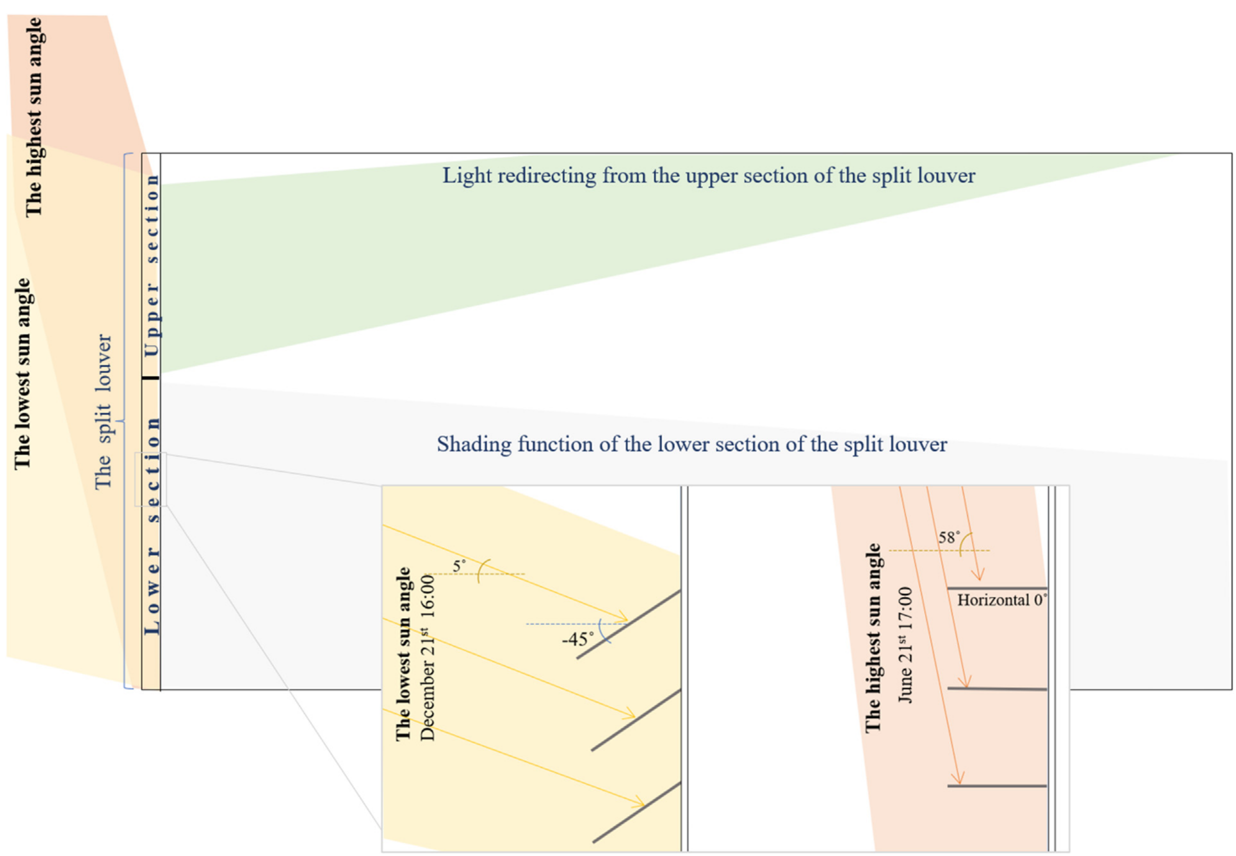
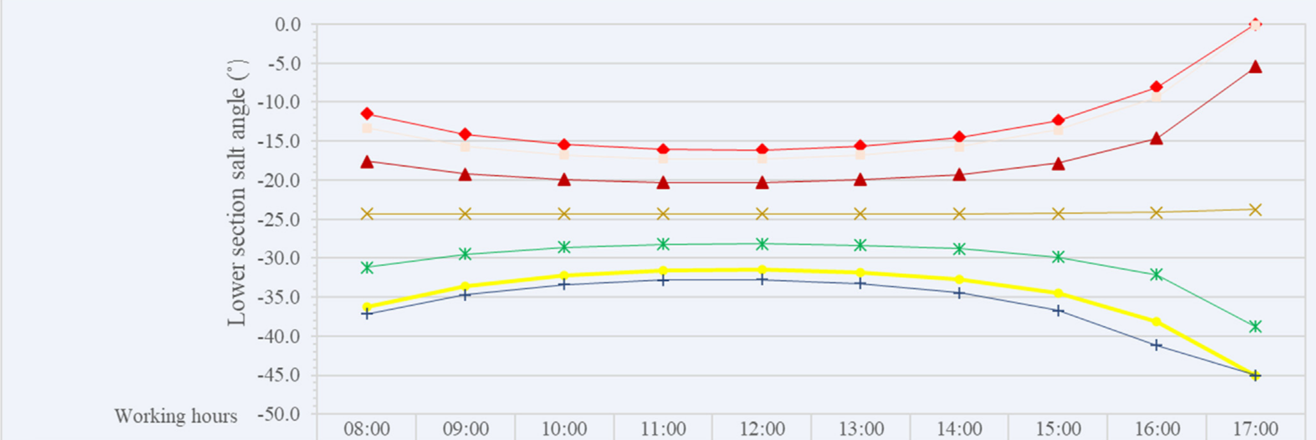


Fig. 8. The slats angle of the lower section responding to the lowest and highest sun angles.

mental control) is gradually modified and analyzed. The comparison chooses a specified local time (at 12:00 pm on March 21st) as a reference case, then at different working hours on June 21st and December 21st for the improved design. Additionally, for each step of design improvement, an hourly percentage coverage within $UDI_{150\sim750\ lx}$ and the uniformity ratio are examined.



Working hours	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
June 21st	-11.5	-14.1	-15.5	-16.1	-16.1	-15.7	-14.5	-12.4	-8.1	0.0
May and July 21st	-13.3	-15.7	-16.8	-17.3	-17.3	-16.8	-15.7	-13.6	-9.4	-0.2
April and August 21st	-17.6	-19.2	-19.9	-20.3	-20.3	-19.9	-19.3	-17.9	-14.6	-5.5
March and September 21st	-24.3	-24.4	-24.4	-24.4	-24.4	-24.3	-24.3	-24.3	-24.1	-23.8
February and October 21st	-31.2	-29.5	-28.6	-28.2	-28.2	-28.3	-28.8	-29.9	-32.2	-38.8
January and November 21st	-36.3	-33.6	-32.2	-31.6	-31.5	-31.8	-32.7	-34.5	-38.1	-45.0
December 21st	-37.2	-34.7	-33.4	-32.8	-32.8	-33.3	-34.5	-36.7	-41.2	-45.0

Fig. 9. The proposed scheduled slat angle for the lower section (all slats) of the split louver.

The split louver is proposed to overcome the limitations of the conventional single louver in daylight distribution inside the space. Different combinations were investigated for both the upper and lower sections of the split louver in this comparison study. The lower section slats are inclined downwards to the exterior at different angles to prevent overheating and glare. The parametrically incremental control is used in the upper section. In this comparison study, (1) common blinds are attached to the split louver system in the first improvement. (2) Different reflectivity values of the slats are studied in the next step of improvement regardless of the state of the lower section. Subsequently, the third step of improvement is (3) testing different lower section slats angle selections. The last improvement is based on the concept of (4) the scheduled angle for the two sections of the split louver in section 2.4, with consideration of the previous improvements.

3.1. Combination of split louver and blinds

In previous studies, reflective blinds were hinged with dark tinted slats from one side to absorb any downward light to avoid glare near the window and reduce potential scattered light [14,44]. However, this comparison is performed to highlight the utility of the blinds in the split louver with parametrically incremental control in the upper section and horizontal slats in the lower section on three typical days. The illuminance maps in Fig. 10 reveal that the blinds can clearly reduce penetration near the window, particularly on December 21st. The blinds improve daylight distribution without any indirect penetration that may cause glare. Both $UDI_{150\sim750\ lx}$ and uniformity levels are increased by using the blinds system. $UDI_{150\sim750\ lx}$ increases dramatically from 0% to 66% on December 21st, followed by that on March 21st (from 38% to 76%). Moreover, adding the blinds helps increase the required illuminance range percentage for a longer period compared to the system without blinds, as shown in Fig. 11. Annual hourly percentage coverage within $UDI_{150\sim750\ lx}$ between September and April increases from around 0% to 70% and above.

3.2. Split louver with different slat reflectivities

The study of various reflectance and specularity factors is notably important for providing guidelines and recommendations for split louver design and control. Therefore, the daylighting performance of the split louver with different surface reflective features (diffused, semi-mirrored, and mirrored) is discussed in this section. Radiance material definitions require reflectivity (red, green and blue), specularity and roughness values to be set. The Radiance reference manual does not provide a precise definition of specularity [45]. Specularity is the ratio between specular and total (specular + diffuse) reflectivity of a material [45]. The ratio of the diffuse-reflected proportion to the total-reflected proportion is known as the shining factor (1 represents a perfect diffuser, and 0 represents an ideal specular reflector)[46,47]. In this work, reflectivity, specularity, and roughness of the three slat surfaces are set to 80%, 0.10, and 0.10 for diffused slats, 80%, 0.80, and 0.05 for semi-mirrored slats; and 100%, 1, and 0 for mirrored slats. The illuminance maps in Fig. 12 show the difference among the three reflectors at the desk level at noontime on three typical days. In addition, annual hourly percentage coverage within $UDI_{150\sim750\ lx}$ is shown in Fig. 13.

The diffused slats reflected the daylight into the deep area on December 21st and into the middle area on March 21st and June 21st with high illuminance coverage percentages within $UDI_{150\sim750\ lx}$ above 94% and undesired daylight uniformity levels below 0.30. The semi-mirrored slats achieved more uniform light distribution up to 0.60 of uniformity level and significant illuminance coverage percentage up to 100% within $UDI_{150\sim750\ lx}$. However, these percentages decrease during the winter months (November to February) because illuminance greater than 750 lx is delivered. On the other hand, the illuminance of the mirrored reflective slats exceeded 1000 lx across the whole space. Table 3 compares the different slat reflectivities that correspond to daylighting performance. The level and distribution of daylighting in the office space were compared using prior illuminance maps

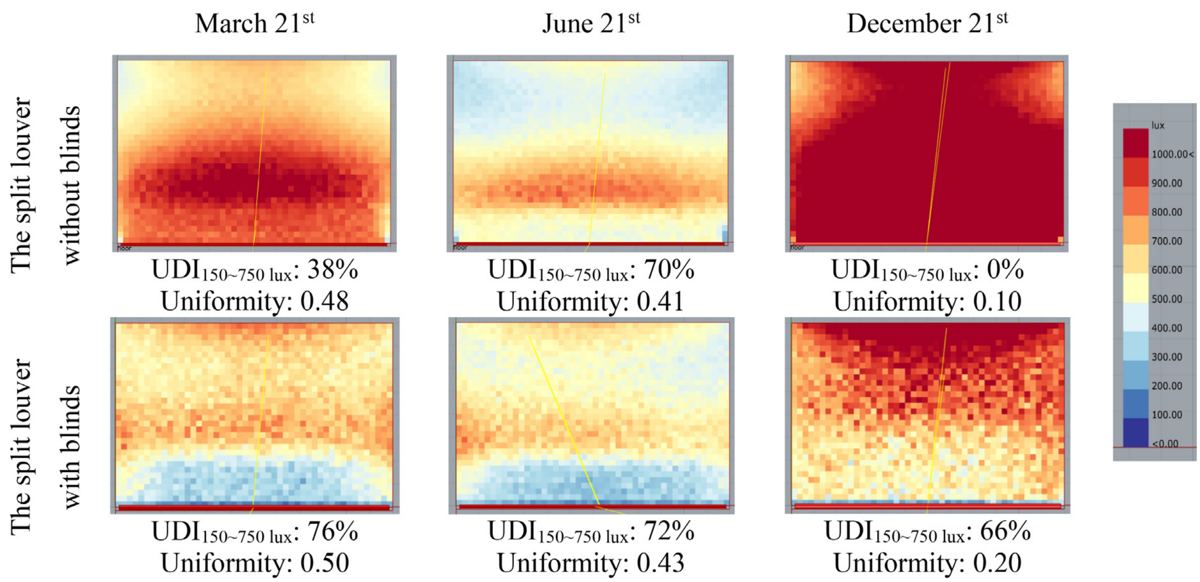
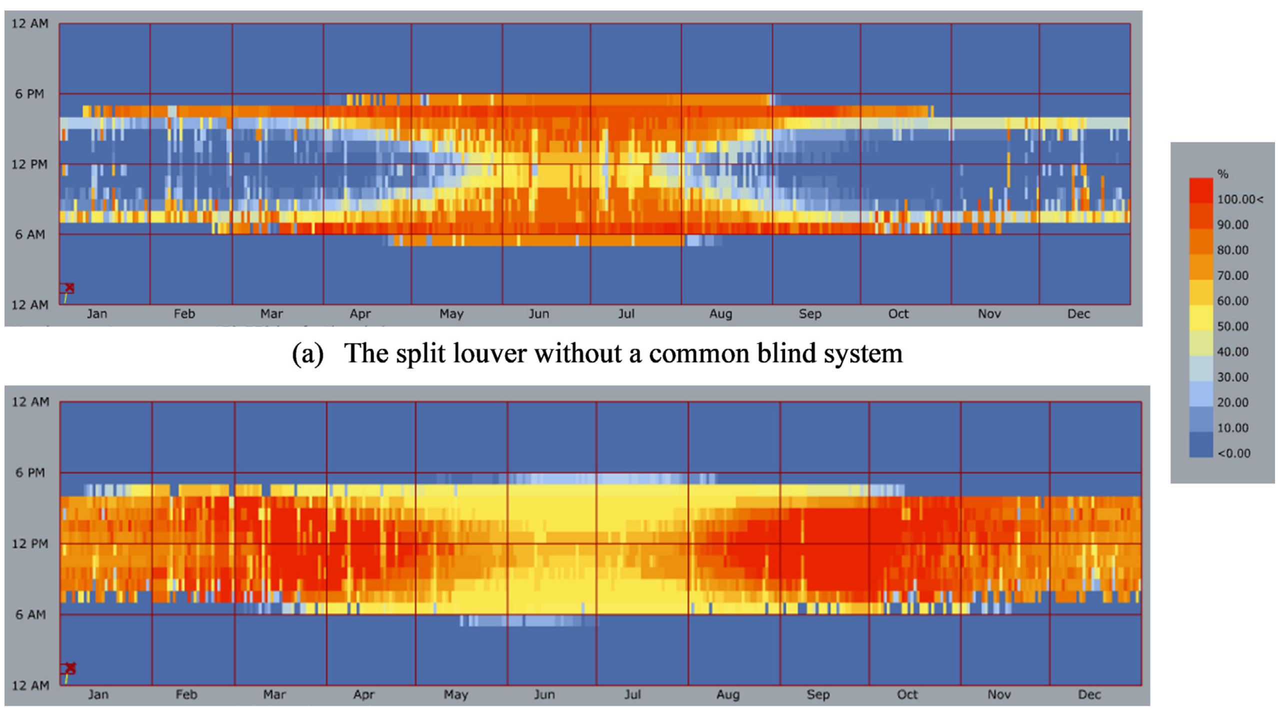


Fig. 10. Illuminance maps for the split louver and blinds system on the three typical days at 12:00 pm.



(a) The split louver without a common blind system

(b) The split louver with a common blind system

Fig. 11. Annual hourly percentage coverage within UDI$_{150\sim750\ \mathrm{lx}}$ showing the blinds performance in the split louver.

and the annual hourly percentage coverage of useful daylight illuminance. The semi-mirrored slats give the highest average percentage of 84% within UDI$_{150\sim750\ \mathrm{lx}}$, although 12% above 750 lx and 4% below 150 lx are also attained. Diffused slats, on the other hand, lead to higher percentages of 32% below 150 lx and lower percentages of 5% above 750 lx as well as 63% within UDI$_{150\sim750\ \mathrm{lx}}$. A coverage percentage of 100% above 750 lx is only obtained in the case of the mirrored slats. The semi-mirrored slats stand for the most uniform daylight distribution, with a 0.47 uniformity, followed by diffused slats, with a 0.25 uniformity. However, the mirrored slats fail to achieve daylight uniformity.

3.3. Split louver with different lower section angles

In this section, the daylighting performance of the split louver based on the previous improvements (parametrically incremental of the upper section, integrated blinds, and semi-mirrored slats) along with different angles of the lower section (−90°, −60°, −30°, and 0°) is also evaluated using floor illuminance maps at the desk level at noontime on three typical days. The illuminance maps in Fig. 14 show the difference between the daylight distribution, coverage range, and uniformity levels. The lower section with varying slat angles performs differently in terms of daylight distri-

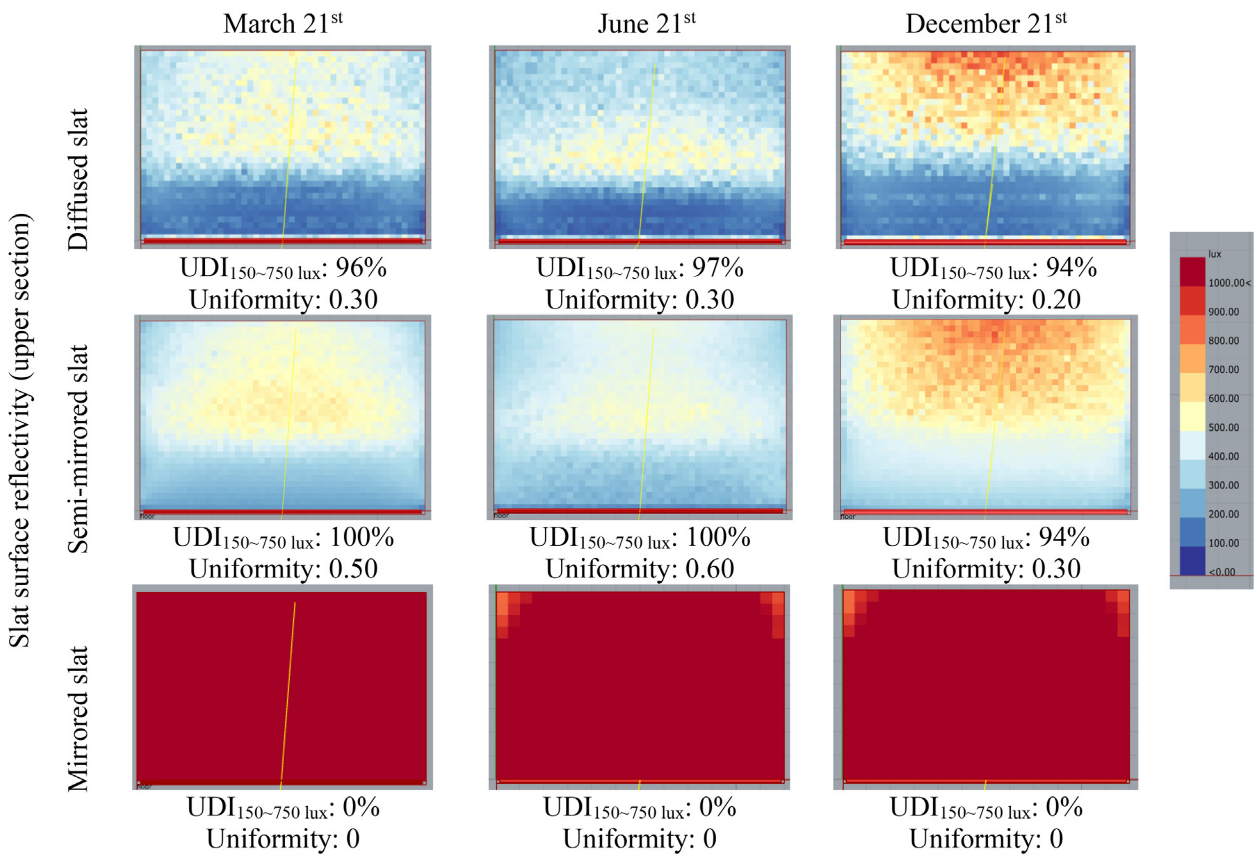


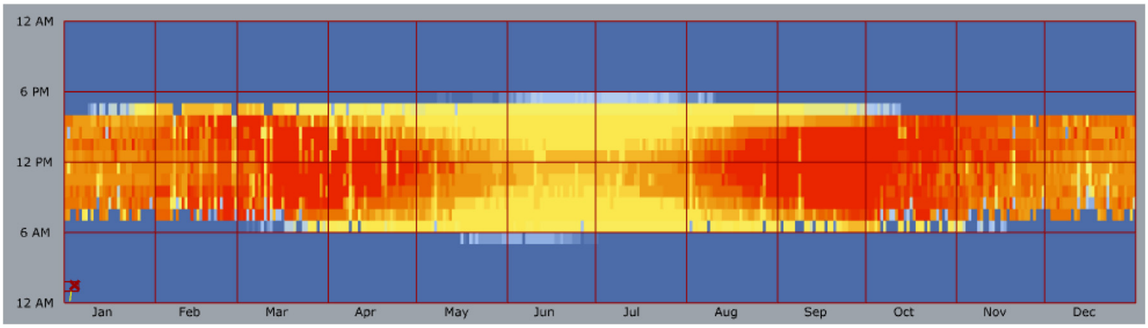
Fig. 12. Illuminance maps for various combinations of the split louver with different slat surface reflective features in the upper section (closed lower section) on three typical days at 12:00 pm.

bution and illuminance levels from one typical day to another. With a lower section angle of −90° and −60°, daylighting near the window can be limited but with unfavorable distribution and levels, particularly on June 21st due to the high solar angle. The improvement in the required $UDI_{150\sim750\ lx}$ and uniformity levels besides cohesive light distribution varies accordingly. For example, on March 21st, the optimum lower section slat angle is −30°, while on June 21st is between 0° and −30° and on December 21st is between −30° and −60°. These optimum slat angles for the lower section on each day achieve 100% coverage within $UDI_{150\sim750\ lx}$ and an acceptable level of uniformity between 0.40 and 0.60. Fig. 15 presents the annual hourly percentage coverage within $UDI_{150\sim750\ lx}$ of split louver with two different states of the lower section (fully closed and fully open) to reveal the general influence of the extreme state of the lower section for the whole year. The entire opening of the lower section increases the illuminance to above 750 lx in the winter season. However, it maintains higher percentage coverage within $UDI_{150\sim750\ lx}$ in the summer season due to higher solar angle .

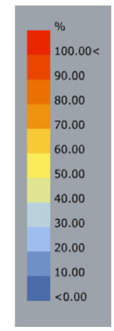
3.4. Split louver with scheduled slat angles

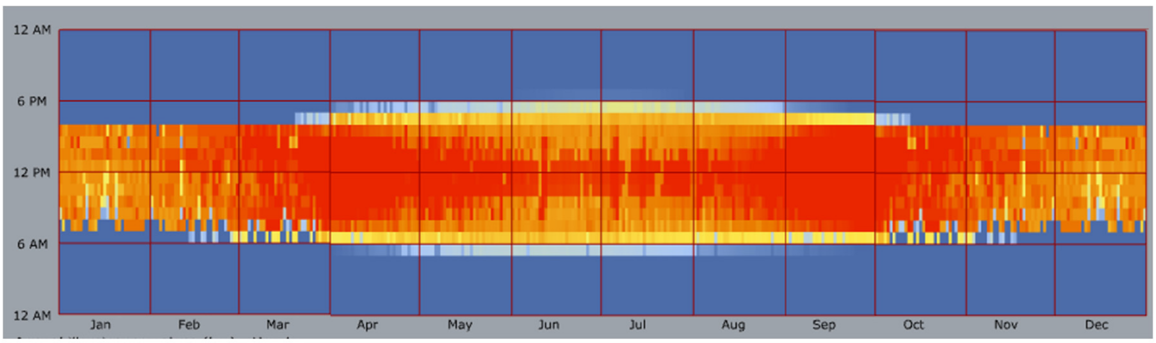
The daylighting performance of the split louver based on the previous improvements (parametrically incremental control of the upper section, integrated blinds, and semi-mirrored slats) along with scheduled slat angles at different times (8:00 am, 10:00 am, and 12:00 pm) on three typical days is demonstrated in Fig. 16. The illuminance maps show that the scheduled split louver offered sufficient daylighting in the front of the room with a more consistent and uniform distribution at most of the time where uniformity values of around 0.60 and $UDI_{150\sim750\ lx}$ of above 95% are achieved at 12:00 pm on all three days. Similarly, at 10:00 am, the proposed system performs efficiently to achieve at least 87% and 0.60 within $UDI_{150\sim750\ lx}$ coverage and uniformity, respectively. In the early morning (e.g., at 8:00 am), higher coverage is achieved in the space (above 86%) on March 21st and June 21st. However, the penetration of the direct sun due to the low solar angle results in only 54% coverage within $UDI_{150\sim750\ lx}$ on December 21st.

When compared to the split louver without the scheduled angle improvement, annual hourly percentage coverage within $UDI_{150\sim750\ lx}$ for the split louver with scheduled slat angle increases by varying percentages depending on season and time of day, see Fig. 17. At noon in most months, a higher percentage within 150–750 lx is achieved between 90% and 100% coverage. The new strategy helps improve the daylight distribution by achieving 100% of the space within $UDI_{150\sim750\ lx}$ in most working hours on March 21st and September 21st. Furthermore, the required illuminance range is achieved throughout the rest of the year, with the lowest percentage occurring in the early morning and late afternoon, but not less than 50%. From both the illuminance maps and annual performance maps, the split louver delivers higher illuminance levels of above 750 lx and inconsistence distribution on the sidewalls in the early morning and late afternoon (particularly in winter months), which is considered a limitation of the scheduled slat angle combinations. Overall, the split louver with different configurations performs better than the conventional single louver. It is also meaningful to investigate other elements such as slat modifications and other innovative glazings for enhancing daylighting performance to meet the requirements during all working hours throughout the year [48,49].

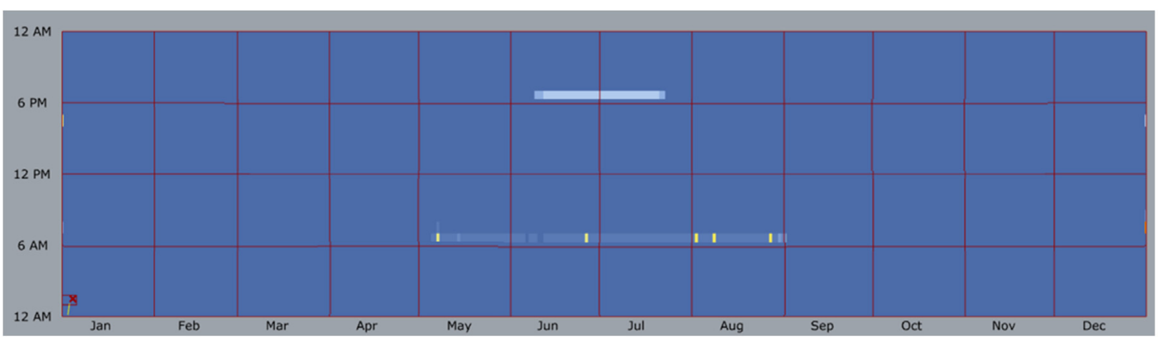


(a) The upper section of the split louver with diffused slats.





(b) The upper section of the split louver with semi-mirrored slats.



(c) The upper section of the split louver with mirrored slats.

Fig. 13. Annual hourly percentage coverage within $UDI_{150\sim750\ lx}$ of the split louver with different slat reflective features in the upper section.

Table 3
Daylighting performance comparison of the three different slat surfaces.

Slat surface type	Slat surface properties			Daylight level and distribution			
	Reflectivity	Specularity	Roughness	Average percentage coverage within $UDI_{150\sim750\ lx}$	Average percentage coverage lower than 150 lx	Average percentage coverage higher than 750 lx	Average uniformity
Diffused slats	80%	0.10	0.10	63%	32%	5%	0.25
Semi-mirrored slats	80%	0.80	0.05	84%	4%	12%	0.46
Mirrored slats	100%	1	0	0%	0%	100%	0

4. Discussion

Glare may become more noticeable as the desktop level illumination rises to 750 lx [33]. Therefore, a glare potential analysis was carried out in order to evaluate the visual comfort inside the space using the proposed split louver system. The term "DGP" stands for Daylight Glare Probability, which has an impact on the office room's occupants' visual comfort [16,50,51]. Glare is defined as the phenomenon whereby bright light sources reduce contrast in the visual field, or where there is a contrast between a bright and dark area, or even where light is reflected from a shiny surface [52]. How discomfort glare is for a person in space depends on the

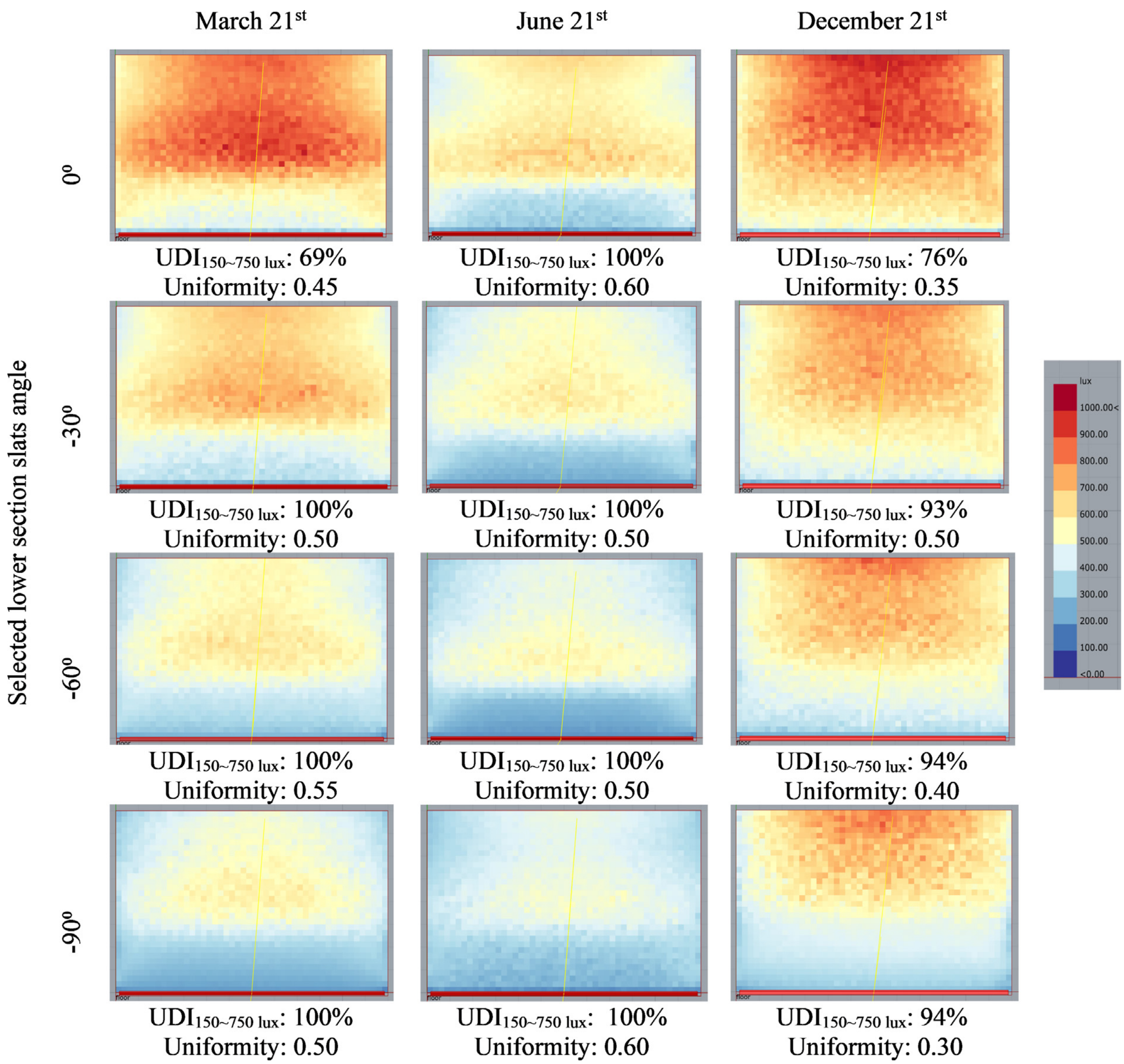


Fig. 14. Illuminance maps for various combinations of different slat angles of the lower section of the split louver and semi-mirrored parametric slat in the upper section on the three typical days at 12:00 pm.

field of view, the background luminance, excessive daylight, and material reflectance [53]. The DGP is chosen as the method for evaluating the glare in order to assess the level of daylight comfort in the indoor space.

The DGP values were divided into four bins: lower than 0.35 is "imperceptible," between 0.35 and 0.40 is "perceptible," between 0.40 and 0.45 is "disturbing," and more than 0.45 is "intolerable" [52]. The DGP was measured at the desk level for the proposed split louver with the scheduled slat angle using the Honeybee Radiance plugin for Grasshopper. Fig. 18 presents the DGP of the split louver with scheduled slat angles at 8:00 am and 12:00 pm. In general, for the three typical dates, the DGP values are in an acceptable range lower than 0.35, which is considered imperceptible glare. On all typical days, the DGP values at 8:00 am are considered as acceptable for visual comfort with values between 0.20 and 0.30, which are classified as imperceptible glare. However, the DGP values at 12:00 pm on March 21st and June 21st are higher than those at 8:00 am, at about 0.27 and 0.20, respectively, which are considered as imperceptible glare. On December 21st, the glare increases to 0.36, which is considered as perceptible glare.

5. Conclusions

Finding a balance between changeable parameters including solar altitude and intensity, window size, and shading device design to maintain the required uniform daylighting coverage at the desktop level is crucial to fulfilling design practicability and occupant visual comfort. The split louver is a significant component of automated building systems for improving overall daylight performance. The current study proposed a split louver system through scheduling parametrically controlled slat angles in both upper and lower sections of the split louver that can redirect sunlight to illuminate the ceiling while regulating daylight spatial distribution and visual comfort in the workstation.

The most appropriate design of the split louver system, including (slat adjustment control, elements integration, and slat materials) in its different sections (upper and lower), was parametrically determined using the parametric tool "Grasshopper" to provide almost preferred daylight performance. The daylighting performance of the parametric split louver design with different systems of the parametric slat angle: unanimous, incremental, fully para-

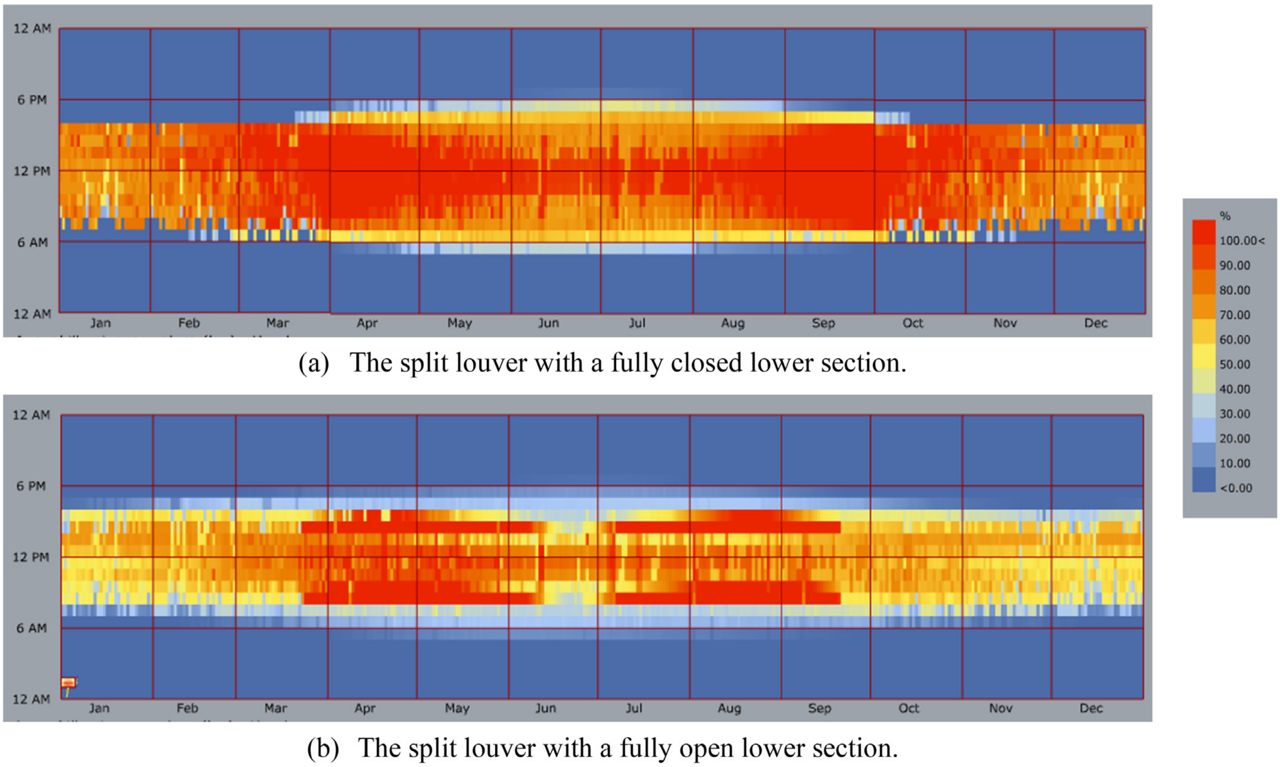


Fig. 15. Annual hourly percentage coverage within $UDI_{150\sim750\ lx}$ of the split louver with two different states of the lower section (fully closed and fully open).

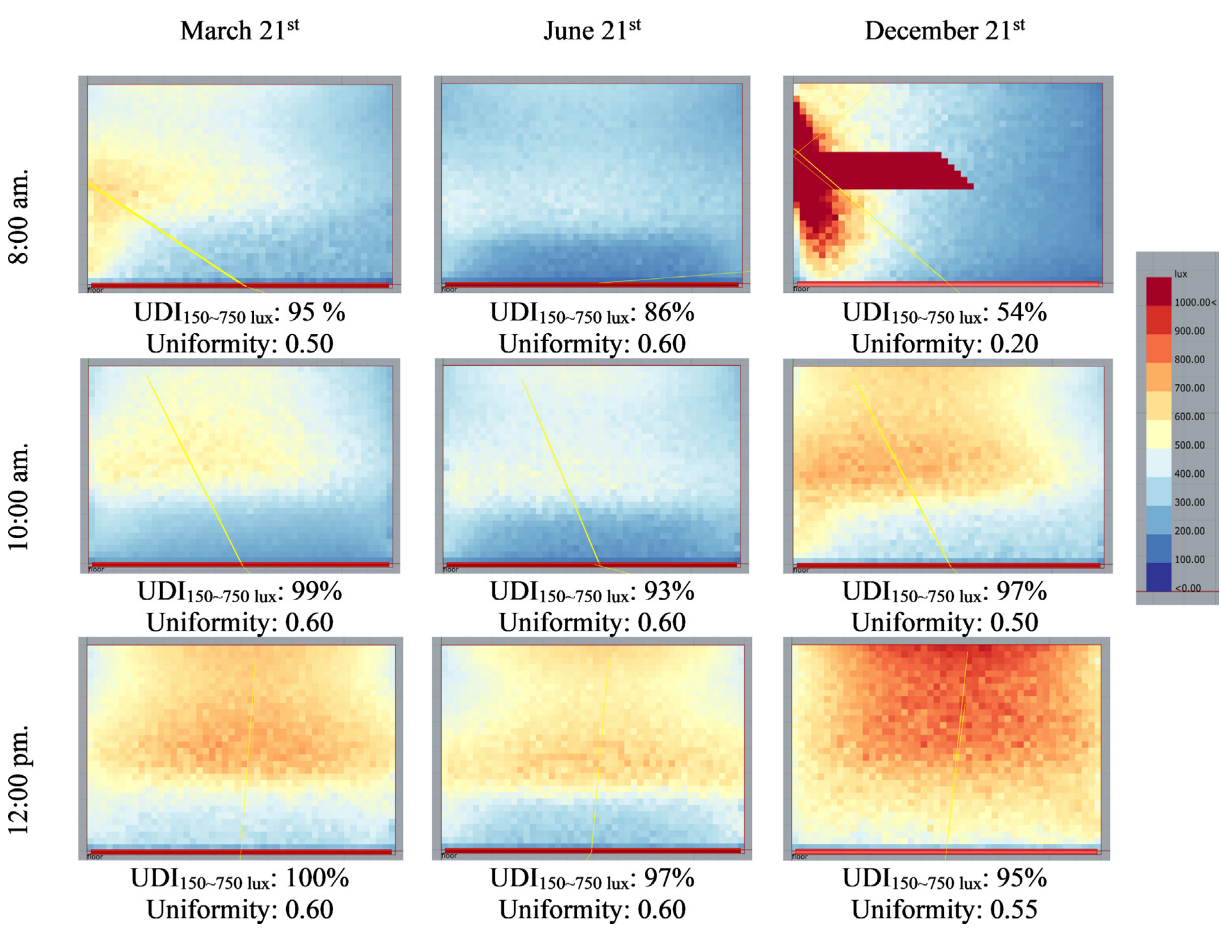


Fig. 16. Daylight distribution maps of the scheduled split louver at different times on three typical days.

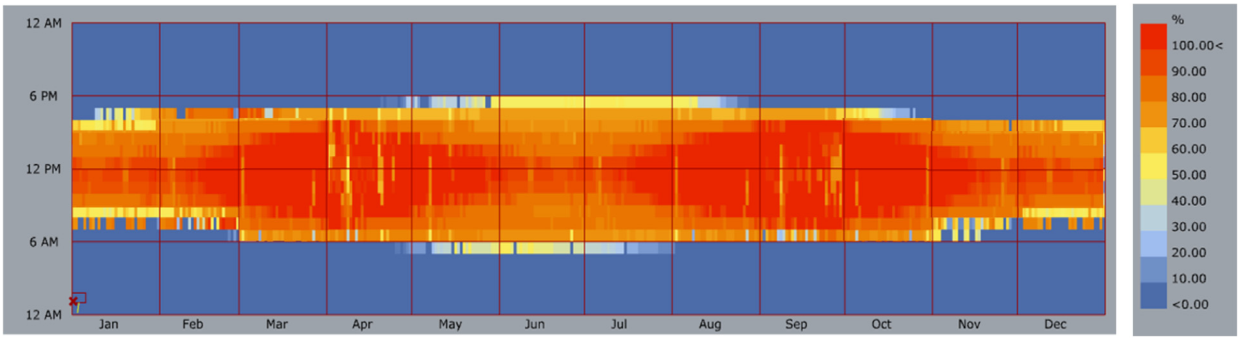


Fig. 17. Annual hourly percentage coverage within $UDI_{150\sim750\ lx}$ for the split louver with scheduled slat angle for both upper and lower sections.

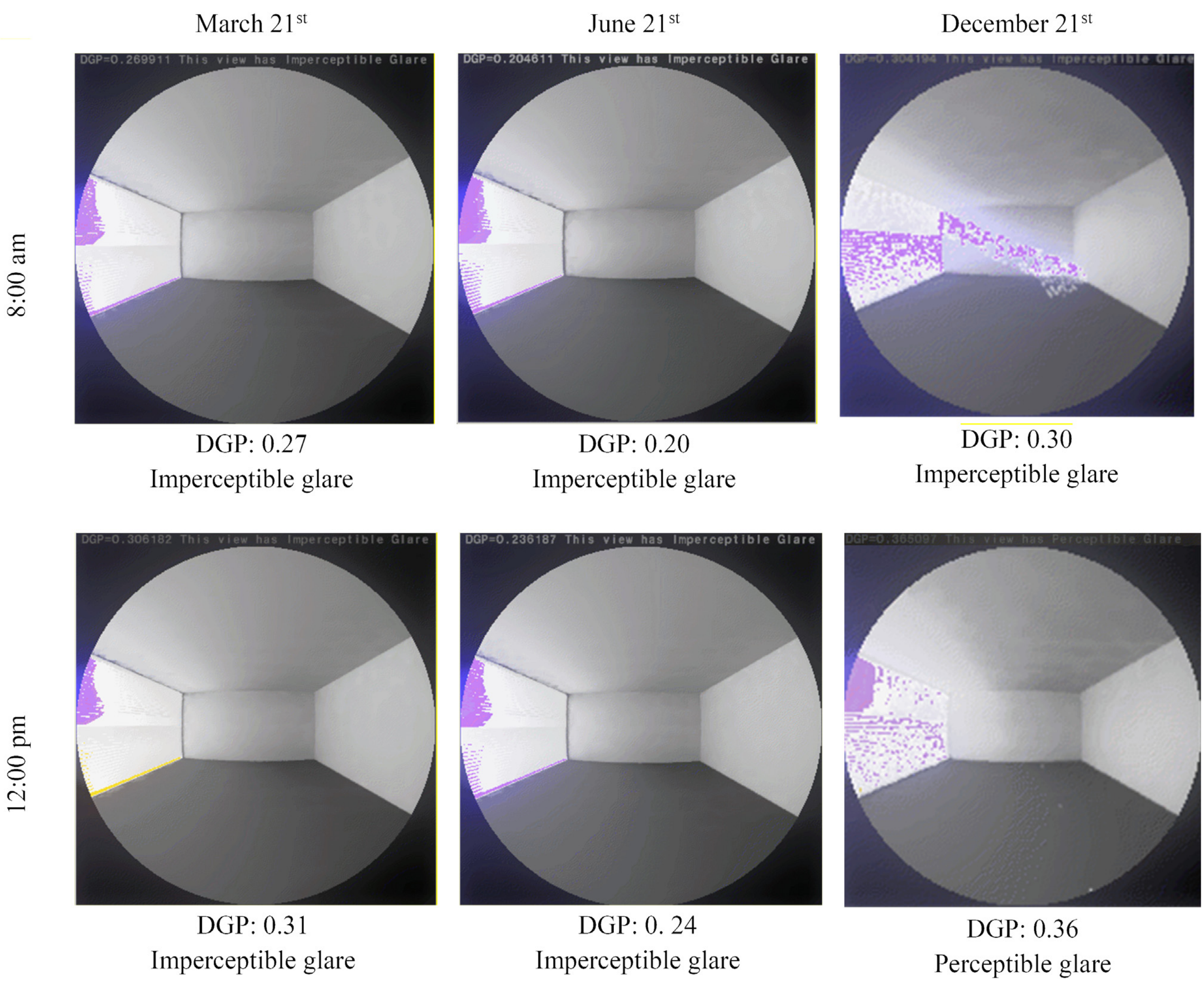


Fig. 18. Daylight glare probability (DGP) of the split louver with scheduled slat angle.

metric, and parametrically incremental angle, is extremely similar regarding the daylight quantity. On the other hand, the daylight distribution is slightly more uniform and consistent in the fully parametric and parametrically incremental angle control cases than in the other two systems. However, the latter is the most practical and applicable system, as it involves just one target and one variable in the automation process. The system with blind integration was tested and used in the rest of the gradual steps of the split louver improvement. The semi-mirrored slat surface achieves adequate illuminance coverage and consistency distribution among the studied slat surface materials. The lower section was also determined to be parametrically managed as solar shading. It can collaborate and schedule with the upper section to meet the multiple daylighting targets, including the visual connection.

The proposal of scheduled split louver angles in both sections presents the most optimal combinations to achieve balanced daylighting levels in both the front and back of the space. Along with a glare-free environment with imperceptible glare indices, an acceptable daylight uniformity level of up to 0.60 is achieved, as well as a high percentage coverage within $UDI_{150\sim750\ lx}$ between 90% and 100% at noon and no less than 50% throughout the rest working hours throughout the year. It can be inferred that a parametrically controlled split louver provides better overall daylighting performance and is considered practical and easy to implement in a real-world setting.

Data availability

Data will be made available on request.

Declaration of Competing Interest

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.

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