

Full Length Article

Optimizing daylighting performance and energy efficiency through the integration of parametric split louvers in office buildings[☆]

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ABSTRACT

The incorporation of split louvers into building systems provides substantial potential for enhancing daylighting performance and, consequently, reducing lighting energy consumption. This study focuses on the critical aspect of determining the optimal positioning of split louver sections to ensure well-distributed daylight in indoor spaces and adding parametric control as a daylight redirection system. This research aims to investigate indoor daylight environments by modifying the relationships and configurations of split louver sections and enhancing the efficiency of daylighting performance through the parametric control of the split louver. In addition, it investigates the energy-saving potentials of using the parametric split louver through the reduction of electric lighting consumption. The study demonstrates that the daylighting performance of the split louver depends upon the status of each section. Specifically, the effects of the upper section of the split louver are predominantly apparent in the rear area of the room, whereas the lower section markedly enhances illumination in the frontal area near windows, particularly during winter months when the lower solar angles. Secondly, the daylighting efficiency of the parametric split louver outperforms that of the conventional single louver in terms of daylight distribution and availability. The efficient daylight performance is evident in the uniform distribution of illuminance within the useful daylight illuminance (UDI) range of 300–500 lux on all typical dates, reaching 44 % and 55 % during the morning and noon, respectively, on March 21st. Additionally, the electric lighting efficiency of the parametric split louver surpasses conventional louver throughout the day for all typical dates, resulting in notable lighting energy savings, with average percentages 69.9 % and 63.5 % on March 21st and December 21st, respectively, while June 21st shows lower efficiency with 43.63 % savings. This study contributes valuable insights for architects and designers seeking to create energy-efficient and well-illuminated indoor environments through the integration of parametric split louver.

1. Introduction

Window systems play a significant role in influencing indoor air quality, thermal comfort, lighting, and overall visual satisfaction, consequently affecting the energy consumption of artificial lighting systems [1,2]. Meeting lighting requirements, which encompass adequate illumination, glare mitigation, and establishing a visual connection with the exterior, is paramount in this context [3]. Shading devices integrated into the window system contribute to meeting these specifications, depending upon detailed design considerations [4].

Conventional louvers often introduce a constant tilt angle for all slats across the window [5]. In many instances, occupants manually adjust

these conventional shades based on personal preferences, which may not align with specific lighting or visual needs [6]. As a result, conventional shading systems are frequently considered ineffective when integrated into daylighting strategies [7]. In addition, both manually and mechanically controlled shading devices typically share the same design across all sections of a window at any given time, regardless of their proposed function or their position within the window's height [7,8]. Therefore, it becomes essential to implement multiple shading control strategies for different sections of a window to serve diverse functions [9] while keeping the window system's control mechanisms as uncomplicated as possible [8]. Some studies have explored the positioning of shading devices within the upper and lower parts of the window [10]. Other research has

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introduced a tripartite approach, segregating the window into top, middle, and bottom sections, each serving daylighting, viewing, and shading purposes [8,11]. Different glazing components, shading types, and control systems may be designated for each window section [12]. Segmenting the window shading mechanism into upper and lower sections is efficient in meeting lighting requirements for glare-free workspaces and optimizing illumination in deep-plan areas. The front workspace should receive not more than 2000 lux, while the back area should not fall below 300 lux [13].

Daylighting systems encompass both static and dynamic devices strategically positioned on or near a building's façade to capture and redirect daylight into the interior, thus enhancing daylighting performance and decreasing energy consumption [14]. However, previous studies on split blinds have primarily focused on manually operated systems, highlighting the need for an automated control approach to enhance their environmental performance [10,15].

The incorporation of daylight-responsive controls ensures that interior spaces consistently achieve acceptable light levels and quality [16]. Moreover, precise configurations of louver slats in relation to the sun's altitude enable the regulation of quantitative light distribution [17] in different building types and shapes [18]. Consequently, achieving an optimal balance between changing factors, including solar altitude, window dimensions, and shading device design, becomes pivotal in providing uniform daylighting coverage at the desktop level, further underscoring its potential for optimizing energy efficiency in lighting [19,20]. In an earlier study, parametric control was suggested and examined for a southern facade with the goal of ensuring more stable and uniform daylight illuminance throughout the day, resulting in a reduction of over 80 % in electricity consumption [21]. Another research effort demonstrated that the implementation of parametric control can yield an average energy saving of 40 % in electric lighting consumption when employed consistently throughout the entire year [19].

This study is of considerable significance in considering the dynamics of daylight patterns within indoor spaces and the performance of the split louver through the investigation of different solar conditions. In addition, it establishes a criterion for model space selection and delves into the initial design considerations of the split louver sections. Furthermore, the examination of parametrically controlled split louvers adds a novel dimension, revealing their impact on both daylight distribution and availability. This exploration is pivotal for architects and designers seeking innovative ways to create well-lit and energy-efficient indoor environments. Additionally, the investigation encompasses not only the foundational aspects of the parametric controlled split louver but also explores diverse combinations to explain their impact on daylighting performance and, subsequently, lighting electricity consumption. In essence, this research advances our understanding of daylight management strategies, offering valuable guidance for sustainable and visually comfortable built environments. It should be noted that the present study is entirely simulation-based and does not include experimental validation. Ongoing work involves developing a physical prototype and conducting empirical testing to validate the control strategy and daylight performance under real-world conditions.

2. Research methodology, tools, and the study location

This section provides a comprehensive overview of the research methodology, tools utilized, and the specific study location. The foundation of the study lies in a case study involving a proposed system integrated into a virtual model of a reference building. Leveraging the capabilities of Rhinoceros and Grasshopper, a visual algorithmic programming language for parametric modeling, the research employs a strategic approach to manipulate design parameters and evaluate daylighting performance. Building upon prior studies demonstrating the potential of parametric methods in generating diverse design options for office buildings in specific geographical locations.

2.1. Methodology

The foundational framework of this study relies on a case study involving the integration of a proposed split louver system into a virtual model of a reference building using parametric modeling. The strategic implementation of parametric modeling enables the manipulation of diverse design parameters and facilitates the subsequent evaluation of daylighting performance. Notably, this methodological approach draws upon prior research that has demonstrated the effectiveness of the parametric method in generating varied design options [21]. Moreover, it extends its scope to encompass the assessment of daylighting performance and lighting electricity consumption, with a particular focus on specific geographical locations.

The parametric system is designed to respond to real-time solar conditions. However, the current study evaluates performance through fixed-time simulations conducted at 9:00 am, 12:00 pm, and 16:00 pm, on key solar dates (solstices and equinox). These time points were selected as representative of typical morning, midday, and afternoon solar conditions.

2.2. Study tools

This approach is demonstrated through the utilization of Rhinoceros and Grasshopper, which represents a visual algorithmic programming language designed specifically for parametric modeling [22]. Within this methodological framework, two critical environmental software plugins, Ladybug and Honeybee, play a pivotal role in parametric modeling and simulation. Ladybug offers access to a comprehensive array of weather data, encompassing solar radiation, shading analysis, and energy estimation [23], from the extensive epw (EnergyPlus Weather) database [22]. Using the EPW weather database, this study builds on an annual hourly data analysis for Alia International Airport in Amman, Jordan.

Meanwhile, Honeybee interfaces with the Radiance [24] and Daysim, lighting simulation tools [22]. Daysim is integrated with the building energy simulation EnergyPlus tool, allowing for comprehensive analyses that include both energy and daylighting considerations [25]. In contrast, Radiance, with the use of photon maps, replicates indirect illumination and handles complex geometries featuring various surfaces and materials [22]. The application of Radiance for climate-based daylight modeling was initially introduced by John Mardaljevic in 1995 [26], with comprehensive documentation and validation of its utility for illuminance calculations [27] under varying sky conditions [28,29]. This all based on the ray-tracing approach and utilised for grid-based solar irradiation and daylighting studies [22]. Honeybee test points with a grid size of 50 cm were used to assess the daylight level and distribution on the Rhinoceros viewport screen at the desktop work plane (80 cm above the floor).

The Grasshopper software was utilized to regulate the proposed design of the split louver parametrically. This involved employing a built-in formula that not only defined the model parameters but also dynamically adjusted to respond to the movement of the sun. This systematic analysis provides in-depth insights into the internal dynamics of daylighting, offering a more thorough understanding of the performance and impacts associated with different configurations of split louvers, particularly those controlled through parametric design. Fig. 1 illustrates the Grasshopper modeling and simulation process, presenting the scripting and the tools employed for daylight and energy analyses. The ambient values in Table 1 are necessary to specify the Radiance parameters of the daylight simulation in order to obtain accurate results and take into account the effects of the model surface materials. It is suggested that high accuracy Radiance parameters be used in order to obtain simulation results for both opaque and highly reflective materials [24].

The lighting in this simulation depends on an auto-dimming implementation with the inclusion of occupancy sensors. Sensor points (sen-

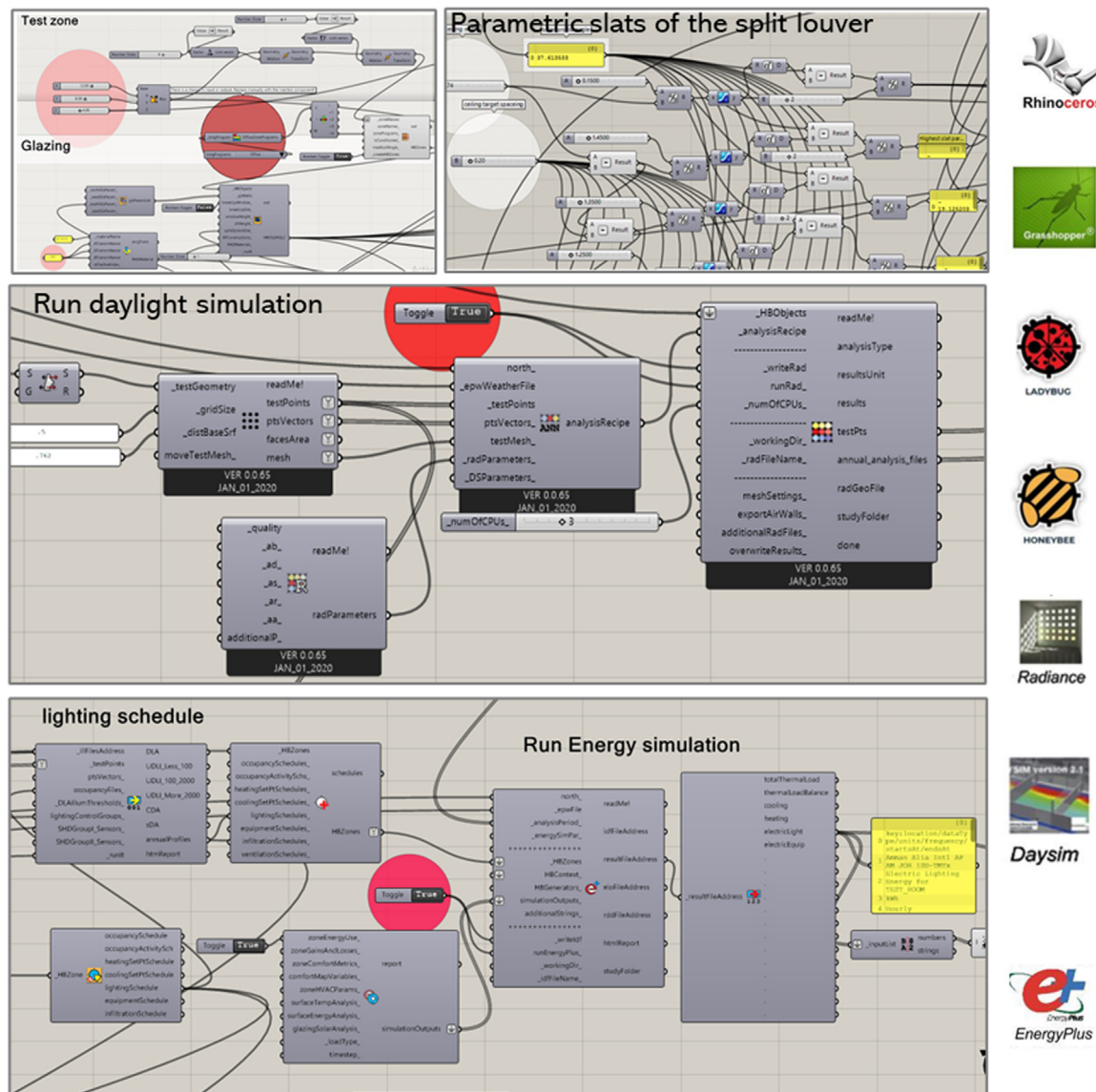


Fig. 1. Grasshopper modeling and simulations (daylight and energy) for the studied model.

Table 1

The radiance settings used in the simulation.

Radiance parameter	Description	Value
-aa	Ambient accuracy	0.2
-ab	Ambient bounces	3
-ad	Ambient divisions	2048
-ar	Ambient resolution	64
-as	Ambient super-samples	2048
-dr	Direct relays	1
-dp	Direct pretest density	256
-lw	Limit weight	0.01
-lr	Limit reflection	6
-st	Specular threshold	0.5

sortPoints_), are placed strategically within the test region in order to detect real-time illuminance on the 50 cm grid with a number of 384 points. The points serve as reference nodes to dynamically control light intensity. The system functions to deliver a target illuminance value, defined as the lighting setpoint (*lightingSetpoint*), of 300 lux by default. If there is sufficient natural lighting available that can reach or exceed this setpoint, the lighting system automatically dims to conserve energy. Further, there is an occupancy sensor programmed to switch off

artificial lighting entirely when the room is unoccupied, so that energy is not wasted. The total lighting power (*lightingPower*) is set at 250 W by default, which serves to reduce energy consumption.

2.3. Study location

This section presents essential insights regarding the case study's location, namely, Amman, Jordan, positioned at a latitude of 31.9° N and a longitude of 35.9° E. Jordan's climate reveals a distinctive pattern, characterized by a relatively wet season from December to April, followed by an extended period of hot and arid conditions throughout the remainder of the year, with the zenith in August [30]. Amman predominantly experiences clear sky conditions, offering optimal daylighting during the day. The average daily solar radiation varies between 4 and 7 kWh/m², and the region has around 300 sunny days annually, leading to an average annual solar radiation range of 1400–2300 kWh/m² [31].

The building sector, for instance, consumes approximately 60 % of the total electricity in Jordan [32]. In particular, new constructions in Amman often feature extensive openings and fully glazed facades, which, in turn, escalate the dependence on air conditioning systems due to the challenging climate. It is against this backdrop that there has been a noticeable surge in awareness concerning the importance of sus-

tainable practices and the implementation of energy-efficient building regulations in Amman.

To comprehend the underlying hypothesis of our study, three distinct typical dates were considered, spanning from summer to winter (March 21st, June 21st, and December 21st). During the winter season, it is worth noting that the intensity of insolation decreases. This reduction in solar intensity is primarily due to the sun's rays assuming a more steep angle, resulting in the distribution of sunlight across a larger surface area. Consequently, the amount of energy delivered per unit area is notably reduced. For instance, precisely at noon on December 21st, the recorded maximum solar intensity amounted to 580 W/m^2 . To put this into perspective, this intensity level is approximately close to the solar intensity observed at 9:00 on September 21st (572 W/m^2) and at 8:00 on June 21st (507 W/m^2). Considering the significant variations in solar radiation throughout the year in Amman, it becomes evident how these climatic factors play a crucial role in the energy dimensions.

3. Model description and grasshopper-based parametric modeling

3.1. The benchmark model and the solar settings

A case study was conducted within a virtual office environment in Amman, Jordan, to assess the daylighting performance of the split lou-

ver system. The base space model dimensions are 12 m in length, 8 m in width, and 4 m in height. The split louver divides the space into two sections. The south window utilizes 6 mm single glazing with an 88 % visual transmittance. To ensure optimal daylighting in modern high-rise open-plan offices, the design follows the widely accepted guideline of 2.5 H to 3.6 H (2.5 to 3.6 times the window's height) for shading design [33]. The virtual model simulates an office room with an 8-meter depth and a 95 % window-to-wall ratio [34]. Therefore, the split louver system is designed with two sections: an upper section measuring 1.50 m and a lower section measuring 2.5 m. The floor is a typical grey color with an 18 % reflectivity, while the walls and ceiling are finished with matte white, with a reflectivity of approximately 80 % [35]. The daylight levels and distribution at the desktop work plane, positioned 80 cm above the floor, were assessed within the Rhinoceros viewport screen. Honeybee test points spaced 50 cm apart measured the illuminance at each point. The cumulative illuminance data from these points was used to calculate the average illuminance percentage for the entire area.

The daylight patterns across four typical days within the space of the benchmark model, regardless of the shading system employed, are illustrated in Fig. 2. The maps representing sunlight hours for the model space on these days reveal the proportion of time when direct sunlight enters the area, influenced by the sun's altitude. The chosen time corresponds to the equinox (March 21st and September 21st), when the

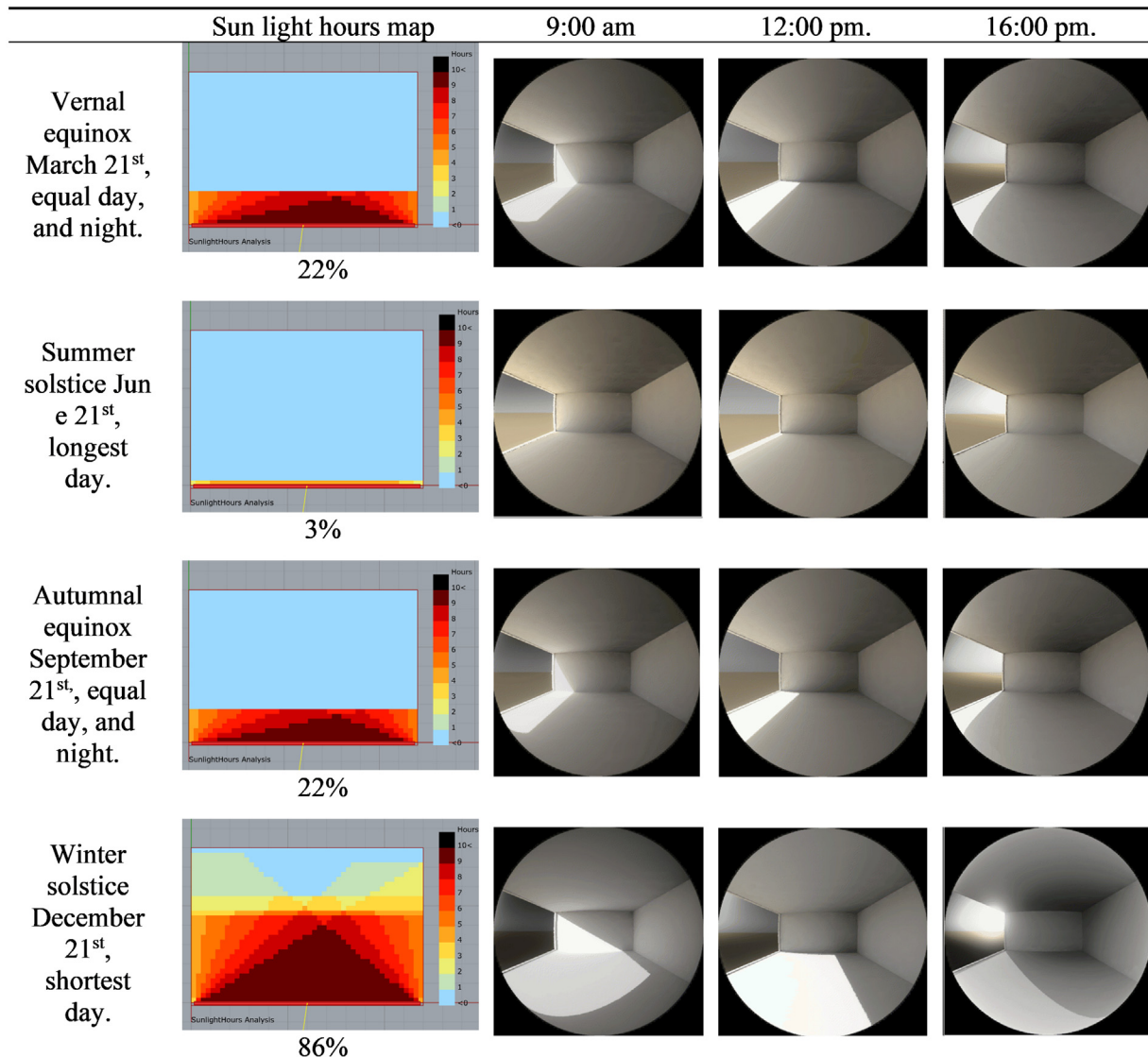


Fig. 2. Maps of sunlight hours in the benchmark model space on four typical days in Amman, Jordan.

sun's beams have a moderate inclination between the summer and winter solstices. Subsequently, December 21st and June 21st were selected to illustrate the system's adaptability and effectiveness at various times and days throughout the year, covering all possible sun exposure scenarios. For instance, during the autumn equinox on September 21st and the vernal equinox on March 21st, when day and night have equal duration, direct sunlight only encompasses 22 % of the space. In contrast, on December 21st, the winter solstice, when daylight hours are at their shortest, direct sunlight covers over 80 % of the room. The summer solstice, occurring on June 21st, represents the longest day of the year, where the sun is positioned vertically at zenith time. This results in minimal penetration of light due to the sun's steep angle, rendering the room relatively dim, with sunlight accounting for a mere 3 % of the space. It is worth noting that the sun's position in the Skydome plays a substantial role in the distribution of daylight within the space [36]. A well-lit area is consistently observed near the wall's left side during late hours and similarly on the right side in the morning.

Considering the placement of the proposed split louver on the south façade, an examination of solar radiation levels on three specific days: March 21st, June 21st, and December 21st, representing the equinox, maximum (summer solstice), and minimum (winter solstice) periods of sunlight throughout the year. The amount of radiation, expressed in Wh/m^2 , focuses on the tested model, with particular emphasis on the south façade, as depicted in Fig. 3. Solar radiation reaching the vertical

surface exhibits variations based on solar angles. At noon, the highest level of radiation, around 800 Wh/m^2 , occurs on December 21st, while the lowest, around 770 Wh/m^2 , is observed on June 21st. The model used for this experiment features a substantial glazing ratio, ensuring significant sun coverage across all seasons.

3.2. The proposed design of the two-section split louver system

The proposed split louver system is installed on the model's glazed south façade. This split louver consists of two sections designed to manage daylighting levels and distribution throughout the entire space [37,38]. The upper and lower sections work together to respond to the sun's movement and intensity. The distinct tilt angles of the slats in each section serve specific purposes: the lower section's slats are tilted outward to reduce glare and overheating, while the upper section's slats are angled inward to direct light toward the ceiling and deeper into the room, thereby enhancing the overall light levels.

The upper section's slats redirect direct sunlight toward the ceiling of the deep-plan office room, effectively turning the illuminated ceiling into a light source for the space. Meanwhile, the slats in the lower section are responsible for controlling the level of illumination near the window. The proposed split louver with two sections with the upper section spans 1.5 m, while the lower section extends to 2.5 m, see Fig. 4. The slats are narrow, measuring 12 cm in width for both sections, with 15 slats in the upper section and 23 in the lower section. These dimensions were chosen based on commercial shades' specifications. The slats reflectance values are 80 % diffuse reflection on the front and non-reflective on the back for the upper section, and 30 % diffuse reflection on the front and non-reflective on the back for the lower section. The slat angle is defined as the angle formed between the horizontal plane and the slat plane, with a zero-degree angle for horizontal slats, a negative angle for slats tilted outward, and a positive angle for slats tilted inward. The highest slat is configured to target the point nearest to the window, whereas the lowest slats in the upper section are adjusted with positive angles to parametrically target the deepest corner of the ceiling, minimizing the risk of glare.

3.3. Parametric sunlight redirection system using the split louver sections

The fundamental idea of this system revolves around redirecting incoming sunlight towards the ceiling to serve as a diffused light source for the room, all achieved through precise parametric control. The slats are systematically angled, each having a specific rotation angle to reflect light onto designated points on the ceiling. These slats adjust their positions in response to the sun's movement, maintaining a constant focus on these predetermined targets on the ceiling.

The design takes into account the solar profile angle and the specific target locations on the ceiling, considering both horizontal and vertical distances based on mathematical equations. This entire process is executed parametrically through Grasshopper and responds to changes in the date and time. To illustrate, altering the date and time within Grasshopper triggers calculations connecting the solar profile angle with each target point on the ceiling for every slat. Notably, the first slat in the upper section is adjusted to focus on the deepest ceiling point. Each slat is parametrically angled, rotating in alignment with the sun's movement, and each possesses a distinct angle to effectively direct incident light to specific target areas on the ceiling, serving as a dynamic source of interior illumination. Furthermore, these target locations can be dynamically adjusted based on the room's depth to ensure comprehensive and adaptable light distribution.

As defined by the works of [37] provides a critical insight into the intricate world of solar louver design. Specifically, it enables the precise determination of the slat angle in the upper section. The slat angle, denoted as β , plays a pivotal role in optimizing the performance of the solar louver. It directly affects how incident sunlight interacts with the louver system and, consequently, impacts the distribution of

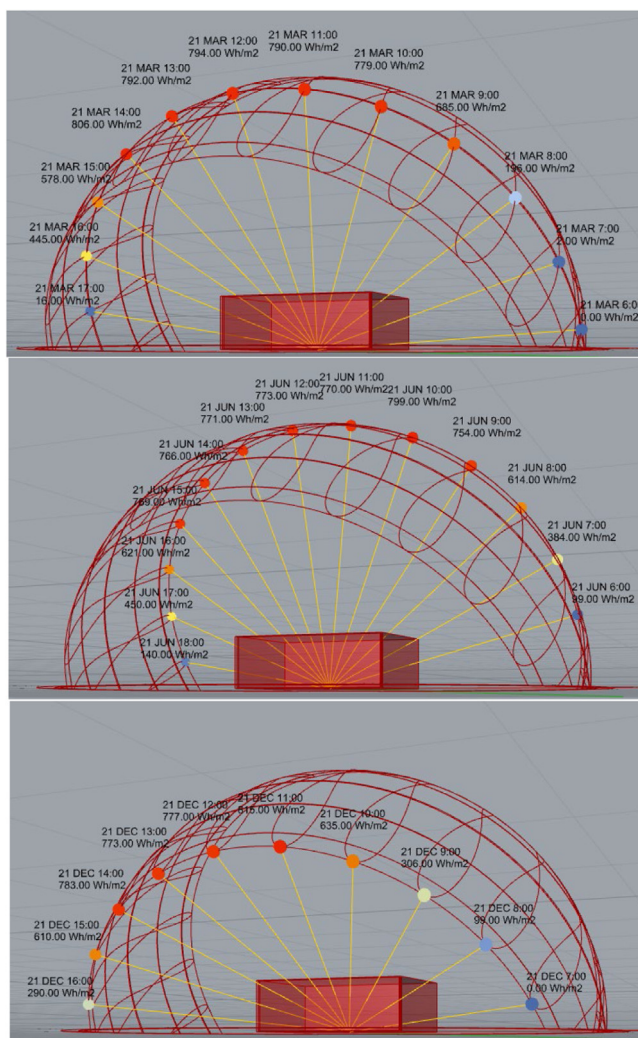
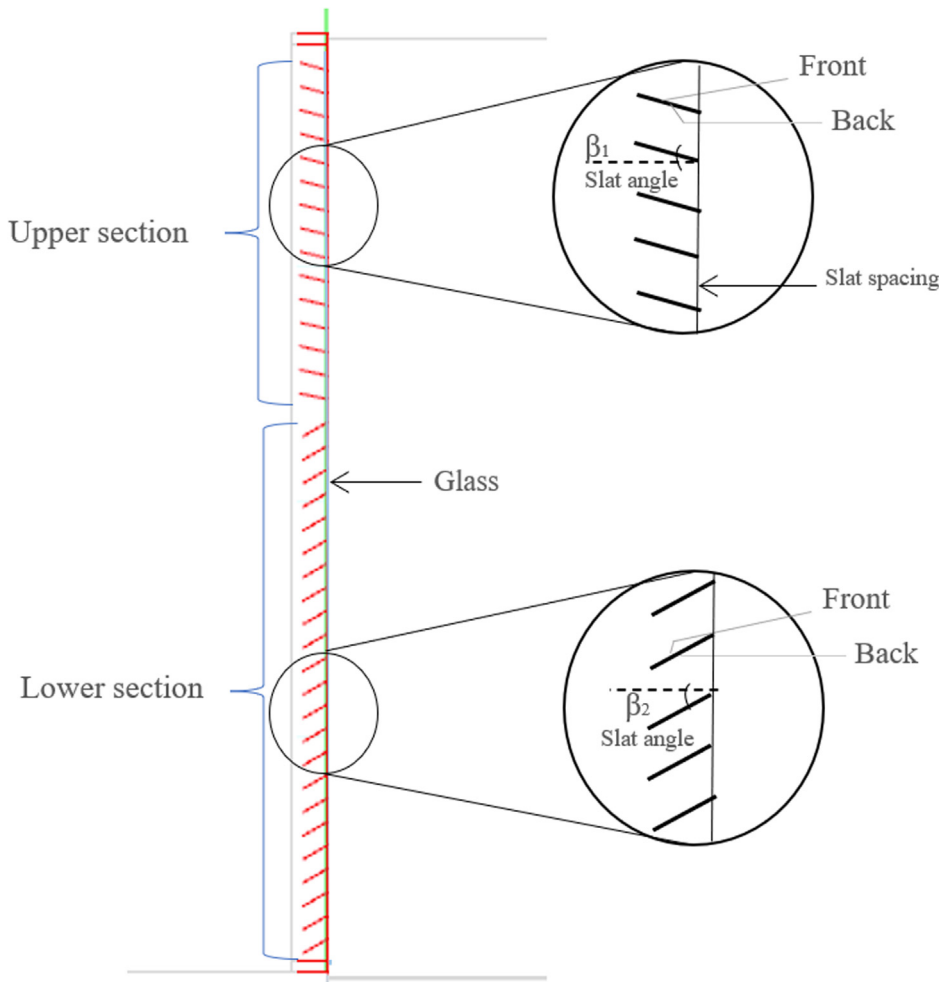


Fig. 3. Sun position and solar radiation on the south façade in Amman, Jordan, on March 21st, June 21st, and December 21st.

Fig. 4. The split louver design.



daylight within the architectural space. This mechanism results in reflected light forming a light source to illuminate the space, ensuring uniform distribution of reflected light across the workspace [14]. The pattern of light reflection on the ceiling follows a predictable sequence: the highest slat directs light toward the nearest target, the subsequent slat guides light to the subsequent target, and so forth. The three-dimensional model perspective with ray tracing visualization is presented in Fig. 5 (left). The critical angle, known as the cut-off angle, represents the point beyond which direct sunlight is not allowed to pass through the slats. In the previous research [14], the configuration of slats, including their quantity and spacing, was adapted to accommodate variations in sun altitude and maintain the desired cut-off angles [14,39].

Fig. 5. (right) visually demonstrates how the rotatable slats redirect sunlight to the ceiling at specified angles. The parametric process for adjusting the slat angles of the upper section of the split louver takes into account several factors, including the solar profile angle (Ω) and the vertical and horizontal distances (V and U) between a slat and a target point on the ceiling by controlling the slat tilt angle (β) parametrically. It's important to note that the solar profile angle (Ω) is influenced by factors such as surface orientation, the sun's altitude, and azimuth [40], which collectively determine the vertical angle between the window's normal and the sun's beams perpendicular to the window plane [41]. The slat angle (β) in the upper section is determined using the formula [37]:

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

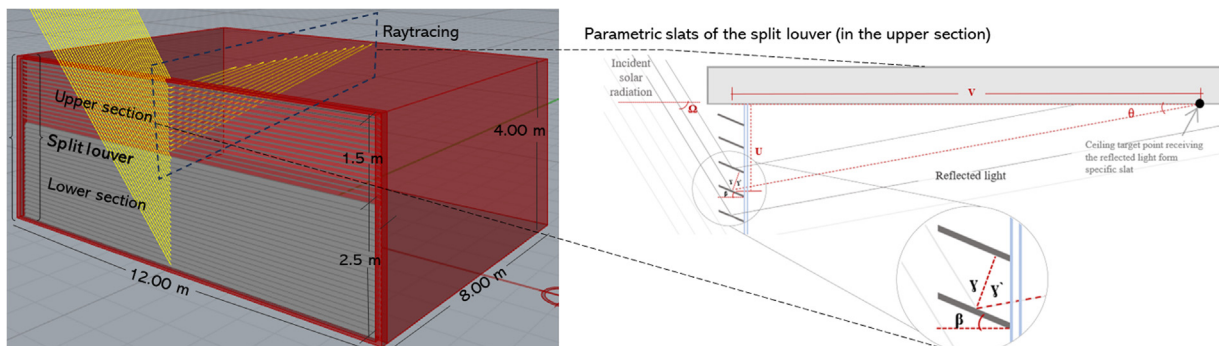


Fig. 5. (left) Three-dimensional model ray tracing (right) cross-sectional view of rotating slats of the parametric louver design sunlight.

Where:

Ω is the solar profile angle ($^{\circ}$),

U is the vertical distance between a slat and the ceiling (cm),

V is the horizontal distance between a slat and a point on the ceiling (cm).

The pseudocode in Fig. 6 represents a structured algorithm for calculating and adjusting the angle of sunlight redirection slats based on solar profile angles, time steps, and geometric parameters to optimize indoor daylight distribution.

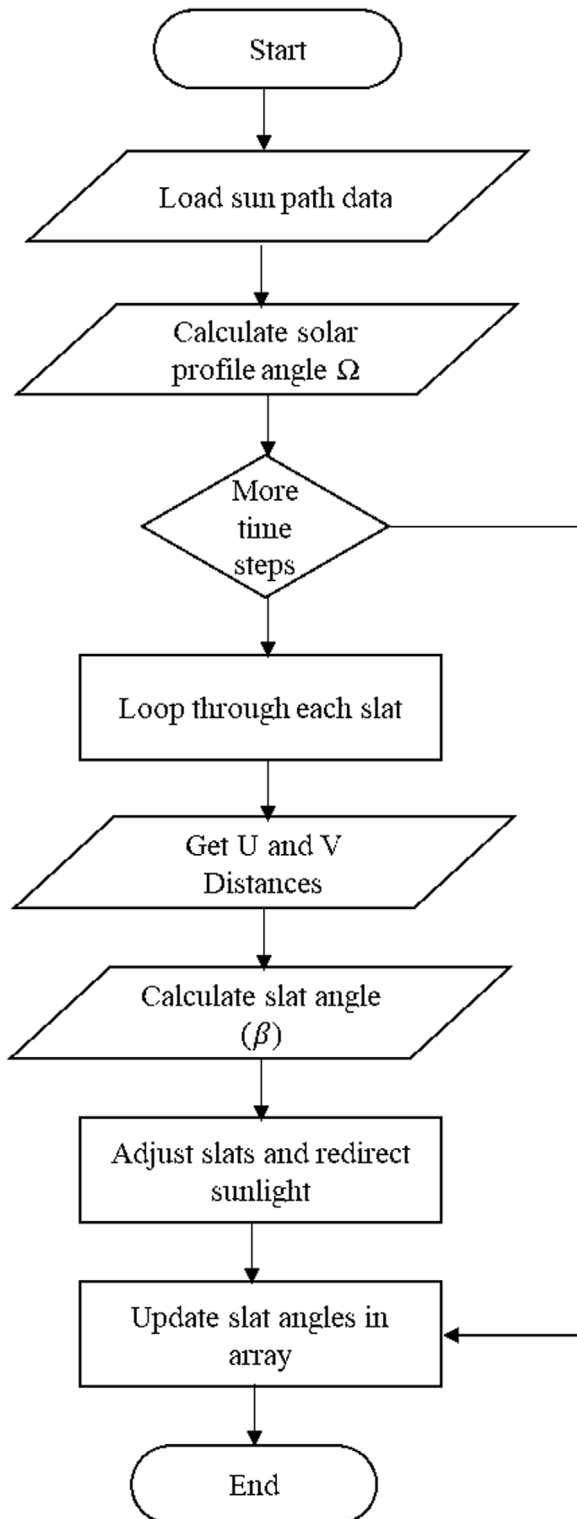


Fig. 6. Pseudocode for sunlight redirection using parametric louver control.

4. Comparison studies and results

The section demonstrates a sequential analysis conducted for the integrated assessment of daylight performance and lighting energy efficiency in the model space employing split louver systems. In-depth analyses were carried out to assess the internal daylighting performance of the foundational model, employing essential split louver principles and configurations. These investigations encompassed:

- Independent assessment of daylighting performance in the upper and lower sections of the split louver.
- A thorough examination of conventional single louver and parametric split louver in terms of daylight distribution.
- Extensive assessments of both conventional and parametric split louver in relation to electric lighting consumption targeting useful daylight illuminance (UDI) levels of 300–500 lx and below DGP 0.35.

4.1. The daylighting performance of the upper and lower sections of the split louver

An examination was conducted to understand how the upper and lower sections of the split louver perform under different configurations, including fully closed and fully opened states, in order to assess their impact on daylight distribution within the space and any potential sunlight penetration. As the performance of the split louver in terms of daylighting varies depending on the configuration of each section, an analysis is conducted by altering the state of each section to gain a more comprehensive understanding of individual performance. The sectional illuminance distribution graphs in Fig. 7 illustrate different scenarios with varying upper and lower section configurations. On all typical days, opening the upper section has a more pronounced impact on the rear area of the space, while in contrast, particularly in December, the front area near the window is notably more illuminated when the lower section is open. These findings align with earlier research and underscore the notion that the upper and lower sections exert differing effects on daylight distribution in the front and rear of the space. Furthermore, the lower percentages of illuminance observed on December 21st reinforce the idea that the lower section wields greater influence when the sun is at a lower angle, which resulted in excessive illuminance from 500 lx up to 1200 lx.

4.2. The daylighting performance of parametric slat angles and conventional single louver

4.2.1. Daylight availability analysis

This section investigates the daylight performance for the parametrically controlled split louver in terms of daylighting distribution and availability, as mentioned earlier, for three typical days at noon. An assessment of the daylight performance of the parametric split louver in terms of daylight distribution is studied and presented in raytracing and illuminance maps, as illustrated in Fig. 8. The Radiance maps illustrate variations in the brightness patches on the ceiling, influencing the uniformity of daylight distribution throughout the space. Investigating daylight distribution patterns shows noteworthy disparities across the three typical days. Daylight uniformity greatly influences the workspace, while the interplay between slats, sunlight, and building orientation uniquely demonstrates the three typical days. Moreover, in December, when the steep sun's angle exposes slat surfaces to direct sunlight. This configuration results in a modest parametric tilt angle, producing a substantial amount of reflected light on the ceiling. Conversely, June presents a distinctive scenario due to the high solar angle relating to the south window. These observations give insights into the intricate and seasonally nuanced interplay of slat angles.

In order to evaluate the daylight performance concerning daylight availability, a comparison is presented between the conventional louver and the parametric split louver in Fig. 9 and Fig. 10. The radiance maps

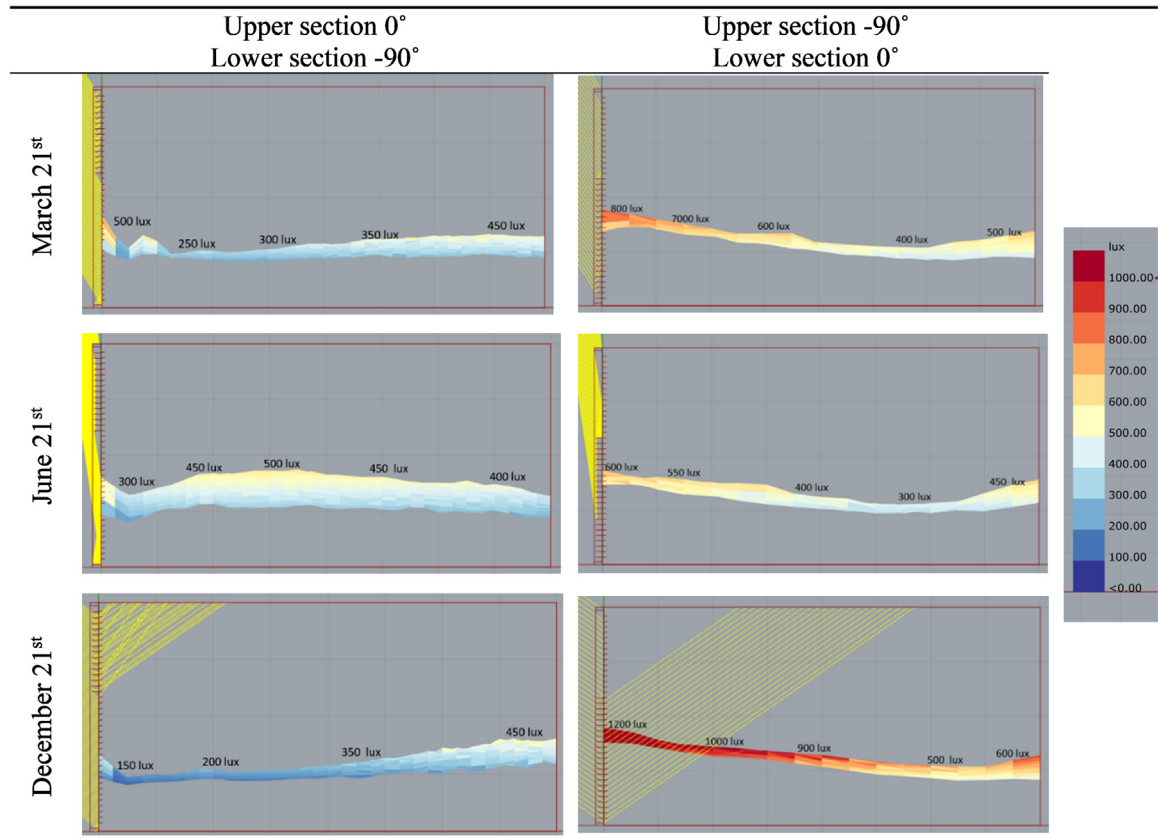


Fig. 7. Daylight levels along the midline of the space at 12:00 on three typical days.

provide a detailed assessment of daylight performance, specifically focusing on achieving UDI within the prescribed target range of 300–500 lx. At noon (12:00) and 9:00 am, the conventional single louver consistently shows no achievement daylight within $UDI_{300-500\text{ lx}}$, while the parametric louver percentages reach 52% at noon and 55% at 9:00 am on March 21st. When considering illuminance levels above 300 lx, the conventional louver consistently reaches 100% for all typical dates in the two studied hours of the day (9:00 am and 12:00 pm), showing over-illumination. However, the parametric split louver presents more subtle results, with percentages ranging from 80% to 90% on March 21st at 9:00 am and 12:00 pm, respectively. This highlights the parametric split louver's ability to dynamically respond to different daylight conditions, achieving more balanced and optimized illuminance levels within the specified target range.

It might be interpreted that the conventional single louver outperforms the parametric system in terms of electrical energy savings throughout the year. However, it falls short of meeting other crucial criteria related to visual comfort. Specifically, the conventional system fails to achieve high UDI at 300 lx and even exceeds 1000 lx, resulting in glare during various times on the three specified dates.

As highlighted in the study [38], the lower section angle of the split louver system is adjusted dynamically based on the solar profile angle throughout the year. During the summer months, when the solar profile angle is higher, the lower section angle is set to a more horizontal position to reduce direct sunlight penetration. In contrast, during winter months, the slats are rotated to allow more sunlight penetration due to lower solar profile angles. The angle of the lower section is calculated using a mathematical formula, with the range of angles set between 0° and 45° to avoid glare and ensure that the workstation receives adequate natural light while preserving the visual connection to the outside environment. This dynamic adjustment of the lower section, based on solar changes, not only enhances daylighting performance but also con-

tributes to occupant comfort by reducing glare and maintaining an open visual connection. The strategy involves calculating the appropriate slat angle to balance both light quality and user experience in different seasons.

4.2.2. Daylight glare analysis

To maximise light distribution deep into the space, sunlight in the upper area is redirected towards the interior at a particular angle. The elevation angles of the sun must be taken into account when designing the shading components for the split louver [17,21]. The sun shines at a lower angle in the winter than it does in the summer, when it is at a much higher angle. When designing the slat angle of the shade system, high summer sunlight must be reflected at a higher angle and vice versa, while low winter sunlight is deflected at a lower angle into the deep part of the room. To reduce direct glare, the lowest slat in the upper section is angled upward slightly [9,17,42]. Reduced contrast in a visual field due to bright light sources, a contrast between a bright and dark area, or even light reflected from a polished surface is known as glare. A popular metric for evaluating daylight glare in modern building design is Direct glare probability (DGP). One of the main climate-based daylighting measures used to assess daylight quality is DGP [43]. DGP is evaluated while standing, about 1.70 m above the ground, at eye level and facing the viewer.

Fig. 11 shows the comparison of DGP values for the conventional louver and split louver for the three typical dates at noon time. The comparison shows that the parametric split louver consistently outperformed the conventional single louver in glare reduction across all dates. On March 21st and June 21st, it experienced imperceptible glare levels, while the conventional louver experienced perceptible glare. The difference was most significant on December 21st, where the conventional louver results in disturbing glare, compared to the parametric louver's maintained imperceptible glare.

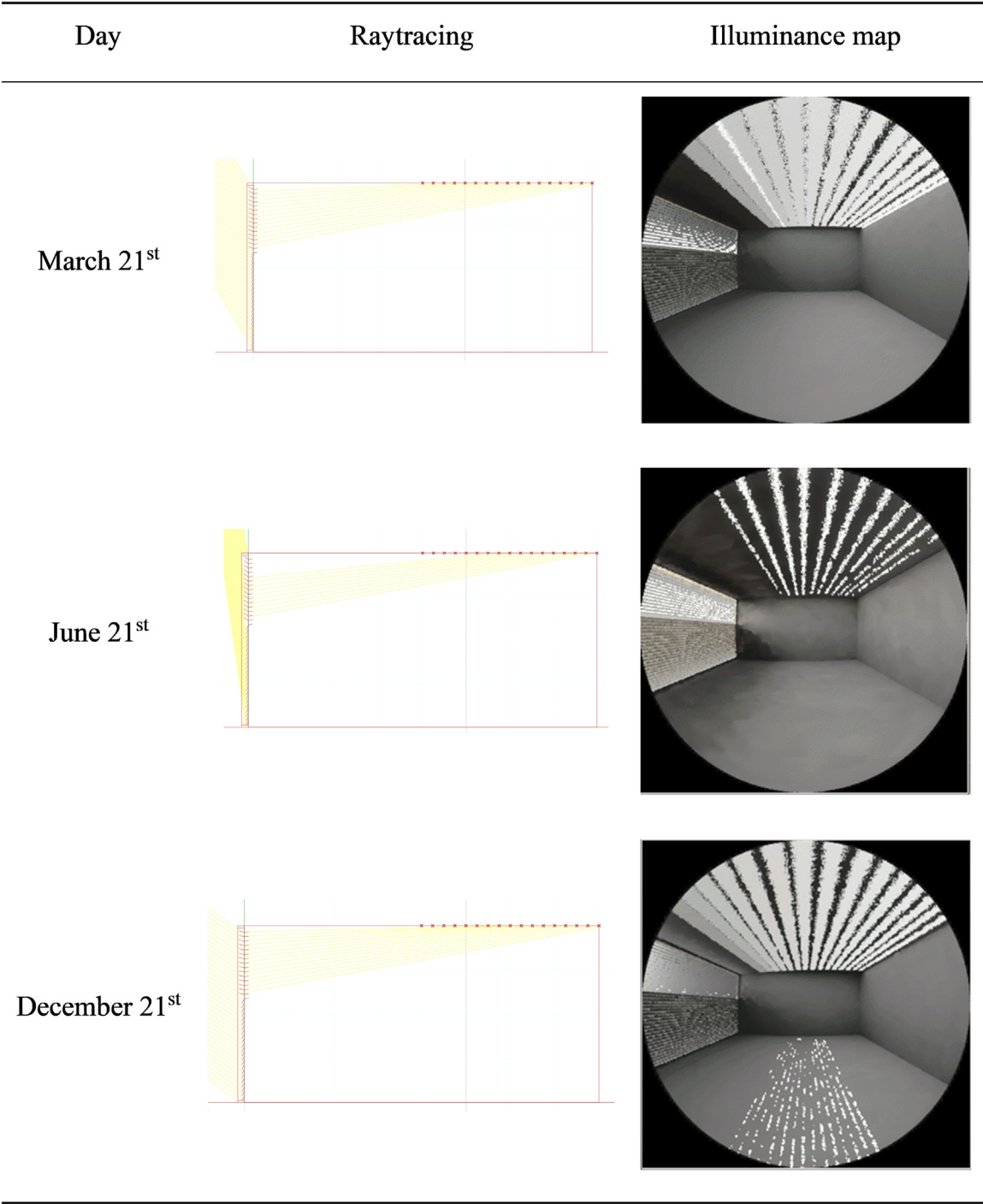


Fig. 8. Reflected light distribution on the ceiling at noon for parametric slat control in Amman, Jordan, on three typical days.

4.3. Lighting energy performance of the parametric split louver and conventional single louver

To examine the energy efficiency of the parametric split louver, the comparison analysis is conducted on the electric lighting energy consumption of the parametric split louver-equipped window system throughout the year. The simulation takes into account the necessity of using artificial lighting to supplement insufficient daylight, aiming to achieve the recommended 300–500 lx with minimum risk of glare. The lighting systems with a default lighting power of 250 W, managed by a schedule and occupancy control, utilizing auto-dimming functionality along with switch-off occupancy and daylight sensors. The investiga-

tion involved assessing the percentages of daylight coverage at various illuminance thresholds exceeding 300 lx without considering a maximum threshold of 500 lx. This analysis was conducted during working hours. Additionally, the study examined the electric light required to supplement the illumination needs beyond 300 lx within the office room.

Ensuring optimal visual comfort within the 300–500 lx range while avoiding glare and use of electric lighting required to achieve illuminance levels below 300 lx inside the room. Consequently, an analysis was conducted for three typical dates during working hours, specifically from 8:00 am. to 17:00 pm., to assess the lighting needs for maintaining an illuminance environment within the specified range.

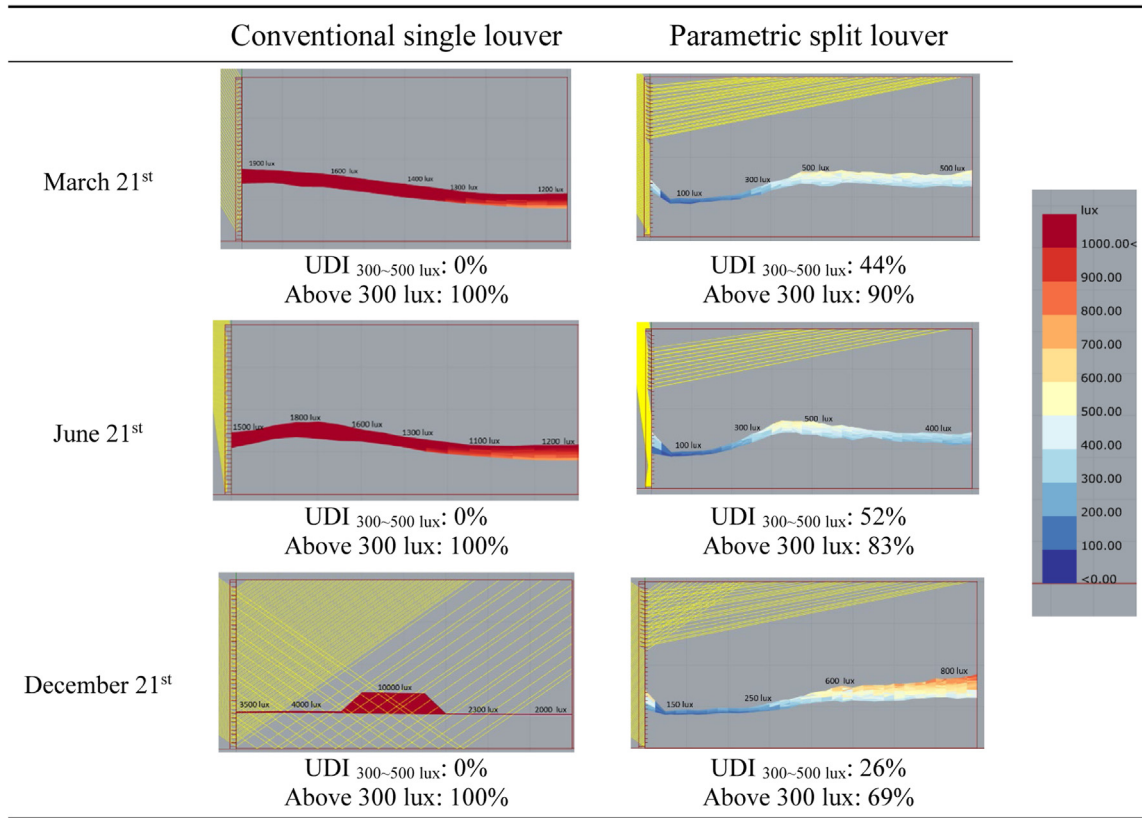


Fig. 9. Daylight levels along the midline of the space for conventional single louver and parametric split louver at 12:00 on three typical days.

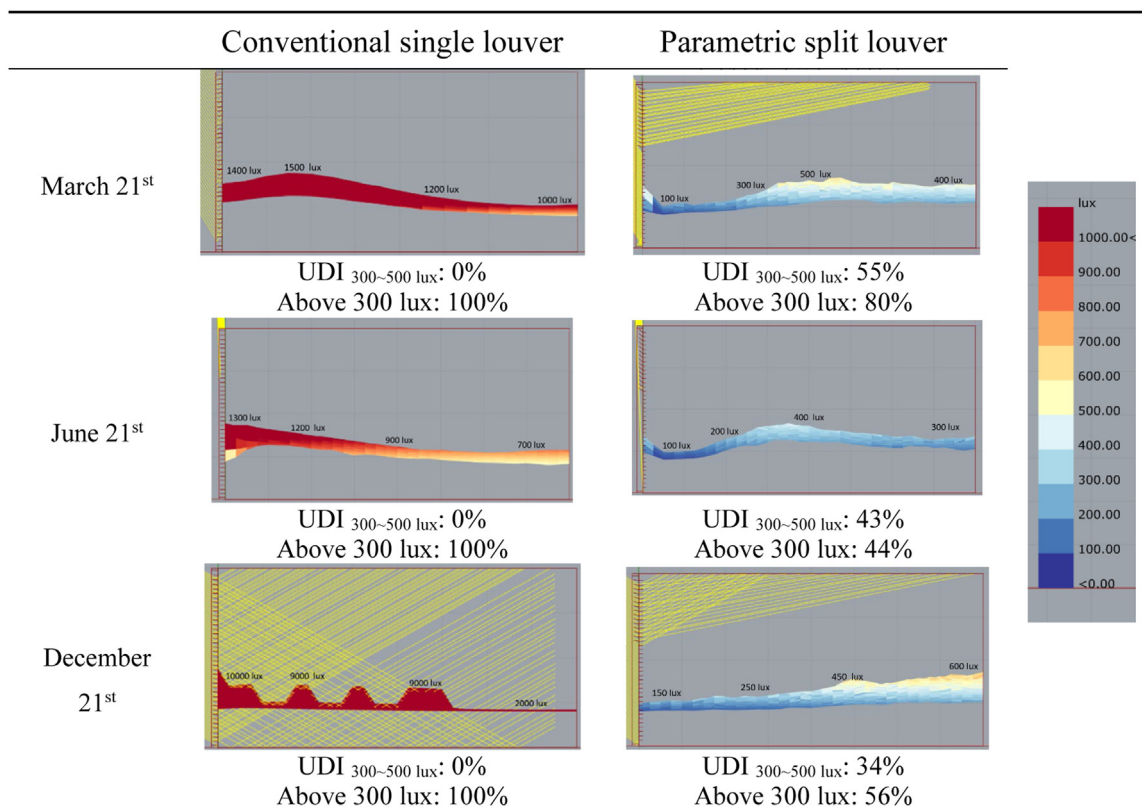


Fig. 10. Daylight levels along the midline of the space for conventional single louver and parametric split louver at 9:00 on three typical days.

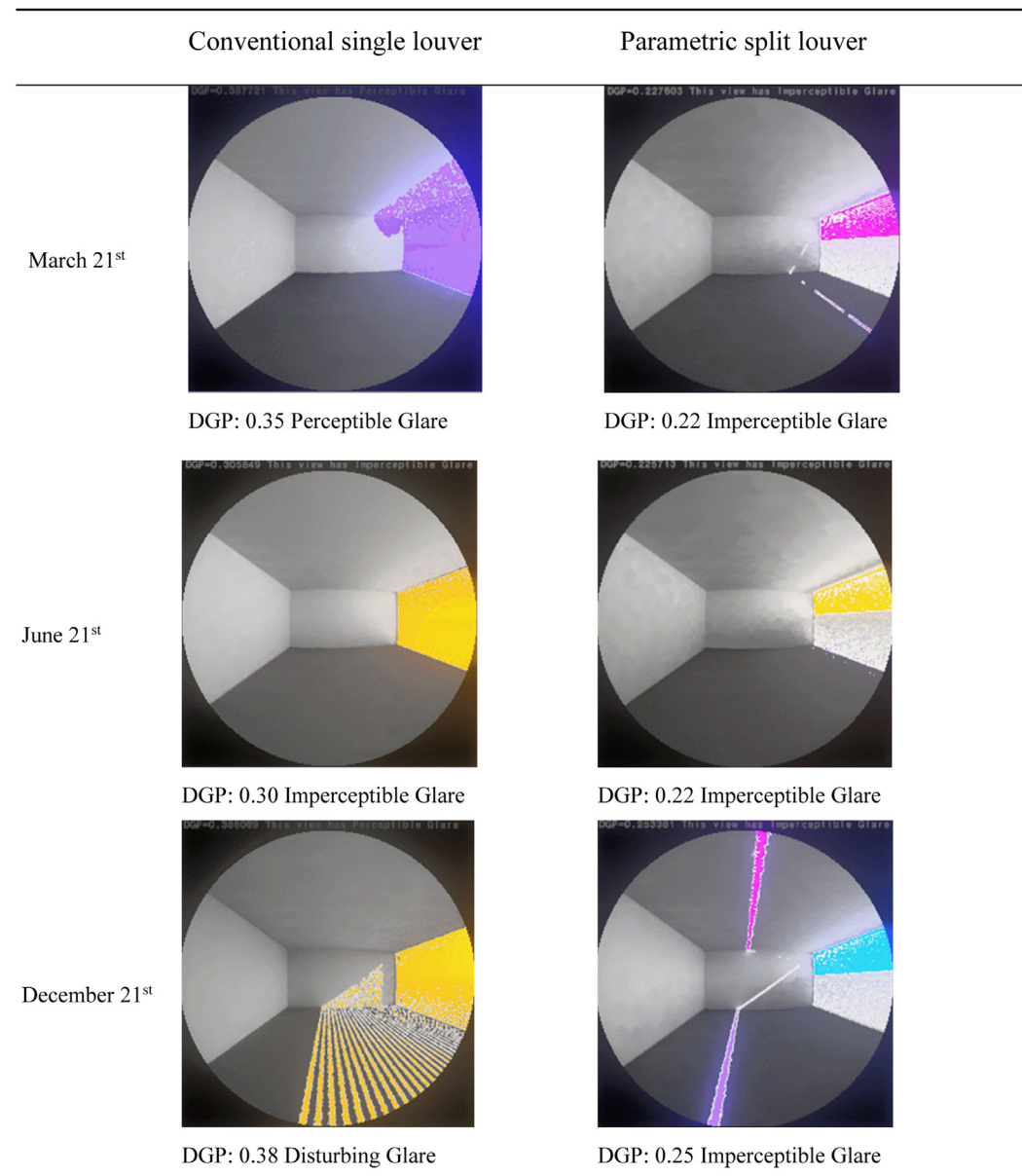


Fig. 11. DGP for the split louver and conventional louver for the three typical dates at noon.

Fig. 12 shows daylight availability at three fixed times on the selected solar dates. These snapshots offer a partial representation of system performance. Fig. 12 shows the percentage of time during the daytime on three typical dates when the illuminance levels fall below 300 lx, which indicates a need for additional artificial lighting in the office room. The values are given as percentages, reflecting the proportion of time during which the natural daylight is insufficient to meet the desired illuminance levels. For example, on March 21st at 8:00 am, 34 % of the time requires additional lighting as the illuminance is below 300 lx. Similarly, for June 21st at 11:00 m, 22 % of the time indicates a need for supplemental lighting.

Fig. 13 describes the comparison between the conventional single louver and the parametric split louver and provides a breakdown of electric lighting consumption (in Wh/m²) at different times throughout the day for the three typical dates. In the case of the conventional single louver, its design tends to cause an uncomfortable environment with glare issues, leading to the continuous closure of the louver and, consequently, blocking daylight and reliance on electric lighting throughout the day to achieve the desired UDI_{300~500} lx. As a result, the electric lighting con-

sumption remains consistently high at 0.24 Wh/m² for all three typical dates and throughout the daytime hours. On the contrary, the parametric split louver system demonstrates energy-saving capabilities; notably, it adapts dynamically to varying daylight conditions, leading to varying energy consumption levels. The parametric system showed less lighting demand from daylight during the day, notably between 10:00 am and 14:00 pm. Peak occurred at noon, during which usage was often below 0.05 Wh/m². Even in December, where sun intensity is at its lowest, it still achieved substantial savings.

Fig. 14 presents the percentage of energy savings achieved by the parametric split louver system in contrast to the conventional single louver (closure state) for the three typical dates at various hourly intervals during working hours. The average energy-saving percentages are noteworthy, highlighting substantial reductions in lighting consumption. On March 21st, the parametric split louver achieved significant savings with an average of 69.9 %, particularly at 11:00 am and 12:00 pm (90 %). December 21st presented savings as well with an average of 63.5 %. while, on June 21st, energy savings were peaked 83 % at 12:00 pm with an overall average of 43.6 %.

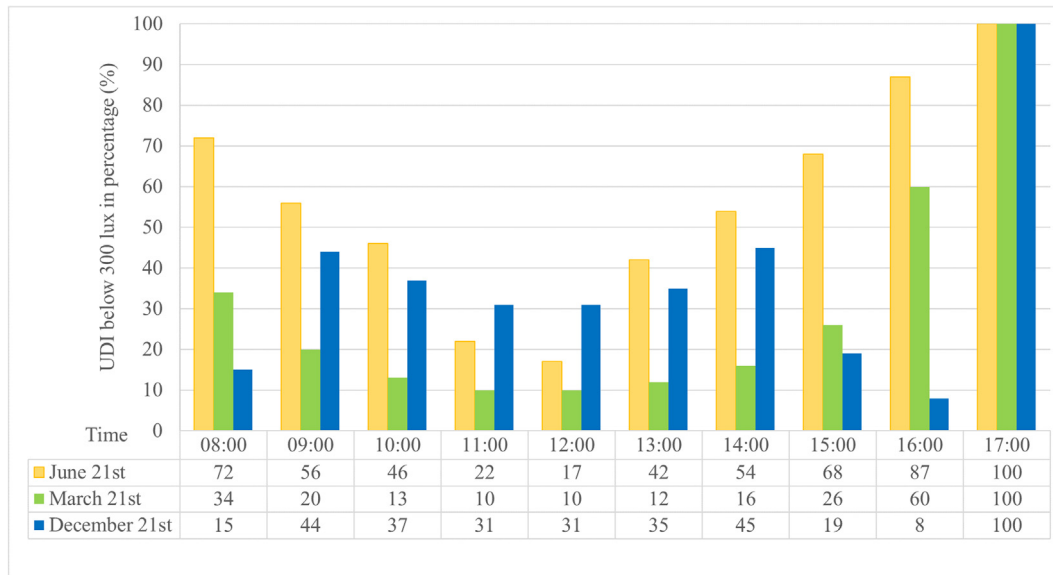


Fig. 12. UDI below 300 lx percentages achieved using the parametric split louver.

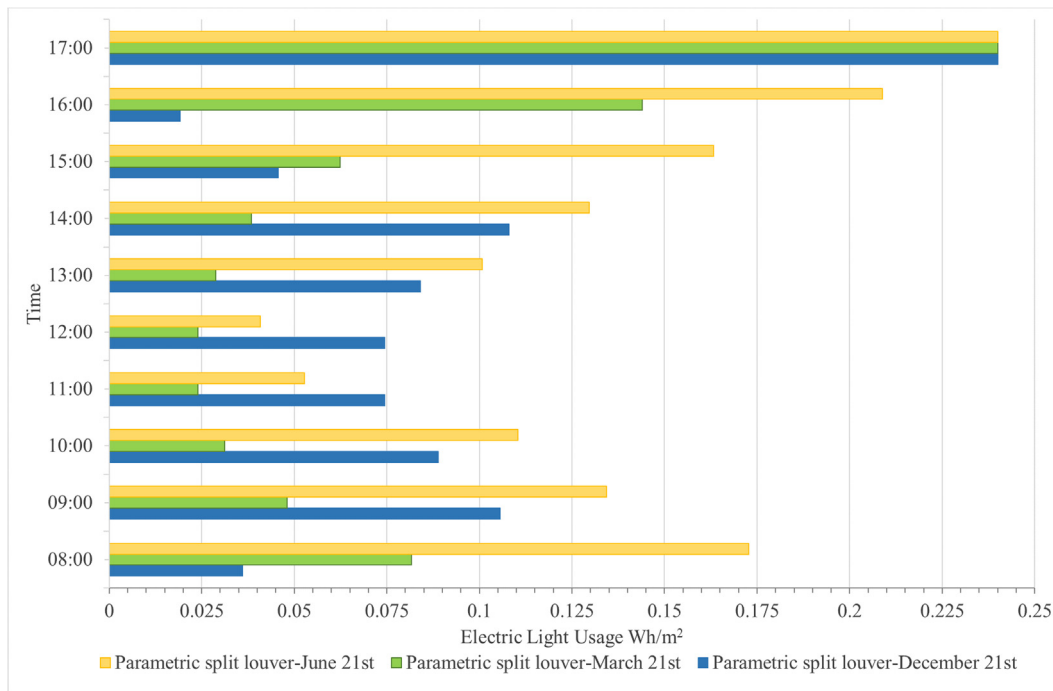


Fig. 13. Electric light usage (Wh/m²) to achieve UDI_{300~500 lx} using parametric split louver at all three typical dates.

5. Discussion

The comparative evaluation of the conventional louver system versus the parametric split louver highlights key differences in daylighting performance, especially when considering assumptions of manual user behavior. The conventional louver, tested under the assumption that users adjust angles in response to solar position (best practice). It is necessary to simultaneously achieve a free glare environment and daylight availability of UDI_{300~500 lx} in order to evaluate the practical differences between the parametric louver and the conventional louver in terms of lighting consumption.

Therefore, depends on the time of day and sun angle and the glare study in previous section, Table 2 displays the expected best practice for user control of the conventional louver system. During December, the

Table 2

The schedule of the anticipated best practice of conventional louver operation.

Time	December	March	June
08:00–10:00	Closed	Closed	Closed
10:00–12:00	Partially closed	Partially open	Partially open
12:00–14:00	Partially open	Partially open	Open
14:00–16:00	Partially closed	Partially open	Partially open
16:00–17:00	Closed	Closed	Closed

sun is at a lower angle throughout the day. The slats should be maintained completely closed from 8:00 to 10:00 am and 16:00 to 17:00 pm in order to block glare from the east and west. The partially closed state, scheduled between 10:00 am–16:00 pm, may be shortened due to the

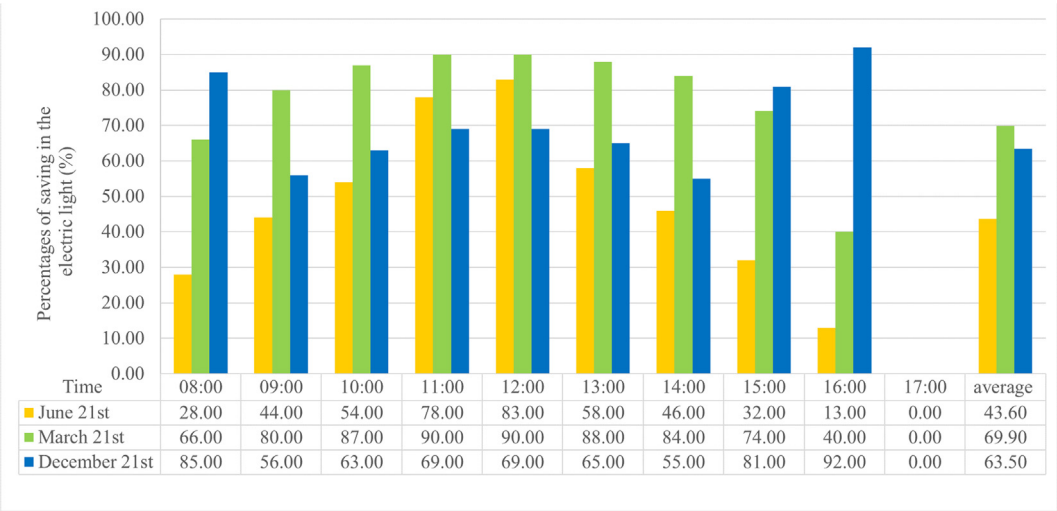


Fig. 14. Percentages of saving in the electric light consumptions for the parametric split louver.

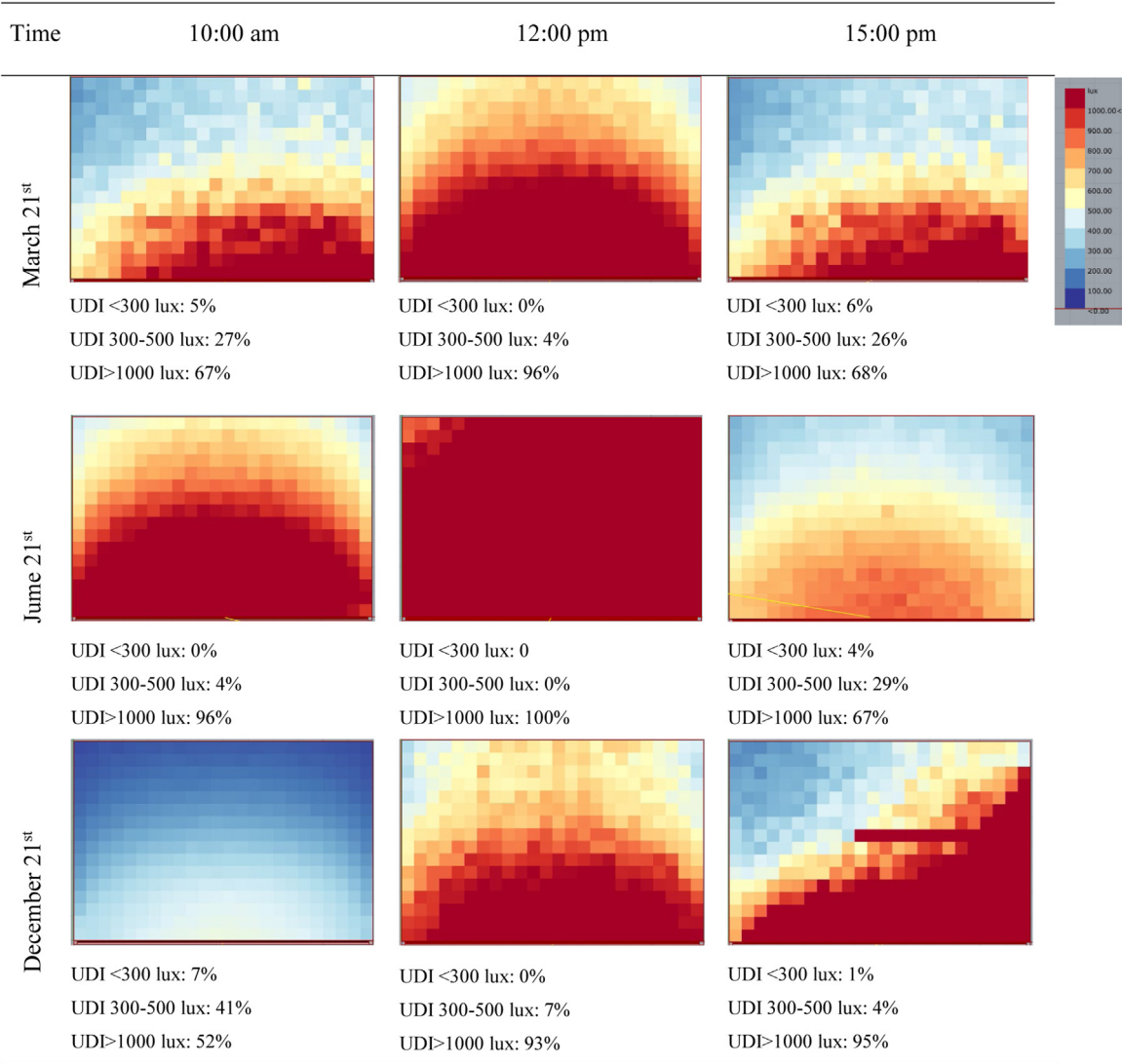


Fig. 15. The floor plan illuminance maps for the scheduled operation of the conventional louvers.

lower sun path and partially open at noon. March, on the other hand, offers a more balanced sun path, which fits in properly with the suggested schedule. In response to higher sun angles, the slats remain closed in the morning and evening and partially open in the morning and afternoon. During June, the sun maintains a much higher angle for longer periods, the open angle can be extended during midday, while the closed states in the morning and late afternoon may be shortened.

The limitations of the conventional louver system (with the scheduled operation) in providing efficient daylighting performance are evident from the simulation results of the floor plan illuminance maps for various times (Fig. 15). In particular, the conventional louver frequently produced excessive illumination levels close to the window, where UDI values were higher than the ideal range of 1000 lx, creating a significant risk of glare in these areas. In some cases, the rear areas of the space consistently receive inadequate daylight below 300 lx, leading to poor spatial uniformity. and an increased dependence on artificial lighting in these zones. Across all tested dates and at various times along the day, the conventional louver fails to maintain illuminance within UDI_{300–500} lx, which remains consistently low—often below 30 %. At noon during the June 21st, for instance, 100 % of the space was overlit. The conventional louver allowed excessive brightness near the window on December 21st despite lower solar intensity, while leaving deeper zones underlit. These results demonstrate that fixed or manually operated louver systems provide little flexibility to control daylight distribution in real time and are generally ineffective under dynamic sky conditions.

In contrast, as previously sections stated, the parametric split louver achieves a more refined daylight performance by and maintains UDI within the optimal 300–500 lx range with high uniformity across the floor area and significantly reduces glare near the window.

6. Conclusions

The present work emphasizes the importance of considering both energy efficiency and visual comfort aspects when evaluating the overall daylight performance of shading systems in virtual office environments. The two distinct sections of the split louver employ differing influences on daylight distribution in the front and rear areas of the room. When the upper section is open, the rear space experiences a more noticeable effect on typical days. Conversely, the area near the window in the front is significantly brighter when the lower section is open on regular days, particularly in December. This increased brightness in the lower part supports the notion that the lower section has a more substantial impact, particularly when the sun is at a lower angle.

Regarding the comparison between the conventional single louver and the parametric split louver. The evaluation of UDI within the 300–500 lx range reveals that the conventional single louver consistently fails to achieve daylight within this target and consistently over-illuminates at 100 % above 300 lx, indicating potential glare. Even with a scheduled operation the conventional louver achieved <30 % UDI_{300–500} lx and poor light uniformity. In contrast, the parametric louver demonstrates adaptability, achieving up to 55 % balanced illuminance level within the specified 300–500 lx range.

Parametric split louver surpasses in electric lighting efficiency compared to the constant high consumption of the conventional louver in respect of maintaining free glare environment and uniform illuminance. Using parametric split louver system is efficient around the three typical dates of March and December, achieving daily savings of 69.9 % and 63.5 % respectively. June, on the other hand, demonstrates efficiency with 43.6 % savings due to higher solar angles. This highlights the parametric split louver's ability to optimize daylight, presenting its effectiveness in minimizing energy consumption.

It is important to note that this study uses static time-based snapshots rather than continuous dynamic simulations. Although the system is intended to respond adaptively to changing solar conditions throughout the day, the evaluation in its current form does not model real-time re-

sponsiveness or slat angle adjustment sequences. Future research should include time-series or annual simulations to more accurately represent the control logic and its dynamic behavior under real-world conditions.

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Muna Alsukkar: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Mohammed Alkhater:** Software, Investigation, Formal analysis. **Yuehong Su:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Adnan Ibrahim:** Writing – review & editing, Visualization, Software, Methodology, Conceptualization.

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