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Simulation-Based evaluation of adaptive light shelf design for daylight uniformity in tropical office buildings

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ABSTRACT

Light shelves represent a quintessential passive design typology, traditionally utilized to augment daylight penetration while simultaneously mitigating glare to enhance interior visual ergonomics; however, conventional static configurations often fail to recalibrate in response to the stochastic fluctuations of solar geometry, particularly in tropical latitudes like Jakarta, Indonesia, where high solar altitudes persist. This study investigates the efficacy of a revolving light shelf system in optimizing indoor illuminance uniformity through DIALux Evo 8.2 simulations, evaluating rotational increments of ±15°, ±30°, and ±45° across four cardinal orientations over five diurnal intervals. The empirical results demonstrate that dynamic adaptability significantly enhances lighting uniformity and facilitates adherence to standardized illuminance thresholds, with the most profound performance gains observed on the east and west facades where solar azimuth and altitude vary most significantly. Conversely, the north and south elevations exhibited relatively stabilized metrics, requiring minimal angular adjustments to maintain optimal conditions. Ultimately, these findings underscore the imperative of integrated, responsive fenestration systems in tropical climates to reduce reliance on supplementary artificial lighting and provide a foundational framework for future automated building management architectures.

Introduction

The integration of natural illumination serves as a cornerstone of indoor environmental quality and systemic energy efficiency, where strategic daylight harvesting enhances both the physiological well-being of occupants and the overall luminous performance of the built form (Krasic, Pejić, and Mitkovic 2013; Mead 2008). In the contemporary context of highly glazed tropical facades, the primary architectural challenge involves orchestrating a balance between pervasive illumination and the mitigation of solar gain and debilitating glare (Abdulahaad, Ra'ouf, and Hasan 2023; Arens, Heinzerling, and Paliaga 2018).

Light shelves (LS) have emerged as a critical tectonic intervention, designed to bifurcate the window plane to redirect high-angle sunlight deeper into the floor plate while simultaneously providing localized shading (Abimaje, Kandar, and Dodo 2018; Lee, Park, and Seo 2018). However, traditional static iterations of these elements achieve peak efficiency only under specific, localized solar altitudes, whereas dynamic systems, capable of modulating reflectance and orientation, have demonstrated superior efficacy in optimizing visual comfort (Lee et al. 2017; Warrier and Raphael 2017).

Previous research has widely investigated the performance of light shelves in temperate climatic regions, primarily emphasizing fixed configurations or systems that are integrated with automated blinds and dimming control technologies. For instance, Lee et al. demonstrated considerable advantages associated with the implementation of a motorized light shelf within the daylight conditions of California. Their findings indicate that movable light shelf systems generally exhibit better performance compared with static configurations. Nevertheless, the study does not clearly specify the precise rotation angle or the direction of movement applied to the system. Consequently, the degree to which the dynamic light shelf achieves optimal performance in relation to indoor daylight availability remains uncertain. Warrier and Raphael, in another investigation, examined optical performance in South India by employing a relatively restricted range of angular adjustments. Despite these contributions, many existing studies tend to overlook the importance of continuous rotational flexibility and are seldom contextualized for fully tropical latitudes, particularly with regard to actual solar trajectories and patterns of building occupancy. The configurations analyzed in the present body of literature are numerous; however, all of them are treated as static conditions. Although the results demonstrate varying levels of performance, the studies do not determine which angle produces the most optimal outcome. Based on the reviewed literature, two important aspects remain insufficiently explored: the angle of the light shelf and the direction of its rotation. These parameters require further investigation, especially considering that light shelves perform dual functions, that is redirecting daylight deeper into interior spaces while simultaneously providing protection against glare (Tiwari 2018).

Although the rotational movement of light shelves has been shown to enhance performance, such effectiveness should be assessed using appropriate evaluation metrics, particularly those related to lighting uniformity (Lee 2020). In addition, the geographical location in which the research is conducted also significantly influences the results. Lee previously carried out a study incorporating a location-aware approach; however, this approach remains relatively general and lacks sufficient specificity, given that the effectiveness of dynamic light shelf systems is highly dependent on geographic location and local climatic characteristics. Investigations examining light shelf performance across different regions inevitably produce distinct configurations and movement strategies. Therefore, defining the geographical and climatic context of a study becomes essential in order to determine the most appropriate and optimal configuration of a light shelf system.

Within the context of Jakarta, a tropical metropolitan area characterized by high levels of solar exposure, the implementation of light shelf systems requires careful and context-sensitive consideration. Unlike subtropical or temperate climates, Jakarta experiences relatively consistent solar paths and fairly stable daylight durations throughout the year. Consequently, the design of light shelves in such an environment must take into account the high solar altitude and the potential risk of indoor overheating. This condition necessitates the use of adaptive geometries (Lim 2014) capable of optimizing both daylight redirection and solar shading simultaneously. Despite the strong relevance of this topic, studies that specifically model the performance of dynamic light shelves under the climatic conditions of Jakarta remain limited. This lack of context-specific investigations highlights the need for simulation-based research tailored to the environmental characteristics of the city (Joarder et al. 2009).

Research conducted by Prasetyo (2014) and Kamaruddin et al. (2021) emphasized that daylighting strategies in Jakarta must address the challenges posed by intense solar radiation and significant glare potential, particularly on east- and west-oriented façades. However, their studies mainly explored static shading devices or fixed louver systems without considering the possibility of dynamic modulation. Furthermore, although several investigations have examined clerestory windows or sun-shading angles within tropical classroom and office buildings in Indonesia, only a limited number of studies incorporate rotational light shelf components that allow real-time adjustments throughout the day (Zhao, Seo, and Lee 2024). The present study therefore seeks to address this research gap by evaluating the design of a revolving light shelf and analyzing the influence of its rotational movement on indoor lighting uniformity under tropical daylight conditions. The novelty of this research lies in its systematic examination of various shelf angles throughout the day across different façade orientations within the urban context of Jakarta.

The principal contributions of this research include the development of a simulation model for a revolving light shelf (LS) system with continuous rotational capability (±45°), a configuration that has not yet been comprehensively evaluated in equatorial regions; a comparative performance assessment of the revolving LS across the four primary building orientations, east, west, north, and south, using a complete set of daily time intervals; and the formulation of recommendations for optimal rotation angles for each façade orientation and time period based on two key criteria, namely lighting uniformity and average illuminance levels. The hypothesis proposed in this study suggests that the revolving LS system will produce a significant improvement in lighting uniformity when compared with conventional static systems, while the optimal performance is expected to vary according to façade orientation and the time of day. In particular, it is anticipated that east- and west-facing façades will benefit most from the rotational capability of the LS due to more pronounced variations in solar angles (Elsiana and S Arifin 2024), whereas the north- and south-oriented façades will demonstrate relatively more stable performance patterns. The study further anticipates that outward rotation will provide optimal performance when the sun is positioned at a low angle, during the morning for the eastern façade and during the afternoon for the western façade, while inward rotation will become more effective when the sun reaches its highest position in the sky.

Methods

A quantitative simulation-based method was employed using DIALux Evo 8.2 to investigate the influence of a revolving light shelf on indoor daylight distribution. The experimental room was modeled as a 5 m × 5 m × 3 m cubic space (figure 1), a configuration commonly used in daylighting studies to minimize depth bias in the evaluation of daylight penetration within interior spaces [10]. The geographical setting of the simulation was defined as Jakarta, Indonesia (6.2°S, 106.8°E) in order to represent environmental conditions typical of a tropical climate [11]. Each façade orientation, north, south, east, and west, was modeled with a single window measuring 4 m in width and 1 m in height, with a sill height of 1.8 m (figure 2). This configuration produces a window-to-wall ratio (WWR) of 26%, a proportion considered appropriate for tropical buildings because it helps reduce excessive solar heat gain while still enabling adequate daylight penetration into the interior space.

Table 1. Simulation Parameters for Experimental Room Model

Parameter	Value/Description
Light Shelf Length	4 meters
Light Shelf Width	1 meter
Installation Position	Interpane (within window glazing)
Installation Purpose	To minimize structural load and mechanical stress during rotational movement
Sky Condition for Simulation	Average sky (intermediate condition)
Simulation Date	September 21st, 2024
Time Points Simulated	08:00, 10:00, 12:00, 14:00, 16:00
Time Interval Purpose	To capture variations in solar altitude and their influence on daylight distribution performance

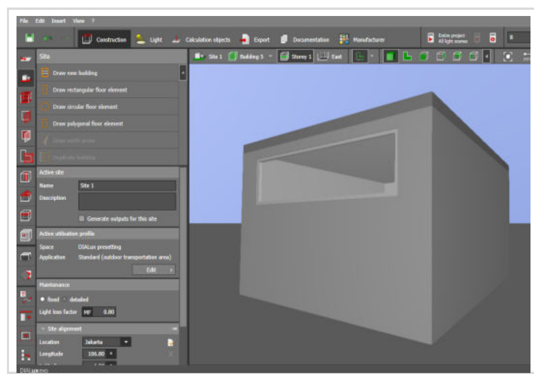

Figure 1. Room model in software Dialux Evo 8.2

The light shelf was modeled with a length of 4 m and a width of 1 m and positioned within the interpane zone of the glazing system to reduce structural loading during rotational movement. The simulations were performed under an average sky condition on September 21, 2024, at five observation times: 08:00, 10:00, 12:00, 14:00, and 16:00. This date was selected because it represents equinox conditions, which are comparable to solar path characteristics observed in March. The solar solstice periods (June and December) were intentionally excluded from the simulation because the significantly lower solar altitude during those periods would require different configurations of light shelf rotation angles.

Table 2. Light shelf and simulation schedule parameters

Parameter	Value/description
Simulation Software	DIALux Evo 8.2
Room Dimensions	5 m × 5 m × 3 m (L × W × H)
Purpose of Room Size	To avoid depth bias in daylight studies
Geographic Location	Jakarta, Indonesia (Latitude: 6.2°S, Longitude: 106.8°E)
Climate Context	Tropical climate
Number of Facades Modeled	4 (North, South, East, West)
Window Dimensions	4 m (width) × 1 m (height), sill height: 1.8 m
Window-to-Wall Ratio (WWR)	26%
Reason for WWR Choice	Appropriate for limiting excessive solar gain in tropical buildings

The revolving light shelf was designed to rotate in two directional modes, namely inward rotation and outward rotation. Four rotational angles were tested for the inward direction (figure 3), while two rotational angles were applied for outward rotation (figure 4). The primary performance indicators measured in this study were average illuminance (lux) and lighting uniformity (LU). Lighting uniformity was calculated as the ratio between minimum illuminance and average illuminance, following the method proposed by Bean (Bean 2014). An LU value approaching 1.0 indicates a more even distribution of daylight across the interior space.

To determine the most optimal rotational angle of the light shelf, a dual-criteria evaluation approach was applied. The criteria consisted of: (a) lighting uniformity (LU) values, and (b) compliance with daylight illuminance standards, specifically a minimum illuminance level of 210 lux for office environments. This threshold represents a 30% reduction from the typical 300 lux office standard, assuming the absence of artificial lighting support (Faraji et al. 2023).

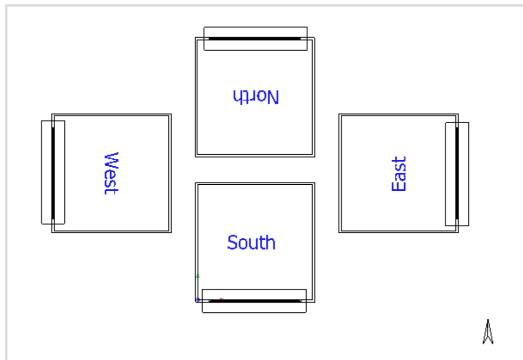

Figure 2. Room models for simulation, facing south, north, east and west orientation

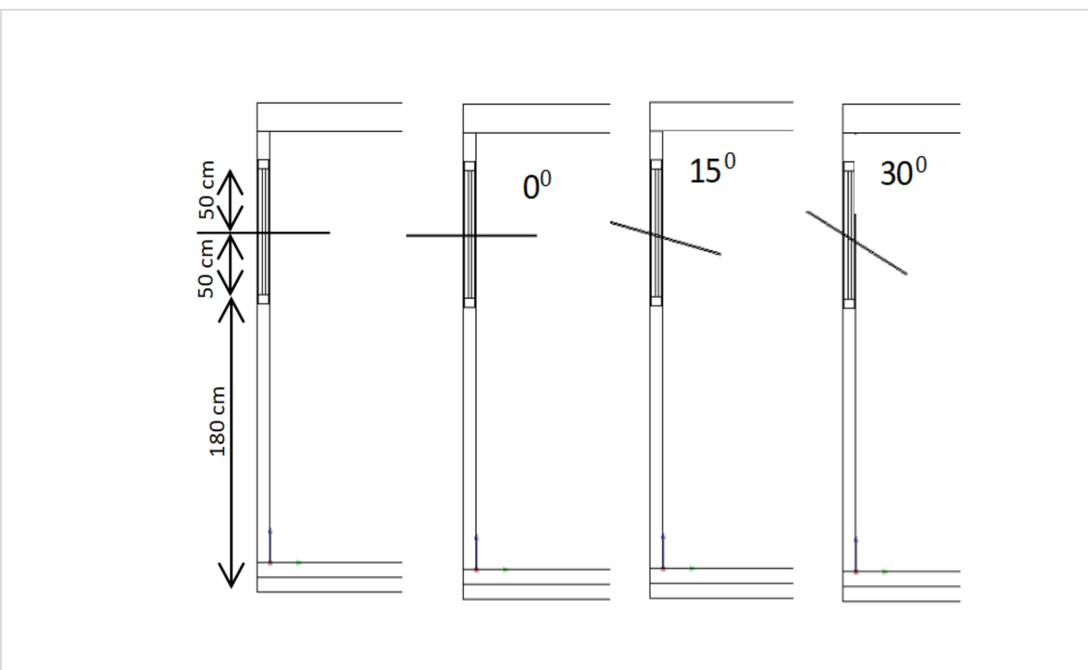

Figure 3. (left) Dimension and position of the windows and LS; (right) angle of revolving LS into the room

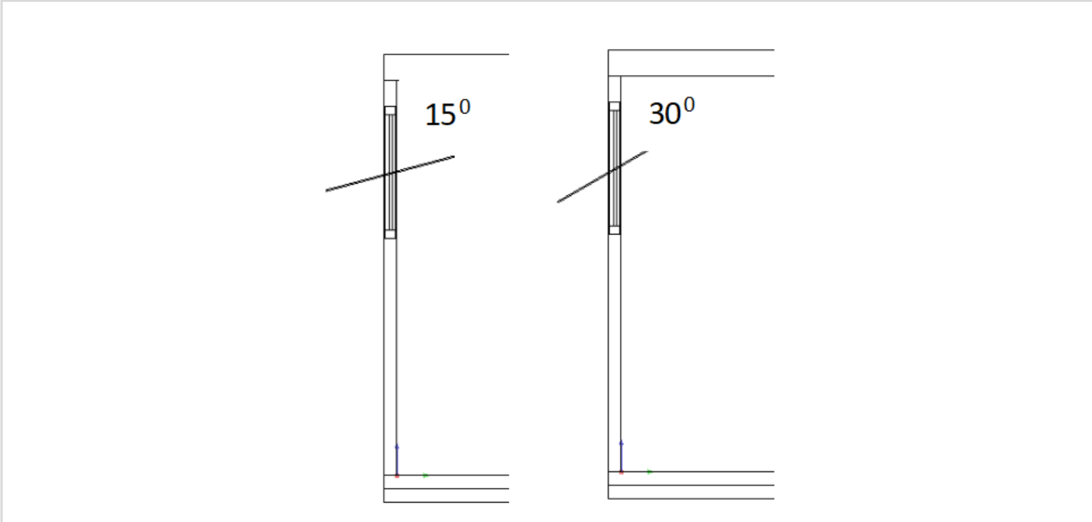

Figure 4. Angles of revolving LS outwards the room

Results and discussion

The simulation results indicate that lighting uniformity (LU) varies considerably across different façade orientations and time intervals, depending on the rotation angle and direction of the revolving light shelf (LS). LU values range from 0 to 1, where higher values represent more uniform daylight distribution within the interior space. In addition to uniformity, average illuminance levels were also evaluated to ensure compliance with the minimum office daylighting requirement of 210 lux, which reflects the adjusted standard under natural lighting conditions.

The results reveal a complex interaction between lighting uniformity and average illuminance levels. In several cases, high average illuminance corresponds with relatively low LU values due to the presence of direct solar radiation, which produces localized bright areas near the window and reduces the overall uniformity of daylight distribution. Conversely, scenarios with lower average illuminance often demonstrate higher LU values because the difference between minimum and average illuminance becomes smaller. However, higher uniformity under these conditions does not necessarily guarantee adequate lighting for visual tasks. This observation highlights the importance of employing a dual-criteria assessment when evaluating the performance of light shelf systems.

As illustrated in figure 5, the east-facing façade achieves its optimal LU values during the morning period, when the LS is rotated outward by 15°, resulting in an LU value of 0.49 at 08:00. Although higher LU values were recorded at other rotation angles, those configurations were excluded because they failed to satisfy the required average illuminance level. As the day progresses, inward rotation of the LS becomes more effective. At 12:00, for example, an inward rotation of 45° produces an LU value of 0.24. This pattern corresponds closely with the daily solar trajectory, where low-angle morning sunlight benefits from outward rotation to improve redirection and shading, while higher solar altitudes around midday require inward adjustment to prevent excessive daylight penetration and glare.

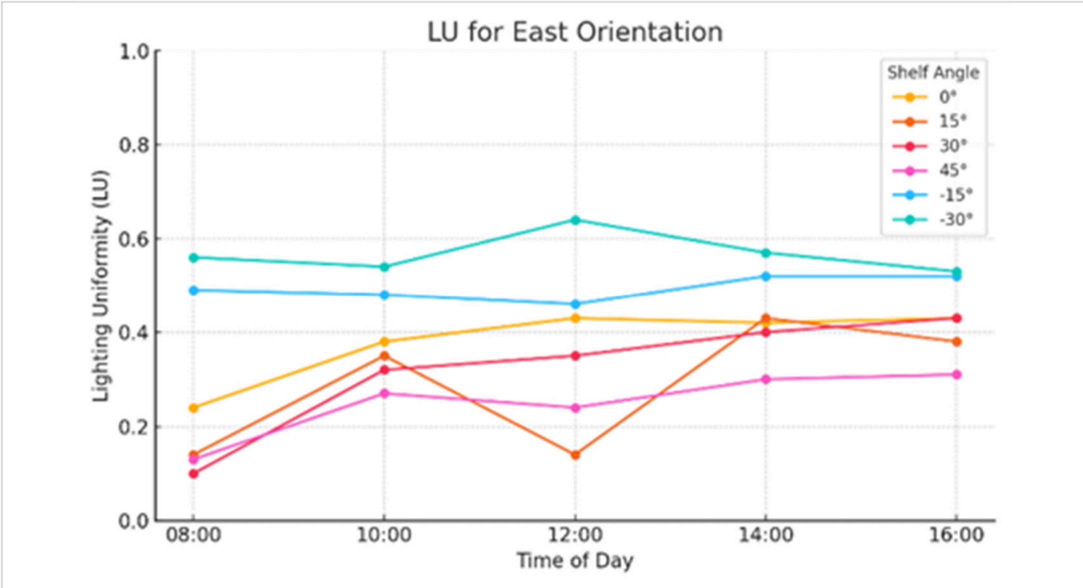

Figure 5. Value of LU in East orientation

For the west orientation (figure 6), optimal LU performance occurs during the afternoon period, when direct solar radiation reaches the façade. At 14:00, an outward rotation of 45° produces an LU value of 0.53, while at 16:00, an outward rotation of 15° yields an LU value of 0.56. During the late afternoon, the intensity of direct sunlight increases the risk of glare, which is reflected in reduced LU values at certain rotation angles. In contrast, during the morning hours the LS system is less effective on the west façade because the surface receives minimal direct solar radiation at that time.

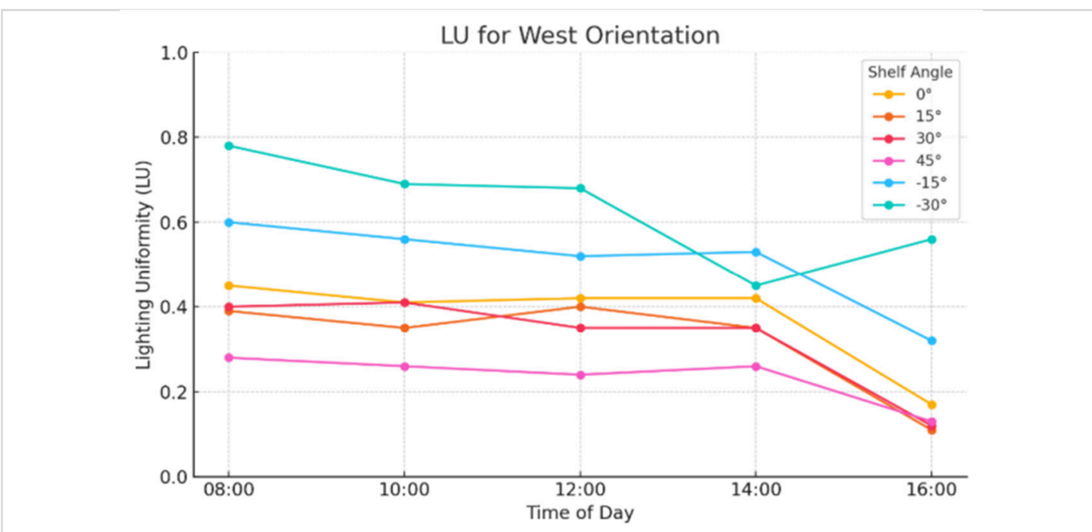

Figure 6. Value of LU in West orientation

As shown in figures 7 and 8, the north and south façades exhibit more stable patterns of both average illuminance and lighting uniformity throughout the day. These orientations primarily receive diffuse skylight rather than direct solar radiation, which results in less dramatic variations in daylight performance. For the north orientation, an inward rotation of 30° at 08:00 provides an LU value of 0.32, with relatively minor changes observed at later time intervals. Similarly, the south façade achieves an LU value of 0.32 with a 30° inward rotation in the morning, and only small adjustments are required throughout the day. The absence of strong low-angle sunlight on these façades reduces the need for frequent or extreme rotational adjustments of the light shelf.

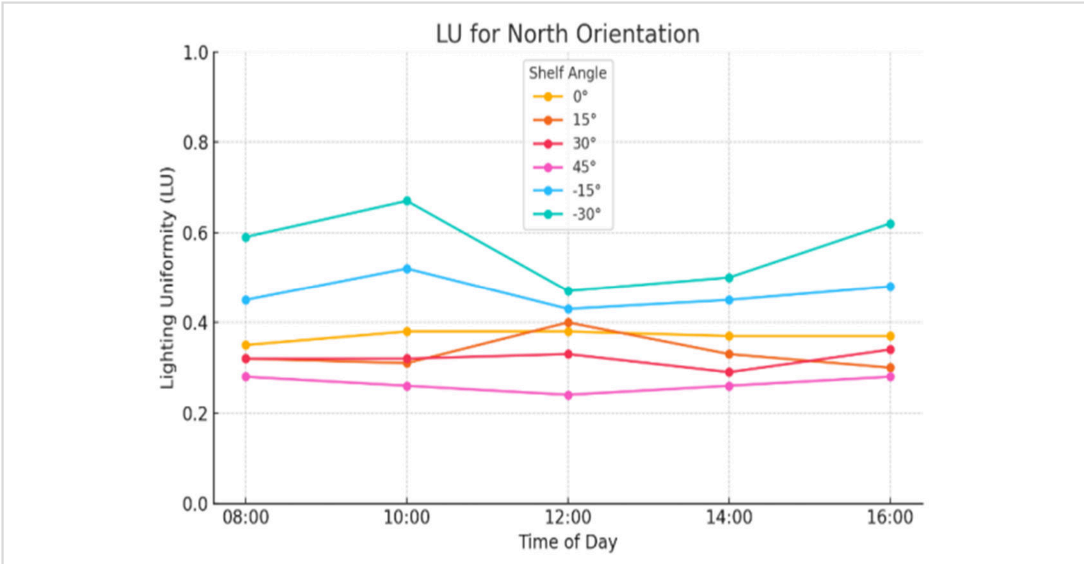

Figure 7. Value of LU in North orientation

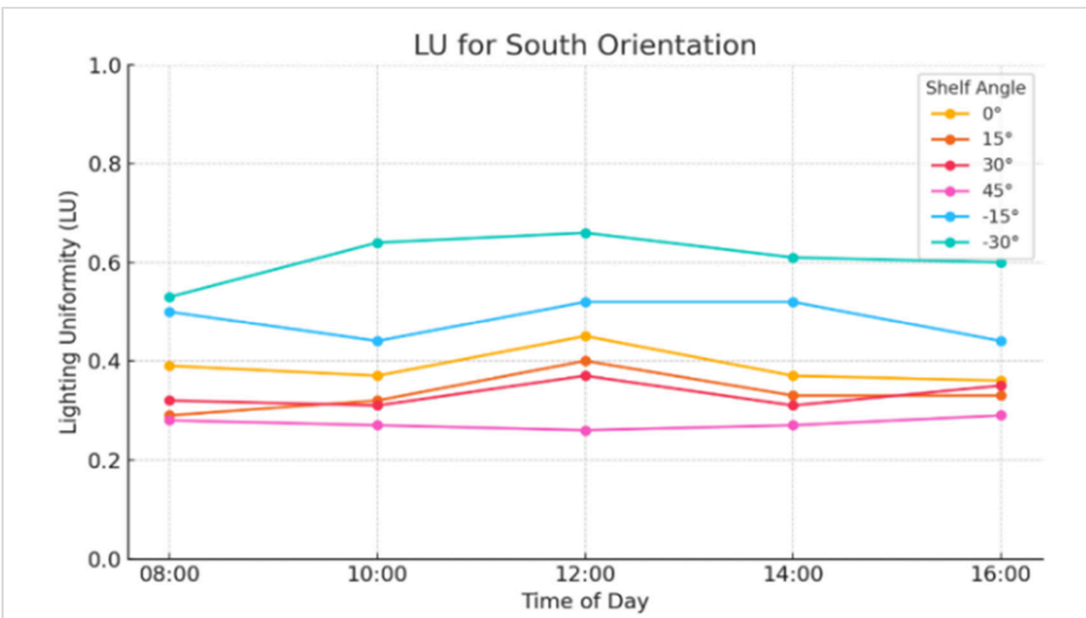

Figure 8. Value of LU in South orientation

From a physical standpoint, the variations observed in illuminance and lighting uniformity can be explained by the interaction between solar incidence angles, reflective characteristics of the light shelf, and room geometry. When the shelf rotates outward during periods of low solar altitude, such as morning hours on the east façade or afternoon hours on the west façade, it intercepts direct sunlight and reflects it deeper into the interior space. This process increases both the penetration depth of daylight and the uniformity of illumination. This mechanism follows the principle of specular reflection, where the angle of incidence equals the angle of reflection. Under these conditions, the light shelf effectively acts as a secondary reflective surface, redistributing incoming sunlight and reducing the contrast between highly illuminated areas near the window and darker zones deeper in the room. Conversely, during midday periods when the sun reaches its highest altitude, inward rotation of the shelf helps reduce excessive solar penetration, thereby limiting glare and potential overheating while still allowing diffuse daylight to enter the interior through upward reflection.

The findings of this study are consistent with the work of Lee, who demonstrated that dynamic light shelf systems significantly improve daylight penetration and lighting uniformity when compared with static systems. However, unlike the studies conducted by Warrier and Raphael, which investigated only a limited range of rotation angles and did not fully address the high solar altitudes typical of tropical climates, the present research demonstrates that continuous rotational adaptability is essential for maintaining optimal daylight conditions in equatorial regions. Similarly, while Moazzeni and Ghiabaklou emphasized the importance of light shelf geometry in educational buildings in Tehran, the results of the present study indicate that in tropical office environments, both the timing and direction of rotational adjustments are equally critical due to the persistent intensity and high elevation of the sun throughout the year (Moazzeni and Ghiabaklou 2016).

According to Fantozzi, the recommended lighting uniformity value for office environments is approximately 0.6 (Fantozzi et al. 2017). The simulation results indicate that several measured LU values approach or even exceed this benchmark. Such results can be considered favorable, as lighting uniformity is a fundamental requirement for visual comfort in office environments. Values approaching the recommended standard suggest that artificial lighting demand could potentially be reduced. When uniformity levels approach 0.6, only localized artificial lighting may be required in specific areas where illuminance levels remain insufficient. This targeted approach offers the potential to reduce overall energy consumption within office buildings.

Overall, the physics-based analysis confirms that the revolving light shelf functions simultaneously as a reflective and shading device, dynamically adapting to changing solar positions to maintain a balance between daylight distribution and visual comfort. This dual functionality is particularly advantageous in tropical climates, where static shading solutions often fail to respond adequately to rapid changes in solar intensity and angle. The results therefore support the adoption of adaptive light shelf systems as an effective daylighting strategy for buildings located in regions with high solar exposure.

The simulation outcomes support earlier studies indicating that static light shelf systems are less effective in tropical climates, where solar angles shift dynamically and solar radiation intensity remains consistently high. The revolving light shelf (LS) system demonstrates significant advantages in responding to temporal and directional variations in daylight conditions, thereby improving both illuminance levels and lighting uniformity within the interior space. The dual function of the light shelf, as a daylight reflector and shading device, is especially evident on the east and west façades. In these orientations, outward rotation of the LS under low-angle solar conditions allows deeper daylight penetration into the interior while simultaneously reducing glare caused by direct sunlight.

Nevertheless, the analysis also reveals several inherent performance trade-offs. Achieving the highest level of lighting uniformity (LU) does not always correspond with attaining the recommended illuminance levels, particularly during periods of intense direct solar exposure. This finding highlights the necessity of integrating revolving light shelf systems with additional daylight management technologies, including automated dimming systems or glare-detection sensors, to ensure consistent occupant comfort while maintaining energy efficiency.

Certain limitations of the present study should also be acknowledged. The simulations were conducted for a single representative date (21 September) under average sky conditions, which may not fully represent seasonal variations in solar altitude or daylight availability. Moreover, the experimental room model is intentionally idealized, without interior furniture, partitions, or varied surface reflectance properties that would influence daylight behavior in real architectural environments. In addition, other relevant performance variables such as visual comfort, potential thermal impacts, and overall energy savings were not directly evaluated in this investigation.

Future studies should therefore broaden the simulation framework to include multiple dates, seasonal solar conditions, and different sky models, along with more complex room geometries and occupancy scenarios. Further integration with advanced daylight-responsive control technologies and empirical validation through field measurements in actual buildings is also recommended to better assess the practical performance of revolving LS systems in tropical architectural contexts.

Conclusions

The revolving light shelf system significantly enhances the distribution and uniformity of daylight in tropical office environments, particularly on east- and west-oriented façades. Optimal performance requires dynamic adjustment of the light shelf angle in response to changing solar positions, while considering both lighting uniformity and average illuminance levels. The findings provide an important basis for the continued development of adaptive daylighting strategies in regions characterized by high solar exposure. The results also indicate that the placement of the light shelf (LS) on each façade orientation, combined with specific rotational adjustments, produces different LU values at each simulated hour. This study therefore contributes meaningfully to the field of daylighting research in tropical office buildings by offering a comprehensive simulation-based evaluation of revolving light shelf systems across multiple façade orientations and time intervals. The outcomes emphasize the importance of dynamic daylight control in achieving optimal lighting uniformity and appropriate illuminance levels, particularly in climates with consistently strong solar radiation. From a practical perspective, the findings suggest that revolving light shelves with programmable rotational schedules, adjusted according to building orientation and local solar patterns, can significantly improve visual comfort while reducing reliance on artificial lighting systems. For future research, it is recommended that further investigations incorporate empirical validation in real building environments, evaluation of visual comfort indicators such as glare indices, and integration with automated daylight-responsive control technologies. Additionally, examining the long-term energy performance and occupant satisfaction associated with adaptive light shelf systems in various building typologies would provide stronger support for their implementation within sustainable tropical architectural design.

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