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Enhancing Daylight Performance in Educational Spaces using Light Shelves (Case Study: Architecture Studio, Shahrood University of Technology)

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Abstract

Daylight serves as a fundamental element in the design of sustainable buildings, significantly contributing to energy efficiency and occupant visual comfort. However, the uncontrolled penetration of natural light may result in issues such as glare and uneven daylight distribution within interior spaces. This study explores the effectiveness of light shelves in enhancing daylight performance during the summer solstice, particularly in zones within a studio that receive lower levels of natural light. Initially, illuminance levels at nine selected points were measured on the day of the summer solstice. A case model was subsequently developed using Rhino and Grasshopper software. For the daylight simulations, the Ladybug and Honeybee plugins were employed. Following model development, the simulation data were validated to ensure accuracy and reliability. Proposed design scenarios were then applied using the Colibri plugin to improve daylight distribution at three of the darkest rear points, as well as to increase the average illuminance across three rear work surfaces. Finally, the simulation outputs were visualized and analyzed using the Design Explorer platform. The key parameters of the light shelf, including depth, angle, light shelf reflectance, classroom surfaces, light transmittance through the glass, and the height of the light shelf, were evaluated. The analysis was conducted based on illuminance metric. As a result, the implementation of light shelves in the targeted studio contributed to a 22%–30% enhancement in daylight availability.

Keywords: *Light shelf, Educational space, lighting assessment, Illuminance, Daylight simulation.*

1. Introduction

Daylight serves as a natural element that fosters a stronger connection between people and the natural environment [1]. Daylighting has gained significant importance in the design of buildings in recent years [2]. A common starting point in most daylighting studies is the assumption that a space can only be considered daylit if it receives a certain amount of daylight, determined by the specific requirements of the program [3]. Natural light, as a source of illumination across various environmental contexts, is highly preferred due to its numerous qualitative benefits and quantitative advantages [4]. Human vision plays a critical role in perceiving the surrounding environment by delivering essential information regarding the shape and color of nearby objects [5]. Daylighting has the potential to enhance human health, mood, cognitive performance, and overall productivity [1]. Insufficient lighting controls can have adverse effects, such as causing glare, visual discomfort, and a decline in occupant performance [6]. Architectural design is a complex process that entails the integration of the building form, user requirements, and surrounding environmental conditions [7]. Throughout history, architecture and light have consistently influenced one another in shaping spaces. Natural light has long been a key element in architectural design. In traditional Iranian architecture, various methods were employed to effectively incorporate daylight into the architectural layout and living spaces. In building design, daylighting is a key factor that must be carefully considered to enhance energy efficiency and promote sustainability [8]. Therefore, achieving an optimal balance between maximizing daylight utilization and managing the associated risks of discomfort remains one of the most challenging tasks for designers [7]. People naturally prefer daylight over artificial lighting in indoor spaces. Daylight has been recognized as one of the key features in the works of renowned architects such as Le Corbusier. In many of his architectural projects, light and daylighting were employed as fundamental design elements to ensure visual comfort, achieve optimal illumination performance, and enhance the quality of interior spaces [9]. Research has shown that exposure to natural light can significantly improve well-being by reducing headaches, eye strain, and stress [10]. The utilization of natural light holds significant potential for enhancing both energy efficiency and indoor environmental quality in buildings, making it a critical component in many green building certification systems [11]. The integration of daylight in non-residential buildings has emerged as a key strategy for enhancing environmental quality and improving energy efficiency by reducing reliance on artificial lighting as well as heating and cooling demands [12]. Daylighting in school buildings has long been a topic of interest and serves as a critical criterion in the design of educational spaces. It contributes to creating a pleasant learning environment, enhances academic performance, supports better health, and enables substantial energy savings [2]. Visual comfort can be achieved through both daylighting and artificial lighting. Enhancing daylight availability in educational spaces is particularly desirable, as it contributes to a sense of health, well-being, and alertness, while also preserving visual comfort and reducing the need for electric lighting[6]. In school buildings, especially learning spaces, good daylight and thermal conditions are important to promote the educational process, as unsatisfactory comfort levels can reduce physical and intellectual performance for both teachers and pupils.

Furthermore, one of the main contributors to carbon emissions in buildings is electricity consumption, which accounts for approximately 30–40% of total energy use in commercial buildings [13]. The International Energy Agency (IEA) has gathered concerning data on the impacts of energy consumption.

According to the data, from 1984 to 2004, primary energy consumption increased by 49%, and consequently, CO2 emissions rose by 43% [14]. Furthermore, energy consumption in buildings in the European Union was estimated at 38.1% in 2014 [15]. The Annual Energy Outlook 2021 by the U.S. Energy Information Administration reports that lighting accounts for 9% of total energy consumption in buildings, making it the second-largest energy consumer after space heating, refrigeration, and cooling [16]. Daylight control systems can reduce electricity consumption by 20% to as much as 60% in certain cases [17].

Over one hundred thousand schools have been constructed with an energy consumption exceeding 160 kWh/m², approximately 2.5 times higher than the average of 65 kWh/m² observed in typical schools in developed countries [7]. Finally, given the significance of the issues discussed and the fact that lighting in educational buildings accounts for 14% of total energy consumption, the necessity of this research is well justified [18]. The study of daylight in educational buildings has been a focus for many years. In fact, daylight plays a critical role in the design of educational spaces, perhaps more so than in any other type of building. Studies have shown that optimal daylight in schools, particularly when integrated with dynamic daylight control systems, not only creates a pleasant environment but also enhances academic performance and well-being. Additionally, it significantly contributes to energy savings. For this reason, the importance of daylight in schools has been internationally recognized, and the utilization of daylight has become a key design parameter for architects [19]. As daylight is dynamic, there is no one common solution for all scenarios [20]. In many cases, professionals in the building industry assume that all issues can be solved with a single window [21]. However, a single window is not sufficient to provide adequate light to a built space, and the use of appropriate strategies tailored to the specific space is required. In educational environments, daylight plays a crucial role in enhancing the performance and productivity of both students and staff. However, achieving effective daylighting in classrooms remains challenging due to their considerable depth and the diverse range of activities conducted within these spaces [22]. One of the secondary benefits of optimizing daylight is the reduction in cooling costs, achieved by minimizing heat gain through daylight control systems [17]. One of the most effective approaches for optimizing natural light is shading devices. The light shelf system enhances daylight distribution by reducing the contrast in illumination between areas near the window and those farther away [23]. Properly designed shading systems play a crucial role in achieving optimal daylight conditions tailored to the specific needs of each space, and they are recognized as essential factors in improving the well-being of users in built environments. Light shelf with a diffuse surface could result in an increase in interior daylight uniformity [24]. Directing natural light into living environments has the potential to enhance energy efficiency and improve indoor environmental quality in buildings. This feature is considered a key criterion in most green building certification systems. In this study, a light shelf has been utilized to enhance daylighting in the designated areas. Light shelves are generally positioned above eye level and may be incorporated both internally and externally within the façade plane [23]. The internal portion was designed to block direct sunlight from the window area above the shelf while the exterior portion shades the surface area closer to the window [25]. Internal shading devices are effective in controlling both glare and daylight. Additionally, they offer greater user flexibility, allowing for adjustments such as rotating the angle, raising or lowering the shade, or modifying its position to suit individual preferences [20]. Over the past decade, numerous metrics have been developed to evaluate daylight performance, which are generally classified into two main categories: static metrics and dynamic metrics [26]. Static metrics, which are based on moment-in-time evaluations, include daylight factor, view to the outside, avoidance of direct sunlight, uniformity, and illuminance. In contrast, dynamic metrics encompass daylight autonomy (DA), continuous daylight autonomy (cDA), useful daylight illuminance (UDI), spatial daylight autonomy (sDA), and annual sunlight exposure (ASE) [26]. Achieving appropriate illuminance levels for each specific activity is essential for fostering a productive learning environment [6]. Illuminance is the total luminous flux incident on an area divided by the area [4]. In addition, this study employed an interior light shelf to investigate the effectiveness of daylight in reaching the darkest areas of the studio space, using both static and instantaneous illuminance indices to assess lighting performance.

2. Location and climate

This study was conducted in Shahroud County, located in Semnan Province, Iran. Shahroud has a mid-latitude desert/arid cool climate (Köppen-Geiger classification: BWk) and lies in or near the cool temperate moist forest biome..[27]. It is located at latitude 36°25'N and longitude 55°01'E [28]. This research was carried out in one of the architectural studios at Shahrood University of Technology, located in Semnan Province, Iran. The selected studio space measured 9.80 by 9.80 meters and featured two windows, each three meters in length, located on the southern façade. The windows had a sill height of 1.2 meters. Interior light shelves were installed at a height of 2.5 meters, while the total height of the studio ceiling was 3.40 meters. The geographical location of the case study is presented in figure 1.

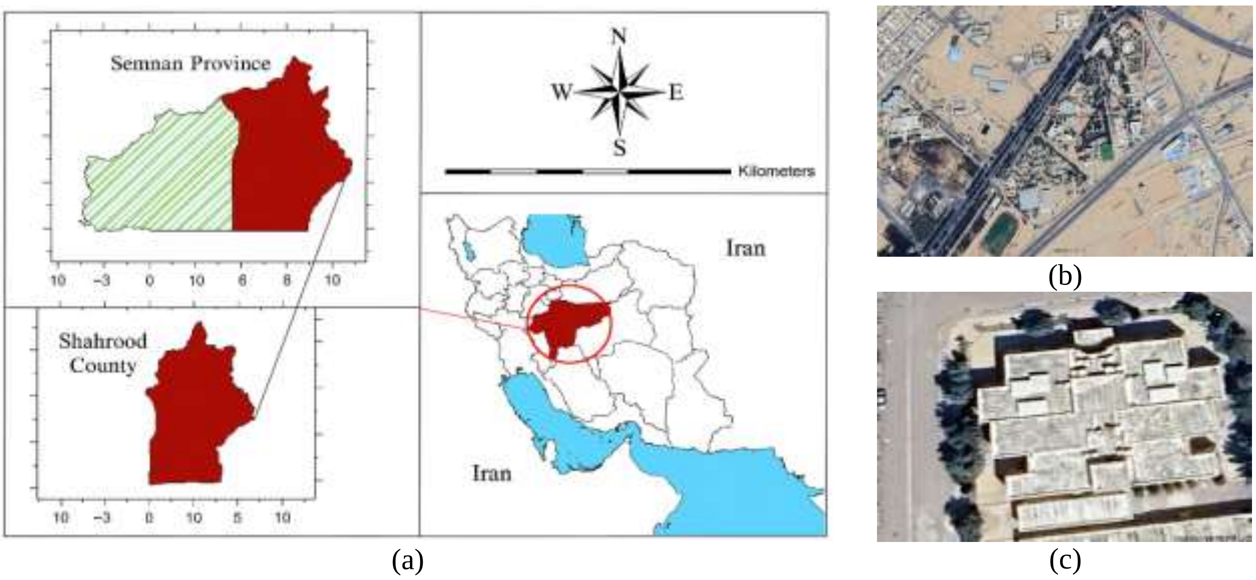


Figure 1. Geographical location of Shahrood in Iran (a), Shahrood University of Technology (b), and the location of the studied studio within the campus (c).

3. Lecture review

In this section, a number of studies related to light shelves are reviewed. Previous research has assessed multiple daylighting configurations to optimize indoor light quality. In one study, ten daylighting designs were compared with a baseline condition, using illuminance uniformity and luminance as key performance indicators. Although illuminance levels in the optimized scenarios decreased by 34.1% to 62.0% compared to the baseline, the uniformity of light distribution significantly improved, with increases of up to 178.6%. These findings highlight the importance of balancing light quantity and quality in daylight optimization strategies [29].

Some studies have focused on the impact of movable and perforated light shelves in different seasonal conditions. In one investigation, four designs—including a fixed light shelf and two movable ones with angles ranging from −10° to 30°—were analyzed across winter, spring, and summer. The proposed perforated light shelf design aimed to reduce wind pressure effects while maintaining daylight performance. Results showed that although the perforated shelves led to an increase in lighting energy consumption by up to 48.3% compared to non-perforated shelves, they also offered significant energy savings—up to 74.0%—compared to configurations without any light shelf or with a fixed horizontal one [30].

In efforts to simultaneously address cooling and lighting efficiency, researchers have examined hybrid shading systems incorporating internal light shelves. One such study evaluated seven design scenarios and identified that a configuration with a 2-meter overhang, a 0.6-meter light shelf, and a 30-degree angle yielded the best results. This setup achieved a combined reduction of lighting and ventilation energy consumption by up to 31.2%, demonstrating the potential of integrated shading strategies for improving energy performance [31]. The integration of photovoltaic technology into daylighting systems has also been explored. A study introduced a light shelf design that partially incorporated solar modules to enable both daylighting and electricity generation. Four designs were tested across different seasons, and the results emphasized that optimizing the tilt angle and solar panel coverage can enhance overall energy performance. However, increased coverage of the photovoltaic panel was associated with reduced lighting uniformity, pointing to a trade-off between power generation and visual comfort [32]. Some investigations have examined the application of light shelves in high-rise buildings with sloped windows. In one study, four combined internal and external shelf configurations were evaluated for their impact on daylight penetration and energy efficiency. The results showed that angled light shelves effectively reflected daylight into interior spaces even when installed on sloped façades. The configuration led to a 34% improvement in daylight performance and reduced energy consumption by over 25%, highlighting the adaptability of angled shelves for non-vertical window applications [33].In previous studies, various daylight control strategies have been investigated to enhance visual comfort and energy performance in educational spaces. One such study explored the effectiveness of combining curved light shelves, semi-transparent ceilings, and diverse window configurations in classroom environments. A total of fifty-five daylighting scenarios were evaluated based on illuminance levels and illuminance uniformity, using the existing classroom design as a baseline. The findings indicated that while the absence of a light shelf yielded the highest illuminance, it was associated with lower uniformity. The integration of light shelves and semi-transparent ceiling structures enabled all tested configurations to surpass the minimum standard illuminance of 300 lux. Among the evaluated options, the configuration featuring an upward-curved external light shelf, a downward-curved internal light shelf, a 3×6 meter semi-transparent ceiling, and a window divided into four horizontal and six vertical sections, demonstrated the highest performance in terms of both illuminance and uniformity ratio [34]. Furthermore, table 1 compiles a number of previous studies, detailing the evaluated parameters and the key performance indicators used in their assessments.

4. Material and Methods

Several criteria exist for assessing the amount of light in a space, including lighting uniformity (Uo), daylight illuminance (Ep), daylight factor (DF), daylight autonomy (DA), spatial daylight autonomy (sDA), continuous daylight autonomy (cDA), and useful daylight illuminance (UDI). The most commonly used metric among these is illuminance. In order to select an appropriate indicator for evaluating daylight, studies conducted in this field over the past decade were reviewed.

In the present study, illuminance has been used as the primary criterion to evaluate the impact of the

selected strategy. The frequency distribution related to this criterion is presented in table 2.
Illuminance is one of the key metrics for evaluating daylight performance. This criterion is measured in physical units such as lux (lx) and helps assess the quality and efficiency of lighting in different environments. It also represents the lighting levels within the built environment.
As mentioned earlier, illuminance at a point p on a given surface is a physical quantity measured in lux. It is defined as the ratio of the luminous flux incident on an infinitesimally small area (*dArec*) adjacent to the point of interest to the area of that surface [45].

$$EP = \frac{DF}{DA_{REC}} [LX] \quad (1)$$

Field measurements were conducted at nine specific points during two distinct periods: from May 7th to May 20th, and from July 3rd to July 10th, at four different times: 9 AM, 11 AM, 1 PM, and 3 PM. Before the daylight measurements, all windows were thoroughly cleaned to ensure maximum daylight penetration, and curtains were fully drawn aside to eliminate any obstruction. Furthermore, during the second phase, when the light shelf was intended to be evaluated, the light shelf system was properly installed to assess its impact on indoor daylight levels at the designated measurement points. Figure 2 illustrates the architectural plan and section of the case study.

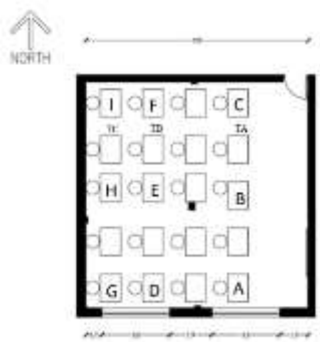
Table 1. Examples of studies conducted on the light shelf.

Ref	Authores(years)	Variable	Primary results
[19]	Meresi (2016)	Width, Heights, Angle , State	Indoor illumination distribution, lighting energy
[32]	Lee (2019)	Width, Reflectance, Angle, Height	Energy Saving, Illuminance
[35]	Bahdad et al. (2020)	State, Width, Height, Angle	Energy Saving, SDA, UDI
[36]	Bahdad et al. (2020)	Orientation, Width, Height, WWR, Sky type, Floor, Internal walls, Ceiling, Glass transmittance	Energy Saving, UDI
[37]	Lee et al. (2022)	Width, Angle	
[38]	Sabbagh et al. (2022)	Width, Height, Angle, State, material	Illuminance
[39]	Ziaee and Vakilnezhad (2022)	Light shelf height, length of the exterior part, length, angle of inner part , WWR	UDI, SDA, ASE, Thermal Comfort
[40]	Hosseini and Sheikh Ansari(2022)	State, Orientations, Width	Illuminance
[41]	Jung and Lee(2023)	Width, Angle,,Height	illuminance distribution, Uniformity
[42]	Sharifian et al.(2024)	Height Light shelf, Position Light shelf, Angle, Material, Depth, Glazing	Energy saving, Glare, UDI
[43]	Keshtkar and Ahmadian (2024)	position light shelves , deep windows	EUI, UDLI, UDI, energy consumption
[44]	Zhao et al. (2024)	Reflectance , angle	Uniformity, Energy Saving

Table 2. Frequency distribution of illuminance indicator in the past decade.

year	Number of articles	Repetition of illuminance parameter	Frequency percentage
2016	7	3	43%
2017	6	3	50%
2018	4	2	50%
2019	2	1	50%
2020	4	2	50%
2021	2	0	0%
2022	5	1	20%
2023	2	2	100%
2024	9	4	44%
2025	5	3	60%

For measuring the illuminance levels at various points with their images provided in figure 2, a calibrated lux meter was used. The device was calibrated prior to the measurements to ensure accuracy, and its model is provided in the figure 3.



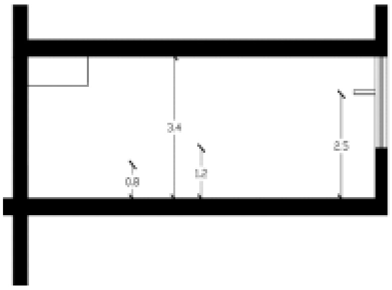


Figure 2. Plan (a) and section models studied (b).

DT 856A LED Light Meter.

Figure 3. Lux meter mod.

After completing the field measurements with their images provided in figure 4, the next step was to simulate the measured space to evaluate its daylight performance. The modeling process was carried out using Rhinoceros software in combination with the Grasshopper plugin. Daylight simulations were performed using the Radiance engine through the Honeybee and Ladybug plugins (version 1.6.0), providing accurate climate-based daylight modeling. Additionally, the Radiance settings applied in this study, based on the guidelines provided in reference [46], are compiled and presented in table 3. The simulation was conducted on a 20×20 grid at a working plane height of 90 centimeters. To ensure the accuracy of the simulation, material properties and specifications of the elements within the space were specified, as summarized and presented in table 2. Subsequently, after conducting the field measurements and performing the simulation, a validation process was carried out. The differences between the measured and simulated values at all nine points were found to be below 15%, indicating an acceptable level of accuracy. The visual representations of these diagrams are provided in figure 5.

Figure 4. Images of the studio space during field measurements.

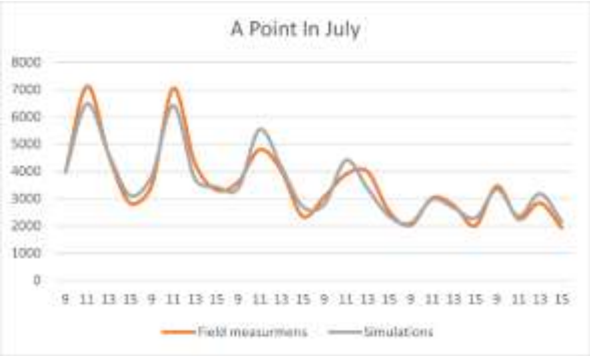
This confirms the reliability of the simulation results. To investigate the improvement of daylight performance, several variables were considered for scenario development. These variables included the width, angle, reflectance, and height of the light shelf, the ceiling reflectance, and the visible light transmittance of the glazing. For each variable, specific scenarios were defined and are presented in table 4. In total, 1,620 scenarios were examined, and finally, the characteristics of the selected scenario aimed at enhancing daylight availability are presente. In total, 1,620 scenarios were examined, and the characteristics of the selected scenario, aimed at enhancing daylight availability, are presented. These scenarios are provided in table 5.

Table 3. Radiance parameter values.

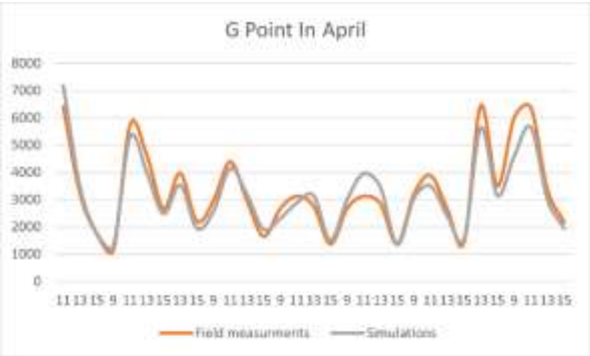
Parameters	Values
aa	0
ab	5
ad	4096
dc	1
st	0
lw	0
as	1024
ar	0
lr	16
dt	0

Table 4. Reflection coefficient of the surfaces.

Classroom surfaces	reflection coefficients
Internal wall	0.85
Ceiling	0.85
Floor	0.5



(a)



(b)

Figure 5. Matching diagram of field measurement and simulation at point A in July (a) and point G in April (b).

Table 5. Variables for evaluating optical shelf performance.

Variables	Range
Width (m)	0.15, 0.3, 0.6, 0.9 0 (internal type)
Angle	-30, -15, 0, 30, 15
Light shelf Reflectivity	0.75, 0.85, 95
Height (m)	1.9 above the floor
Ceiling reflectivity	0.65, 0.75, 0.85
Transmission	0.7, 0.8 , 0.9

The process of utilizing the software and plugins is illustrated in figure 6. The Ladybug plugin was used within the Rhino-Grasshopper platform to evaluate the solar radiation and daylight performance at the case study location. Ladybug is a powerful environmental analysis tool that allows users to process climate data (EPW files) and generate various analytical visualizations, including sky dome diagrams, sun path trajectories, and radiation analysis maps. This study used the sky dome diagram to illustrate the annual distribution of solar radiation across the hemispherical sky vault The visual representations of these diagrams are provided in figure 7.

This visualization highlighted the contribution of different portions of the sky to the total incident radiation, offering valuable insight into dominant solar paths and prevalent sky conditions at the site. The integration of Ladybug with Rhino provided a seamless workflow, enabling both environmental analysis and design development within a single parametric platform. The selection of Ladybug was driven by its high flexibility, compatibility with architectural design processes, and ability to deliver accurate and visually comprehensible outputs essential for daylight and radiation analysis.

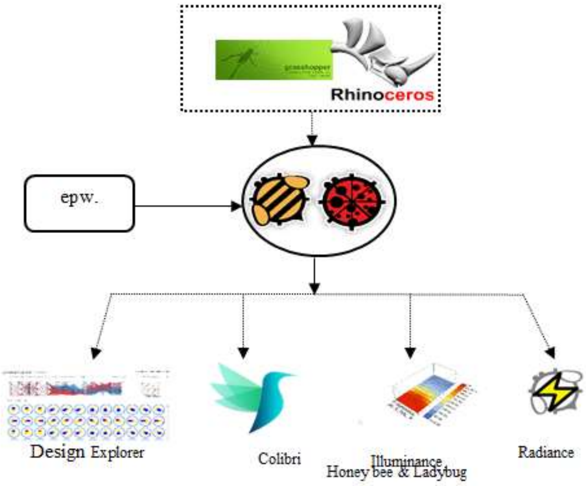


Figure 6. Software and plugins used in the research.

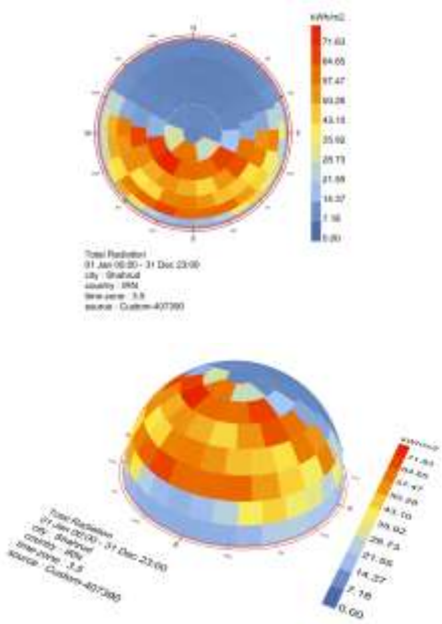


Figure 7. Shahrood city sky dome.

Figure 8 illustrates the overall methodology of the research. Rhino 7 was selected as the primary modeling platform among the software tools examined in this study due to its robust parametric design capabilities and seamless integration with environmental analysis plugins. For daylight performance evaluation and solar radiation analysis, Ladybug and Honeybee 1.6.0 were employed, both of which are widely recognized for their accuracy and efficiency in handling climate-based simulations. These plugins were coupled with the Radiance simulation engine, a validated ray-tracing software known for its precision in predicting light distribution and illuminance levels. The choice of these tools was based on their extensive use in recent scientific literature, particularly in the field of daylighting and energy performance analysis, ensuring both methodological reliability and comparability with existing studies.

Furthermore, to systematically explore a wide range of design alternatives and enhance the accuracy of parametric investigations across various time intervals, the Colibri plugin was utilized. Colibri enabled automated iteration through multiple design scenarios, streamlining the process of generating, running, and evaluating numerous simulation cases. In total, 1620 design variants were analyzed, including various parameters in the table. The final results were visualized and documented using Design Explorer, an interactive web-based platform that facilitates the comparative analysis of large datasets through dynamic graphical representation. This approach ensured a comprehensive assessment of daylight performance metrics, allowing for an informed evaluation of the impact of design modifications on the overall environmental quality of the studied space.

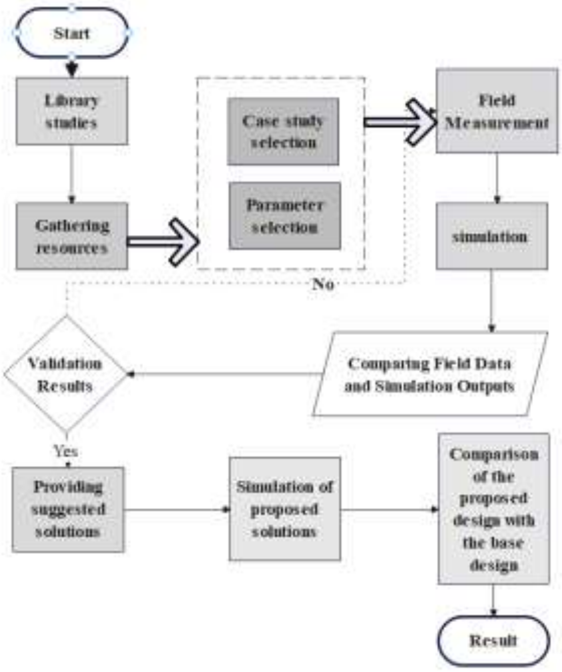


Figure 8. Research process.

5. Results

Three measurement points were deliberately selected on desks A, B, and C, representing the darkest work surfaces within the analyzed space. The selection of these particular desks was based on preliminary daylight assessments, which identified them as critical low-light zones with the greatest potential for improvement through the introduction of a light shelf system. This targeted selection ensured that the effectiveness of the proposed daylighting strategy could be thoroughly evaluated in the most challenging areas, thus providing a more realistic assessment of its practical performance.

The average illuminance across these desks was analyzed during the summer solstice, utilizing the results derived from 1620 parametric simulation scenarios. These scenarios systematically examined variations in spatial configuration, material reflectance, and time intervals, offering a comprehensive analysis of daylight behavior under diverse conditions.

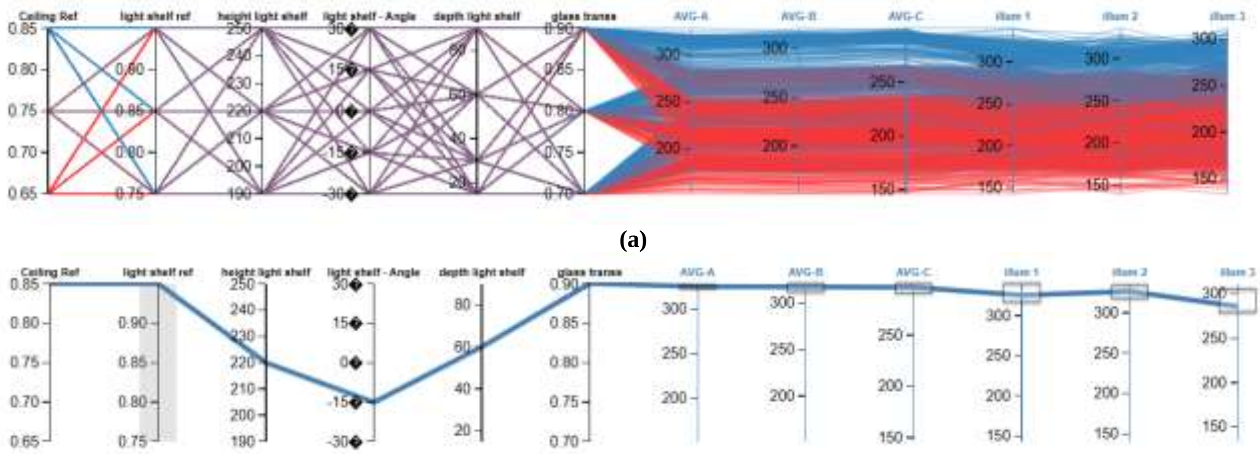
The results revealed that the highest illuminance levels, relative to the baseline (existing condition), occurred at 9:00 AM and 12:00 PM, coinciding with favorable solar angles and maximum daylight penetration. These peak values were carefully documented and presented in dedicated tables for direct comparison.

Furthermore, in order to quantify the improvement achieved by the proposed design modification, the percentage increase in illuminance was calculated for each configuration and reported in the corresponding tables. This comparative analysis clearly demonstrates the extent to which the implementation of the light shelf system enhances the overall daylight performance, thereby improving the environmental quality of these critical work surfaces.

At 9:00 AM on June 21st, within the three target points located at the end of the space, as well as the average illuminance of the final three desks, an increase in daylight availability was detected after the application of the predefined variables, as outlined in the following section. In total, 1620 scenarios were evaluated by systematically altering the key design parameters related to the light shelf configuration. Through this comprehensive parametric analysis, the optimal scenario, which maximized daylight penetration into the target points, was identified. The detailed characteristics of this optimized light shelf configuration are summarized in figure 9. Additionally, table 7 presents the difference between the baseline condition and the selected scenario.

As presented in table 6, at 9:00 AM on June 21st, the optimal configuration for the light shelf was found to have a downward tilt angle of -15 degrees. This configuration directly responds to the relatively high solar altitude in summer, where the sun's rays enter the space at a steeper angle.

The downward inclination of the light shelf facilitates deeper penetration of daylight into the interior, effectively enhancing daylight distribution across the target work plane. In this optimized scenario, the width of the light shelf was set at 60 centimeters, while its installation height was recorded at 220 centimeters above the floor level.



(a)

(b)

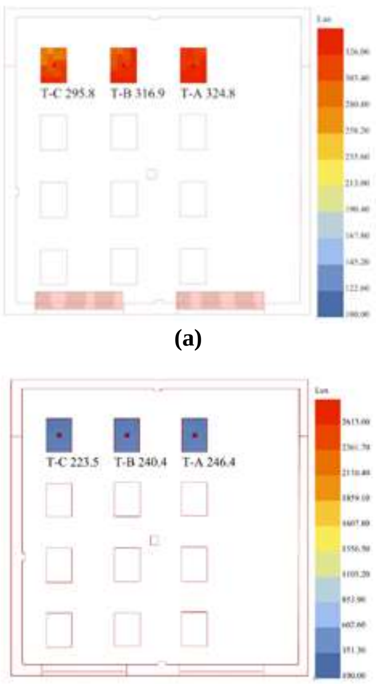
Figure 9. (a) 1620 scenario chart - (b) Selected scenario chart.

Table 6. Selected scenario specifications.

Variables	Coefficients
Width (m)	0.6
Angle	-15
Light shelf Reflectivity	0.95
Height (m)	2.20
Ceiling reflectivity	0.85
Transmission	0.9

Table 7. Difference between the base case and the selected scenario.

Difference in percentage	
Table A	30
Table B	30
Table C	24
Average table A	24
Average table B	24
Average table C	24



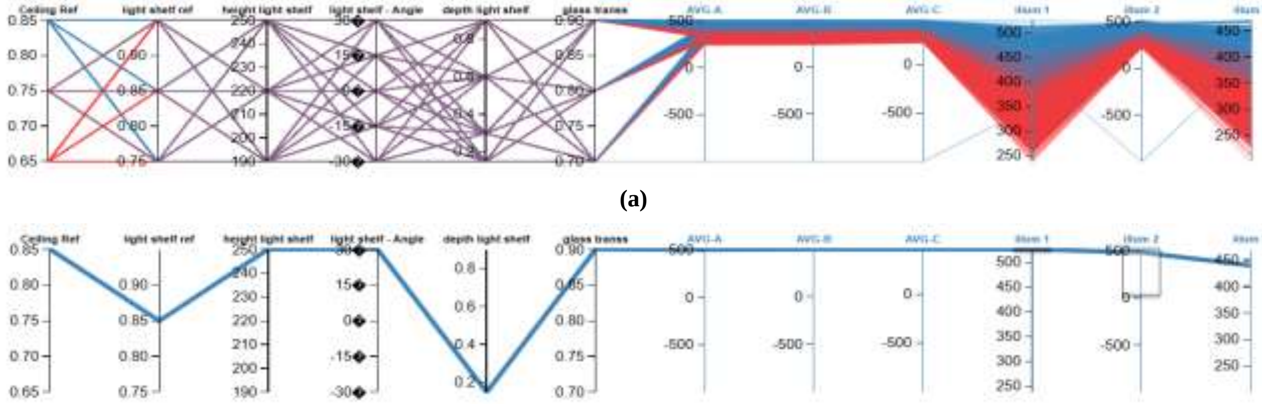
(a)

(b)

Figure 10. Difference between the base case (b) and the selected scenario (a).

As illustrated in figure 10, following the transfer of data obtained from field measurements under baseline conditions, the recorded illuminance levels at the designated measurement points on the selected desks were documented as follows: 227 lux for desk TA, 228 lux for desk TB, and 216 lux for desk TC. Additionally, the average illuminance values across these desks were calculated as 246 lux, 240 lux, and 223 lux, respectively.

Conversely, under the optimized scenario, in which the light shelf was installed and the selected parameters were applied, the illuminance levels at the same measurement points increased to 325 lux for TA, 325 lux for TB, and 285 lux for TC. Similarly, the average illuminance values for the same desks were recorded as 324 lux, 316 lux, and 295 lux, respectively. The relative differences (expressed as percentages) between the measured values under baseline conditions and those under the optimized scenario are presented in table 6, providing a quantitative comparison to illustrate the influence of light shelf installation and parameter adjustments on daylighting performance within the analyzed space.



(a)

(b)

Figure 11. (a) 1620 Scenario chart - (b) Selected scenario chart.

At 12 PM on June 21st, in three endpoint locations, along with the average illuminance of the three end tables, an increase in daylight was observed, as shown in the results presented below. Among the 1620 scenarios provided as variables, the optimal condition resulted from the changes in the mentioned parameters, which are outlined as follows. In this regard, In this regard, figure 12 presents the chart illustrating the 1,620 generated scenarios specifically for 12:00 PM, alongside the chart representing the selected optimal scenario for this time.

s set at 60centimeters, while its installation height was recorded at 220 centimeters above the floor level. Upon the completion of data transfer under baseline conditions, the measured light intensity at the designated points on tables TA = 381, TB = 346, and TC = 339 was documented, with the corresponding mean light levels calculated as TA = 377, TB= 363, and TC = 328, respectively. However, subsequent to the installation of the reflector and the implementation of the defined.

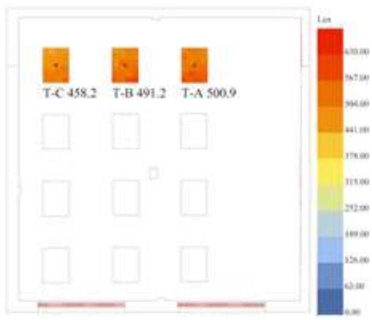
The characteristics of the selected scenario are presented in Table 8. As illustrated in figure 12, a notable increase in light intensity was observed at the scenario points in the selected scenario, with recorded values of 525 lux for TA, 484 lux for TB, and 439 lux for TC. Simultaneously, the average illuminance levels increased to 500 lux, 491 lux, and 458 lux for TA, TB, and TC, respectively. The percentage differences between the baseline and the selected scenario values are detailed in table 9.

Table 8. Selected scenario specifications.

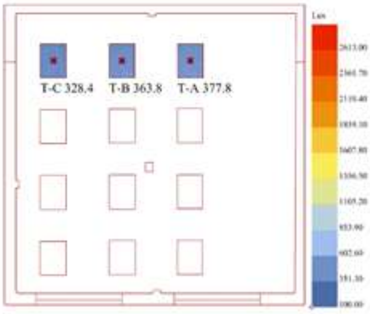
Variables	Coefficients
Width (m)	0.15
Angle	30
Light shelf Reflectivity	0.85
Height (m)	2.50
Ceiling reflectivity	0.85
Transmission	0.9

Table 9. Difference between the base case and the selected scenario.

Difference in percentage	
Table A	27
Table B	29
Table C	23
Average table A	25
Average table B	26
Average table C	28



(a)



(b)

Figure 12. Difference between the base case (b) and the selected scenario (a).

6. Discussion

In this study, the selected scenario was optimized to enhance daylight penetration and distribution within the interior space. To assess the effectiveness of these modifications, a comparative analysis was conducted against the scenario exhibiting the lowest illuminance levels at 9 AM on June 21. This comparison underscores the impact of design modifications on improving daylight availability and distribution.

The analysis revealed that several key adjustments significantly influenced the distribution of daylight. Increasing the ceiling reflectance to 0.85 contributed to enhanced reflection and diffusion of natural light, while raising the light shelf reflectance to 0.95 further optimized daylight redirection. Additionally, modifying the light shelf height from 250 cm to 220 cm and adjusting its angle from 15° to -15° facilitated a more effective distribution of light into the interior space rather than merely reflecting it upward. Expanding the light shelf depth from 15 cm to 60 cm further improved the uniformity of daylight distribution, minimizing unwanted shadows and ensuring a more balanced illumination across the space. Furthermore, increasing the glass transmittance from 0.7 to 0.9 permitted a greater influx of natural light, thereby elevating overall indoor illuminance levels.

A quantitative assessment of these modifications demonstrated that in the optimized scenario, illuminance values at different measurement points ranged between 295.8 and 324.8 lux, whereas in the scenario with the lowest illuminance, these values varied from 177.8 to 191.1 lux. This considerable increase confirms the efficacy of the applied modifications in enhancing daylighting performance.

The findings indicate that adjustments to surface reflectance, light shelf geometry, and glass transmittance play a pivotal role in improving daylight performance at 9 AM on June 21. However, in certain areas, the increase in illuminance may necessitate further assessment to mitigate glare and enhance uniformity. To refine the performance further, adjusting the light shelf angle within the range of 0° to -10° may provide an optimal balance between daylight redirection and glare prevention.

A comparative analysis of two light shelf configurations at 12 PM on June 21 revealed distinct differences in daylighting performance. The key variables influencing daylight penetration included ceiling and light shelf reflectance, shelf height and angle, shelf depth, and glass transmittance. The first scenario, characterized by a light shelf depth of 0.15 meters, a reflectance of 0.75, and a height of 220 cm, resulted in lower overall illuminance levels. With a ceiling reflectance of 0.65 and glass transmittance of 0.7, this configuration produced an average illuminance of approximately 242.5 lux at the front of the space, gradually decreasing towards the interior. The shallow depth of the light shelf limited its capacity to direct light deeper into the space, thereby restricting its effectiveness.

Conversely, the second scenario demonstrated notable improvements due to increased ceiling reflectance (0.85), glass transmittance (0.9), and light shelf height (250 cm). Despite maintaining a light shelf depth of 0.15 meters, these modifications resulted in significantly enhanced daylight penetration and uniformity. The illuminance levels in this scenario ranged from 500 lux near the window to 450 lux in deeper interior zones, highlighting a substantial improvement in daylight accessibility.

While higher reflectance values facilitated improved light redistribution, the limited shelf depth of 0.15 meters remained a constraint. Typically, deeper light shelves (0.3 to 0.6 meters) provide greater potential for redirecting daylight and mitigating glare. However, the increased glass transmittance (0.9) compensated to some extent by allowing more daylight to enter directly.

Despite the observed improvements in illuminance, the potential for glare and non-uniform light distribution warrants careful consideration. Elevated illuminance levels near the window suggest a risk of over-illumination, which may compromise visual comfort. To achieve a more balanced performance, it is recommended that glass transmittance be adjusted to moderate values (e.g., 0.8) or that the light shelf angle be dynamically modified to optimize light distribution while mitigating glare.

Ultimately, while the second scenario demonstrated superior daylighting performance, further refinements in light shelf depth and glass transmittance could enhance both illuminance levels and overall visual comfort. These findings emphasize the intricate relationship between material properties and geometric configurations in effective daylighting strategies.

7. Conclusion

The analysis of daylighting conditions at 9 AM on June 21 confirms that the implemented modifications significantly improved the indoor illuminance levels compared to the baseline scenario (without a light shelf). In the baseline case, the average illuminance at measurement points was 223.5–246.4 lux, whereas in the optimized scenario, the values increased to 295.8–324.8 lux. This represents an overall increase of approximately 31% in daylight availability.

Key Improvements and Their Contributions:

1. Light shelf Integration:
   - The absence of a light shelf in the baseline scenario resulted in lower illuminance levels due to limited redirection of daylight into the space.
   - The introduction of a light shelf with optimized reflectance, height, and angle led to a significant enhancement in daylight penetration.
2. Surface Reflectance Adjustments:
   - Increasing ceiling reflectance (from 0.75 to 0.85) and light shelf reflectance (from 0.75 to 0.95) improved the light redirection and diffusion, contributing to a 10–15% increase in measured illuminance.
3. Glass Transmittance Enhancement:
   - Raising the glass transmittance from 0.7 to 0.9 facilitated a more efficient daylight intake, resulting in higher lux values across all tested points.

Final Assessment and Recommendations:

The comparative analysis demonstrates that the applied modifications successfully enhanced daylight availability by up to 31%, ensuring a brighter indoor environment. However, to further refine daylight uniformity and minimize glare, future studies could explore:

- Fine-tuning the light shelf angle between -5° to -10° for optimal light redirection.
- Evaluating dynamic shading strategies to balance daylight access while preventing excessive brightness variations.

This study highlights the effectiveness of daylighting strategies in improving indoor lighting conditions, emphasizing the importance of light shelf optimization and surface reflectance enhancements in sustainable daylight design.

The comparative analysis between the baseline and optimized light shelf configurations highlights the substantial impact of material reflectance, shelf height, and glass transmittance on daylight performance. In the baseline scenario, the average illuminance values were recorded as TA = 377 lux, TB = 363 lux, and TC = 324 lux. In contrast, the optimized configuration significantly improved daylight distribution, resulting in illuminance levels of TA = 500 lux, TB = 450 lux, and TC = 400 lux.

When evaluated in percentage terms, the optimized scenario exhibited an increase of approximately 32.6% at TA, 23.9% at TB, and 23.5% at TC, demonstrating a marked enhancement in daylight penetration and uniformity across the interior space. These improvements were primarily driven by the increased ceiling reflectance (from 0.65 to 0.85), glass transmittance (from 0.7 to 0.9), and light shelf height (from 220 cm to 250 cm). Notably, despite maintaining a light shelf depth of 0.15 meters, the modifications effectively mitigated some of the limitations of shallow light shelves.

However, while higher illuminance levels improve daylight accessibility, the potential for glare and over-illumination, particularly near the window, remains a concern. The optimized configuration produced high illuminance values close to 500 lux, which, under certain conditions, may exceed recommended visual comfort thresholds. Further refinements could be considered to balance daylight availability and comfort, such as adjusting glass transmittance to moderate levels (e.g., 0.8) or incorporating a dynamic light shelf angle.

In conclusion, this study underscores the critical role of design parameters in daylighting performance. The results demonstrate that strategic modifications to material reflectance and shelf height can significantly improve daylight penetration, even when light shelf depth remains limited. These findings offer valuable insights for daylight-responsive design strategies, emphasizing the need for an integrated approach that optimizes both illumination levels and occupant comfort.

On June 21st, at 9:00 AM and 12:00 PM, assessments were conducted to select the optimal daylighting scenario and determine the most effective light shelf configuration for enhancing daylight penetration. In both selected scenarios, the light transmittance coefficient of the glazing and the ceiling reflectance were set at 0.9 and

0.85, respectively. However, the remaining parameters differed between the two.

At 9:00 AM, the angle of the light shelf was set at -15°, whereas by 12:00 PM, it had increased to 30°, transitioning from a steep angle to a wider one, thereby allowing greater daylight entry. To compensate for the steeper morning angle, the height of the light shelf at 9:00 AM was lower than at noon, aiming to direct the maximum amount of light into the deeper parts of the studio space.

Accordingly, the reflectance coefficient of the light shelf was higher at 9:00 AM compared to 12:00 PM, to enhance internal reflection and ultimately improve illuminance levels. The final parameter examined was the width of the light shelf: it measured 60 cm at 9:00 AM and decreased to 15 cm by noon. This indicates that a larger surface area of the shelf was exposed to daylight in the morning, thereby increasing reflectance.

In conclusion, it can be stated that variations in the range of each parameter may lead to the selection of a different optimal light shelf configuration, and the chosen scenarios are not absolute. For future research, the use of dynamic light shelves in combination with innovative technologies is recommended.

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