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RESEARCH ARTICLE

DETERMINATION OF THE PERFORMANCE OF LIGHT SHELVES FOR MORE EFFECTIVE BENEFIT FROM DAYLIGHT IN BUILDINGS

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ABSTRACT

Studies on the efficient use of daylight in sustainable architectural design and energy conservation are increasing. Indoor lighting methods include daylighting, artificial, and integrated lighting. Basic priorities in lighting are such as "effective use of daylight", "uniform illumination in space", "glare control", "visual connection with the external environment" and "daylight harvesting." Advanced contemporary systems include light shelves and light tubes. Light shelves consist of horizontal or slightly angled elements that can be applied to the inner and outer surfaces of the window openings, usually at eye level, to block the daylight or to reflect it to the ceiling, integrated with the facade, or added later. In this research, light shelves, which is one of the advanced daylighting methods, are emphasized. Daylight analysis method was carried out with the help of a physical model and computer simulation techniques using DiaLux software. To effectively utilize the daylight factor in the internal volume through light shelf, certain parameters such as the height and angle of the light shelf, date and time, and direction of the room's opening, play a crucial role. In daylight analyzes, these parameters were subjected to experimental testing both in physical models and through computer simulations. As a result of the comparison of the obtained data, alternatives that will provide the opportunity to benefit from daylight in the most effective way have been identified. The results obtained have unique value and widespread impact in terms of sustainable architecture and energy saving. The study's originality lies in its specific measurements of the latitude in which it is located, as it is the first time the study is conducted under Eskisehir's conditions. In addition, the examination of the advantages and disadvantages of the light shelf in specific combinations is another original side of the project.

Keywords: Light shelf, Daylight, Efficiency, Illumination, Reflection, Architecture

1. INTRODUCTION

Architectural design has undergone a significant transformation in recent years, owing to the escalating concerns surrounding energy efficiency and environmental sustainability. While technological advancements have brought about improvements in artificial lighting, the quality of illumination provided by daylight remains unparalleled [1]. Daylight is favored by users for the numerous psychological and physiological benefits it offers, including enhanced productivity, well-being, and energy savings. To leverage the advantages of daylight, architects and lighting designers are developing efficient systems for optimal utilization of daylight, leading to improved lighting quality, energy efficiency, and a more sustainable built environment [2]. The integration of daylighting strategies in building design is a fundamental aspect of architectural lighting. This technique is typically accomplished through the installation of windows or skylights, which enable the effective use of daylight while providing a visual connection to the external environment. Critical considerations in daylighting design include the achievement of uniform illumination, the minimization of discomfort glare, and the provision of sufficient light to interior spaces that lack adequate daylight. Advancements in daylighting technology, such as reflective or directional systems, are being developed to illuminate closed volumes that are inaccessible to daylight or have never been exposed to it. Yener suggests that,

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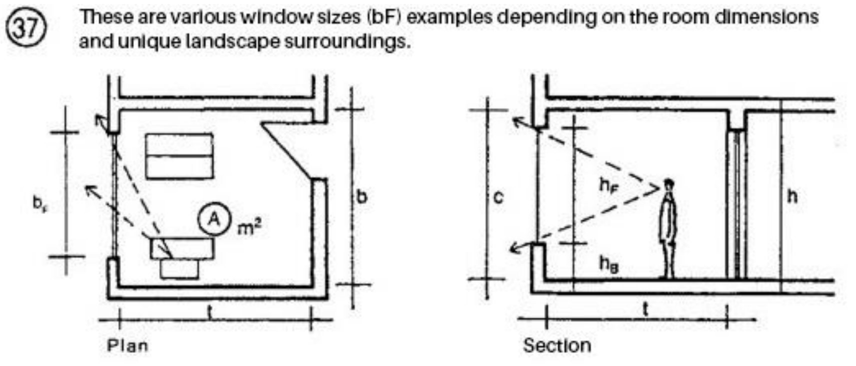
as many states, it is of great importance to illuminate buildings with daylight in terms of sustainable architecture and energy saving. In this sense, the effective use of daylight and the designs aimed at reducing lighting energy consumption are among the priority issues of today's architecture. Moreover, light shelves are recognized as a sustainable design strategy for achieving Leed Point System accreditation, specifically in the "internal quality: daylight and landscape" category. These systems effectively redirect daylight deeper into the building, promoting energy efficiency and reducing the need for artificial lighting [3]. According to Kılıç Demircan and Gültekin, parameters that are effective in the process of energy-effective building design; are the location of the building, building intervals, orientation of the building, building form, building shell, natural ventilation order [4]. In addition, they argued that by using these parameters, it is possible to design buildings effectively through passive and active systems.

Architectural design professionals who focus on the interplay of natural light and building form, often rely on the LEED-NC (version 2.2) Indoor Environmental Quality section's daylight and views credits 8.1 and 8.2 for a performance metric. These credits are crucial in determining the effectiveness of a building's daylighting design. The primary objective of daylighting in architecture is to maximize the effective use of natural light while providing homogeneous lighting in the space and controlling discomfort glares to the eye. Furthermore, daylighting design should provide visual relationships with the external environment. Architects employ various systems to illuminate closed volumes that cannot receive sufficient daylight or have never been exposed to natural light. These systems include those that reflect, direct, or carry daylight to the desired spaces [5]. Adequate and homogeneous daylighting is primarily related to window dimensions. As stated in Neufert, the status of the windows, sizes, and type in the room, affects the influx of daylight. In DIN 5034 standards, suitable window sizes are identified for living and study rooms. According to the aforementioned standards, the ratio of window width to wall width was recommended for maximum 55%. Considering the room area, 1/8-1/10 of this area is recommended to leave a window area. In case of high room height (2.5-3,50m), the window area (Figure 1) was deemed appropriate by less than 30% of the room area [6]. According to Reinhart, in the realm of architectural design, the LEED reference guide is a vital resource for implementing sustainable strategies. One critical aspect of sustainable design is daylighting, which involves the use of natural light to illuminate interior spaces. However, the guide notes that glare control is a common challenge in daylighting strategies and suggests the use of shading devices to mitigate this issue. Beside that, the guide does not provide detailed guidance on how to effectively employ such solar control devices, nor does it present any metrics for measuring their effectiveness [7].



Living rooms	Study rooms		
According to DIN 5034 c ≧ 2,20 m h_B ≤ 0,90 m b_F ≧ 0,55 .b (at least)	Like living rooms according to DIN 5034 h ≤ 2.50 m t ≤ 6,00 m A ≦ 50 m²	According to DIN 5034 < 3,50 m. Window area > 30% b x h	h > 3,50 m c . hB ≧ 1,30 m hB ≤ 0,90 m hB ≤ 0,55 m

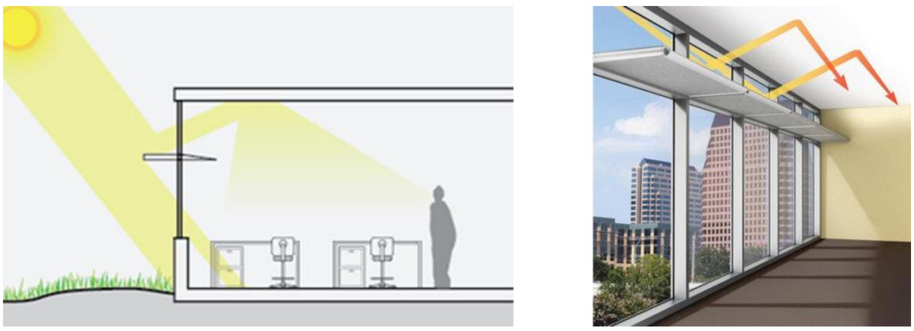
Figure 1. DIN5034 Window openings and room sizes are foreseen for different room dimensions [6].

According to Fabi, Andersen, Corgnati and Olesen; factors that influence occupant behavior can be categorized into five groups: physical environmental, contextual, psychological, physiological, and social factors. Physical environmental factors, such as temperature, air velocity, noise, illumination, and odor, play a crucial role in driving behavior and have a direct impact on energy consumption. Windows can help regulate these factors by providing natural light, ventilation, and views to the outside environment [8].

Contextual factors, such as the insulation of buildings, orientation of facades, heating system type, thermostat type, and more, can indirectly influence occupant behavior. Windows can play a significant role in regulating these factors and help create a comfortable indoor environment. Psychological factors, such as thermal comfort, visual comfort, acoustical comfort, health, safety, and other expectations related to indoor environmental quality, can also impact occupant behavior. Windows can provide natural light and views to the outside environment, which can promote positive behavior. Physiological factors, such as age, gender, health situation, clothing, activity level, and intake of food and beverages, play a significant role in determining the physiological condition of the occupant. Windows can promote a healthy indoor environment and positively influence occupant behavior. Social factors refer to the interaction between occupants, which can significantly influence behavior. Windows can create a sense of community and promote positive social interactions among occupants [8].

According to Erel [9], the windows have no characteristics to reach the depths of the room to the same extent. In order to deliver the light, the windows must be equipped with auxiliary optical elements.
This requirement leads to;
• Reduction of daytime use of artificial lighting or reduce to zero if possible and save electrical energy,
• Increasing interest in energy-active buildings as part of the sustainable architectural movement and designers' focus on the designs and solutions of such buildings,
• Providing enough daylight for insertion and distribution to spaces in order to change user needs,
• To be able to benefit from daylight and components in the most efficient way.

Erel suggests that in traditional architecture, daylighting systems rely on windows that have roof openings and reflective light shelves incorporated into them. With the development of technology, new materials and techniques have emerged. These new materials and technologies are called developed daylighting systems (Figure 2) which are used in traditional daylighting systems [10].



(a) **(b)**

Figure 2. Access to the interior of light through light shelves [10]. (a): section, (b): 3d image

In the realm of advanced daylighting systems, the light shelf plays a vital role in optimizing daylight distribution within a space. This architectural feature is typically a horizontally or sloping placed curtain within a window, designed to reflect incoming daylight onto the ceiling and back of the room. The result is a well-lit space that maximizes the use of daylight, providing a comfortable and energy-efficient environment. As a result, it is stated that the expected benefit depends on the characteristics of the reflective surface and the careful planning by Warrier and Raphael. Variables to determine the performance of a light shelf include the height, width, angle, and material of the shelf; appropriate variable control is required to maximize the performance of the light shelf. Warrier and Raphael, as a result of their model simulation study [11], they achieved an increase of approximately 21% in lighting using horizontal light shelves made of aluminum or glass mirror material. Their study comprises two segments. The initial segment is experimental and entails measurements on a scaled prototype. Regrettably, due to practical constraints, a full-scale prototype was unfeasible to construct. Moreover, the number of configurations that can be experimentally tested is restricted. Therefore, theoretical simulations were integrated into the experiments. The latter segment of the study conducted simulations through Radiance lighting simulation software. The conducted experiments have demonstrated that horizontal light shelves composed of aluminum or glass mirror can lead to an approximate 21% increase in illuminance. Additionally, by rotating the external light shelf, a nearly threefold increase in illuminance can be accomplished. Glass mirror is a superior material for a rotatable shelf when compared to aluminum. Using simulations, it has been determined that the majority of standard architectural spaces can benefit from such light shelves. The use of materials and software is assessed based on achieving maximum efficiency as a percentage. The results are not evaluated in terms of disadvantages, but the maximum efficiency is considered as the focal point of the project. However, if the shelves are planned to be mobile according to the arrival of sunlight, they stated that the lighting could be achieved three time efficient in the lighting.

Barker posits that within educational institutions and classrooms, a plethora of procedures can be executed seamlessly, with the ocular well-being of both staff and students being of paramount importance. However, it is stated that optimal illumination levels not only enhance the learning experience but also promote physical health and productivity among individuals by using light shelves in schools (Figure 3) [12].

Figure 3. Light shelf example at Roy Lee Walker Elementary School [13]

In their study by Kurtay and Esen, the light shelf settlements and yields for 30° and 45° latitudes, including Turkey, were investigated for different heights in a standard office unit. In the calculations, better results were obtained in the internal light shelf settlements in 30° and 45° latitudes under the specified conditions and appropriate shelf sizes were determined accordingly [14].

In the study of Meresi, the lighting performances of the light shelves placed in 6 different ways in a room environment of 7 x 7 meters were examined at different angles. As a result of the study, the shelves located at a height of 2.00 m from the floor, 0.80m (out of the building), 0.20m (internal) width, are operated between 10° and 20°; it has been revealed that it has achieved the best performance both in improving the distribution of daylight and protecting it from glaring [15].

After conducting a thorough literature review, it has become evident that the use of light shelves is imperative for effective daylighting in Turkey. The implementation of such studies is crucial for spreading awareness and promoting the use of light shelves in architecture. This research puts emphasis on the use of light shelves and aims to measure their effectiveness through computer simulation models and physical models. Through this research, lighting levels within a space have been determined. The light shelves, which utilize reflection values and have been recommended, were placed at varying angles of 0°, 10°, and 20°. By comparing the data obtained, alternative approaches were identified and suggestions were made to maximize the benefits of daylight. The most efficient light shelf was determined by testing various parameters. These findings hold significant value in terms of sustainable architecture and energy conservation. This study is particularly noteworthy as it is the first of its kind in Eskişehir, and includes specific measurements of the latitude.

2. EXPERIMENTAL METHOD AND THEORETICAL METHOD

The method of daylight analysis made with a physical model and computer simulation techniques. Furthermore, it explains the process of obtaining the constant parameters that were maintained throughout the experiments.

2.1. Site Surveying and Location Analysis

Architects require assistance to assess the daylighting performance of their buildings. Sky simulators are experimental tools that, when used with pyhsical models, allow for a tangible and intuitive method of approaching the issue. According to Michel and Scartezzini, standard artificial skies and their measurement technology have their limitations. They cannot accurately evaluate the building's performance under a non-standard sky luminance distribution (CIE sky models). Therefore, alternative systems that can reflect, direct or transport daylight are being developed to illuminate enclosed spaces that cannot receive adequate daylight or have never been exposed to it [16]. In this study, in order to evaluate the performance of the building correctly, in the computer simulation measurements, Eskişehir's sky values were taken from Dialux Evo. The values were obtained based on the dates and times of the physical model measurements.

Analyzing the effectiveness of daylighting can be accomplished through experimental measurements and computer modeling. Experimental measurements may be derived from either field measurements or scaled model tests. Chen Y., Liu, Pei, Cao, Chen Q. and Jiang say computer modeling has become an increasingly popular method for analyzing daylighting performance. This method allows architects and designers to simulate various lighting scenarios and make informed decisions based on the results [17].

In order to determine the performance of light shelves, it is necessary to determine the geography and climatic conditions. This study was conducted under the conditions of Eskişehir, which is located in 30° and 45° latitude in the temperate climate zone. In the days when the sky above Eskişehir was devoid of clouds, experimental studies were carried out measurements on the physical model with the help of

Luxmeter. Also, measurements made by computer modeling were analyzed and compared with the results of the physical model.

The computer simulation design of the building was measured according to the sky state of Eskişehir, which is located at 30° East longitude and 39° North latitude. The measurements were compared to the physical model, which was also evaluated in Eskişehir. All computer simulation measurements were conducted under the assumption of an open sky. The measurement location was determined to be the living room of a real house with a window opening of the same living room. The hall has a width of 420cm, a length of 667cm, and a height of 280cm. The dimensions of the window opening are 90cm in height, 140cm in width, and 180cm in length (Figure 4).

According to Selkowitz, Indoor and outdoor model testing are similar to mathematical or graphical daylighting design procedures. However, outdoor testing allows for evaluation under various sky conditions and unique environmental factors, while indoor testing is limited to artificial light sources. The main drawback of outdoor testing is the constantly changing nature of the sky, but it can be mitigated by conducting tests at different times of the day [18]. Furthermore, it is worth noting that the scaled model experiments conducted may not fully align with reality as the reflection values of the materials utilized may not be entirely compatible with the actual environment. To address this issue, the present study aimed to assess the efficacy of the light shelf in improving daylighting performance and compare the results with those obtained from computer simulations. The focus was on determining whether the light shelf height played a significant role in enhancing the daylighting performance of the space.

Among the many available software tools, there are some popular options such as Matlab, Ecotect, Dialux, Velux, Energy Plus, Radiance and Climate Studio. These programs are capable of measuring lighting systems in a computer environment [19]. Among these softwares, Dialux shows the light measurements made in a two-dimensional environment with the colors, isohips, and measurement points. This program is particularly suitable for this study as it provides point data information, which is essential for accurate comparison of computer simulation measurements with scaled model measurements.

Luxmeter was used in measurements with the physical model (Figure 5). DIALux evo software was used in computer simulation measurements. For the open and closed sky, the DIALUX program uses Krochmann's Zenit formula and can calculate the multiplier of the sunlight. When calculating daylight in the program, the daylight environment is added from the guide section. To achieve the correct sky condition in Dialux software, the software takes into account specific date and time information, as well as properties of the sky type DIALux evo software lets input the geographical location (latitude, longitude) and time data of a place to calculate this information for any direction. Additionally, it can be selected the geographical location and time period data for many cities worldwide from the software's library. [20].

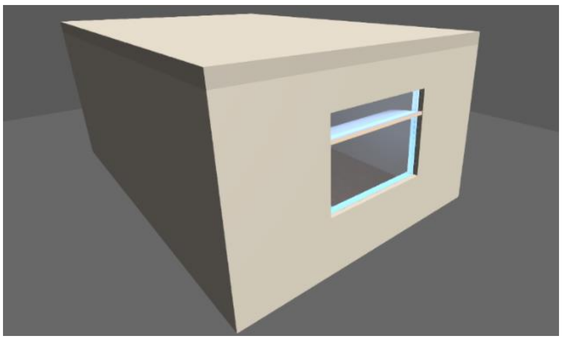


Figure 4. Assessing daylight performance with computer simulation model made in Dialux software.

2.2. Determination of Light Shelf Height with the Help of the Physical Model

To ensure the effectiveness of the light shelf, it is essential that it provides maximum daylight to the innermost areas of the room possible. In this way, the occurrence of shadowy areas in the depths of the room is avoided, and uniform illumination is achieved throughout the space. The height, which is one of the variables in this regard, is one of the parameters that affect light shelf efficiency the most. In this experiment, the optimal height value for this parameter was determined based on the physical model and then compared with the height value obtained through computer simulation measurements to determine its effectiveness. The model's data is compared within its own regions (Table 2-7). The impact of light shelf height on daylighting has been analyzed by comparing different heights of light shelf in specific areas of the model. The daylight analysis with the physical model was based on proportional and comparative results so the reflection values of the physical model's materials were ignored. The results obtained from the computer simulation showed similar proportional results as the physical model.The model was prepared at a scale of 1/10, with a width of 42cm, a length of 66.7cm, and a thickness of 5mm using MDF material (Figure 4). As a result of the physical model's 1/10 rate, the same rate of depth as real room sizes was formed. In this way, how much light shelf height affects the yield has been observed in a close way.

The effect of daylight on the ceiling in order to examine the performance of the light shelf in the deep areas of the room was measured with the help of the physical model and DiWU LX-1010B model Luxmeter (Figure 5). Measurements made with the help of a model and lux metre were compared with the measurements made in the computer environment and provided. Based on these proportional measurements, it is predicted that the light shelf will provide the maximum illumination performance on the ceiling when placed at a height of 185 cm.

(a) **(b)**

Figure 5. (a): Daylight measurement with the physical model. (b): The value obtained from the luxmeter.

In this experiment, light leaks were prevented by using black tape. The photometer sensor of the lux meter is attached to the ceiling and the display is on the outside. (Figure 5, 6). The measured light shelf's heights are indicated by height signs as shown in the photograph (Figure 6). In order to test different openings and shapes, all components of the model are capable of staying intact during both installation and transportation (Figure 6).

(a) **(b)**

Figure 6. (a): Inside the model. (b): Measurement areas and height signs of the light shelf.

2.3. Determining the Light Reflection Values of the Materials Used

In order to determine the performance of the light shelf and provide the closest values to the reality, should be determined the reflection values of the materials situated in the room and on the light shelf. The computer simulation measurement results were measured in lx. The specified reflection values were applied in Dialux software for computer simulation measurements are made. In the study, the contribution of light shelf performance to the uniformity of illuminance in the room was examined based on the specified parameters. The factors that the user can change (furnitures) in the room will not make a great change in these comparative measurements so the models don't contain these factors. The reflection values of the laminated door and window profiles are the same reflection value of the wall, so that the model doesn't contain laminated door and window profiles.

Light reflection values of the materials found in the study (ρ): Laminated door 0.7, wall 0.7, composite light shelf 0.8, aluminum window profile 0.75. The reflection factor values were determined depending on the surface colors of the ceiling, wall. According to the table below, the ceiling reflection value was determined as 0.7 (Table 1).

Table 1. Reflection Values of Materials [21]

Average Reflection Factor of the Ceiling	Average Reflection Factor of the Wall
0.80 ρ shiny white	0.70 ρ light colored
0.70 ρ light white	0.50 ρ dark colored
0.50 ρ dirty white	0.30 ρ darker colored

2.4. Size and Settlement of the Light Shelf

Ruck suggests that light shelves can be installed both on the outer and inner sides of the window in a light shelf application. To determine the appropriate width of light shelves, it is recommended to use a measurement that is at least equal to the window height, or at least 60 cm or more. Placing the light shelf inside of the window is more efficient to reflect the daylight to the deepest points of the volume, no matter what angle of light comes [22]. In this study, the same opinion was reached and the use of light shelf was made in the room. The width of the light shelf is considered to be 60 cm.

3. RESULTS AND DISCUSSIONS

In this part of the study, certain parameters are kept constant. While each measurement is made in computer simulation measurements, only one of the parameters is variable. In this way, the combination that provides optimum efficiency was found by using the most suitable parameters step-by-step. Measurements have been visualized in a work plane. The "work plane" is a flat surface positioned at a certain height from the ground, where daylight measurements are taken and displayed. The figures that represent the daylight measurements on this surface are referred to as the visualized work plane.

3.1. Determining the Light Reflection Value of the Light Shelf

The fact that the daylight reaches deep areas and provides uniform lighting is an indicator showing the efficient use of the light shelf. In the study, which is visualized with isohips, color and point lx values below, was calculated with the help of the Dialux software.

The light shelf height was 185 cm, the direction of the opening was east and the light shelf slope was 0 degrees. It was measured in open sky values of Eskişehir (30° East longitude and 39° North latitude) on 01/08/2021 at 12:00, . Daylight measurement is on 80 cm work plane height.

In the Dialux software, the models generated on a plane are merged into lines by grouping the points that have similar light levels. The reflection value of the reflective shelf is very important for reflecting the light to the depth of the room and providing homogeneous illumination to the room. The Dialux software comes equipped with a library of medium-dark colored wood, composite material, and wood. As evident from the modeling, the reflective value of these materials results in different outcomes.

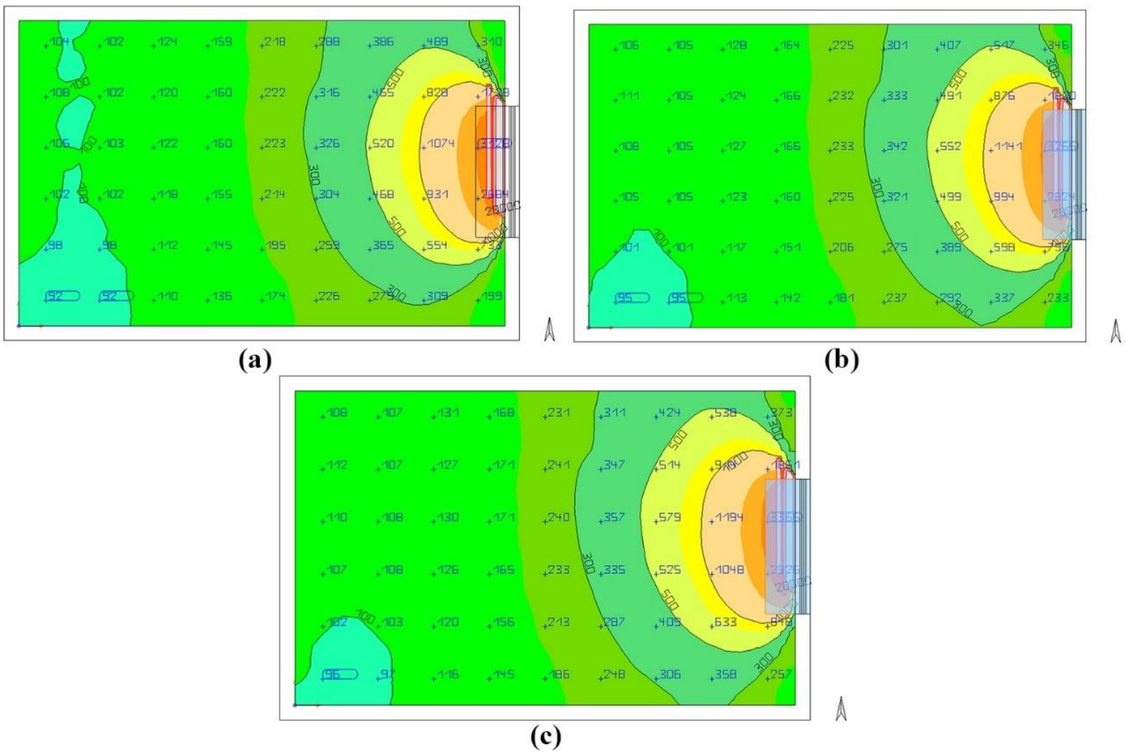


Figure 7. Comparison of light shelf reflection values (a): Reflection value of the light shelf on DiaLux software in default wooden material settings (0.15 ρ). (b): Reflection value of the wooden light shelf (0.50 ρ). (c): Reflection value of the composite light shelf material (0.80 ρ).

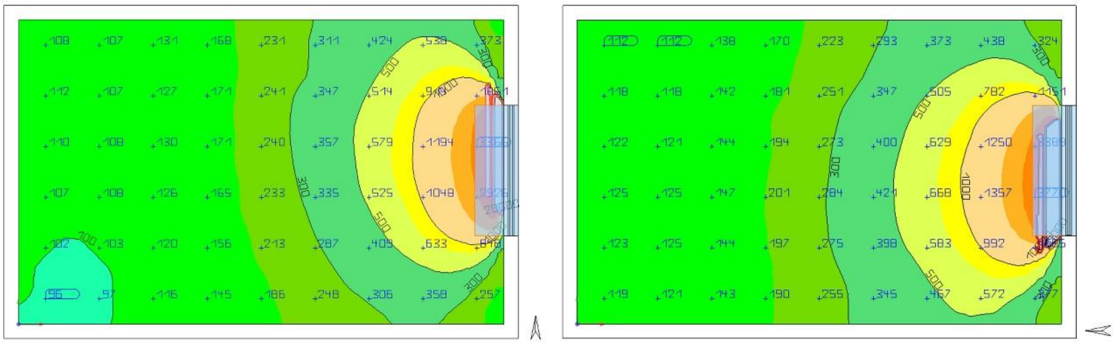
The reflection value of the composite light shelf material is high because it undergoes processes such as varnishing. As a result of these computer simulation measurements, it has been observed that the performance of the light shelf with 0.8 ρ reflection value in terms of reflecting the light to the deep areas of the room and providing homogeneous illumination in the room was more effective (Figure 7).

3.2. Comparison of the Direction of the Opening

To determine the facade where the light shelf performs better in buildings, it's essential to take lighting measurements of the light shelf while the room openings face different directions. These measurements, which are calculated by Dialux software, are visualized (Figure 8) and compared. At the bottom and right of each image, there is a north arrow. The arrows are indicating the southern and east directions of the opening by showing the north and west directions.

According to Ruck: The performance of light shelves in the east and west direction is not good; It is stated that the light shelf is efficient in the south direction in the northern hemisphere (north in the southern hemisphere) and in climates where sunny days are intensely [22]. To obtain the maximum yield of the light shelf, the orientation parameter was kept constant in the southern direction during investigation of the combination.

The light shelf height was 185 cm, the direction of the opening was east and the light shelf slope was 0 degrees. It was measured in open sky values of Eskişehir (30° East longitude 39,90° North latitude) on 01/08/2021 at 12:00. Daylight measurement is in 80 cm working plane height. The light shelf reflection value was 0.8 ρ as determined by previous computer simulation measurement.



(a) **(b)**

Figure 8. Daylight measurements made in different directions of room's opening (a): East direction. (b): South direction.

As a result of these measurements, the dark area was not found in the depths of the room where the light shelf in the south was used and the light scattered in the room was more homogeneous. Therefore, it was concluded that the light shelf in the southern direction would be more effective (Figure 8).

3.3. Comparison of Light Shelf Height in the East Direction

In order to ensure the most efficient use of the light shelf, the height of the light shelf should be optimum value. In the following study, the optimum height was calculated with the help of the DiaLux software and visualized with isohips, color and point in lx values (Figure 9). The use of the light shelf in the south is the most efficient compared to other directions, but this section (3.1.) was performed by assuming the opening of the room in the east direction. Because the comparison conducted in the east direction has demonstrated the substantial impact of efficient utilization.

In the following comparison (Figure 9), the opening of the room was in the east direction and the slope of the light shelf was 0 degrees. At 12:00 on 01/08/2021, in Eskişehir (30° East longitude 39.90° North latitude), the open sky values were measured during daylight measurements taken at a working plane height of 80 cm. The reflection value of the light shelf was 0.15 ρ.

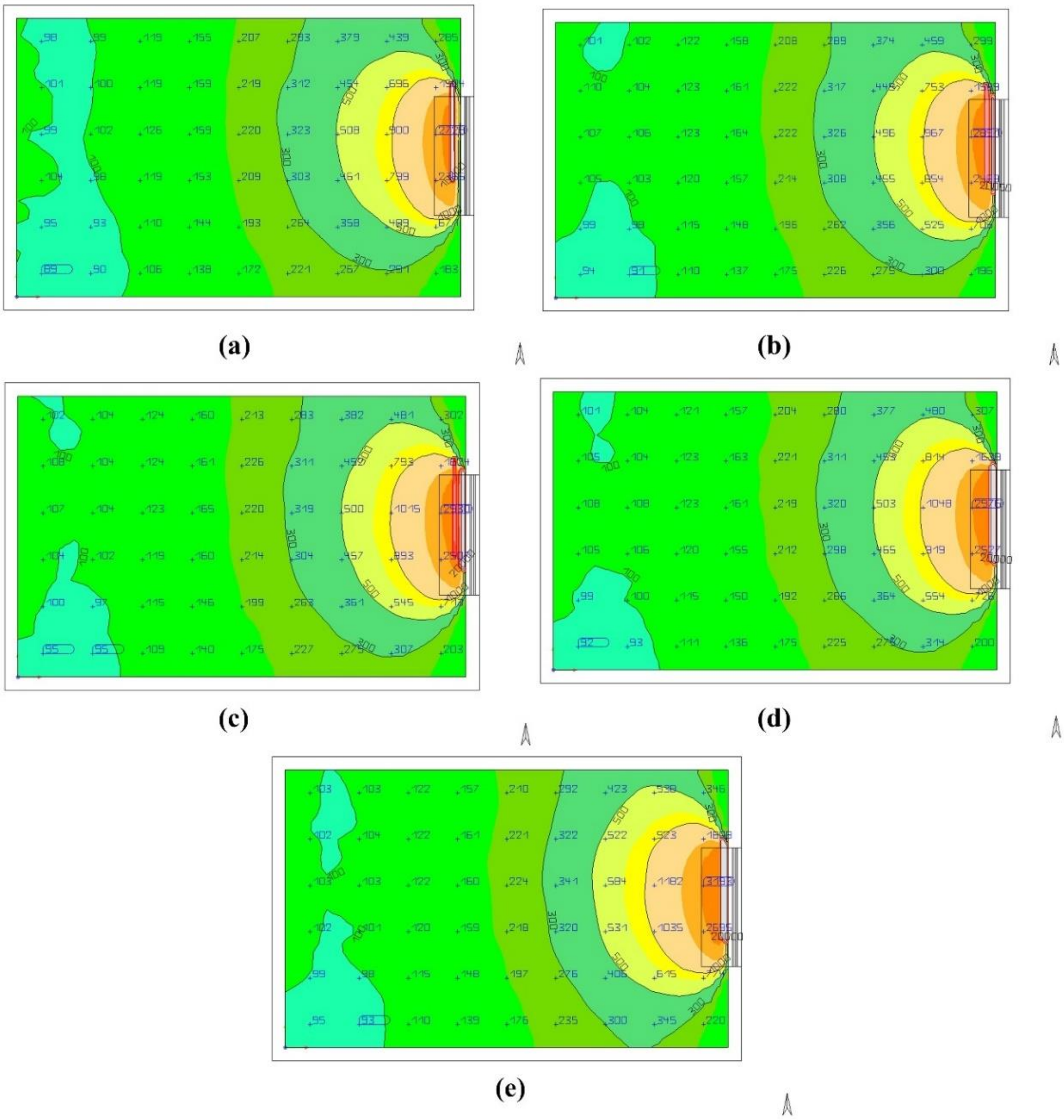


Figure 9. Light shelf height comparison. (a): Light shelf on 170 cm height. (b): Light shelf on 180 cm height. (c): Light shelf on 185 cm height. (d): Light shelf on 190 cm height. (e): Light shelf on 200 cm height.

According to Ruck: The recommended height for light shelves is 2 meters. As the height of the shelf decreases from the ground, the reflection power and daylight amount scattered on the ceiling increases. For this reason, when the light shelves system is intended to implement, it is stated that the ceiling height should be 3 meters [22]. As a result of the measurements, it was observed that the light shelves of 180, 185 and 190 cm height positively affect the performance. Moreover, the study determined that the optimal height for the light shelf was 185 cm in a space with a height of 280 cm. The efficiency was highest at this height, and the most appropriate height ratio was approximately 2/3, which corresponds to a ratio of 185/280 cm.

Ruck suggested a light shelf with a height of 2 meters for a volume of 3 meters. The ideal light shelf ratio was 2/3, and in a space with a height of 280 cm, the light shelf's optimal height was around 185 cm. When this height is tried on the southern facade and on the eastern facade, it was seen that the height of 185 cm was the most suitable height for this room and followed the Ruck's 2/3 ratio proposal [22].

3.4. Determination of Light Shelf's Slope

To maximize the performance of the light shelf, it is advisable to install it on the inside. Figure 10 illustrates the effect of the light shelf slope on the visuals generated using dialux software and light calculations, as well as the efficient utilization of the light shelf in Eskişehir conditions.

In order to examine the penetrative effects of measurements, the orientation of the room was in the east direction. It was measured in open sky values of Eskişehir (30° East longitude 39,90° North latitude) were measured on 01/08/2021, at 12:00, . Daylight measurement is on 80 cm working plane height. The light shelf reflection value was 0.8 ρ and the height was 185 cm.

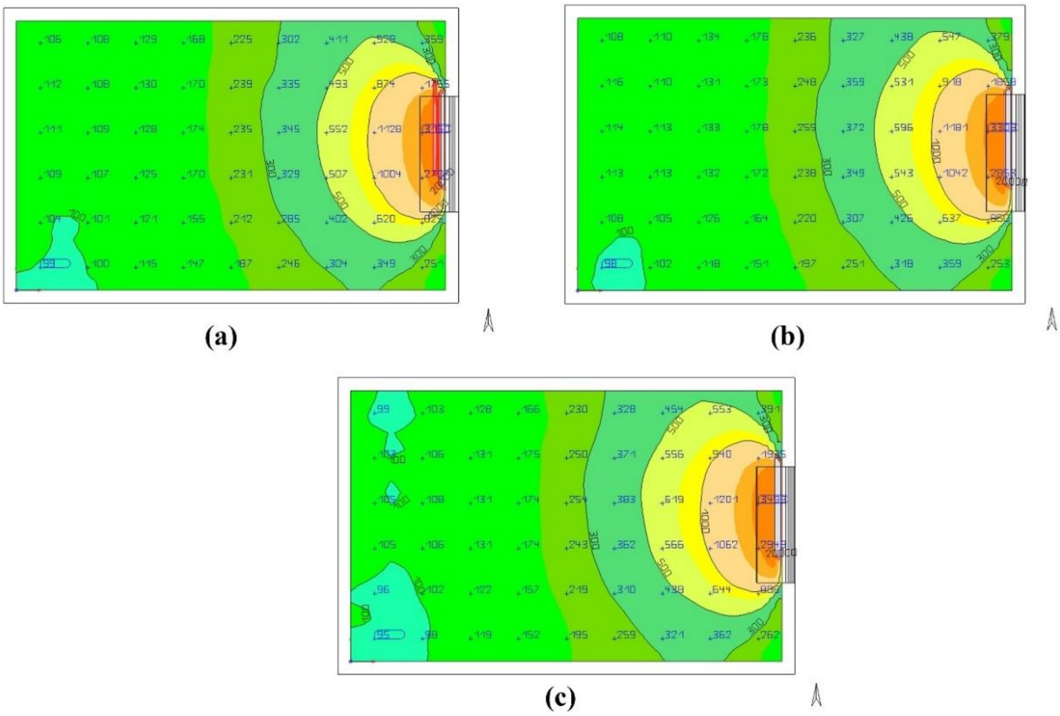


Figure 10. Light shelf slope comparison. (a): Light shelf's slope is 0°. (b): Light shelf's slope is 10°. (c): Light shelf's slope is 20°.

According to Costanzo: The rates are also stated for the most effective use of blinds and roller blinds systems. When the ratio between the wall and window area increases over 40% and 60%, the degree of surface of the plates plays a major role. In this case, the appropriate slope angle is recommended as between 10° to 20° [23].

As shown in the measurements, the performance of the light shelf which has a slope of 10° (Figure 10), was more efficient in reflecting the light to the depths of the room and providing homogeneous light in the room.

3.5. Comparison of Computer Simulation and Physical Model Daylight Analysis

In order to examine the performance of the light shelf in the deeper parts of the room, the effect of daylight on the ceiling (Figure 12-17) was analyzed by comparing both the model (Table 2-7) and computer simulation analyzes. The model measurements were based on results obtained in open sky conditions. The columns in the tables correspond to the specific areas indicated in the image below (Figure 11).

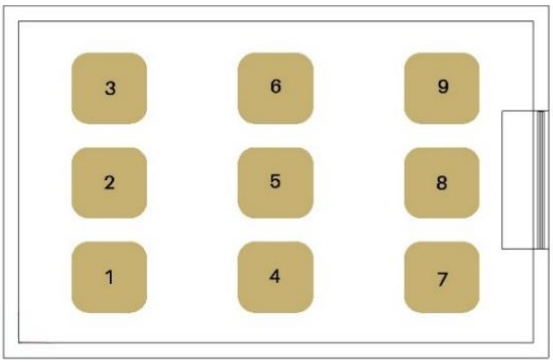
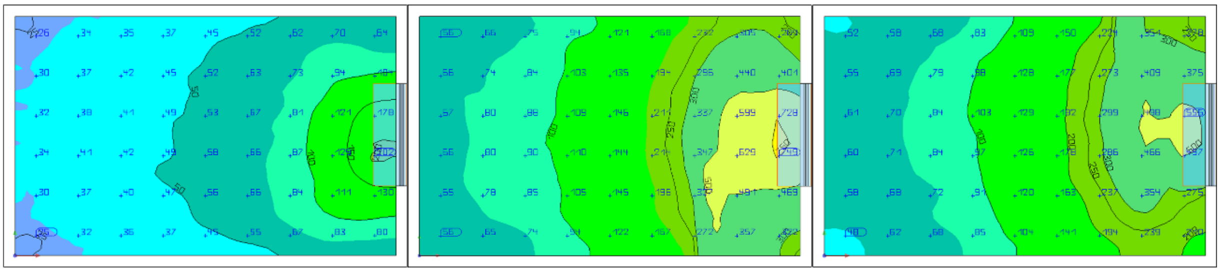


Figure 11. The areas are numbered on the ceiling.

3.5.1. Results of measurements dated 01/08/2021 in lx



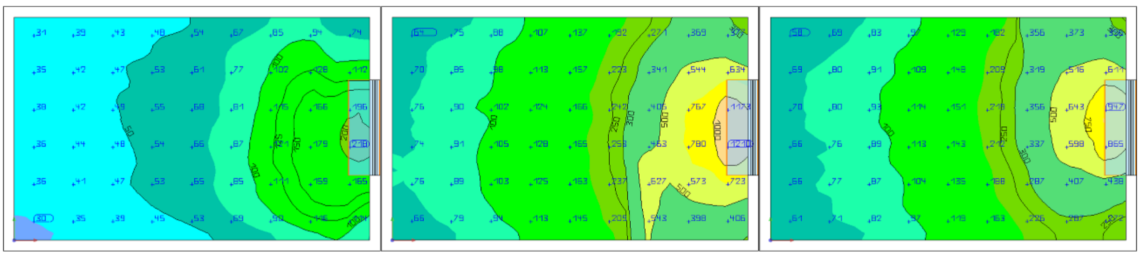
(a) (b) (c)

Figure 12. Images of computer simulation measurements, hours respectively: (a): 09:00. (b): 12:00. (c) 15:00.

Table 2. Results of physical model measurements dated 01/08/2021 in lx

Hours / Areas	1	2	3	4	5	6	7	8	9
09.00	40 lx	43 lx	45 lx	58 lx	68 lx	55 lx	115 lx	291 lx	98 lx
12.00	81 lx	85 lx	79 lx	155 lx	148 lx	136 lx	480 lx	648 lx	450 lx
15.00	72 lx	75 lx	72 lx	125 lx	132 lx	135 lx	361 lx	513 lx	413 lx

3.5.2. Results of measurements dated 15/08/2021 in lx



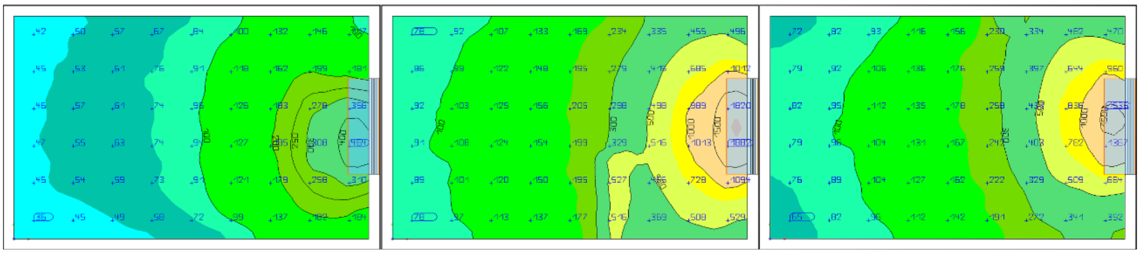
(a) (b) (c)

Figure 13. Images of computed measures, hours respectively. (a): 09:00. (b): 12:00. (c) 15:00.

Table 3. Results of physical model measurements dated 15/08/2021 in lx

Hours / Areas	1	2	3	4	5	6	7	8	9
09.00	46 lx	51 lx	43 lx	67 lx	71 lx	63 lx	163 lx	182 lx	133 lx
12.00	93 lx	98 lx	89 lx	177 lx	183 lx	172 lx	613 lx	820 lx	598 lx
15.00	82 lx	95 lx	83 lx	139 lx	158 lx	152 lx	413 lx	655 lx	523 lx

3.5.3. Results of measurements dated 01/09/2021 in lx



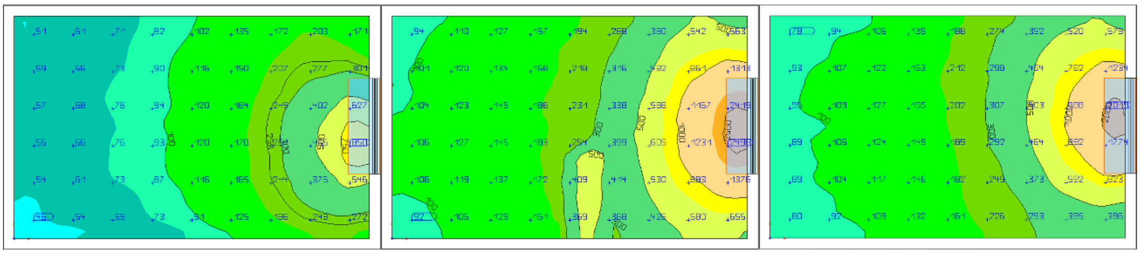
(a) **(b)** **(c)**

Figure 14. Images of computed measures, hours respectively. (a): 09:00. (b): 12:00. (c) 15:00.

Table 4. Results of physical model measurements dated 01/09/2021 in lx

Hours / Areas	1	2	3	4	5	6	7	8	9
09.00	58 lx	59 lx	55 lx	101 lx	123 lx	98 lx	289 lx	320 lx	203 lx
12.00	106 lx	116 lx	107 lx	215 lx	270 lx	202 lx	768 lx	1208 lx	712 lx
15.00	93 lx	98 lx	91 lx	152 lx	154 lx	163 lx	420 lx	730 lx	615 lx

3.5.4. Results of measurements dated 15/09/2021 in lx



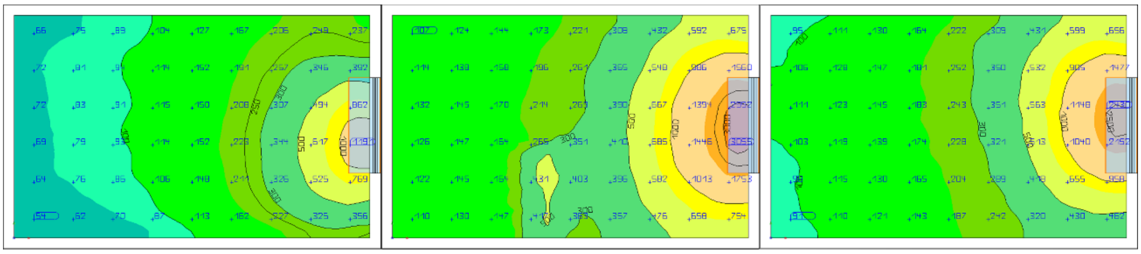
(a) **(b)** **(c)**

Figure 15. Images of computed measures, hours respectively. (a): 09:00. (b): 12:00. (c) 15:00.

Table 5. Results of physical model measurements dated 15/09/2021 in lx

Hours / Areas	1	2	3	4	5	6	7	8	9
09.00	58 lx	61 lx	57 lx	123 lx	129 lx	103 lx	412 lx	432 lx	245 lx
12.00	132 lx	129 lx	135 lx	352 lx	331 lx	312 lx	935 lx	1276 lx	928 lx
15.00	112 lx	135 lx	122 lx	194 lx	235 lx	202 lx	694 lx	1325 lx	945 lx

3.5.5. Results of measurements dated 01/10/2021 in lx



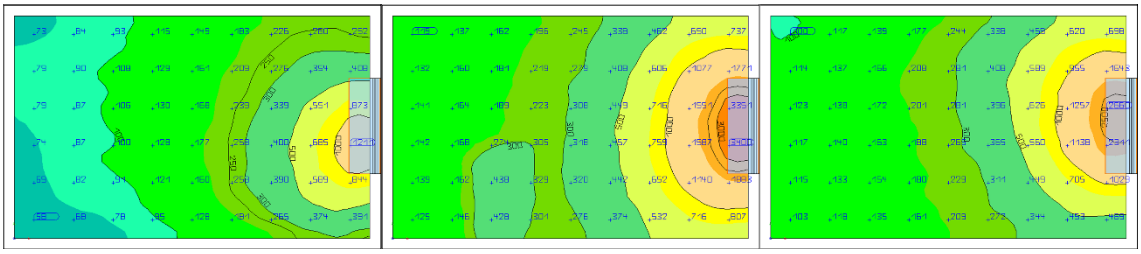
(a) **(b)** **(c)**

Figure 16. Images of computed measures, hours respectively. (a): 09:00. (b): 12:00. (c) 15:00.

Table 6. Results of physical model measurements dated 01/10/2021 in lx

Hours / Areas	1	2	3	4	5	6	7	8	9
09.00	81 lx	96 lx	68 lx	163 lx	187 lx	149 lx	557 lx	698 lx	361 lx
12.00	152 lx	159 lx	147 lx	423 lx	436 lx	278 lx	1188 lx	1565 lx	1147 lx
15.00	126 lx	146 lx	132 lx	215 lx	265 lx	271 lx	687 lx	1328 lx	1154 lx

3.5.6. Results of measurements dated 15/10/2021 in lx



(a) **(b)** **(c)**

Figure 17. Images of computed measures, hours respectively. (a): 09:00. (b): 12:00. (c) 15:00.

Table 7. Results of physical model measurements dated 15/10/2021 in lx

Hours / Areas	1	2	3	4	5	6	7	8	9
09.00	89 lx	95 lx	85 lx	184 lx	196 lx	172 lx	614 lx	706 lx	425 lx
12.00	152 lx	159 lx	145 lx	256 lx	278 lx	200 lx	752 lx	1103 lx	856 lx
15.00	136 lx	145 lx	132 lx	226 lx	294 lx	268 lx	759 lx	1056 lx	1125 lx

In the following comparison (Table 8) where the room opening faced the east direction and the light shelf had a slope of 0 degrees. Open sky values were measured in Eskişehir (30° East longitude 39.90° North latitude) on 01/08/2021 at 12:00. Daylight measurement is on the ceiling with the help of the lux meter.

Table 8. Results of physical model measurements dated on 01/08/2021 in lx

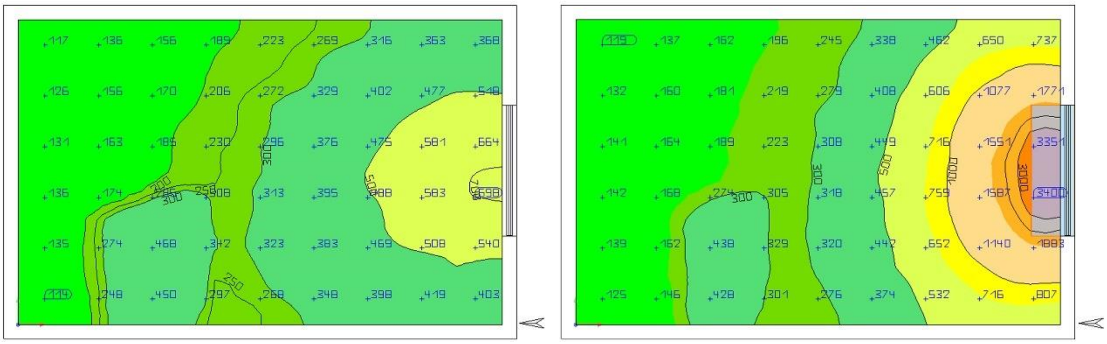
Heights / Areas	1	2	3
170	236 lx	335 lx	245 lx
180	289 lx	365 lx	270 lx
185	335 lx	423 lx	350 lx
190	315 lx	410 lx	330 lx
200	180 lx	220 lx	170 lx

During this phase of the study, the measurements obtained from the physical model were compared with each other. Moreover, computer simulations were conducted under the same conditions and their outcomes were compared with the physical model results. This approach was taken to examine the consistency of the simulation results with the physical model. The findings were found to be proportional to each other, which enhances the accuracy of the research. Table 8 includes measurements that examine how the height of the light shelf affects the illumination of daylight. As part of this study, light measurements were taken on the ceiling in 1, 2, and 3 areas (Figure 11). A similar study was also illustrated (Figure 9). The results of both studies indicate that the most efficient height is 185 cm at a volume of 280 cm.

3.6. Investigation of Situations in Which the Light Shelf is Advantage-Disadvantage

The primary purpose of light shelves is to allow light to penetrate deeper into the interior of a space, illuminating even the darker areas while ensuring uniform illumination throughout the space. However; The height of the light shelf, the light reflection value of the light shelf (ρ), the angle of the light shelf, the direction of the opening in the room, the daylight in Eskişehir conditions according to different date and different hours are examined in different combinations. During the use of the light shelf with maximum efficiency in Eskişehir's conditions, certain combinations were found to have a negative impact on specific dates and hours.Rather than using a specific lx value as a criterion, the advantages and disadvantages have been evaluated through a comparison of scenarios where light shelves are used versus scenarios where they are not used. If the light shelf has improved the room's illumination, it is considered an advantage, but if it hasn't, it is considered a disadvantage.

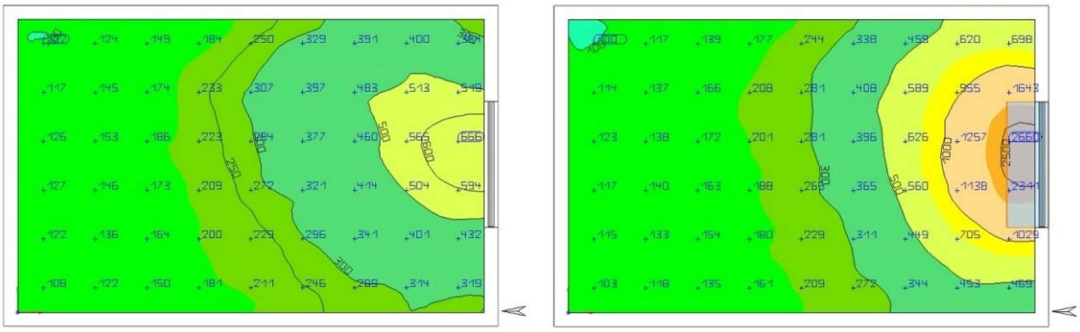
The computer simulation measurements (Figure 18) compare the quality of illumination in the room on October 15th at 12:00, with and without light shelves installed, for a window opening on the southern facade. With the light shelf; The homogeneous lighting in the room is provided and the positive impact is seen in reflecting the light in front of the window onto the ceiling. In addition, it is seen that daylight is reflected in the deep areas of the room successfully.



(a) **(b)**

Figure 18. Comparison of no light shelf and with light shelf measurements (a): Without light shelf. (b): With light shelf.

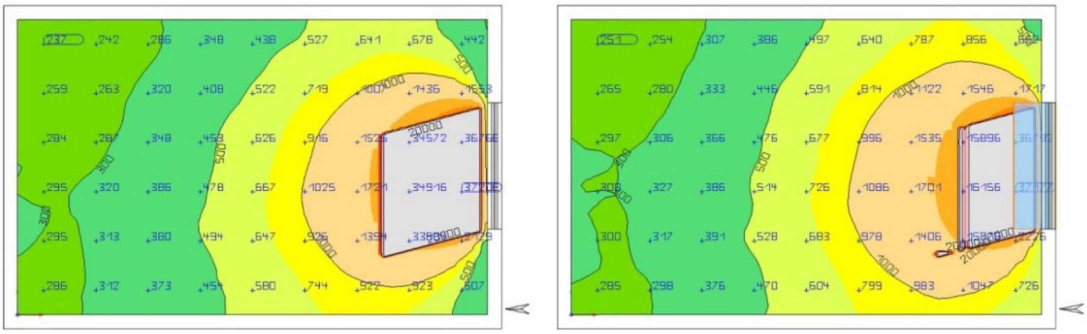
The computer simulation measurements (Figure 19) compare the quality of illumination in the room on October 15th at 15:00, with and without light shelves installed, for a window opening on the southern facade. With the light shelf; The homogeneous lighting in the room is provided and the positive impact is seen in reflecting the light in front of the window onto the ceiling. However, deficiencies have been observed in terms of the transmission of light to the deeper parts of the room.



(a) (b)

Figure 19. Comparison of no light shelf and with light shelf measurements (a): Without light shelf. (b): With light shelf

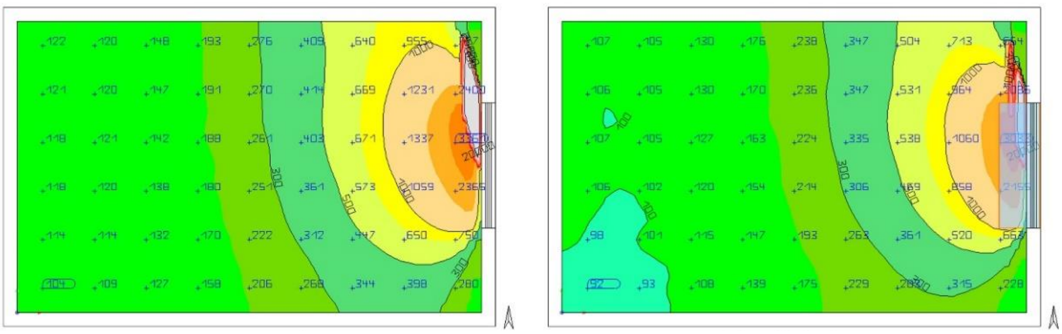
The computer simulation measurements (Figure 20) compare the quality of illumination in the room on October 15th at 12:00, with and without light shelves installed, for a window opening on the southern facade. In this comparison daylight measurement is on a 80 cm working plane height. The homogeneous lighting in the room is provided with light shelf. In addition, it is seen that daylight is reflected in the deep areas of the room successfully.



(a) (b)

Figure 20. Comparison of no light shelf and with light shelf measurements (a): Without light shelf. (b): With light shelf.

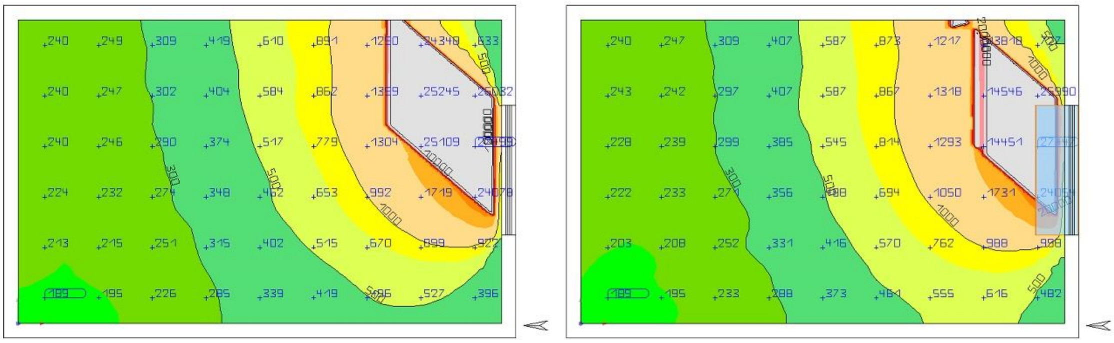
The computer simulation measurements (Figure 21) compare the quality of illumination in the room on October 15th at 12:00, with and without light shelves installed, for a window opening on the southern facade. In this comparison daylight measurement is on a 80 cm working plane height. There was no positive impact on scattering daylight to the room. It was found that it had a negative impact on reflecting daylight to the deep areas of the room.



(a) (b)

Figure 21. Comparison of no light shelf and with light shelf measurements (a): Without light shelf. (b): With light shelf.

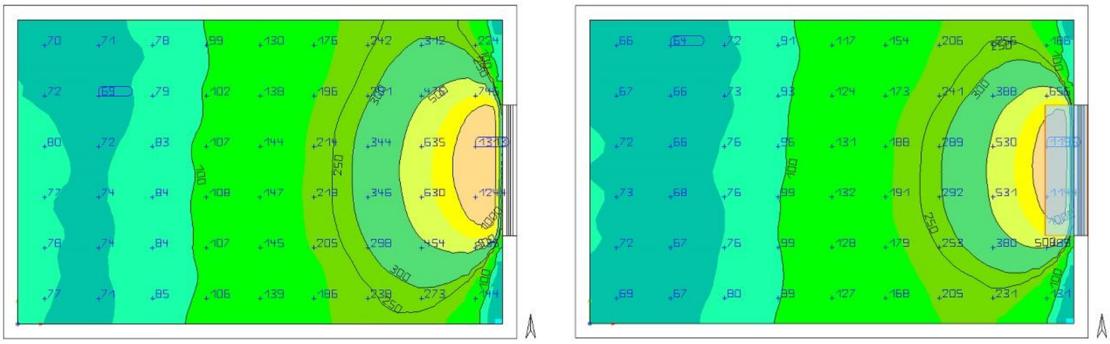
The computer simulation measurements (Figure 22) compare the quality of illumination in the room on October 15th at 15:00, with and without light shelves installed, for a window opening on the southern facade. In this comparison daylight measurement is on a 80 cm working plane height. The homogeneous lighting in the room is provided. It has been observed that the light shelf has only partially succeeded in reflecting light to the deeper parts of the room.



(a) **(b)**

Figure 22. Comparison of no light shelf and with light shelf measurements (a): Without light shelf. (b): With light shelf.

The computer simulation measurements (Figure 23) compare the quality of illumination in the room on October 15th at 15:00, with and without light shelves installed, for a window opening on the easthern facade. In this comparison daylight measurement is on a 80 cm working plane height. Light shelf has not positive impact on scattering the daylight to the room is provided. It was found that it had a negative impact on reflecting daylight to the deep areas of the room.



(a) **(b)**

Figure 23. Comparison of no light shelf and with light shelf measurements (a): Without light shelf. (b): With light shelf.

4. EVALUATION AND CONCLUSION

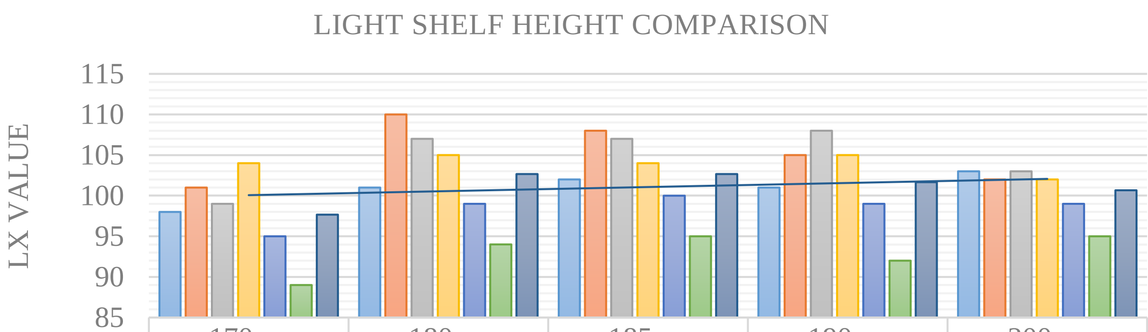
The research and observations conducted indicate that increasing the reflection value of the light shelf has a positive effect on the even distribution of daylight in Eskişehir's conditions. However, the measurements revealed that excessive daylight reflecting from the light shelf can result in discomfort in certain situations that may not occur otherwise.

As a result of the research and observations, it was concluded that the light shelf application is more appropriate and efficient to use the daylight for buildings on the southern facade.

As stated in the figure below, the measurements made in A, B, C, D, E, and F areas (Figure 24) are compared with the help of a graphic (Figure 25). The measurements taken at 12:00 under the open sky conditions in Eskişehir, comparing the performance of a light shelf with a 0° slope and a light shelf with a 0.15 ρ reflection value (Figure 25). The study examines the lighting performance at different heights of the light shelf in the deepest points of the room, with lx values recorded on the ceiling. In this way, the effect of light shelf height in deep regions has been observed more accurately. The graph shows that the most efficient lighting is achieved at a light shelf height of 185cm, as per the obtained data.

Figure 24. Areas compared in the graph (Figure 25)

Through experimental methods, the most efficient height for the light shelf to reflect daylight into the deeper areas of the room was determined to be 185 cm (Figure 25). This finding was further confirmed by computer simulation measurements. The research showed that light shelves placed at a height corresponding to 2/3 of the room height provided accurate data, which was confirmed through experimentation and measurements in Eskişehir's conditions. The impact of light shelf height on efficient use was found to be more clearly visible than the case where the window is facing east.



	170cm	180cm	185cm	190cm	200cm
A	98	101	102	101	103
B	101	110	108	105	102
C	99	107	107	108	103
D	104	105	104	105	102
E	95	99	100	99	99
F	89	94	95	92	95
Average	97,66666667	102,6666667	102,6666667	101,6666667	100,6666667

A B C D E F Average Linear

Figure 25. Light shelf height comparison with computer simulation techniques

As a result of computer simulation measurements in determining the light shelf slope, there was no significant difference in the use of the light shelf in the south direction compared to east. The application of a 10° slope for the light shelf in the east direction has enabled us to obtain the most effective comparisons in reflecting daylight to the deeper areas of the room. Based on the data obtained from the experiment's measurements and evaluations, the research determined that the light shelf with a width of 60 cm and a height of 185 cm should be placed facing south for the maximum benefit.

Experimental measurements were conducted using both computer simulation and physical models to analyze the impact of daylight on the ceiling and evaluate the light shelf's performance in reflecting daylight to the deeper areas of the room. In the measurements made with the physical model, in the open sky results are taken as basis. After conducting model and computer simulation measurements, it was observed that the outcomes did not completely coincide with each other. However, they displayed a certain level of similarity in terms of proportion. These measurements on the ceiling were measured and the maximum daylight on the ceiling was obtained with the same parameters to reflect the maximum daylight to the depths of the room.

Upon examining the scenarios where the light shelf could be advantageous or disadvantageous, it was discovered that in Eskişehir conditions, the light shelf may not always have a positive impact, even during the dates and hours where it was most efficient. However, at these dates and hours where the light shelf is seen inefficient, the light shelf may become more efficient than the reflective variables at the base of the room. In the room where the study was conducted, it was assumed that there were no objects present. However, in a room with reflective objects like carpet rugs that absorb light, the light shelf may enhance efficiency by reflecting the light towards the ceiling in the disadvantageous scenario.

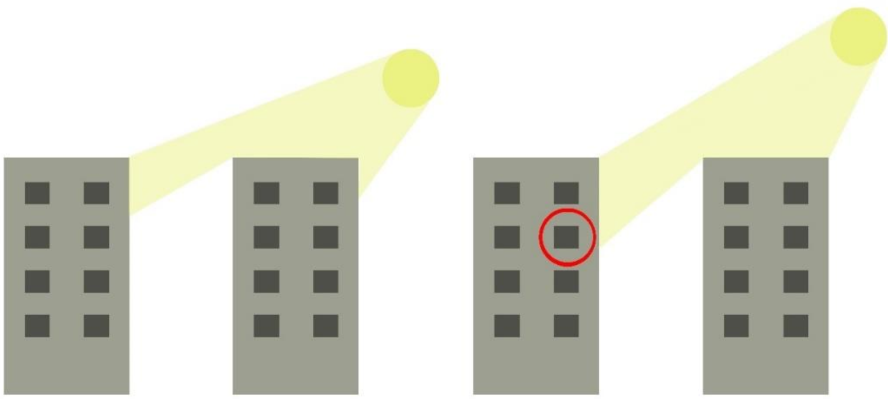


Figure 25. Apartment samples benefiting from daylight according to the angle of the sun rays.

Based on these findings, it is recommended to use a light shelf with the parameters that were found to be most effective under Eskişehir conditions. Especially in buildings that cannot take the horizontal daylight into the room (Figure 25), it is concluded that the use of the light shelf on the southern facade is the most appropriate use by preventing the daylight in front of the window and reflect to the ceiling when the daylight enters the room with a steeper angle.

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In the article, national and international research and publication ethics are complied with. Ethics Committee permission was not required in the study.

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CONFLICT OF INTEREST

The authors stated that there are no conflicts of interest regarding the publication of this article.

AUTHORSHIP CONTRIBUTIONS

The manuscript was written by Furkan Meral, who took on the role of corresponding author. Meanwhile, Doç. Dr. Hatice Günseli Demirkol provided consultancy during both the research project and manuscript writing stages. Therefore, both authors made equal contributions.

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