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Energy-Efficient Lighting Design: An Investigation of Optimal Daylight Use in Different Window Models and Furniture Colors

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Daylight factor,
Window size,
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Energy savings

Abstract: This study presents an investigation aimed at achieving energy savings in lighting by using the ideal window concept and other parameters to optimally benefit from daylight. The study has been applied under overcast sky and deep room conditions, which represent the worst-case scenarios. As an alternative to time-consuming mathematical calculations, the Velux Daylight Visualizer lighting simulation program was used to create three-dimensional designs for horizontal, vertical, square, and roof windows separately, and the effects of these windows on the daylight factor were analyzed. The impact of different furniture colors in the interior space was also examined. Following the investigations, it was observed that roof windows produced more daylight compared to others, with the average daylight factor value at 1.9%. However, since roof windows cannot be used in multi-story buildings, a comparison was made between horizontal, vertical, and square windows, and it was concluded that horizontal windows placed close to the upper wall were more efficient than the others, with the DF value recorded averagely at 1.7%. In addition, it was observed that lighter-colored furniture, among the light and dark furniture, produced more daylight compared to the other.

Enerji Verimli Aydınlatma Tasarımı: Farklı Pencere Modellerinde ve Mobilya Renklerinde Optimum Gün Işığı Kullanımı Üzerine Bir Araştırma

Anahtar Kelimeler
Gün ışığı faktörü,
Pencere boyutu,
Velux daylight visualizer,
Enerji tasarrufu

Öz: Bu çalışma, gün ışığından optimum seviyede faydalanmak için, ideal pencere kavramını ve diğer parametreleri kullanarak aydınlatmada enerji tasarrufu sağlamaya yönelik bir araştırma sunmaktadır. Çalışma en kötü durum senaryolarını temsil eden bulutlu gökyüzü ve derin oda koşulları altında uygulanmıştır. Zaman alıcı matematiksel hesaplamalara alternatif olan aydınlatma simülasyon programı Velux Daylight Visualizer ile yatay, dikey, kare ve çatı pencereleri için ayrı ayrı üç boyutlu tasarım yapılıp, bu pencerelerin gün ışığı faktörüne etkileri analiz edilmiştir. Ayrıca iç ortamda bulunan farklı mobilya renklerinin etkisi de incelenmiştir. Yapılan incelemelerden sonra, çatı pencerelerinin diğerlerine kıyasla daha fazla gün ışığı ürettiği görülmüştür ve ortalama gün ışığı faktörü değerinin %1,9 olduğu görülmüştür. Fakat çatı pencereleri katlı binalarda kullanılamayacağından yatay, dikey ve kare pencereler arasında karşılaştırma yapılmış ve üst duvara yakın yerleştirilen yatay pencerelerin %1,7'lik ortalama gün ışığı faktörü ile diğerlerine göre daha verimli olduğu sonucuna ulaşılmıştır. Buna ek olarak, açık ve koyu olarak sınanan mobilyalardan açık renkli olanların diğerine kıyasla daha çok gün ışığı ürettiği görülmüştür.

1. INTRODUCTION

In Türkiye, the use of renewable energy sources is increasing day by day to reduce dependence on foreign energy and meet energy needs in a clean and uninterrupted manner. Among renewable energy sources, the sun, which is the source of many types of energy found in nature, is considered a significant input. Today, all new technologies are based on solar energy, an unlimited, cost-free, and clean energy type. In this context, one of the areas benefiting from solar energy is natural lighting, also known as daylight. Daylight is the most effective primary light source for creating a visual environment and useful energy savings in buildings [1-4]. From the past to the present, it has been scientifically proven that daylight helps people become happier, calmer, healthier, and more productive. Additionally, using daylight in lighting reduces heat exchange between indoor and outdoor spaces to a minimum, which is important for energy savings in buildings [5]. The benefits of effective use of daylight can be categorized into two main groups: visual comfort and energy savings.

According to the European standard EN 12665, visual comfort is described as "a subjective condition of visual well-being induced by the visual environment" [6]. Visual comfort constitutes a crucial element in the design of daylighting systems. Daylight can provide natural lighting that is beneficial for health and well-being, but it can also cause discomfort glare if not properly managed [7, 8]. Several studies have investigated strategies to reduce discomfort glare from daylight [9]. Such strategies encompass the employment of shading mechanisms, innovative side and top daylighting systems, and electric lighting control systems. Modern transparent and/or translucent glazing can also be utilized to avoid glare and diffuse light to wider areas of floor space. Effective daylighting design should include top-lighting, side-lighting, electric lighting controls, and a building explicitly designed to maximize the advantages of daylight. Light shelves, surface colors and textures, ceiling height, and room dividers are some of the building features that can affect visual comfort in daylighting design.

Energy savings is the efficient use of energy without any reduction in production, comfort, or workforce. The rapid and unconscious consumption of our energy sources has led humanity to seek new energy-saving methods. Efficient lighting design and its effective use in buildings are important parameters for achieving energy savings. One of the most significant ways in which daylight can contribute to energy savings is through the use of natural lighting in buildings [10]. By designing buildings with large windows and skylights, it is possible to reduce the need for artificial lighting during the day. This can result in significant energy savings, as lighting accounts for a significant portion of a building's energy consumption. Lighting constitutes one of the most significant electricity consumers in both the residential and commercial sectors. Globally, lighting accounts for approximately 20% to 30% of total electricity consumption [11]. However, by transitioning to more energy-efficient lighting technologies, substantial energy savings can be achieved [12]. Trifunovic et al. [13] demonstrated that energy savings of up to 27% in residential and 30% in commercial sectors are possible through the adoption of energy-efficient lighting technologies. On the other hand, the use of large windows may lead to higher energy requirements for space heating due to the insulation properties of glass not being as effective as insulation materials in walls.

The design and placement of windows can significantly impact the amount of natural light that enters a building, which can have a profound effect on the well-being and health of its occupants [14]. Additionally, windows can also contribute to the energy efficiency of a building by reducing the need for artificial lighting and heating or cooling systems [15, 16]. To optimize the quality of daylight in a building, windows should be strategically placed to allow for maximum natural light penetration. The size and orientation of windows should be carefully considered to ensure that they provide adequate illumination while minimizing glare and heat gain. A well-designed window system can provide ample natural light while minimizing heat gain and loss, resulting in a more comfortable and energy-efficient indoor environment.

Several studies have been conducted about daylight, energy savings and window size, orientation and position. Hopkinson et al. [17] have developed a simple formula to calculate the indirect component of the daylight factor (DF). Additionally, they assumed that the total DF obtained by adding the direct and indirect components of daylight is an important factor in determining natural lighting in a room design.

To calculate the DF in an indoor space, Ibarra and Reinhart [18] preferred a classroom model in an L-shape with 69 students. The calculations were simulated using ECOTECH and RADIANCE programs and compared. According to the comparison, the data obtained from the ECOTECH program was found to be lower than that obtained from the RADIANCE program. It was considered more appropriate to use the RADIANCE program for daylight simulations in buildings.

Li [19] made predictions of daylight and energy savings under various sky conditions through mathematical calculations. As a result of the calculations, it was concluded that daylight-dependent lighting contributes significantly to energy efficiency.Vanhoutteghem et al. [20] investigated the impact of façade window design on energy consumption, daylighting, and thermal comfort in nearly zero-energy houses. The study evaluated the relationship between window size, orientation, and glazing properties for different room geometries using EnergyPlus and DAYSIM. The results showed that low U-values are needed in both north- and south-oriented rooms before large window areas lead to reductions in space heating demand.

Mushataha and Shadid [21] measured the indoor light levels with a lux meter to evaluate the daylight performance at the archaeological museum located in Kuwait, and simulated it using computer programs such as ECOTECH and REVIT. Based on the data obtained, they concluded that 45% energy savings could be achieved.

Mangkuto et al. [14] examined how different characteristics of window systems, including wall reflectance, window-to-wall ratio (WWR), and window orientation, influenced daylight metrics and electricity consumption for lighting purposes. Their research focused on an office room in a tropical climate and was among the first to show that the visual aspects of window systems can be included in an optimization process.

Dino and Üçoluk [22] created a tool for optimizing design in high-performance buildings, which they utilized to enhance energy efficiency and daylighting performance across various architectural layouts and building apertures. Fang and Cho [23] improved basic building shapes, as well as the dimensions and positioning of windows and skylights, to enhance energy efficiency and daylighting performance. By employing a genetic algorithm, they achieved an increase of over 28% in daylight performance and a reduction of more than 17% in energy usage across various climatic conditions.

De Gastines and Pattini [24] conducted simulations using the EnergyPlus program under Argentine climate conditions to determine the factors that are effective in energy savings in buildings. They considered window type and location, building geometry, and WWR as simulation parameters. Based on the data obtained, they have proven that the most energy-efficient windows are not the highly insulated ones but the ones with low total solar energy transmittance. They have also shown that adequate architectural design can provide significant energy savings by offering alternative strategies to high-performance window technologies.

This study aimed to achieve energy savings in lighting by utilizing the ideal window concept. The methodology was implemented under simulated conditions representing challenging scenarios with overcast skies and deep rooms. Ankara has been chosen as the location, and the building orientation is set to the north. The main contributions of this paper are as follows:

- To analyze the influence of different window types, including horizontal, vertical, square, and roof windows, the Velux Daylight Visualizer program was used to create three-dimensional designs for each window type separately.
- In addition, the existing literature focuses on increasing energy efficiency by considering factors such as window type, location, and building geometry. However, in this study, the impact of different window sizes on interior daylight is examined and specifically evaluated.
- The resulting DFs were analyzed to evaluate the impact of these window types.
- The study aims not only to contribute to energy savings by maximizing natural light indoors but also to enhance the quality of life by improving the natural lighting of the interior space.
- Furthermore, the study examined how various furniture colors affect the interior space.

The paper is structured as follows: In Section 2, a brief overview is given regarding the Velux Daylight Visualizer simulation software and daylight. In Section 3, results are provided and analyzed. Finally, we end the paper with the discussion and conclusions.

2. MATERIAL AND METHOD

In order to apply the optimal window design, a room with a length of 8 meters, a width of 4 meters, and a height of 3 meters was selected for the study. To observe the impact of window size on daylight distribution in the interior space, window models of five different sizes with an area of 2.5 m^2 were considered. The Velux Daylight Visualizer program was used to determine the daylight factor in the room and analyze it for different positions and sizes of windows. The Velux Daylight Visualizer program is designed for natural lighting design and allows for the modeling of three-dimensional spaces and the design of openings such as windows. It also provides a visual output of brightness and glare values, as well as DF values, for all relevant designers [25]. Numerous investigations have verified the proper functioning of this computational tool [26, 27], confirming its precision by implementing the CIE (Commission International de l'Eclairage) test cases [28]. At present, several studies focused on daylighting employ this simulation program [29-32].

2.1. Velux Daylight Visualizer

Velux Daylight Visualizer is a useful program for determining the orientation and lighting levels of buildings [33]. As the name suggests, the program carries out daylight studies that have been developed and verified according to CIE test cases [26]. The simulation software offers the ability to select sky conditions (overcast and clear skies), location, interior furnishings, and various window models. As shown in Figure 1 and Figure 2, windows of different sizes and features are available within the program.

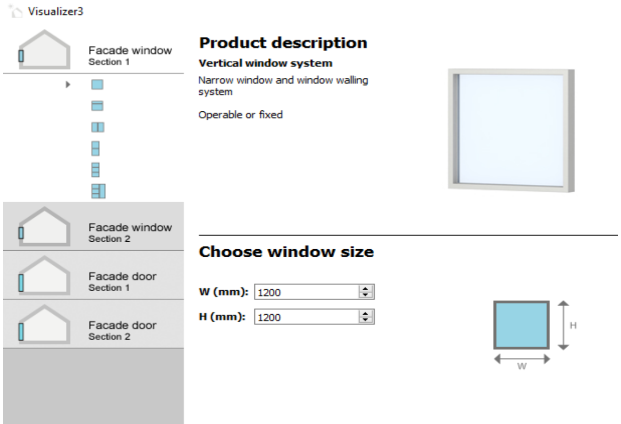

Figure 1. Facade windows in Velux Daylight Visualizer

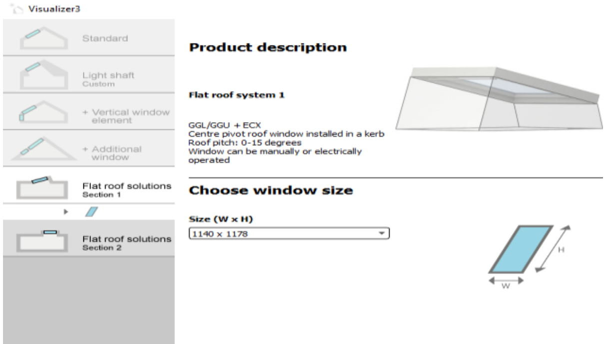

Figure 2. Flat roof windows in Velux Daylight Visualizer

Additionally, the selection of location and various sky conditions (overcast, intermediate, and sunny) is possible (Figure 3).

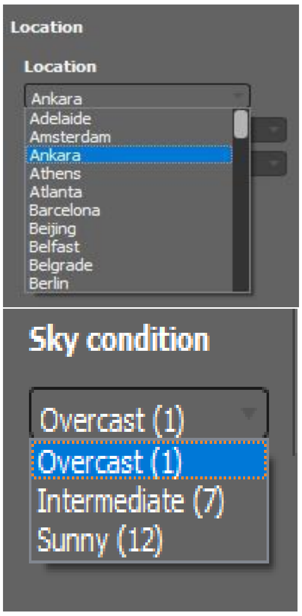

Figure 3. Selection of location and sky conditions in Velux Daylight Visualizer

The DF is directly proportional to the illumination rate of the space. Spaces with the highest degree of illumination are represented in red, while the amount of illumination decreases towards blue [34]. Figure 4 shows the DF color indicators.

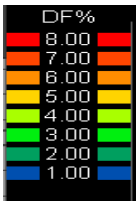

Figure 4. DF color indicators

2.2. Natural Lighting (Daylight)

Natural light has always been the ideal choice for humans, as our eyes naturally adapt to this source of illumination. Taking daylight into consideration in a building provides significant psychological benefits to its occupants. Additionally, it can increase efficiency in the space by reducing the burden of artificial lighting requirements.

The DF is commonly used to measure the amount of natural light in a space, as it illustrates the potential of natural light under unfavorable conditions, such as an overcast sky. The DF is expressed as a percentage and is defined as the ratio of horizontal indoor to outdoor illumination by daylight, assuming constant overcast sky conditions. If the DF is 3%, it means that the illumination present at that point within the building is 3% of the overall external horizontal illumination that has been scattered [35]. The equation (1) below demonstrates how to determine DF from illuminance levels [36].

$$DF = \left(\frac{Ei}{Eo}\right) x100 \quad (1)$$

where

E_i = illuminance level inside the space
E_o = illuminance level outside the space

The illuminance at a point inside a building can be divided into three components [37, 38]:

1. Sky Component (SC): This is the direct light coming from a visible portion of the sky at the specific point being considered.
2. Externally Reflected Component (ERC): This refers to the light that is reflected off external surfaces before reaching the point in question.
3. Internally Reflected Component (IRC): This component accounts for the light that reflects off interior surfaces before arriving at the considered point.

Each of these three components is computed separately, and the DF is derived from the sum of these values. Figure 5 shows three components of daylight that contribute to the illuminance on a work plane in a room.

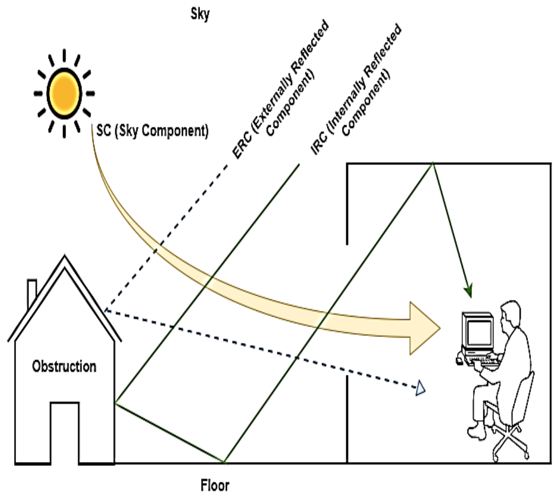

Figure 5. Components of daylight that add to the illuminance at a point within a room As indicated in Table 1, there is inadequate illumination in the environment when the DF value goes below 2%. If it exceeds 5%, there is too much illumination, which causes glare. Glare is recognized as a significant issue in ensuring visual comfort [39]. Ideally, DF should be between 2% and 5%.

Table 1. DF values and their meanings

DF		
Inadequate	(yellow)	DF < 2%
Optimal	(green)	2% < DF < 5%
Glare	(red)	DF > 5%

To achieve energy savings and visual comfort conditions in lighting, a comprehensive and efficient approach to daylight design is required without compromising illumination quality. Therefore, it is recommended to start by addressing certain design criteria for daylighting. These design criteria are as follows:

- Building design
- Window size and features
- Sky conditions

2.2.1. Building design

In building designs, aesthetic value is often taken into consideration. Alongside the exterior appearance of the building, the distribution of daylight in the interior environment is an important input during the design phase. This is because correctly designed daylight in buildings provides dynamic areas that promote an individual's visual comfort and actions while also reducing the building's energy consumption.

External obstructions and reflections (buildings, trees, ground surfaces, etc.) in the surrounding environment greatly affect the amount of natural light reaching the interior. In an effective architectural design, buildings should be positioned so as not to obstruct the intake of daylight into the interior. In accordance with this goal, skylights, as illustrated in Figure 6, are less impacted by surrounding obstructions and provide a larger view of the sky than facade windows [40].

Figure 6. Components of view-roof window and view-facade window situations [40]

2.2.2. Window size and features

One of the primary purposes of using windows is to allow daylight to enter the building; therefore, the design of their dimensions and location directly affects natural lighting design [41]. Appropriately selected windows in terms of size, features, and location increase the amount of energy savings within the building and minimize glare problems that may occur in the interior environment. Window systems play a significant role in heat exchange processes and managing solar energy gains. For this reason, the energy efficiency factor should be considered during the design phase.

2.2.3. Sky conditions

CIE has mathematically defined 15 general sky conditions [41]. Among these sky conditions, CIE clear sky and CIE overcast sky are two widely used sky models in lighting design and are shown in Figure 7. These sky models are used to determine the amount of natural light that enters a building and to evaluate the lighting system's energy performance.

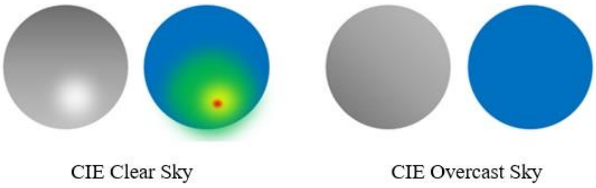

Figure 7. CIE standard clear sky and overcast sky [42]

CIE clear sky represents a cloudless sky with no atmospheric disturbances [43]. This model assumes that the sun is at an altitude greater than 5° and that the brightness of the sky is uniform in all directions. The CIE clear sky model is commonly used to evaluate the amount of direct and diffuse solar radiation that enters a building, as well as the distribution of sunlight throughout the day.

On the other hand, CIE overcast sky represents a cloudy sky with uniform cloud cover. This model assumes that the sun is completely covered by clouds and that the brightness of the sky is uniform in all directions. The CIE overcast sky model is used to evaluate the amount of diffuse radiation that enters a building on cloudy days [44].

3. RESULTS

In the first model, a vertical window model with a width of 1.25 meters, a height of 2 meters, and positioned 50 cm above the floor was chosen. Figure 8 illustrates the results for the vertical window model. Due to the smaller glass surface of vertical windows compared to other window models, the DFs produced at the side points were correspondingly lower. The DF value near the window was measured to be an average of 0.8%. Additionally, it was observed that the daylight distribution was not uniform.

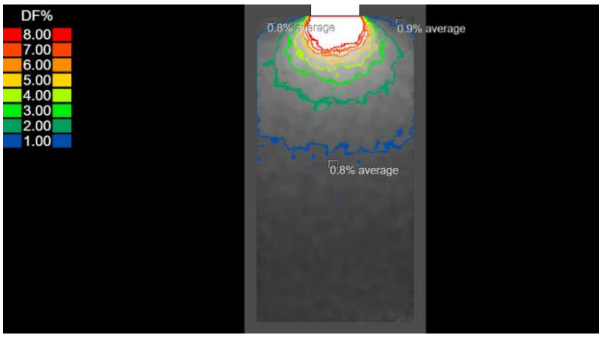

Figure 8. DF for the vertical window model

In the second model, the square window model with a width and length of 1.58 meters was tested. Figure 9 shows the results for the square window model. In this model, the average DF value was measured as 1.1% at the side sections, indicating insufficient transmission of light to the deeper parts of the room.

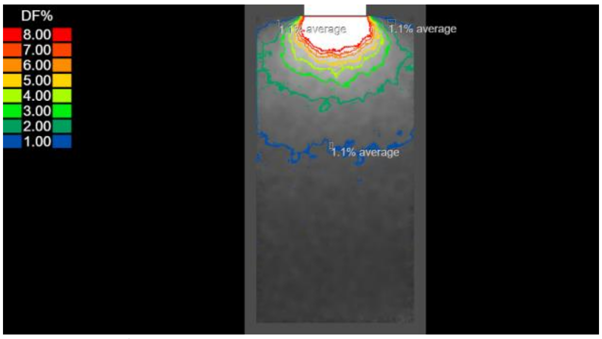

Figure 9. DF for the square window model

In the third model, the horizontal window model with a width of 1.25 meters and a length of 2 meters was selected. Figure 10 depicts the results for the horizontal window model. When compared to the square window model, which is the most similar in terms of shape, the horizontal window model is weaker at transmitting sufficient daylight to the extremities of the room. The average DF value near the window was calculated as 1.7%. Therefore, horizontal windows provide more daylight to a wider area near the window compared to square windows, but as you move away from the window, the amount of sunlight in the middle areas of the room decreases.

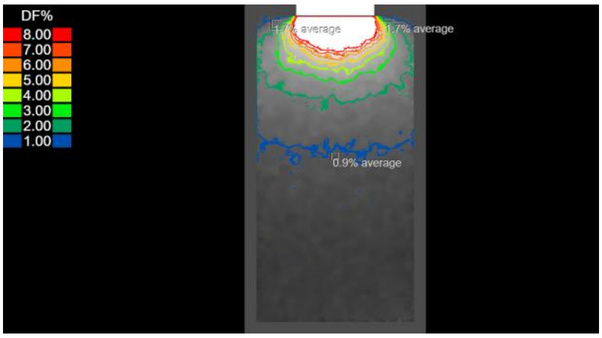

Figure 10. DF for the horizontal window model

The fourth model is the horizontal roof window model, with a width of 1.34 meters and a length of 1.6 meters. Figure 11 illustrates the results for the roof window model. The average DF value was calculated at 1.9%. When compared to the other three windows, it is evident that daylight is distributed more uniformly in the roof window model.

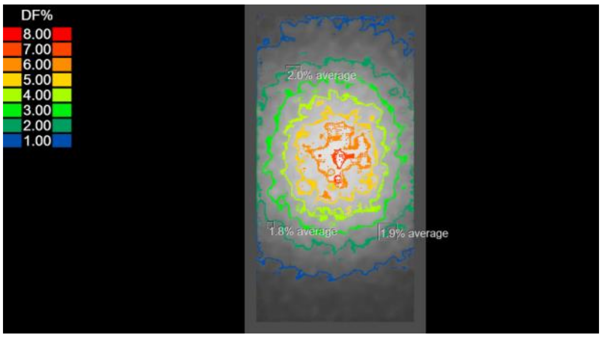

Figure 11. DF for the roof window model

As the fifth and final model, the horizontal window model with a width of 1 meter and a length of 2.5 meters is positioned close to the ceiling at a height of 1.8 meters from the floor. Figure 12 shows the results for the horizontal window model positioned close to the ceiling. There were no daylight factor values of 5% or higher, indicating glare issues. It also proved to be much more effective in transmitting light to the centre points of the room compared to other window models.

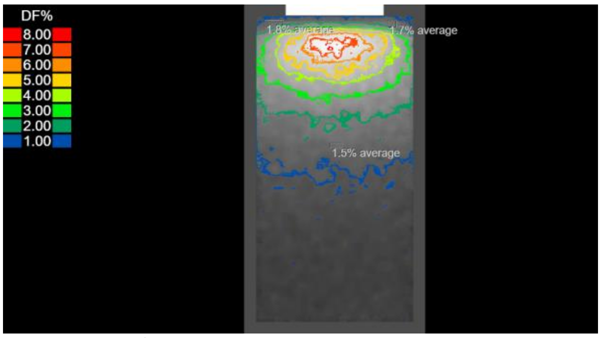

Figure 12. DF for the horizontal window model positioned close to the ceiling

The objects in the indoor environment also have specific reflection values. These values significantly affect daylight performance. In Figure 13, the impact of light and dark-colored furniture on the daylight factor in the indoor environment is observed in the system created with the Velux Daylight Visualizer Program under the same room condition and window type, with the dimensions of length and height of 1.2 meters and 2 meters, respectively. Light-colored furniture reflected more light into the indoor environment compared to dark-colored furniture, with an average DF value of 2%.

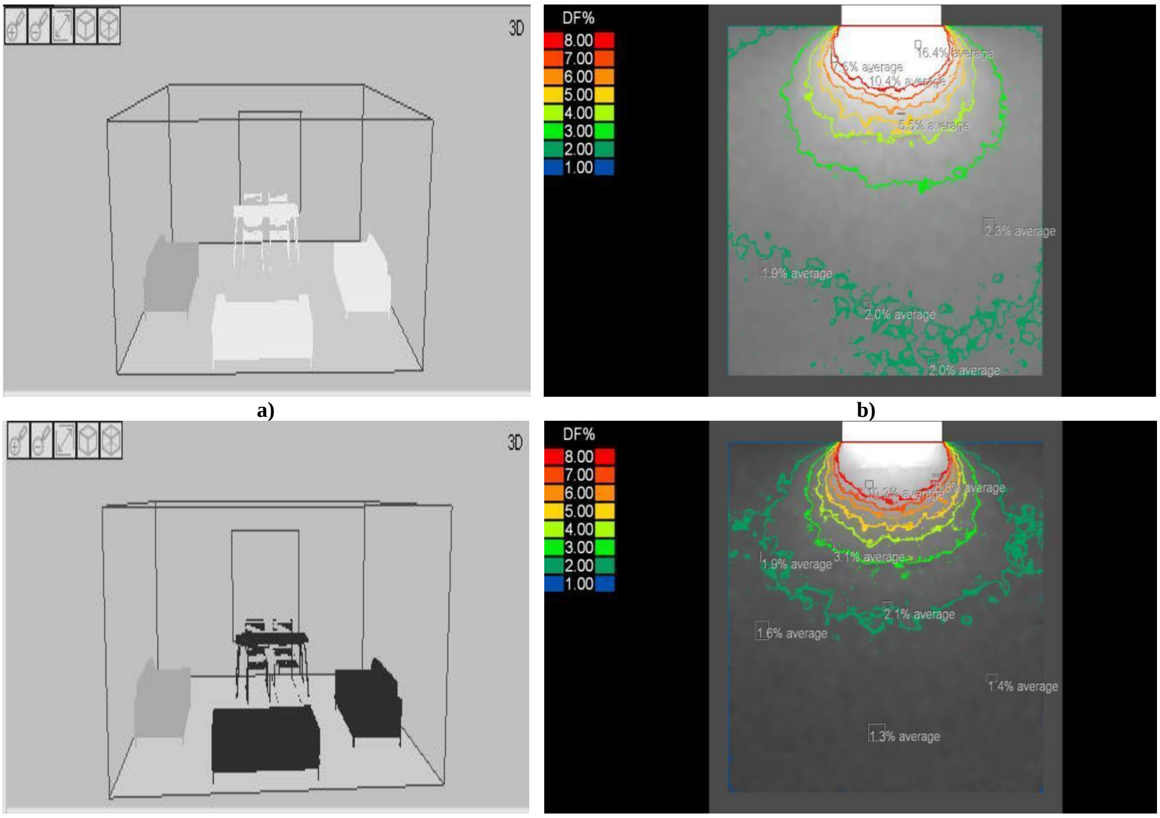

Figure 13. a) Three-dimensional design of white-gray furniture b) DF in the interior space with white-gray furniture with the window type of vertical c) Three-dimensional design of black-gray furniture d) DF in the interior space with black-gray furniture with the window type of vertical

4. DISCUSSION AND CONCLUSION

This study investigated the concept of an ideal window for maximizing daylight utilization in indoor environments and the parameters affecting the distribution of daylight indoors. To reduce costs associated with artificial lighting, the impact of different window sizes was analyzed using the computer simulation software Velux Daylight Visualizer.

The literature usually says that the optimal DF values are between 2% and 5%. However, the values found in this study are not exactly in that range because they were calculated in difficult conditions like deep rooms and overcast skies. Vertical windows have shown very poor performance in distributing daylight homogeneously. The small glass surfaces (1.25 meters) of these windows have been particularly insufficient in delivering light to the lateral axes. Horizontal windows exhibit a similar trend to the square window model in transmitting daylight to nearby points. The daylight factor is high near the window, but light transmission decreases as the distance increases. However, horizontal windows contribute significantly to energy savings by allowing more light into the interior due to their width, with the DF level at 1.7%. Square windows have shown a more homogeneous distribution compared to vertical and horizontal windows. Although they produce similar results to horizontal windows at close points, it has been observed that they are better at transmitting light to the middle points of the room compared to horizontal windows, by the DF level of 1.1% at the middle point. Roof windows have produced the most ideal light distribution compared to all other window models. However, since they can only be used in attics, more emphasis has been placed on the other three window models. Horizontal windows placed in the upper position have been more effective in delivering light to the far ends of the room. Being in the upper position has prevented potential glare problems near the window. In addition, since it allows more light into the interior with the DF level at 1.5%, its contribution to energy savings has come to the forefront. In conclusion, the horizontal window model placed in the upper position of the wall will greatly contribute to energy savings by reducing the need for artificial lighting. Under challenging conditions, there may be a decrease in overall light levels, which can impact the performance of window models. In these conditions, it has been observed that horizontal windows contribute more to achieving a homogeneous distribution by allowing more light to enter due to their widths. However, optimal DF values have not been reached.

The light-colored furniture used in the study has contributed to a broader distribution of daylight in the indoor environment by enhancing the reflection of natural light. Light colors can increase the overall light level in the interior by reflecting light rather than absorbing it. On the other hand, dark-colored furniture tends to absorb light and reflect less. This can result in the creation of more shaded areas in areas where furniture is present, making the room darker. In fact, in environments where white furniture is used, an average DF value of 2% is obtained, whereas with dark furniture, this value is determined to be 1.5%.

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