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Enhancing lighting efficiency in deep-plan classroom: Artificial lighting and daylighting

Derin planlı sınıfın aydınlatma verimliliğini artırma: Yapay aydınlatma ve gün ışığı

***Yazar(lar) (Author(s))**: Ecenur KIZILÖRENLİ[1], Yonca YAMAN[2], Ilknur UYGUN[3]*

ORCID[1]: 0000-0002-3992-1363

ORCID[2]: 0000-0003-4393-5490

ORCID[3]: 0000-0002-1387-7296

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Enhancing Lighting Efficiency in Deep-Plan Classroom: Artificial Lighting and Daylighting

Derin Planlı Sınıfın Aydınlatma Verimliliğini Artırma: Yapay Aydınlatma ve Gün Işığı

Highlights

- ❖ *The study investigates strategies to improve daylighting and reduce energy use from artificial lighting in a university classroom by using horizontal daylight tubes and overhangs.*
- ❖ *Integration of Rhinoceros, ClimateStudio, and DIALux for simulations yielded successful outcomes in improving daylight performance and reducing energy consumption caused by artificial lighting in the classroom.*

Graphical Abstract

The study examines a series of proposals. The study consists of four steps and is summarized as follows:

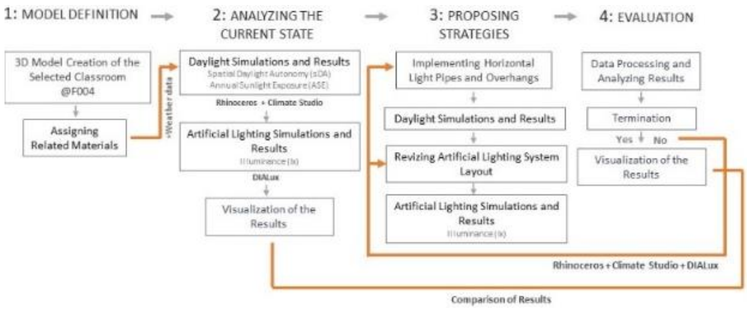

Figure. Graphical Abstract of the Study

Aim

The objective is to achieve Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) values within the designated analysis area that comply with the daylight evaluation criteria outlined in the LEEDv4 standards. Additionally, reducing energy consumption is among the objectives when evaluating the proposed daylight and artificial lighting systems.

Design & Methodology

In this study, a horizontal daylight tubes, overhangs, and a new artificial lighting system layout are proposed to enhance the daylight performance of a classroom receiving light from a single façade by using. Rhinoceros, ClimateStudio and DIALux.

Originality

The integration of systems used to evaluate daylight performance according to LEED requirements and to analyze energy performance through artificial lighting for the proposed improvements in an educational building highlights the originality of this study.

Findings

When compared to the base case, the desired values in sDA and (ASE) were achieved in accordance with LEED criteria. The implementation of the new artificial lighting plan and the selection of appropriate lighting elements effectively ensured the desired illumination levels and uniformity in each area. Additionally, a significant improvement in total energy consumption was achieved, with reductions reaching up to 72.34%.

Conclusion

The results demonstrate that the proposed solutions were successful in improving daylight performance as intended. Furthermore, the implemented artificial lighting system achieved the illumination levels required by standards and reduced energy consumption.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Enhancing Lighting Efficiency in Deep-Plan Classroom: Artificial Lighting and Daylighting

Research Article

Ecenur KIZILÖRENLİ*, Yonca YAMAN[2], İlknur UYGUN[3]

[1]Department of Architecture, Faculty of Architecture, Yaşar University, Türkiye
[2] Department of Architecture, Faculty of Architecture, Dokuz Eylul University, Türkiye
[3] Department of Interior Architecture and Environmental Design, Faculty of Architecture, Yaşar University, Türkiye

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ABSTRACT

Insufficient light distribution throughout the classroom has a negative impact on students. Therefore, it is crucial to implement effective daylighting and artificial lighting strategies in educational buildings. To address this issue, a combination of a horizontal daylight tubes and an overhang was proposed for a classroom at the selected university. The aim was to enhance the availability of daylight, reduce glare and improvement of the artificial lighting system performance. The goal is to achieve a Spatial Daylight Autonomy (sDA) of at least 55% and an Annual Sunlight Exposure (ASE) of no more than 10% in the designated analysis area, as stipulated by the daylight assessment criteria outlined in LEEDv4 standards. In addition to the improvements in the daylight performance of the classroom, an artificial lighting system was proposed to replace the existing system, which creates homogeneous and sufficient lighting. Reducing the energy consumption of the proposed system is also among the desired targets while evaluating the proposed systems, Rhinoceros and ClimateStudio were used for daylight simulations and DIALux was used for artificial lighting simulations. The results show that proposed solutions were successful as intended. The sDA value for the zone with the lowest initial value was improved from 1.6% to 59.1%, while the ASE value for the zone with the highest initial value was improved from 16.1% to 9.7%. Additionally, energy consumption was reduced by 72.34%.

Keywords: Educational buildings, daylight performance, artificial lighting, horizontal light tubes.

Derin Planlı Sınıfın Aydınlatma Verimliliğini Arttırma: Yapay Aydınlatma ve Gün Işığı

ÖZ

Sınıf genelinde yetersiz ışık dağılımı öğrenciler üzerinde olumsuz bir etkiye sahiptir. Bu nedenle, eğitim binalarında etkili gün ışığı ve yapay aydınlatma stratejilerinin uygulanması son derece kritiktir. Bu sorunu ele almak için, seçilen üniversitedeki bir sınıfa yatay bir gün ışığı tüpü ve bir çıkma kombinasyonu önerilmiştir. Amaç, gün ışığının kullanılabilirliğini artırmak,parlamayı azaltmak ve yapay aydınlatma sisteminin iyileştirilmesi olarak belirlenmiştir. Hedef, LEEDv4 standartlarında belirtilen gün ışığı değerlendirme kriterlerinde öngörüldüğü gibi, belirlenen analiz alanında en az %55'lik bir Mekansal Gün Işığı Otonomisi (sDA) ve %10'dan fazla olmayan bir Yıllık Güneş Işığı Maruziyeti (ASE) elde etmektir. Sınıfın gün ışığı performansındaki iyileştirmelere ek olarak, mevcut sistemin yerine homojen ve yeterli aydınlatma sağlayan bir yapay aydınlatma sistemi önerilmiştir. Önerilen sistemin enerji tüketiminin azaltılması da istenen hedefler arasındadır. Önerilen sistemler değerlendirilirken gün ışığı simülasyonları için Rhinoceros ve ClimateStudio, yapay aydınlatma simülasyonları için ise DIALux kullanılmıştır. Sonuçlar, önerilen çözümlerin amaçlandığı gibi başarılı olduğunu göstermektedir. Başlangıçta en düşük sDA değerine sahip olan alan için bu değer %1,6'dan %59,1'e iyileştirilirken, en yüksek ASE değerine sahip olan alan için bu değer %16,1'den %9,7'ye iyileştirilmiştir. Ayrıca, enerji tüketimi %72,34 oranında azaltılmıştır.

Anahtar Kelimeler: Eğitim yapıları, gün ışığı performansı, yapay aydınlatma, yatay ışık tüpleri.

1. INTRODUCTION

The rapid growth of the global population, industrialization, and the increasing diversity of human needs have significantly increased the demand for energy, leading to the enhanced reduction of the world's energy resources. This situation necessitates more efficient utilization of limited energy sources and a reduction in energy consumption across all sectors, particularly in construction [1-2]. Energy resources are essential for heating, lighting, and various production processes. While building energy use accounts for around 30% of the total energy consumption, electrical energy usage, predominantly for lighting, plays a significant role in other areas [3]. Therefore, energy-efficient and integrated daylighting and artificial lighting solutions are essential, especially, in educational buildings. The design of classrooms is important for the learning activities that take place in it and because it affects the cognitive processes of all students regardless of age [4-6]. It is known that when daylight is used effectively in such areas, students have higher academic achievement scores, better concentration, and alertness [7-8], and increase their general well-being [9]. In addition, natural

* *Corresponding Author*
e-mail : ecenur.kizilorenli@yasar.edu.tr

light has positive benefits such as increasing the aesthetic quality of the interior and showing the objects in their real colors [10]. In this direction, the correct selection and use of the details that make the daylight design effective is a critical process. Natural light and artificial light should not be considered separately from each other and should be handled with a holistic approach. This integrity raises the visual comfort to a good level in the interior, while providing significant electrical energy savings [11-13].

Besides the benefits mentioned above, due to the changing nature of daylight, it is necessary to control and direct natural light in order to complement or replace artificial lighting [14-16]. If not controlled, overheating of the interior indoors can cause an increase in the amount of energy consumed for cooling, heating and artificial lighting, and glare can occur due to excessive light penetrating the interior [17-19]. When such issues are investigated in the literature, studies examining daylight performance in schools with different strategies can be found [20-24]. Nurrohman et al. [12] draws attention to the use of daylight and artificial lighting together in architecture studio classroom. In their first simulation, they examined how effective daylight was in the space without using lamps. Where it was not sufficient, an additional artificial lighting was needed, and two different lamp groups were designed. In both designs, they concluded that the annual energy consumption was considerably improved compared to the base case. Bayram and Kazanasmaz [25] produced 9 scenarios with different shading devices and luminaire type/arrangement for 6 rooms in a university building. They used DIALux for simulations. As a result of the study, the reduction in electricity use was realized in the range of almost 56-83% with the contribution of LED luminaires, layout, transmissivity of glasses and shading devices. Freewan and Al Dalala [26] investigated daylight performance and energy consumption through real-time experiments and simulations in a university classroom, using strategies such as light shelf, anidolic systems, translucent materials, and light shelf combined with external reflectors. They concluded that with these strategies, they can provide a significant increase in illumination levels, improve homogeneous distribution, and reduce disturbing glare rates. They also stated that the amount of energy consumed for lighting decreased by 40-50%. On the other hand, Ishac and Nadim [27] suggested replacing the window as a daylight strategy in a three-sided classroom in a university building in Egypt. In addition, he proposed an optimization study where the light shelf and vertical fin are separate and combined. It is seen that the results are compatible with previous studies in that region and improvements in daylight performance have been achieved with the alternatives investigated. Wen et al. [28] conducted an optimization study in a university library with 4 different shading elements to minimize glare and maximize the visual satisfaction of the building occupants. They concluded that while all shading devices were found to be effective in reducing glare in the Shanghai climate, the device with two shading devices failed compared to the original situation to increase visual satisfaction. Erlalelitepe et al. [29] investigated how shading strategies of different sizes affect daylight performance for five spaces located in different orientations in a university building in Izmir by making measurements. According to the results, they observed that some improvements were achieved while others were not, and they emphasized that the right elements should be selected according to the orientation. Cılasun and Kızılorenli [30] proposed tubular daylight guidance systems (TDGS) and moving shading elements to a studio in an architecture faculty. According to their results, they stated that the two systems could work together efficiently and significantly improved daylight performance. As mentioned in the last study in the literature review, one of the biggest problems encountered in educational buildings is that large and deep classrooms with single windows have lower illumination levels in the rear parts compared to the front parts, resulting in low visual comfort. A low level of uniformity occurs in these spaces. Therefore, it is necessary to apply the right daylight strategy in these places. These should be strategies to improve daylight, direct and distribute daylight, and reduce glare and energy consumption. It has been proven by many studies that horizontal daylight tubes (or light pipes) and the use of overhangs are effective strategies for transmitting daylight deeper into space [26-27-31-32-33]. However, there are a limited number of studies examining these strategies in an integrated manner in university buildings. In the scope of this study, using light tubes, overhangs, an efficient artificial lighting system and layout, the aim is to evaluate daylight performance according to LEED requirements and examine energy performance through artificial lighting analysis, while at the same time proposing these systems for a deep-plan classroom, which highlights the originality of the study. The selected area is a classroom on the ground floor of an existing educational building. Since this space is actively used, recommendations for improvements are being made. In line with, in this study, the authors suggested horizontal light tubes and overhangs to control the light entering the interior, in other words, to spread the light evenly in the interior, and to reduce the glare that may occur in front of the window. This is the stated primary purpose and is to predict the indoor daylight performance (sDA and ASE) of these control systems through simulation. The secondary aim is to both improve the visual performance (uniformity, Unified Glare Rating (UGR) and illuminance) in the interior and reduce the amount of energy consumed by changing the artificial lighting system available in places where daylight is not enough.

2. MATERIAL and METHOD

This section outlines the methodology for evaluating proposed strategies to improve the daylight and artificial lighting performance of a selected classroom, in comparison to the current situation. Figure 1 illustrates the workflow of the study, which involved using simulation tools and employing specific strategies to achieve the desired goals.

To create a three-dimensional model of the classroom, the technical drawing file was imported into the Rhinoceros program. In order to assign the materials to the three-dimensional model, first of all, the glass transmittance in the building was determined as approximately 43% using the Testo435 Multifunction measuring instrument. The suitable materials were then applied to the model's opaque surfaces, and working zones were defined at table height. The optical properties of the material are given in Table 1.

Table 1. Building material optical properties.

Elements	Assigned Materials	Reflectance
Wall	Beige Painted Wall	68.10%
Ceiling	Wood Panel	54.55%
Floor	Light Wood Floor	52.00%
Table	Faux Wood Table	55.41%
Seating	Blue Cubicle Fabric	6.21%
H. Light Tube	Polished Silver	95.98%
Door	Beige Wooden Door	78.95%
		Transmittance
Window Glass	Clear - Clear	43.00%

Then, the artificial lighting system and layout were evaluated by measuring the illuminance using DIALux. Strategies for performance improvements were proposed based on the base case performance results performed after creating separate work planes for each platform in the class. Under the proposed plan, the existing artificial lighting would be replaced by positioning the light tubes, considering the constraint of a flattened ceiling. The objective was to develop a new and suitable artificial lighting layout while ensuring that the illuminance level in educational buildings (for auditorium and lecture halls) reaches an average of 500 lx, and as modified 750 lx which is the required standard [35].

Given the context of an educational environment focused on architecture, a target of 750 lux is established for illuminance levels. Additionally, the uniformity value, which indicates the even distribution of light throughout the space and is an architectural design criterion, should be above 0.6 [35] compared to the base case scenario. Another metric evaluated in the study is Unified Glare Rating (UGR), which estimates the amount of irritating glare produced by a lighting system. The maximum recommended value for educational buildings according to EN 12464-1 standards is 19. Lastly, the goal was to

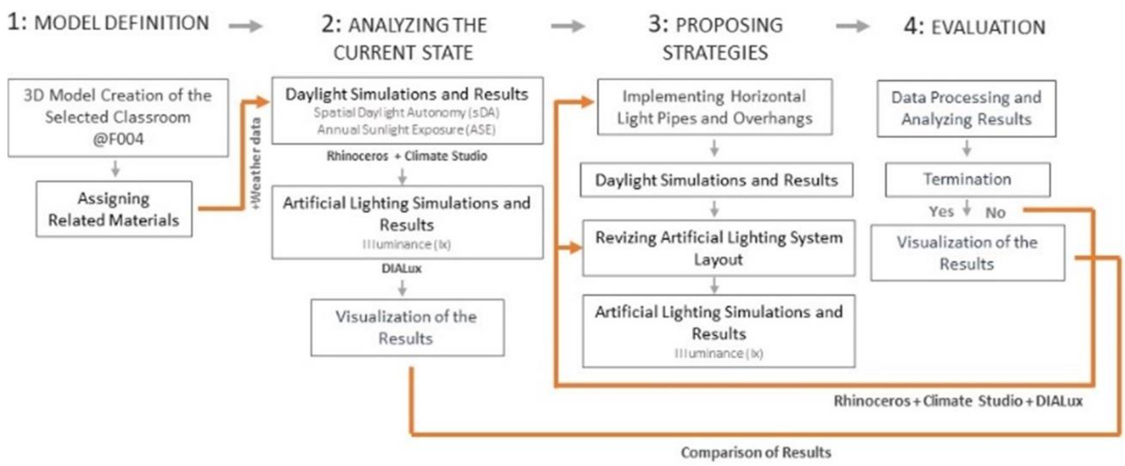


Figure 1. Workflow of the study. Source: Created by authors

Next, ClimateStudio, a Rhinoceros plugin, was used to conduct a daylight analysis and assess the current state of the classroom. The analysis was performed using the LEED v4.1 rating system, which emphasizes the importance of daylight simulation and recommends the use of Annual Sunlight Exposure (ASE) and spatial Daylight Autonomy (sDA) criteria [34]. ASE (1000/250) allows assessment of the potential risk of excessive daylight penetration of an interior zone, while sDA allows assessment of the adequacy of daylighting [34]. In order to get a score in LEED, sDA 300/50% > 55% (credit 2 points) or sDA 300/50% > 75% (credit 3 points) and ASE 1000/250 h < 10% should be obtained from the simulations. To meet the specified requirements, the proposal focuses on implementing regulations regarding glass permeability, incorporating horizontal light tubes, and utilizing overhangs.

enhance energy efficiency through the new lighting layout and the use of lighting elements. In line with these goals, the simulations were repeated for each proposed improvement and the data obtained was visualized and compared.

Overall, the methodology involved creating a detailed three-dimensional model, evaluating the current state of the classroom, and proposing and assessing strategies for improvement using daylight and artificial lighting simulations.

3. CASE STUDY

The selected classroom is located on the ground floor of Building F at Yaşar University, İzmir, Turkey. The orientation of the classroom's glass is towards the southwest due to the building's location. The dimensions of the classroom were determined as 15.47 meters in depth and 8.55 meters in width (Figure 2).

Given that the selected classroom has a glass transmittance of 43% and receives daylight from only one direction, and its depth is 15.47 meters, horizontal light tubes were proposed to address this issue, as suggested by Heng et al.'s work in 2020 [33]. To prevent glare in areas, close to the glass, overhangs were recommended based on the horizontal tubes, as depicted in Figure 3. During the analysis, five distinct working zones were established, given that the classroom is configured as a lecture hall with five levels (as shown in Figure 3). Furthermore, modifications were made to the artificial lighting layout, as outlined in the methodology section.

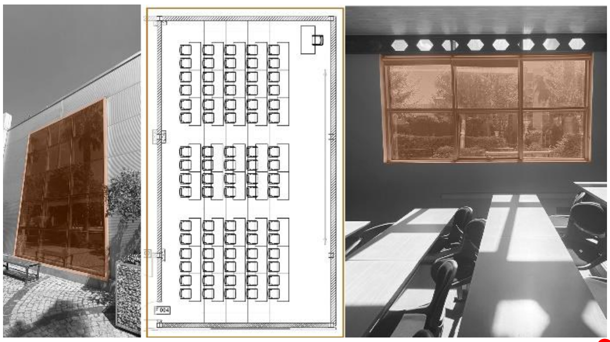


Figure 2. Exterior view, class from interior, plan drawing (from left to right). Source: created by authors.

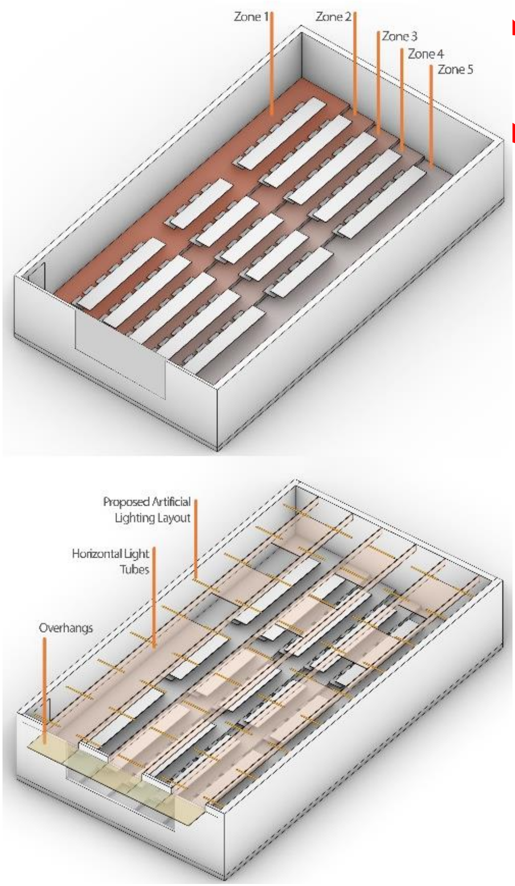


Figure 3. Working zones (top), proposed strategies (left). Source: created by authors

4. COMPARATIVE SIMULATION RESULTS AND DISCUSSION

4.1. Daylight Performance Analysis

In order to thoroughly evaluate the daylight performance of the selected classroom and explore potential avenues for improvement, daylight analyses were conducted for each level. The assessments involved moving each test surface to student desk level and defining grids with 0.5 intervals to facilitate accurate simulations. Spatial daylight autonomy (sDA) and annual sunlight exposure (ASE) values were obtained for each zone (Figure 4) utilizing selected software tools such as Rhinoceros 3D and ClimateStudio. For each specific zone within the classroom, the resulting sDA and ASE values were obtained and recorded. Starting from the lowest level within the classroom to the highest level, the sDA values were 7.5%, 22.6%, 22.6%, 19.4%, and 1.6%. Similarly, the ASE values for the respective zones were 2.7%, 16.1%, 16.1%, 16.1%, and 0%.

Upon closer examination of the results, it is seen that there is no glare problem in zones 1 and 5. However, the sDA values in these areas fall significantly below the targeted value of 55%. This shows that the amount of daylight entering these areas is insufficient, which may have an effect on the users' overall wellbeing and level of visual comfort. zones 2, 3, and 4 show substantially higher sDA values than zones 1 and 5, in contrast. These values, however, are still below the desired threshold, indicating that additional adjustments can be made to improve the daylight performance in the classroom. In zones 2, 3, and 4, the ASE values are high, which is interesting to note given the lower sDA values. This suggests that even though these areas receive a lot of light, there may still be room for improvement in terms of the spatial distribution and quality of that light.

These findings clearly highlight the potential for improving the daylighting conditions in the assessed classroom. By implementing selected strategies such as implementing overhangs, or light redirecting elements such as horizontal light tubes, it is possible to improve both sDA and ASE values across all created zones within the classroom. These improvements not only enhance the students' and instructors' visual comfort but also contribute to energy efficiency by reducing the need for artificial lighting.

Several actions were taken in an effort to improve the classroom's daylight performance. In order to allow for more natural light to enter the space, the glass transmittance was first raised from 43% to 77%. This modification aimed to decrease reliance on artificial lighting by maximizing the use of daylight as a primary light source. Three horizontal light tubes were mounted on the ceiling to ensure that daylight would enter the classroom from the back. These light tubes, which each measured 15 meters in length and 1.5 meters in width, were spaced 125 cm apart. These light tubes opened up a path for daylight to penetrate farther into the classroom, illuminating previously darkened spaces. Three openings were made in the back of the classroom to facilitate light transfer. These openings, which have widths of 150x150 cm, 150x150 cm, and 80x150 cm, were created to efficiently channel daylight into the area.

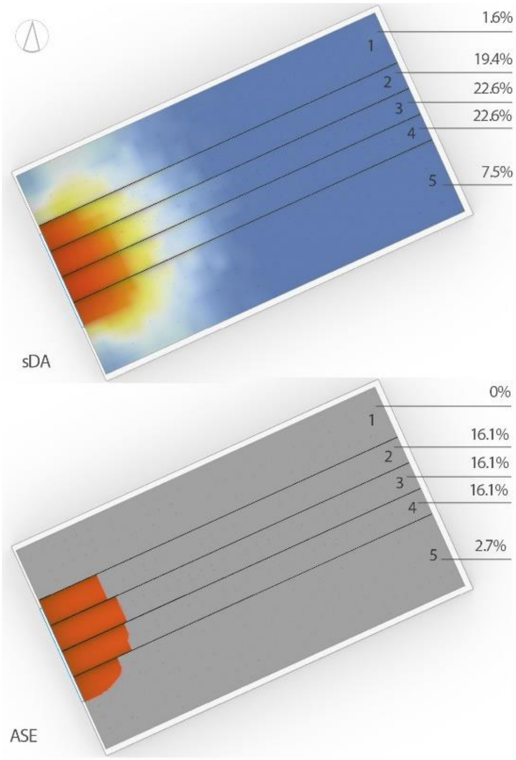


Figure 4. Simulation results of base case daylight performance

After a series of trials, it was determined where and what size these openings were needed to allow the desired amount of daylight penetration. Additionally, overhangs were added to the building to control the lighting in the classroom and reduce glare. With a length of 100 cm, these overhangs were positioned to block direct sunlight while letting diffuse light in. This modification improved the lighting environment, establishing better visual conditions for the instructors and students.

The daylight simulations were rerun for each classroom level after these modifications had been made. The outcomes demonstrated a significant improvement in ASE values and sDA values while maintaining the desired threshold of 55% (Figure 5). The sDA values for each level were recorded as 55.1%, 58.1%, 59.7%, 66.1%, and 59.1% respectively, indicating that the desired levels of daylight autonomy were achieved. Additionally, the ASE values were obtained and documented as 0.1%, 6.5%, 9.7%, 9.7%, and 2.2% for each level, demonstrating effective control over annual sunlight exposure. These outcomes signify that the adjustments, including increased glass transmittance, placement of horizontal light tubes and openings, as well as the overhangs, have collectively contributed to a substantial improvement in the classroom's daylight performance. The improved distribution of daylight not only promotes a healthier and more productive learning environment but also brings about energy savings by reducing the need for artificial lighting during daylight hours.

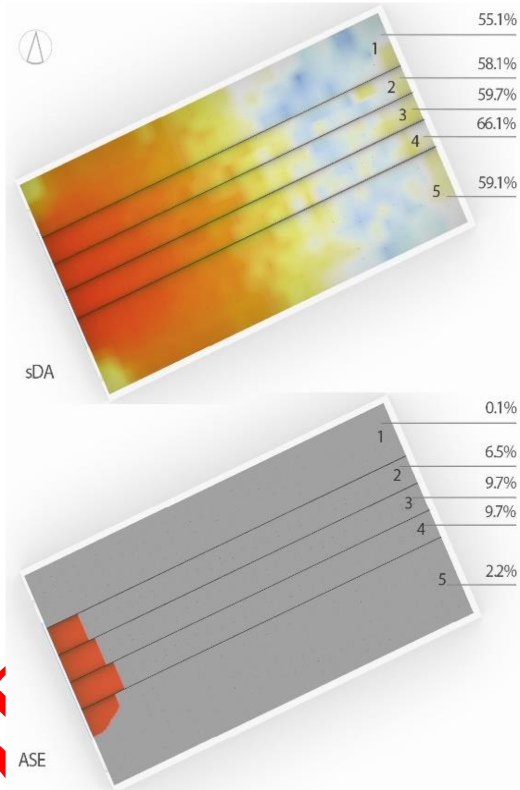


Figure 5. Simulation results after performance ımprovements

4.2. Artificial Lighting Performance Analysis

After implementing strategies to improve daylight performance in the classroom, the next step was to evaluate the existing artificial lighting system. The first step to achieve this is to identify the brands and codes of existing fixtures and fluorescent lamps. It has been determined that the total luminous flux value of the existing lighting elements is 4500 lm and the connected load is 78 W, Navigator RPerformance Louver NB-SH-2T8-DL3, and the information of this lighting element is included in the DIALux program. The AutoCAD drawing file utilized for creating the three-dimensional model was then used as a basis for modelling the classroom in DIALux. The installation of the artificial lighting system was aligned with the existing layout of the system, followed by a base case analysis. In the existing layout, the lighting elements are positioned parallel to the glass. In the arrangement placed in 5 rows, there are 3 lighting elements in each row. As in daylight performance analyses, separate work planes were created at the height of student desk for each step to run artificial lighting analyses. Following the analyses, the desired objectives were established, which included achieving an illuminance level exceeding 500 lx, a uniformity ratio value above 0.6 and a unified glare rating below 19 [35]. During the simulation conducted in DIALux, separate outcomes were obtained for each of the designated working planes. The average illuminances for the defined zones were determined as 239 lx, 164 lx, 251 lx, 224 lx, and 207 lx for zone 1 to 5, respectively. Simultaneously, the uniformity values were calculated as 0.17, 0.20, 0.14, 0.17, 0.22 for the respective zones. The obtained UGR values are 15.3, 14.0, 12.9, 13.0 and 12.6, respectively (Table 2).

A closer examination of the data reveals that the targeted illuminances could not be reached in any of the zones. Although zone 1 and zone 3 are the closest to the targeted value, it is seen that the values are significantly below the target. On the contrary, when the uniformity values of these zones are examined, it is seen that the zones with the lowest values are these mentioned two zones. When Zone 5, which has the closest uniformity value to the target, is examined, it is seen that the average illumination value remains at 207 lx. When the uniformity values are examined in parallel with these data, it is seen that the min illumination value was calculated as 34.9 lx while the maximum illumination value was calculated as 483 lx in the zone with the lowest uniformity value. In zone 5, which has the highest uniformity value, the min illumination value is 46.3 lx, while the maximum illumination value is 357 lx. There is a significant inequality between the measurement minimum and maximum illumination values for all the zones. Such a wide range means a lack of homogeneity in light distribution in the zones, resulting in an uneven and inconsistent lighting experience for users (Figure 6). Upon analyzing the outcomes in relation to the (UGR), it becomes evident that the intended objective is deemed suitable. However, this occurrence can be considered typical as the illumination values significantly fall short of the desired levels. In addition to all this information, as a result of the simulations, the potential annual energy demand of the lighting fixtures was calculated as 940 kWh/a. It is clear that further adjustments are necessary to achieve the desired illuminance levels and uniformity throughout the different zones.

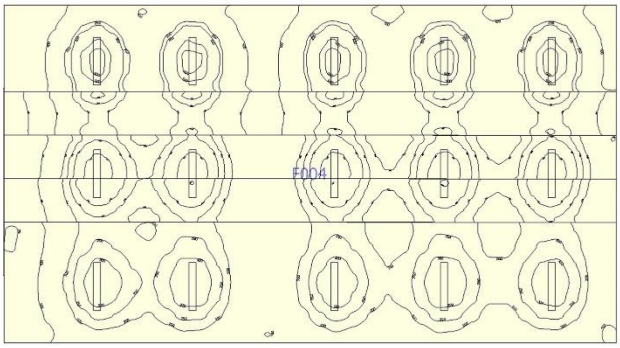


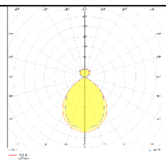
Figure 6. Simulation results of base case artificial lighting performance

Table 2. Illuminance and uniformity values in the working plane for the base case.

Zones	Z1	Z2	Z3	Z4	Z5
Average (lx)	239	164	251	224	207
Min (lx)	41.7	32.7	34.9	37.6	46.3
Max (lx)	673	325	483	407	357
Uniformity	0.17	0.20	0.14	0.17	0.22
UGR	15.3	10.4	12.9	13.0	12.6

In order to improve the obtained values and create a more comfortable working environment for the students and also for instructors, a new artificial lighting layout has been proposed with different lighting elements. While recommending this layout, the horizontal light tubes, and its layout, which is implemented to improve the daylight performance of the classroom, has been considered and it is aimed not to block the openings on these tubes. It was crucial to ensure that the proposed lighting layout does not obstruct the openings on this tube, as it serves as a vital aspect of the design. To address this constraint, the lighting fixtures were positioned according to the tube layouts. Trials were conducted, resulting in the selection of Philips LL512X XA 1 xLED31S/840 WB with a total luminous flux value of 3150 lm and a connected load of 18 W as the primary lighting element. The information and lighting distribution curve diagrams of the lighting elements used in the base case and included in the proposed scenario are given in Table 3. The lighting

Table 3. Properties of the lighting fixtures.

Zones	Existing Luminaire	Proposed Luminaire
Lighting Fixture	239 Cooper Lighting Solutions Navigator RPerformance Louver NB-SH-2T8-DL3	Philips LL512X XA1 xLED31S/840 WB
Connected Load (W)	78	18
Total Luminous Flux (lm)	4500	3150
Light Distribution Curve		

elements were arranged in a total of nine rows, with each row and each row consisted of five lighting elements.

During the evaluation of this new artificial lighting layout, a similar approach was followed as in the base case analysis, with the same surface reflectance values. Each working zone was defined separately, and analyses were conducted accordingly. This approach, as before, allowed for an assessment of the lighting performance and its impact on each specific zone. The results reveals that the illuminances obtained for zone 1 through zone 5 were 974 lx, 992 lx, 986 lx, 983 lx, and 922 lx, respectively. The uniformity values were determined as 0.71, 0.65, 0.62, 0.61, and 0.63 for the respective zones. Additionally, UGR values are 19.0, 18.8, 18.1, 17.7 and 17.4, respectively (Table 4). Notably, both the illuminances and uniformity values have successfully reached the targeted thresholds. Significant improvements have been observed in terms of illuminances and uniformity compared to the base case scenario. The variation between the minimum and maximum illuminances within each zone has been significantly reduced, indicating a more consistent and balanced lighting distribution. Moreover, the uniformity values have shown remarkable enhancement, reflecting a more evenly spread illumination throughout the zones. Furthermore, each zone now provides the required illuminances, fulfilling the objective of creating a well-lit working environment. Although the UGR values have increased compared to the base case scenario, it is seen that it still complies with the value suggested by the EN 12464-118 standards (Figure 7). The implementation of the new artificial lighting layout and the selection of appropriate lighting elements have effectively achieved the desired lighting levels, uniformity, and glare rating in each zone. Additionally, an evaluation of the potential annual energy demand resulted in a calculated value of 260 kWh/a. This assessment considers the energy consumption associated with the artificial lighting system. The data suggest that the improvement attempt in each evaluation criterion has been successful, leading to improved lighting conditions while maintaining a reasonable energy demand. Overall, these findings indicate that the efforts invested in improving the lighting layout have yielded positive outcomes. The targeted illuminance levels, uniformity values, and energy efficiency objectives have been met, ensuring a more comfortable and visually satisfying working environment for the users.

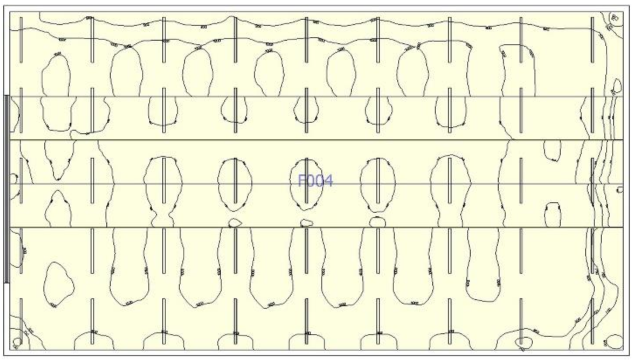


Figure 7. Simulation results of base case artificial lighting performance

Table 4. Illuminance and uniformity values in the working plane for the base case.

Zones	Z1	Z2	Z3	Z4	Z5
Average (lx)	974	992	986	983	922
Min (lx)	696	644	613	596	581
Max (lx)	1075	1056	1077	1084	1053
Uniformity	0.71	0.65	0.62	0.61	0.63
UGR	19.0	18.8	18.1	17.7	17.4

5. CONCLUSION

Educational buildings require careful consideration of both natural daylight and artificial lighting design to optimize various aspects of the learning environment. The strategic utilization of daylight not only enhances visual comfort but also yields numerous benefits such as improved learning performance, increased motivation among students and employees, and enhanced work productivity. In studies concerning indoor performance enhancements as documented in the literature, efficient use of daylight and appropriate artificial lighting systems significantly contribute to energy conservation by reducing dependency on heating and cooling systems.

The impact of lighting design in classrooms extends far beyond visual comfort; it is a catalyst for creating an optimal learning environment. As indicated, the provision of sufficient daylight in educational spaces has been found to have a positive effect on the academic achievements of students and lecturers alike. This underscores the critical role that lighting design plays in creating an optimal classroom environment that supports academic performance and enhances the overall learning experience. From this perspective, the findings of this study demonstrate significant improvements in both daylight performance and artificial lighting efficiency through the implementation of suggested modifications, thus contributing to the literature in this regard. By incorporating these recommendations, the classroom not only benefited from increased availability of useful daylight, but also effectively mitigated issues related to glare, in accordance with the LEED criteria. Moreover, a new artificial lighting layout was proposed, leveraging existing fluorescent lighting fixtures to ensure a uniform distribution of light, thus providing an equal learning experience for each student. Additionally, the proposed layout and its implementation exhibit a substantial enhancement in energy utilization efficiency.

In summary, this study serves as an effort in addressing the challenges associated with efficient daylighting and artificial lighting solutions for deep plan classrooms. As a result, recommendations have been made for the integration of optimal natural and artificial lighting design strategies in the selected educational structure's classrooms, yielding positive outcomes. However, the presence of fixed student desks indoors within the scope of this study creates a fundamental constraint on the improvement of the artificial lighting system and layout, while the lack of exterior connections on other walls of the relevant classroom prevented the creation of additional openings. Nevertheless, the implemented systems have contributed to performance improvement and supported energy efficiency while enhancing visual comfort. As mentioned, these proposed systems and methodology have the potential to improve daylight performance in deep plan spaces. By being applied in different climates and building types, they allow for the evaluation and enhancement of performance.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Ecenur KIZILÖRENLİ: All authors contributed equally in the preparation of the manuscript.

Yonca YAMAN: All authors contributed equally in the preparation of the manuscript.

Ilknur UYGUN: All authors contributed equally in the preparation of the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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