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A design proposal for improving daylight performance of a deep-plan classroom by using tubular daylight guidance systems and movable shading devices

Günışığı tüpleri ve hareketli gölgeleme elemanlarını kullanarak derin planlı bir sınıfın günışığı performansını iyileştirmeye yönelik bir tasarım önerisi

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A Design Proposal for Improving Daylight Performance of a Deep-Plan Classroom by Using Tubular Daylight Guidance Systems and Movable Shading Devices

Highlights

- *A deep-plan classroom was divided into three zones, and an ideal solution with TDGS and movable shading devices was proposed that prioritized uniform illumination in each zone while also enabling increased daylight availability and minimizing glare.*
- *The findings imply that combining TDGS and movable shading devices could provide a highly effective solution for deep-plan rooms, with implications for both new construction and retrofits.*

Graphical Abstract

Within the scope of this study, it is anticipated that the integration of movable shade devices and tubular daylight guiding systems (TDGS) will improve the daylight performance in the examined deep-plan classroom.

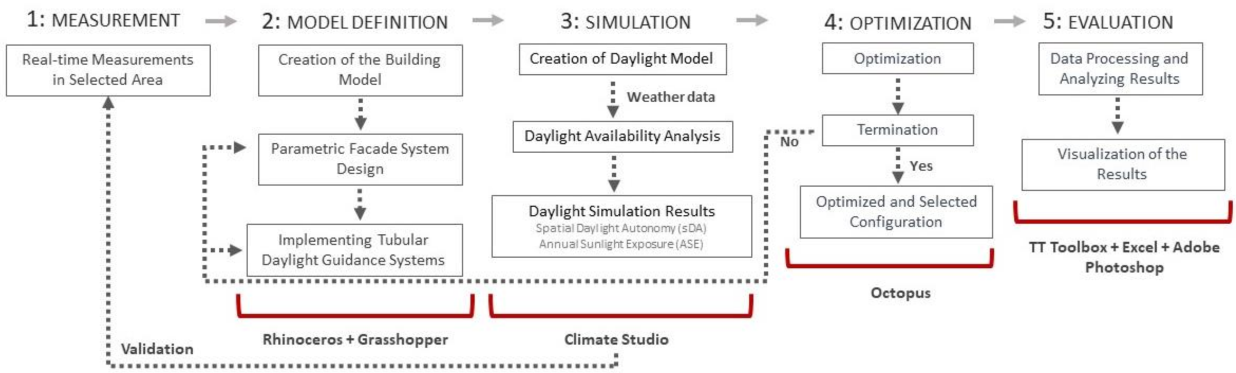

Figure. Workflow of the Study

Aim

To assess the efficiency of TDGS and movable shading devices to increase the daylight performance of a deep-plan layout that receives daylight only from an unshaded south-east façade.

Design & Methodology

Real-time daylight measurement and simulations was performed in this study to analyze the base case situation, and daylight simulations was employed to establish the ideal position for the shadings and TDGS. Rhinoceros 3D and its plugins Grasshopper and Climate Studio were used to complete the daylight simulations.

Originality

The originality of the study is demonstrated by zoning the space for assessment and proposing solutions with both TDGS and movable shadings in the optimum conditions and angles for each zone.

Findings

Compared to the base case scenario, the design proposal increased daylight availability for each zone and achieved the latest LEED daylight criteria, which call for sDA in the working area to be at least 55% and ASE on the occupied floor to be at most 10%.

Conclusion

A deep-plan classroom was investigated, with insufficient daylight availability in the back and glare in the front. The majority of the space in the proposed design strategy met the LEED criteria, proving that the systems work well together.

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.

A Design Proposal for Improving Daylight Availability of a Deep-Plan Classroom by Using Tubular Daylight Guidance Systems and Movable Shading Devices

Research Article

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ABSTRACT

The use of daylight in educational settings has a significant impact on the well-being, attention, and academic achievement of students. However, providing adequate daylighting without glare can be difficult, especially in deep-plan layout classrooms, because daylight is not constant and its strength varies with distance from the façade, necessitating the use of additional solutions frequently. In this study, tubular daylight guidance systems (TDGS) and movable shading devices are proposed to increase daylight availability in the Yaşar University Faculty of Architecture Temporary Studio, which has a deep plan layout and receives daylight only from the southeast facade. The objective was to meet the LEED daylight evaluation requirements for each zone, which require sDA to be at least 55% and ASE to be at most 10% in the selected analysis area. To propose TDGS and movable shadings with the most efficient angles and positions; Rhinoceros, Grasshopper, and Climate Studio were used, and simulation results were validated by real-time measurements. The design proposal simulation results achieved a significant increase in daylight availability in the rear part of the room (zone 2-3), while glare was diminished near the façade (zone1). The proposed design strategy improved daylight availability through the room, demonstrating that the systems perform well together.

Keywords: movable shading device, tubular daylight guidance systems, daylight performance, glare, deep-plan classroom.

Günışığı Tüpleri ve Hareketli Gölgeleme Elemanlarını Kullanarak Derin Planlı Bir Sınıfın Günışığı Performansını İyileştirmeye Yönelik Bir Tasarım Önerisi

ÖZ

Eğitim yapılarında günışığının kullanımı öğrencilerin sağlığı, dikkati ve akademik başarısı üzerinde önemli bir etkiye sahiptir. Ancak, günışığı sabit olmadığı ve mekân içindeki gücü cepheden uzaklaştıkça azaldığı için, özellikle derin planlı sınıflarda, kamaşmaya yol açmadan hacmin genelinde yeterli gün ışığı sağlamak zordur. Bu çalışmada, derin plan düzenine sahip olan ve sadece güneybatı cephesinden gün ışığı alan Yaşar Üniversitesi Mimarlık Fakültesi Geçici Atölye'sinde günışığından yararlanmayı arttırmak için günışığı tüpleri ve hareketli gölgeleme elemanları önerilmiştir. Öneri oluşturulurken, LEED'in günışığı kriterleri olan; sDA için %55 ve ASE içinse en fazla %10'u yakalamak ana hedef olarak belirlenmiştir. Önerilen günışığı tüplerini ve hareketli gölgeleme elemanlarını en etkin açı ve pozisyonda kullanılmak için, Rhinoceros, Grasshopper ve Climate Studio programlarından faydalanılmış, ayrıca simülasyon sonuçları alanda yapılan ölçüm sonuçları ile valide edilmiştir. Simülasyon sonuçlarına göre yapılan öneriyle; sınıfın arka tarafındaki (zone 2-3) günışığı miktarı belirgin şekilde artarken, cepheye yakın alanda yaşanan (zone 1) kamaşma kabul edilebilecek aralığa düşürülmüştür. Önerilen tasarım stratejisi ile hacmin günışığı performansı iyileşmiş ve bu iki sistemin birlikte verimli olarak çalıştığı görülmüştür.

Anahtar Kelimeler: hareketli gölgeleme elemanları, günışığı tüpleri, günışığı performansı, kamaşma, derin planlı sınıf.

1. INTRODUCTION

It is known that efficient daylight is vital for buildings yet among many other types, considering the heavy usage, specific care has to be taken when designing educational buildings [1], [2], [3]. Students spend approximately 30% of their time in educational buildings and a series of activities that are designed to influence students' mental and physical condition take place [2], [4]. Thus, the absence of sufficient daylight can have adverse effects on their health, well-being, performance and learning abilities significantly [4], [5].

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As highlighted by many studies, ensuring efficient daylight usage in educational buildings is a rather complex task due to the series of conflicting activities that are performed in different workplanes. Even the most basic activities like reading and writing require special treatment considering the place of the actions and direction of views such as on a desk or on a writing board [2], [6]. Providing uniform and constant illuminance levels on visual task areas is necessary but at the same time contrast among different zones and view to the outside should be achieved to create an engaging environment. While creating contrast, veiling reflections or glare problems might arise due to the high brightness differences [1]. Thus, depending on the main task taking place, each workplane should be considered separately and comfort conditions should be provided vertically, horizontally, or both.

Despite the above-mentioned importance of daylight, due to dense urban planning and deep plan layouts, insufficient daylight penetration is a frequently encountered problem in current architecture [7], [8]. Room proportions have significant influence principally on daylight penetration and as the distance from the window increase, side lighting decreases rapidly. As Reinhart has examined, in a side-lit room having standard window-head dimensions, "daylit area usually lies between 1 and 2 times the size of the window-head-height" and deeper parts do not receive sufficient daylight [9]. In such cases, it is predicted that increasing the window area will reduce the problem. On the contrary, enlarging window area result with disproportionate amount of daylight near the window area while achieves only small increases of daylight levels at the back part of the room[10]–[12]. Perhaps the most serious disadvantage of this is increased heating-cooling load and the risk of glare.

When side-lighting alone cannot provide sufficient daylight, alternative daylighting systems such as atriums, light wells, skylights, and tubular systems are promising solutions [10], [13]. The decision is often given considering both spatial and physical properties of space. When the room has no or insufficient outward openings, tubular daylight guidance systems (TDGS) can be used to redirect daylight in non-daylit areas. Compared to side-lighting, tubular daylight systems distribute light more evenly into the room and prevent glare [14]. Furthermore, by transmitting less solar heat, they minimize heat gains in the cooling season and heat loss during the heating season [15].

Deep plan configurations in educational facilities can suffer from glare close to the window area, due to direct daylight penetration and incidence angle. Despite the above-mentioned advantages of TDGS, its application alone may not be the solution to all possible visual discomforts. Although the installation of shadings may help with glare problems, glare reduction measures may actually restrict daylight penetration more in deeper portions of the room. In complex situations, these conflicting interventions often require special consideration of both systems in different zones of the room. This can be illustrated briefly in a classroom where TDGS are used in deep parts of the room to allow more daylight while shadings are used near window areas to limit direct light penetration.

This article aims to enhance the daylight performance of a deep-plan classroom where areas near the façade experience glare and the rear part has insufficient illumination. To accomplish this purpose, the case study was first evaluated for present daylight conditions, and then an optimization technique was used to implement two systems—TDGS and shading devices—to meet LEED daylight criteria. This implementation resulted in a considerable improvement in the lighting conditions in the classroom.

2. LITERATURE REVIEW

2.1. Efficiency of Tubular Daylight Guidance Systems (TDGS) and Movable Shadings

Studies on tubular systems are not new; the concept was originally developed by the ancient Egyptians, and the first patented application belongs to Paul Emile Chappuis in London in 1850, using numerous angled mirrors. The first official prototype had been submitted in 1881, but it did not use daylight but only transferred lights within walled hallways [17]. The first concept of a tubular light system has changed since then, and the current form was patented in the 1980s when new materials such as metal covers were applied inside the tubes [18].

TDGS were widely recognized and applied over the past 30 years with various modifications, and several names were used to describe them, such as light pipe, light tube, sun pipe, solar tube, solar pipe, daylight tubes, tubular skylights, sun scoops, etc. [19], [20]. For the sake of simplicity, tubular daylight guidance systems (TDGS) are used in this study.

Despite the variations, all TDGS comprise three main components, which can be briefly introduced as follows:

1- a collector, which is made up of clear glazing to gather daylight. It removes UV radiation and acts as a cap that protects the tube from exterior elements such as dust and water.

2- a tube, which is a channel that transfers the light from the collector to the diffusor. It is covered with highly reflective materials to maximize light transfer while minimizing light absorption.

3- a diffusor, which releases the light in the targeted area. It can be a hemispherical or flat surface with translucent glazing [15], [18], [21].

TDGS are basic systems that reflect the sunlight and diffuse skylight to dark areas of deep-plan buildings and consequently energy consumption can be significantly reduced during daytime [21]. However, autonomous use of these system fails to provide the required illuminance throughout the day due to the excessive variations of daylight conditions, thus they should be integrated by artificial lighting systems [16]. According to numerous studies, these energy savings can change depending on variety of internal and external factors. Internal factors include the dimensions and geometry of all three components, as well as the reflectivity of the tube's interior surface, whereas external factors include solar altitude, sky conditions, and obstructions [22]. To be more specific, efficiency can be enhanced or decreased by altering the TDGS's dimensions. For instance, the energy efficiency is inversely correlated with the diffusor diameter, and when the diffusor width rises from 20 to 80 cm, the efficiency rises from 80% to 87.5. On the other hand, as the tube length increase from 1 m to 5 m, the energy efficiency decreases from 89% to 58% [19]. The effect of various architectural and technical parameters on the efficiency and energy-saving potential of TDGS has been assessed in a number of studies, some of which are provided in Table 1, for various functions (mainly for office buildings).

Application of TDGS has two significant downsides in contrast to the benefits already described. The first is concerned with the effect of TDGS component space occupation on spatial planning. The placement of the tubes frequently restricts the use of available space and necessitates reevaluating architectural plans. The second downside pertains to the inability to compare or assess TDGS performance in advance due to the lack of design standards and guidelines. There aren't many impartial design data sources, thus manufacturer companies typically employ their own documentation created under ideal conditions (which are rarely present in real life) [23].

In reality, each place should undergo a pre-evaluation considering the room's geometry, the climate, the presence of any other visual discomforts than darkness, and the compatibility of the architecture [24]. Integration of TDGS with shading components and/or artificial lighting systems may be necessary after the pre-evaluation is complete. There is very little research on how well TDGS performs when used in conjunction with other systems [25]–[27]. This was demonstrated in the study of Elsiana et al. (2022), which combined the use of horizontal light pipes with shading devices [27]. As a result of using both technologies, the simulations for the East and West facades indicated that glare around the windows was prevented. Another significant result was that the combination of the two technologies improved the ratio of uniform daylight levels up to 800% [27]. In a similar case in Norway, horizontal light pipes were applied to a test room and participants evaluated the space through survey. Results demonstrated that the shading device prevented glare and that participants did not report any dissatisfaction [24]. A recent simulation study that was conducted in a high-rise office building facing South in Penang, Malaysia, also highlighted that using horizontal shading devices with TDGS achieved illuminance increase up to 91.54% and provided good daylight quantity and quality within the area [26].

In addition to TDGS, shading is another important aspect that has an impact on the amount of daylight. Because the building's facade serves as a barrier between the inside and exterior of the space, it is the primary building component through which we may adjust and control external conditions such as daylight. Thanks to the facade components, efficient daylight lighting design and solutions to improve visual comfort can be created [28]. Furthermore, as technology advances, façade systems designed to increase user comfort have the potential to improve control of space comfort [29], [30] and indoor daylight quality [31]–[33].

Many different options are valid for façade systems and among them fixed (also named as static) shading devices have limited potential to respond to internal or external environmental changes during a day or season, but daylight usage can be optimized by designing facades with movable elements that can meet user needs [34], [35]. The systems proposed in latest research have yielded particularly good results as they have great potential to adapt to the environment, reduce building energy consumption, regulate shading and natural ventilation, and improve thermal and visual comfort [36], [37]. Although these movable shading devices appear in the literature in different terminologies are used to name these systems. Movable shading devices mentioned in different studies; They are named differently in different studies as adaptive façades, climate adaptive building shell, acclimated kinetic envelope, responsive facades, movable shading devices [38]–[41]. For the sake of simplicity movable shading devices was used in this study.

Although mentioned systems are named differently, these systems can be used for many different purposes such as daylight control, thermal comfort compensation, visual comfort, and air flow support. Those studies show that those systems can increase the performance of the façade up to 65%, when compared to static systems [42]. Studies in the literature show that these systems, which can provide 20% improvements in carbon emissions, 50% in energy consumption, 30% in user comfort, 20% in cooling load, 80% in balancing heat gain, can also provide an 11% improvement in the cost of artificial lighting [43], [44].

As simulation programs use numerical analytic techniques, it has been able to undertake a relatively accurate and quantitative examination of energy performance by utilizing a simulation program that can selectively apply a basic shading device to a building's facade [45], [46]. While these technologies provide flexibility to the user as they can change their own configurations, they not only adjust the amount of daylight but also try to balance the direct daylight coming to the user. Moreover, systems that have been proposed to balance visual and thermal performance based on different parameters are frequently encountered in the literature. As can be seen in Table 1, systems designed for different functions in different locations have been evaluated by methods such as simulation and real time measurement, and their effectiveness has been proven and contributed to the literature.

Table 1. Studies that focus on TDGS systems and shading devices

	Ref.	Location	Climate Condition	Methodology	Function
TDGS	[47]	Slovakia	Year based -CIE Overcast	Simulation	3 test rooms
	[23]	UK	Nov-Mar 2006	Measurement and survey	15 office buildings
	[16]	Italy	Year based - CIE Overcast sky	Simulation	Plant area room
	[48]	China	Year Based- CIE standard clear sky	Mathematical model calculation	Underground garage
	[49]	Italy, Portugal, Spain, Netherlands, Greece, UK	December- CIE overcast	Calculation	Residence buildings
	[22]	Czech Republic	One Year	Measurement and simulation	Container
	[18]	India	May 2010	Measurement	Test room
	[50]	Romania	For 30 days all around in 2009	Measurement and simulation	Residential house
Shading Devices	[51]	Jaffna	Year based	Survey and simulation	Office building
	[52]	USA	Clear sky	Simulation	An office room
	[53]	Iran	Year based / clear sky	Simulation	A reading room
	[54]	Egypt	Clear sky	Simulation	An office building
	[55]	Italy	Year based	Simulation	An office room
	[56]	USA	from February 1, 2013, till January 31, 2014	Simulation	Office building
	[57]	Jordan	June 21^{st} at 12 pm	Simulation	A typical small office
	[58]	Korea	Clear sky	Simulation	A typical apartment
	[59]	Korea	March, June, December 21 (noon) / Clear Sky	Simulation and prototype	A typical apartment
	[60]	Denmark	June 21, September 21 and December 21 / under sunny sky conditions at 09.00, 12.00, 15.00	Measurement and simulation	An office room

2.2. Preliminary Studies Through Genetic Algorithm

Computational design, modeling, and optimization are considered powerful tools for addressing, evaluating, or proposing solutions to existing problems. At the intersection of the usage of movable shading devices with TDGS through computational design, it is seen that Evolutionary Algorithms (EA) such as Genetic Algorithms (GA) can be used to determine the optimal building envelope design or control strategies for indoor environmental quality and energy consumption. A Genetic algorithm (GA) is a type of optimization algorithm that is inspired by the processes of natural selection and evolution and can be used to find the best solution to a problem by simulating the process of evolution. It is commonly employed in complex situations that take a long time to solve owing to their nature and complexities [61]. In the context of optimizing daylight usage, a GA can be used to determine the best configuration of a tubular daylight guidance system, such as the size, orientation, and spacing of tubes, to maximize the amount of natural light that reaches the interior of a building. The GA can be configured to consider various design parameters, such as the location and orientation of the building, the surrounding environment, and the desired level of lighting inside the building, and can be used to optimize the system design to meet specific performance goals.

Several studies have employed a GA to optimize building envelopes for enhanced performance [61]–[65]. For example, Caldas and Norford (2003) employed a GA to improve the design and operation of HVAC systems by determining window size and location and building form [65]. Similarly, Bahdad et al. (2020) used GA to optimize light-shelfs in a Malaysian office building, by considering factors such as sky type, ratio, and angle of light shelves [63]. In summary, the use of a GA for optimizing architectural elements has been demonstrated to be an effective approach in existing studies.

3. METHODOLOGY

3.1. The Case Study

This case study investigated the potential of the integration of TDGS and movable shading elements to improve daylight availability and uniformity in a deep-plan classroom. The case study referred to in this paper as Yaşar University Faculty of Architecture Temporary Studio (YUFATS) is part of a multi-purpose building block located in Bornova, Izmir. The ground floor of the building is used as an architectural studio, while the upper six floors are partially covered by residential units. YUFATS has only one façade opening facing Southeast (Figure 1) and the distance between the façade and the rear wall is 37m. Unobstructed open plan layouts that exceed 17 m are classified as "deep plans" [10], so YUFATS can also be considered deep-plan where daylight penetration is strong near the window but decreases significantly in deeper parts of the room, influencing the type of intervention required.

To increase daylight availability in YUFATS, TDGS systems' suitability was assessed through the preliminary evaluation (including climate, building properties, lighting system) that is described in Lu et.al.'s (2020) study [66]. Following the assessments, TDGS system was proposed for areas where the roof is not occupied by the residential block. Despite the fact that the presence of a six-story residential block reduces the performance of TDGS by limiting daylight access [22], TDGS is determined to be one of the most feasible solutions that may be provided.

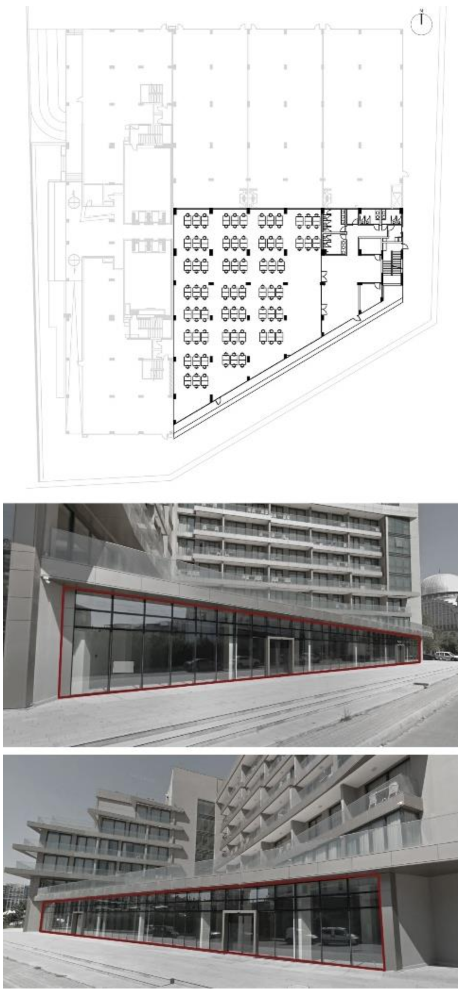

Figure 1. Plan drawing and pictures of the YUFATS

3.2. The Process of Achieving the Design Proposal

To provide visual comfort for the entire area in the selected building (Figure 2), and prevent over-illumination in specific areas affecting the average, the room was separated into three zones as shown in Figure 3 and every zone was evaluated individually. Different approaches have been applied for these three zones. Since Zone 1, located in the area close to the full-length window on the façade, receives a lot of daylight and experiences glare, horizontally rotating shading elements were applied to the window in that part (Figure 3). The mentioned tubular daylight guidance systems will be used to adjust the daylight level in Zones 2 and 3. Considering the current ceiling plan for both zones, 2 rows of 4 tubular systems were placed at equal intervals (Figure 3). Since these systems can be modified at certain angles, the separate movements of these two rows are connected to each other. These adjustments were made to direct the daylight, which is difficult to reach on the back side of the area due to the large depth of the building. At the same time, it is intended to improve uniformity in that zone by allowing daylight into the back parts.

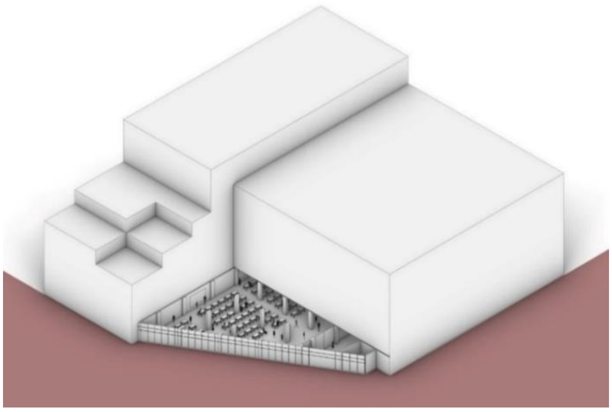

Figure 2. Computer generated model of the selected building

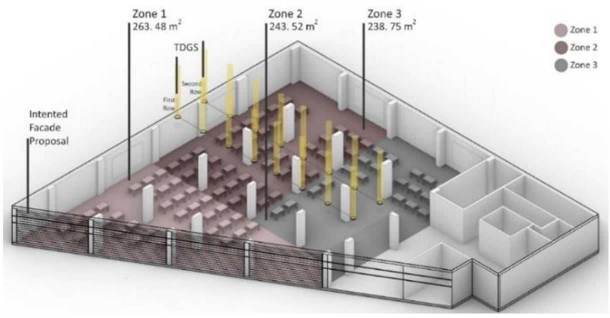

Figure 3. Working zones of the selected area

In order to determine the movable shading device, four steps were followed, respectively (Figure 4, 5).

Step 1: The aluminum joinery on the existing façade was taken as a basis for the proposed shading device; thus, three separate groups were formed.

Step 2: Using the Grasshopper, all three groups were divided into 20–25 cm intervals based on the distance between the joinery, and rectangles were formed by determining the other edges to extend along the vertical joinery. These rectangles were grouped linearly among themselves, and then the surface was created.

Step 3: Movable surfaces were constructed by designating the upper border of each surface as the rotation axis.

Step 4: To shorten the optimization time, the movement angles of the panels are arranged in multiples of five and copied first vertically, then horizontally, to achieve the final shading design proposal.

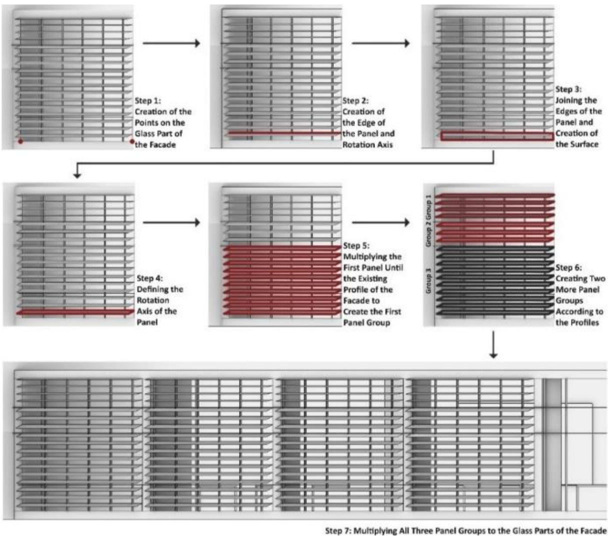

Figure 4. Steps of the proposed movable shading device creation

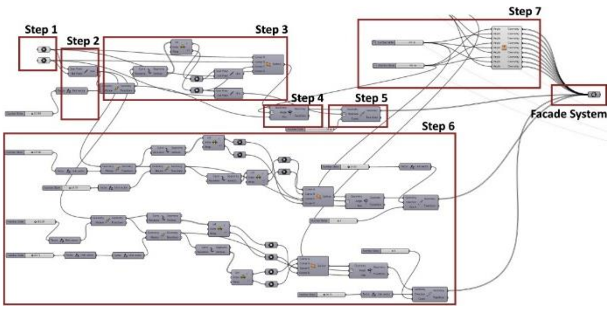

Figure 5. Grasshopper definition of the proposed movable shading device

3.3. Dynamic Daylight Metrics: Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)

For assessing and optimizing daylight availability while providing a comfortable and glare-free environment at YUFATS, dynamic daylight metrics were used. Dynamic daylight metrics are capable of considering factors such as the amount of light entering a building, the distribution of light within the building, and the impact of daylighting on energy consumption [67]. Spatial daylight autonomy (sDA) is a dynamic daylight metric that measures the percentage of a room's floor area that receives an acceptable level of daylight for a specified time period. It is calculated by dividing the floor area that receives a minimum level of daylight (usually 300 lux on working areas) by the total floor area of the room [68]. The result is expressed as a percentage, indicating the proportion of the room that has access to sufficient daylight. sDA is a dynamic metric in the design and evaluation of buildings, as it considers the spatial distribution of daylight within a room rather than just the average illumination level. High sDA values indicate that a room has good access to natural light, which can improve visual comfort and reduce energy consumption by reducing the need for artificial lighting. According to the latest LEED standards, the minimum level should be 55% to achieve a preferable interior space [69] . Although it is desired to increase the daylight availability as much as possible, there is another metric called annual sunlight exposure (ASE) that defines the presence of excessively bright or direct daylight in order to regulate and control the glare indoors. This metric defines the percentage of floor area that receives intense daylight exceeding 1000 lux over 250+ hours of use per year. This metric is also mentioned in LEED, and this metric limits sDA and it is stated that ASE should not be over 10% [69]. Both sDA and ASE are common metrics in the design and evaluation of buildings, as they provide information about the effectiveness of a building's design in terms of daylight and visual comfort. High sDA and low ASE values indicate that a building is well-lit, energy-efficient, and comfortable for occupants.

3.4. Overall Summary of the Consecutive Phases

The study is conducted in five individual phases that are illustrated on Figure 6.

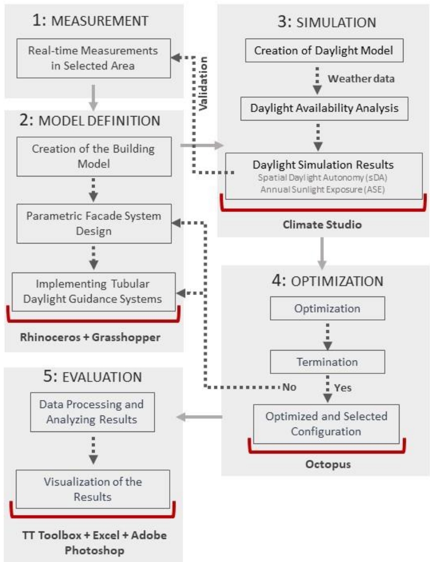

Figure 6. Workflow of the study

Phase 1-Measurement: To assess the current condition of YUFATS, real-time measurements were taken during the winter solstice in 2022. The column alignments were used to determine measurement points in order to determine which parts of the space receive and do not receive enough daylight. Data was collected at these determined points by taking measurements and using the table alignments as a reference for the height from the ground. The three-dimensional model of the building was then created in Rhinoceros in order to perform daylight analyses on the selected area (Figure 7).

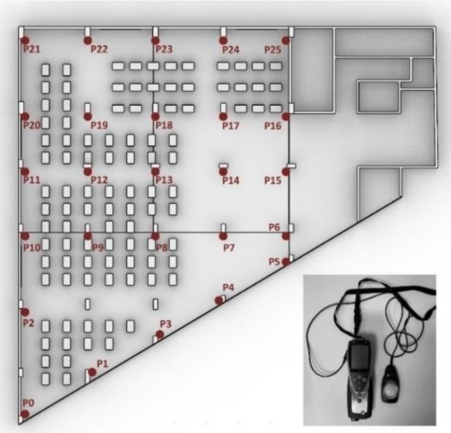

Figure 7. Selected real time measurement points and Testo435 multifunction measuring instrument

Phase 2-Modeling: Parametric shading devices were designed using Grasshopper plug-in to be adapted to the façade. For the remaining zones, tubular daylight guidance elements were placed with the help of Climate Studio which is a plugin for Rhinoceros.

Phase 3-Simulation: By using Climate Studio, simulations were performed separately for each zone and sDA and ASE values were evaluated. Accordingly, parameters such as the number and angle of tubular daylight guidance elements were updated and modified, and the simulations were repeated.

Phase 4-Optimization: For the shading components, optimization was made to find the right angle. It is aimed to reach the most efficient result by updating the model according to the obtained data.

Phase 5-Evaluation: All the results obtained were examined comparatively and the configurations with the highest sDA and lowest ASE values were selected and visualized.

4. RESULTS

4.1. Validation of Simulation Results

The findings of real-time measurements were compared to simulation results. Based on the comparison results (that are seen on Table 2), for most of the measurement points, the differences were less than 10%. Despite the fact that the measurement equipment was properly calibrated and Climate Studio is capable of producing accurate simulations that have been validated by previous studies [70]–[73], the mentioned difference can occur due to a variety of factors, including mistakes made when addressing the measurement points in both methods, unexpected weather conditions during measurement, or incorrect material property assignments (which can influence the reflectance and transmittance properties of surfaces and materials).

4.2. Simulation Results of The Proposal

The analysis started with an assessment of the current space's daylight performance to be able to compare with the final performances (Figure 10). As described in Section 3.2, separate studies were conducted for each zone of the specified space by creating different analysis surfaces. As a result of these assessments, zone 1 receives significantly more daylight than zones 2 and 3. This, however, raises the ASE level and diminishes user comfort. Despite the fact that the ASE values for zones 1 and 2 are quite low, the obtained sDA value falls short of the desired level.

As the base case results for sDA and ASE were 99.11% and 61.33%, respectively, it was first intended to keep the ASE value below 10% without lowering the sDA value below 55% for Zone 1. This goal was achieved by using the Octopus tool, a Grasshopper plugin, to optimize these values in order to balance them with the proposed shading device. When utilizing Octopus, the default settings were used and the angles expressing the rotating movements of three separate groups in the shading device were defined as design variables. To simplify the optimization, these angles are set to rise by 5 degrees. As objectives, sDA and ASE values were determined, with the goal of increasing sDA and decreasing ASE. The elitism value was set to 0.5, the mutation probability to 0.2, the mutation rate to 0.9, and the crossover rate to 0.8. The population was limited to 75 people, with a maximum generation of 5. It took approximately 67.87 seconds to obtain simulation results for each configuration. As a result of this optimization, all configuration and obtained values were recorded with the data recorder component, and all data was exported to Excel using TT Toolbox at the end of the procedure (Figure 8). The table shows that there are multiple configurations that can be used to achieve the desired results (Table 3). To arrive at a decision, the alternative with the greatest difference between sDA and ASE was sought out and selected. The sDA value is 97.04% and the ASE value is 1.19% when the components in group 1 are positioned at an angle of 80 degrees and those in

Table 2. Selected real-time measurement points and simulation results for validation

Points	**P00**	**P01**	**P02**	**P03**	**P04**	**P05**	**P06**	**P07**	**P08**	**P09**	**P10**	**P11**	**P12**
Measurement	8856	8360	8360	9727	8829	8753	8613	829	670	410	187	50	73
Simulation	8918	8348	8156	9810	8754	8419	8709	749	605	314	193	67	96
Points	**P13**	**P14**	**P15**	**P16**	**P17**	**P18**	**P19**	**P20**	**P21**	**P22**	**P23**	**P24**	**P25**
Measurement	169	311	338	68	85	46	29	24	14	16	23	36	33
Simulation	203	397	349	79	79	65	51	31	17	16	20	23	51

groups 2 and 3 at an angle of 65 degrees (Figure 9). It may be said that the system and optimization worked effectively together because this performance is significantly higher than the desired values. Table 3 presents only the 10 most effective configurations. Acquiring several efficient results demonstrates why this system is not used as a static system (by keeping it constant at one angle), and it reveals that a design choice can be made available to both the user and the designer.

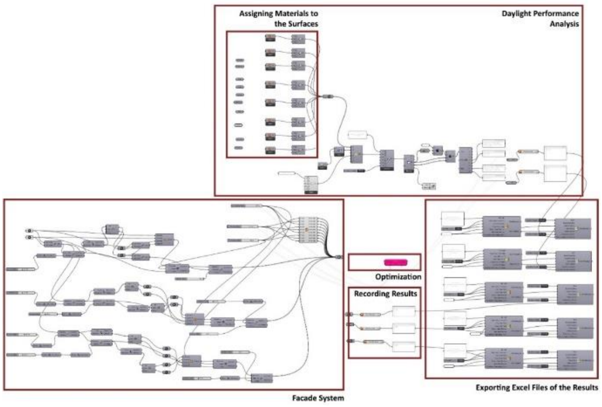

Figure 8. Grasshopper definition of the daylight simulation and optimization

Table 3. Selected Optimization Results of the Proposed Movable Shading Device

	Configurations			sDA (%)	ASE (%)	Fitness Function
	G1	G2	G3			
1	80^0	65^0	65^0	97,04	1,19	95,85
2	75^0	90^0	60^0	97,63	1,78	95,85
3	85^0	60^0	75^0	97,48	1,78	95,7
4	75^0	80^0	60^0	96,89	1,19	95,7
5	85^0	80^0	65^0	97,63	2,07	95,56
6	85^0	80^0	50^0	96,74	1,19	95,55
7	80^0	80^0	60^0	96,59	1,19	95,4
8	65^0	85^0	65^0	96,89	1,63	95,26
9	70^0	70^0	75^0	97,19	1,93	95,26
10	75^0	80^0	60^0	96,44	1,19	95,25

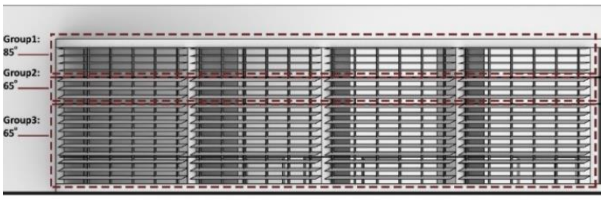

Figure 9. Selected configuration and angular states of the shading device

In Zones 2 and 3, unlike Zone 1, the aim is to increase the amount of daylight received rather than reduce it in a balanced manner. Because of the plan shape of the space and its proximity to the window, Zone 2 receives more daylight than Zone 3. The outcomes of the base case simulation were analyzed, and they were as follows: sDA of 40.7% and ASE of 2.3%. The ASE value is within the acceptable range, however the sDA value can be increased. To increase daylight availability eight TDGS are proposed to be installed at equal intervals in two rows. The location of the rows was determined with the ceiling area not occupied by the higher residential block in mind. The second row is placed as close to the back of the room as possible to permit daylight to enter areas where TDGS cannot be used. Because these tubular devices' orientation angles can be adjusted, several configurations have been tested to increase efficiency. As a result, the first-row tubular device is maintained at 90 degrees, and the second-row options with 90, 60, 45, and 30 degrees are, correspondingly, simulated. According to the results shown in Table 4 below, the desired outcome is achieved when the first row is at 90 degrees and the second row is at 45 degrees. When the obtained results were compared to the existing condition, the sDA value increased from

Table 4. Simulation results of the zone 2 with TDGS

Zone 2 Results	**First Row: 90^0 Second Row: 90^0**		**First Row: 90^0 Second Row: 60^0**	
	sDA	ASE	sDA	ASE
	50.4	2.2	54.6	2.3
	First Row: 90^0 Second Row: 45^0		**First Row: 90^0 Second Row: 30^0**	
	sDA	ASE	sDA	ASE
	55.7	2.4	53.1	2.2
	Base Case			
	sDA		ASE	
	40.7		2.3	

40.7% to 55.7% and the ASE value increased to 2,4, which could be characterized as not disturbing.

For zone 3, the same procedure was followed, but due to its remote location from the window, zone 3 has a major daylight availability problem. The base case situation for zone 3 is a sDA value of 17.8% and an ASE value of 0, implying that the sDA value is substantially lower than it should be. In zone 3, four TDGS in two rows (for a total of eight) were planned and tested in various angle applications to increase daylight availability. Even though it is suggested to use twice as many tubular devices as in zone 2 for zone 3, this will not be sufficient to achieve uniform distribution and a 55% sDA throughout zone 3. As a result, the goal was to maximize the sDA value using the seven evaluated alternatives, which are listed in Table 6. All of the configurations increased sDA, but the arrangement with the tubular devices in both rows at a 60-degree angle generated the greatest sDA values, 44.7%, while ASE remained at 0.

Table 5. Simulation results of the zone 3 with TDGS

Zone 3 Results	**First Row: 90^0 Second Row: 90^0**		**First Row: 60^0 Second Row: 60^0**	
	sDA	ASE	sDA	ASE
	41.3	0	44.7	0
	First Row: 90^0 Second Row: 60^0		**First Row: 90^0 Second Row: 45^0**	
	sDA	ASE	sDA	ASE
	41.9	0	43.5	0
	First Row: 45^0 Second Row: 45^0		**First Row: 30^0 Second Row: 30^0**	
	sDA	ASE	sDA	ASE
	43.2	0	43.5	0
	First Row: 90^0 Second Row: 30^0		**Base Case**	
	sDA	ASE	sDA	ASE
	42.1	0	17.8	0

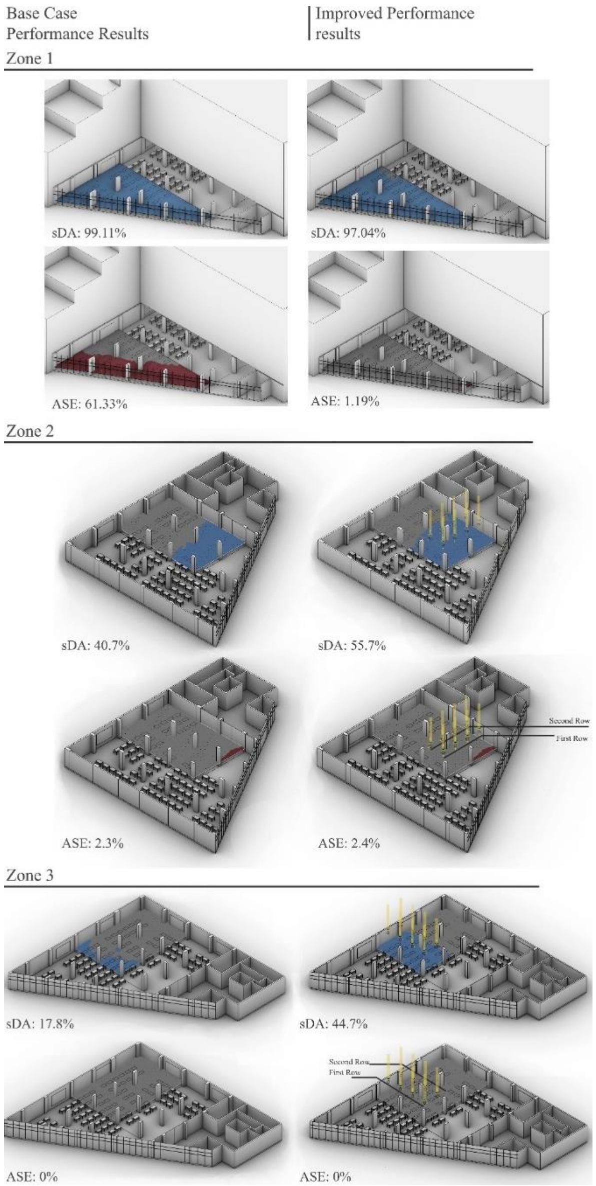

Figure 10. Daylight performance results for base case conditions and results after performance improvement

5. CONCLUSION and DISCUSSION

The purpose of this study is to optimize daylight availability and control glare in a deep-plan classroom in Izmir with a full-glazed façade. To accomplish this, the classroom was separated into three zones, after individual assessments TDGS and movable shading devices were proposed. In-situ lighting illuminance measurements were used to analyze the base-case scenario for the entire classroom, as well as to validate the simulation model for dynamic daylight and glare analyses. Using simulations conducted on the Climate Studio, a Grasshopper plugin, visual comfort was analyzed. The well-known dynamic daylight metric, Spatial Daylight Autonomy (sDA), was utilized during evaluations for daylight availability, while annual sun exposure (ASE) was used for glare. Objectives were established to meet the most recent LEED standard specifications, which call for sDA in the working area to be at least 55% and ASE on the occupied floor to be at most 10%. In the base case scenario, daylight penetrating through the fully glazed and unshaded southeast-facing façade led to unequal daylight access, resulting in significant disparities in illumination levels (varying from 9727 to 50 lux). As a result, movable shading elements were proposed, and the angle positions were established through optimization.

Due to the distance from the façade, for zone 3, the initial sDA was only 17.8% while the ASE was %0, so TDGS were proposed to increase daylight availability. Due to the fact that the ceiling of the classroom is partially covered by a higher residential building, two rows of TDGS were proposed, with the second row being positioned as close as feasible to the classroom's back to allow daylight into the room's depths. To ensure the most uniform light distribution, the diffusor component of the TDGS was evaluated for a variety of angle configurations. Ultimately, the TDGS in the rows were positioned at 60 degrees. Despite the fact that the proposed system did not achieve sDA above 55%, it did achieve greater uniformity, and the initial sDA was increased to 44.7% while ASE was still %0.

For Zone 1, though the initial sDA value was 99.11%, a glare problem was detected with an ASE value of 61.33%, which is significantly higher than recommendations. For the purpose of limiting the excessive daylight penetration, a movable shading device was proposed. Due to the size of the glass façade, three component groups were developed, and optimization was employed to identify the ideal angle. The optimization iteration converged after more than 300 configurations, and the optimal angles for shading are as follows: 80 degrees for group 1 components and 65 degrees for groups 2 and 3. The design proposal of Zone 1 results with a slight decrease in sDA (97.4%) although substantial success was achieved by reducing ASE from 61.33% to 1.19%, one can deduce that glare problem was diminished. The visual comfort objectives for Zone 1 were met without the usage of any TDGS.

While the sDA in Zone 2 in the base-case scenario was slightly lower (40.7%) than the threshold of 55%, using TDGS in two rows provided an opportunity to meet the criteria. When the first row of TDGS is positioned at 90 degrees and the second row is positioned at 45 degrees, the sDA value reaches 55.7% however the ASE value remains below 5%, as expected. Zones 2 and 3 demonstrated the TDGS system's effectiveness in providing daylight to the back part of a deep plan room.

This study is notable for its exclusive emphasis on the efficiency of utilizing TDGS and moveable shading devices together. While previous research examined the benefits of these technologies independently, our study attempted to determine how their combination could enhance daylight availability and visual comfort. The great potential of this approach was demonstrated by analyzing real-world performance data and running simulations. The findings suggest that the use of TDGS and movable shading devices together could offer a highly effective solution for sustainable building design, with implications for both new construction and retrofits. This research tries to contribute to the field, although there are several restrictions regarding the case study building. Since the YUFAT's roof is partially covered by the six-story residential block, TDGS could only be applied to non-covered regions, limiting the required uniformity for the entire area. External obstructions can cause light to be redirected or scattered in ways that reduce the amount of daylight that reaches the interior of a building, limiting the performance of tubular daylight guidance systems. The proposed TDGS devices' performance may have been impeded by the adjacent six-story residential block, which rises to a height of over 25 meters. The impact of external obstructions on TDGS performance is a crucial topic, and it is worth noting that further research on this subject is needed.

DECLARATION OF ETHICAL STANDARDS

The authors 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

Arzu CILASUN KUNDURACI: All authors contributed equally in the preparation of the manuscript.

Ecenur KIZILÖRENLİ: 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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