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Research Article

Optimizing Faceted Loft Shading Modules: A Design Framework for Office Environments

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Abstract

Digital tools for estimating interior daylight conditions facilitate the optimization of shading elements, which can also enhance energy efficiency. However, studies often neglect the necessity for these elements to be adaptable in terms of size and form. The use of shading elements designed with complex forms and intricate movements limits their applicability whereas basic forms may still meet all necessary performance requirements. This paper proposes a design framework for shading elements based on modularity and visual comfort within an office environment through single-objective optimization. The geometry chosen for optimization is the open-ended faceted loft, which was adapted to three different office dimensions: 3.2 x 7.6, 4.8 x 6.9, and 12.0 x 13.8 m, all with a floor height of 3.2 m. The design framework was conducted in two phases, focusing on the Scale Factor (SF) and orientation of the lofts as the primary optimization parameters for daylight performance. At first, daylight performance was evaluated using metrics such as Useful Daylight Illuminance (UDI), Daylight Autonomy (DA), Spatial Daylight Autonomy (sDA), and Annual Sunlight Exposure (ASE) to verify illuminance thresholds. After determining the volume that matched the module and thresholds, the optimization continued to define the specific SF and orientation of the shading modules to optimize glare conditions using Rhino Grasshopper Galapagos evolutionary solver, 10 generations, each featuring 600 analyses, were performed. Upon completion of the 10th generation, results indicated that the Spatial Daylight Glare (sDG) value decreased from 58.1% to 12.9% in the optimized scenario.

Keywords: Daylight performance; Design framework; Single-objective optimization; Sun-shading element

Highlights

- The design framework consists of two steps (simulation and optimization) decreased the Daylight Glare Probability (DGP) while providing required UDI, sDA and ASE thresholds.
- A basic geometry was utilized to design a shading element that meets performance requirements without the need for complex mechanisms.
- The effect of the SF which determines the window-to-wall ratio (WWR) and the orientation of modules on daylight performance was revealed.

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1 Introduction

Shading design alongside orientation, façade geometry, WWR, and glazing type is one of the most significant factors determining the daylight performance of a façade system. Thanks to advanced construction technologies and computer-aided design methods, such as parametric modeling in Rhino and Grasshopper, it is now readily possible to predict a design's performance through simulation tools like Ladybug, Honeybee, and Daysim before implementing it on-site (Panya et al., 2020; Samadi et al., 2020). This potential has led to an increase in complex geometries and the use of advanced mechanisms in architecture, and parallel to that, enhanced sun control strategies (Brzezicki, 2024).

Sun control strategies are either active or passive systems integrated into the building envelope. These strategies respond to diverse environmental changes; some may adapt every second, while others exhibit seasonal adjustments that are only subtly perceptible. Architectural design addresses these environmental stimuli through the implementation of these dynamic or static control methods (Loonen et al., 2013). Improvements in computer engineering, cybernetics and artificial intelligence contributed to development of active facade systems that are equipped with sensors, actuators and command wires and called “intelligent systems” (Thun et al., 2012). While these systems perform changes (stimulus) at a macro scale, there have been some systems explored that perform changes by using different states of materials. These are smart materials that “embedded with technological functions”, involve specific environmental responses “operating either through internal physical property changes or through external energy exchanges” (Addington & Schodek, 2005).

Despite their ability to adapt to natural cycles, kinetic systems involve high investment costs and significant maintenance challenges due to the complex actuators and sensors required for motion. Furthermore, much of the current research remains focused on the design and performance of kinetic shading elements, often employing complex geometries -such as origami-inspired, tessellation-based, or biomimetic forms- to optimize efficiency (Sharaidin & Salim, 2012). On the other hand, active shading elements designed using smart materials (such as shape memory alloys or polymers) remain largely at the prototype stage. They have not yet been implemented at full scale due to obstacles such as mechanical constraints, high dependency on weather conditions, and concerns regarding material durability (Wijewardane et al., 2025). Given the significant concerns about active systems, this paper focuses on static shading design, creating a novel design framework utilizing single-objective optimization and daylight simulation methods.

2 Single Objective Optimization for Daylight Performance

In architectural design, performance can be predicted quantitatively through simulation and systematically refined design variables toward peak efficiency through single or multi-objective optimization, while design alternatives can be evaluated qualitatively through structured decision-making frameworks such as decision trees, the analytic hierarchy process, or decision support systems (Yi, 2019). In the context of daylighting, the ability to quantitatively measure interior illuminance and luminance allows simulation to generate the precise datasets necessary to optimize for the most efficient design options.

2.1 Daylight Performance Metrics

The quantitative assessment of indoor daylighting conditions necessitates a prior determination of the outdoor illuminance level. Various institutions and organizations conducting meteorological measurements worldwide measure cloud cover levels. These measurements are reported as data, and the outdoor illuminance level can be determined by utilizing values such as hourly global radiation and the clearness index. In cases where the outdoor illuminance level cannot be measured directly, it is calculated according to various sky models (such as CIE Overcast, CIE Clear, CIE Intermediate, and All-sky models) (Şener, 2009). The simulation engines calculate the outdoor illuminance level for a specific time and location using these sky models and meteorological data. In this way it becomes possible to predict how much light reaches a specific point indoors by defining the brightness of every point in the sky dome based on the sun's position and atmospheric conditions.

According to EN 12665:2018, visual comfort is a subjective state of visual well-being that depends on both eye physiology and the physical quantities describing the amount and distribution of light. This distribution begins at the source -such as the sun in daylighting- measured as luminous flux. Defined by the Illuminating Engineering Society, luminous flux is the time rate of flow of radiant energy, evaluated by its capacity to produce a visual sensation, and is measured in lumens. The process concludes with the "arrival" of light onto a specific surface area, a quantity known as illuminance, which is measured in lux (IES, 2011). Because illuminance quantifies the amount of light reaching a surface, it serves as the primary basis for evaluating daily or annual lighting conditions across a space or workplane using various developed climate-based metrics.

Daylight metrics are primarily divided into two categories: static (which represent conditions at a specific point in time under a single sky model) and dynamic (which analyze the sun's position and climate data throughout the entire year). The daylight factor is a static metric based on the ratio of interior illuminance to simultaneous exterior illuminance under an overcast sky (Reinhart et al., 2006). Since, it addresses the question of "how much sunlight a space receives when the sky condition is overcast" this metric is not used in the scope of the study, the optimization process requires identifying the best design options for the entire year, particularly in a location with a climate characterized by rare overcast days.

2.2 Genetic Algorithms and Optimization

Genetic algorithms are being used to scan the search space of alternative solutions to a design problem to identify which ones best fit specific goals or an optimum. These algorithms work by creating a set of solutions (a population) and running a simulation engine for each solution to compare them in terms of fitness that the degree to which they meet performance goals. The next population is then generated from the best 'parents' with the highest fitness values and this cycle continues until a previously set generation number is achieved or the engine is stopped manually (Gagne & Andersen, 2012).

Multi-objective optimization works in two different ways: the first is based on classical mathematical models, which require assigning weights to different criteria (the traditional method); the second is the non-traditional approach based on stochastic (probabilistic) rules. The latter method is able to generate Pareto front clusters, which consist of a set of optimal trade-offs between two or more conflicting objectives (Yi, 2019).

Unlike multi-objective optimization, which balances competing goals to find a trade-off, Single-Objective Optimization (SOO) focuses on a single, clear fitness metric. While SOO still utilizes genetic mechanisms like mutation to maintain population diversity, it avoids the complexity of generating a Pareto front. Consequently, SOO was selected for this study because it offers greater controllability, simplifies the result analysis, and provides a more straightforward path to a convergent optimum.

2.3 Design Framework for Daylight-Driven Shading

The process begins with defining modular shading elements with a "faceted loft" geometry that can be adapted to different room sizes and floor plans. Then, different scenarios created by varying the SFs of these modules are tested through simulations using dynamic daylight metrics such as UDI, sDA, and ASE. In the subsequent steps of the design framework, glare analyses are performed by determining the most suitable SF based on the obtained data, and the final form is created through SOO, maximizing the use of daylight while minimizing the risk of excessive brightness and glare that impairs user comfort.

3 Methodology

The steps involve modeling an office building using Rhinoceros, Grasshopper, and Honeybee programs to prepare the simulation model. This process involves assigning functions to the Honeybee model, defining schedules, choosing material properties from Climate Studio's library. Additionally, geometry was modeled in Grasshopper and imported into Climate Studio. Climate data was uploaded using the .epw file that is named as TUR_IC_Mersin.173400, and results were obtained by running simulations for different unit sizes. Daylight simulations for illuminance and glare were conducted on an hourly basis over the course of one year. For daylight simulations, the sensor grid was positioned aligned with the working stations' upper plane; 0.85 m above the ground level and spaced 0.50 m apart. The reflectivity values for the floor, walls, and ceiling were set equal to or lower than 0.2, while values of 0.5 and 0.7 were also utilized considering the values given at TS-EN 17037:2019.

To comprehensively determine the optimal sizes and configurations of a faceted loft, particularly in the context of utilizing prismatic sun control devices, this study engaged in modeling three distinct office room sizes. The dimensions of the office rooms were specifically chosen as follows: 3.2 x 7.6, 4.8 x 6.9, and 12.0 x 13.8 m. Notably, the dimension of 3.2 x 7.6 m has been established as a reference 'shoe box' office model (Reinhart et al., 2013). Analyses were conducted for a south-facing orientation in Mersin, Turkey, a city characterized by a mild Mediterranean climate (Csa) according to the Köppen climate classification system. The transparent façade has been positioned on the southern side.

The dimensions of the sun control devices-including their height, width, and depth-were established through the creation of a modular design concept. This module was essentially designed to be adaptable, thereby allowing it to coordinate seamlessly with the specified dimensions of the office rooms. The study focused on investigating modules measuring 0.8 x 0.8 m, ensuring that they could effectively integrate with the different office configurations (Figure 1).

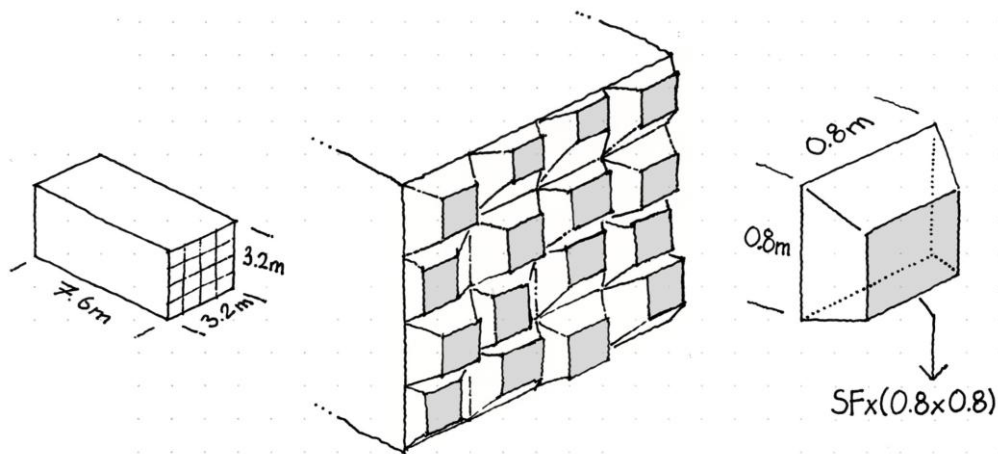


Figure 1. The “shoe box” model of the office room and the shading element design (Source: Authors).

Furthermore, the SF that affects the WWR of the facade was evaluated through a series of illuminance analyses. Given that office spaces inherently require higher levels of illuminance to facilitate productivity and comfort. The selection of appropriate SFs for each office volume was methodically executed, taking into account the specific lighting needs of each configuration. Finally, for each designated office volume, one specific SF was chosen to examine its corresponding glare probability. By assessing glare levels, the study aimed to identify the visual comfort conditions applicable to each scenario.

According to the Illuminating Engineering Society of North America, the sDA metric quantifies the extent to which an interior environment receives an adequate level of daylight, specifically defined as 300 lux, during more than 50% of its occupied hours (Reinhart, 2019). Furthermore, DA does not impose an upper limit on the level of illumination. ASE measures the percentage of floor area that receives a minimum of 1000 lux of sunlight for at least 250 occupied hours annually. This metric establishes a threshold that must not exceed 10% of the total floor area.

DGP has been classified into four categories: imperceptible (30-35%), perceptible (35-40%), disturbing (40-45%), and intolerable (45-100%) (Pellegrino et al., 2017). DGP was calculated at various points within the simulation model, corresponding to the occupants' positions as defined in the floor plan. Climatic and luminance-based metrics were simulated to evaluate the performance of kinetic façade design alternatives on key astronomical dates, including the solstices (December 21 and June 21) and the equinoxes (March 21).

4 Results

The results of the first phase of the proposed design framework are maintained for metrics regarding illumination levels (UDI, sDA, and ASE). The simulation was performed five times for each plan scheme corresponding to the five SFs applied to the shading elements' openness, ranging from 0.4 to 0.8. Overall, both sDA and ASE values increase in parallel with the SF. This is expected, as the SF represents the openness of the shading element, which allows more light into the room. For the first plan type, sDA and UDI values change dramatically between the 3rd and 4th simulations, whereas ASE values increase at a more consistent rate (Table I). Specifically, Table I demonstrates a significant jump in sDA from 0.711 to 0.999 between scenarios 2 and 4, marking the transition where the room achieves nearly full

spatial daylight autonomy and scenario 4 provides the optimal balance for UDI_autonomous before the increased openness leads to a higher risk of over-illumination.

Table I. The UDI, sDA and ASE simulation results of the first plan scheme (3.2 x 7.6 x 3.2 m).

Plan Scheme	Scenario	SF	UDI_autonomous	UDI_exceeded	sDA	ASE
	1	0.4	0.5218	0.0168	0.555	0.0666
	2	0.5	0.6517	0.0346	0.711	0.0777
	3	0.6	0.7374	0.0601	0.933	0.1222
	4	0.7	0.7611	0.1356	0.999	0.1333
	5	0.8	0.7503	0.1668	0.999	0.1888

The second plan scheme got higher sDA and ASE results than the first, aligning with expectations due to its greater width-to-depth ratio. In Scenario 8, sDA reaches 0.957 (21% increase over Scenario 7) yet this likely triggers higher DGP since its ASE value nearly doubles. Notably, despite the increased openness, Scenario 8 does not show improved UDI results. This suggests that while more sunlight enters the space, a significant portion fails to effectively illuminate the designated work planes, resulting in over-illumination rather than useful daylight (Table II).

Table II. The UDI, sDA and ASE simulation results of the second plan scheme (4.8 x 6.9 x 3.2 m).

Plan Scheme	Scenario	SF	UDI_autonomous	UDI_exceeded	sDA	ASE
	6	0.4	0.5655	0.0197	0.632	0.0769
	7	0.5	0.7077	0.0339	0.794	0.1282
	8	0.6	0.7706	0.0576	0.957	0.2222
	9	0.7	0.7872	0.0887	1	0.2136
	10	0.8	0.7874	0.1101	1	0.2222

The third plan scheme's sDA results fall below both the required thresholds and the performance levels of the other plan types. While these low sDA values correspond to lower ASE results -potentially lower DGP results too- the average UDI is also markedly lower (Table III). In this context, the reduced ASE is not necessarily a sign of better daylight performance but rather an indication of an underlit environment where natural light fails to reach the primary task areas. These sDA, ASE, and UDI findings show that the sun control device dimensions are considerably suboptimal for this specific architectural volume and its width-to-depth ratio. Although these results require a more detailed optimization of the shading modules' geometry to balance illumination levels with glare control, such an analysis was excluded from the current study due to simulation constraints and the defined research scope.

Table III. The UDI, sDA and ASE simulation results of the third plan scheme (12.0 x 13.8 x 3.2 m).

Plan Scheme	Scenario	SF	UDI_autonomous	UDI_exceeded	sDA	ASE
	11	0.4	0.3269	0.0113	0.364	0.0370
	12	0.5	0.4177	0.0192	0.464	0.0941
	13	0.6	0.4916	0.0344	0.550	0.1172
	14	0.7	0.5438	0.0530	0.621	0.1388
	15	0.8	0.5804	0.0684	0.683	0.1604

Following the UDI, sDA, and ASE simulation results, another model was established for comparing the same plan scheme scenarios without a shading element and with a fully transparent glass curtain wall façade. The third simulation model, which was determined as Scenario 3, reduced the percentage of time during which occupants experience disturbing glare (sDG) from 58.1% to 27.4% (Figure 2). The 9th simulation model, which was determined as Scenario 7, reduced the glare even more, from 59.5% to 16.5%. Considering that the SF also determines the WWR, this is an expected result, and the next step involving optimization aims to further enhance glare conditions.

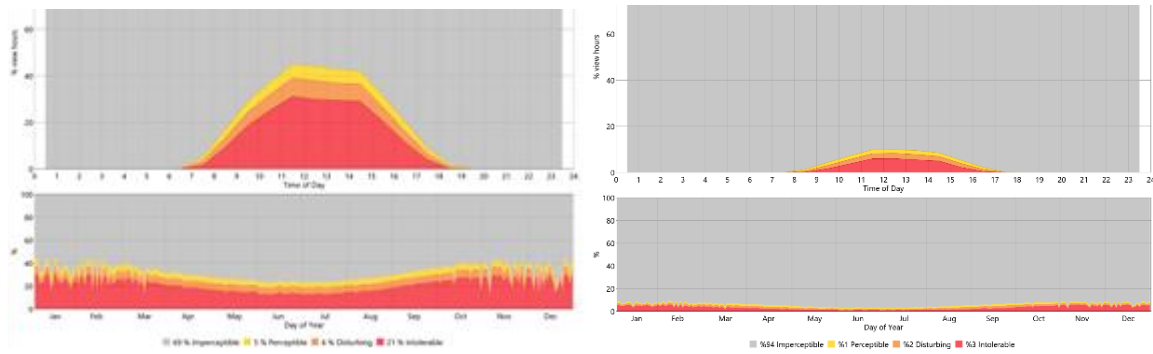
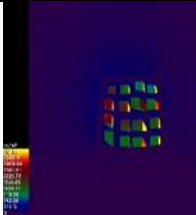
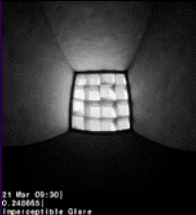
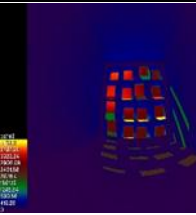
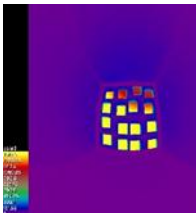
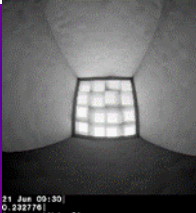
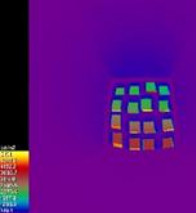
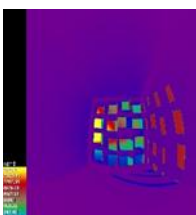
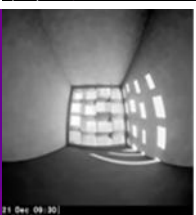
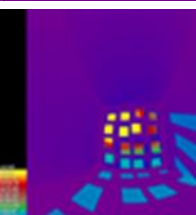


Figure 2. Annual DGP analysis result of first plan scheme a- without a shading element, b- with shading element.

To conduct single-objective optimization, 10 generations were created by Grasshopper Galapagos, with each generation consisting of 30 stagnant iterations and a population size of 20, amounting to a total of 600 analyses. The orientation of each shading element module was used as a variable parameter. The optimization was stopped after the 10th generation due to time limitations and the observation that the results had begun to converge, with fitness scores showing minimal improvement. The optimum solution was, as the last step, used to validate the enhancement of DGP results through the point-in-view analysis shown in Table IV. The point-in-view analysis of solstices and the equinox demonstrated that the optimized shading design provides imperceptible glare for all these dates at 9:30 a.m., 12:30 p.m., and 3:30 p.m. Moreover, the annual performance of the optimized sun control device shows notable improvement when compared to previous scenarios. This enhancement is particularly evident during December and at midday hours on other key dates, where the device performs better and when compared to scenarios with the same orientation (perpendicular to the facade plane) and devices of equal size that were examined in earlier simulations.

Table IV. The point-in-view analysis of DGP results for specified times.

Date	9.30 a.m.	12.30 p.m.	3.30 p.m.
March 21			
June 21			
December 21			

5 Discussion

The proposed model has demonstrated an enhancement of effectiveness in static shading design by applying a simple design method, which includes a simulation-based determination of the WWR and a subsequent SOO to find the optimum configuration of the entire shading system. Daylight metrics - UDI, sDA, ASE, and DGP - were evaluated for three different office room plan schemes, bridging the gap between the use of an interior space and shading element design in visual comfort studies. The study also demonstrates the success of a hybrid digital design process where the designer determines which alternative to use for optimization.

However, the study has certain limitations, such as the size of the shading elements, evaluating only one orientation (south), assuming that the room has only one exterior wall, and evaluating only one location. Another limitations are not including qualitative criteria, like aesthetic value or users' relation with the exterior. Although there are some quantitative methods to evaluate the facade as a barrier between the user and the exterior (sky view ratio), they do not perfectly meet the psychological perception of the user. It is predicted that incorporating these subjective parameters into the proposed method will be possible in future studies, thanks to advancements in the field.

Further research is needed to expand the scope of the study, including different materials with different reflectivity or the possibility of generating a kinetic shading element design by improving the same method. Even though the static shading design met the performance requirements and the visual comfort of the defined office environment, user preferences may vary, and manually actuated mechanisms can be integrated into this model. Other performance requirements, like thermal comfort, can also be examined in the future in relation to energy consumption and the effect of the shading element integrated into the facade system.

6 Conclusions

This study aimed to find a method to design a shading element with a basic geometry for an office building's façade. The basic geometry, a faceted loft, showed that it is possible to adapt it to different sizes easily and that it efficiently controls the sunlight, even though it does not have a complex geometry with a lot of mechanical equipment like actuators and sensors. The main findings of the study show that adjusting the SF and orientation parameters through a SOO process can improve visual comfort by 78%, reducing glare values from 58.1% to 12.9%, which is a satisfactory decrease in terms of DGP values. Another contribution of this study is that it demonstrated how the use of parametric design and evolutionary algorithms in the early design phase-and including the designer's decisions in the process-can improve visual comfort. In order to choose between clusters of many alternatives, a designer actively takes a role in the process and does not rely totally on some mathematical models or functions. The main limitation of the study is that the analyses are limited to SOO and do not fully address the balance between energy efficiency and visual comfort. In the future, investigating the effects of this modular system on thermal comfort and energy loads using multi-objective optimization methods and validating performance data through physical prototypes can give us a better understanding of how a faceted loft system performs. As a result, this study shows how to design a shading system that has a low cost and provides ecological sustainability by using daylight more efficiently.

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Data Availability Statement

The simulations were performed using the EPW weather file for [Mersin, Turkey].

Conflicts of Interest

No potential conflict of interest was reported by the authors.

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