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# Occupant-Centric Visual Comfort Assessment and Optimization of Passive Solar Façade Shading Systems through View-Based Analysis of Daylight Glare Probability, View Content, and Spatial Frequency Distribution

***Martin Ivanov,* Jun Sato***

*The University of Tokyo, Kashiwa, Chiba, 277-8563, Japan*

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## ABSTRACT

This study introduces a comprehensive computational framework integrating image-based simulations, spatial frequency analysis, and multi-objective optimization to evaluate and optimize passive solar shading devices from an occupant-centric perspective. While traditional façade optimization primarily addresses daylight performance and glare control, critical gaps remain in objectively and simultaneously quantifying visual comfort and preference, as well as external view content and quality—both essential to user satisfaction and psychological well-being. To bridge these gaps, spatial frequency metrics, historically utilized in image classification and visual assessments, are proposed as quantitative indicators for evaluating shading devices. The methodology employs first-person interior views analyzed through advanced computational techniques—daylight glare probability, image segmentation and power spectrum analysis—to objectively assess visual comfort, view content and spatial frequency composition. The proposed framework employs an adaptive optimization algorithm that iteratively generates and refines shading device configurations, effectively balancing glare reduction, external visibility, and visual complexity. Two experimental studies validate the approach: the first systematically evaluates multiple predefined shading patterns to identify optimal characteristics, while the second demonstrates that algorithmic optimization of highly irregular shading configurations can simultaneously improve multiple visual comfort metrics, significantly outperforming regular shading patterns in terms of glare reduction, view preservation, and spatial frequency performance.

**Keywords:** visual comfort, passive solar shading, optimization, spatial frequency analysis

## 1. INTRODUCTION

### 1.1. Multi-objective analysis of shading systems

The design of building envelopes significantly influences indoor environmental quality (IEQ), shaping occupants' comfort, well-being, and satisfaction. Façade systems regulate light, thermal conditions, and views while also having a strong impact on psychological and emotional well-being. Beyond meeting environmental performance standards, façade aesthetics play a crucial role in occupants' perceptions, fostering satisfaction and even increasing tolerance for minor discomforts [1]. This underscores the need to integrate aesthetic and emotional dimensions into façade evaluations alongside functional performance.

Passive solar shading systems—ranging from simple louvers to complex, irregular configurations—play a critical role in enhancing visual comfort, particularly in environments with high solar exposure. Double-skin façades offer a highly effective framework for integrating passive solar shading systems, enabling the simultaneous optimization of occupant visual comfort and building energy performance. Beyond modulating daylight and reducing excessive heat gain, they also contribute to architectural expression and promote occupant well-being by enhancing interior visual quality [2,3].

*Corresponding author.
martin.ivanov359@gmail.com (M. Ivanov)
junsato@edu.k.u-tokyo.ac.jp (J. Sato)

Computational tools and optimization techniques enable the development of high-performance solutions by refining shading geometries and materials to minimize solar heat gain while ensuring adequate daylight. Research consistently highlights their role in enhancing thermal comfort and reducing overall energy consumption, making them a valuable component of advanced façade design. Parametric design methods, characterized by their ability to systematically vary and explore architectural forms through digital modeling, have significantly advanced the design of shading devices. Combined with multi-objective optimization (MOO) techniques, parametric design enables the simultaneous consideration of competing factors such as daylight performance, energy efficiency, and visual comfort. Recent studies emphasize that MOO can effectively guide façade configurations toward optimal lighting conditions, balancing illumination, glare mitigation, and external visibility [4-8].

Biomimicry in façades offers an integrative approach to improving energy efficiency, occupant comfort, and visual appeal. Inspired by natural systems, biomimetic façades enhance thermal regulation, ventilation, and daylighting while adapting to environmental changes [9,10]. These designs often leverage intricate geometries, balancing energy efficiency with aesthetic appeal. Patterns inspired by natural phenomena, such as komorebi—the organic diffusion of light through layered foliage—can guide shading design, integrating environmental performance with aesthetic appeal. Such biomimetic approaches leverage intricate geometries to evoke positive emotional responses, aligning closely with biophilic design principles emphasized by international standards like LEED [11]. Moreover, the inherent cooling effect of trees highlights how strategies derived from this concept can integrate environmental performance with aesthetic appeal.

Analyzing daylight conditions is fundamental to visual comfort assessment. Glare analysis remains a key approach to evaluating visual comfort in naturally illuminated spaces. The widely recognized Daylight Glare Probability (DGP) metric quantifies the likelihood of discomfort from excessive brightness or contrast, serving as a reliable predictor of visual disturbances [12]. When thoughtfully designed, passive shading devices have the potential to balance natural illumination and glare control, helping to enhance visual comfort and reduce energy consumption—while avoiding reliance on complex adaptive systems. By applying the DGP metric, this research evaluates how various passive shading geometries influence glare mitigation, underscoring the importance of carefully designed shading devices that support visual comfort without compromising daylight quality.

Along with mitigating glare, it is vital to evaluate view content to maintain the visual connections that support occupant well-being. In evaluating view quality, unobstructed exterior views can be measured using parameters such as view angles, openness, and the presence of obstructions to ensure that structures and shading devices provide adequate visual access to the sky, greenery, and surroundings—supporting compliance with LEED and EN-17037 standards for visual comfort and connectivity [13]. Views to the outside can be integrated with daylight analysis techniques to facilitate MOO [14,15]. More advanced techniques, such as image-based view analysis and semantic segmentation, enable a finer examination by dividing images into meaningful regions to identify and quantify the composition of views—including structural elements, sky, greenery, and built structures. This precise content analysis can reveal how shading patterns influence the access and quality of views, ultimately aligning with biophilic design principles and enhancing occupant well-being by reinforcing connections to nature.

Spatial frequency analysis provides an effective method for examining the spatial composition of a visual scene. Long utilized in early computer vision research, this technique facilitates global semantic classification by analyzing spectral templates that encode dominant orientations and spatial scales [16]. It effectively evaluates the structural characteristics of an image, distinguishing between built and natural environments by quantifying the degree of naturalness in a scene [17]. By analyzing the 2D power spectrum (2D PSA), fractal-like patterns in images can be identified—patterns associated with visual comfort and aesthetic preference due to their evocation of naturalness and stress reduction. Fractal geometry, characterized by repeating patterns across multiple scales and orientations, plays a central role in visual complexity and is commonly found in natural elements such as clouds, branches, and leaves. These statistical patterns also appear in art and other creative domains, reinforcing the connection between spatial frequencies and aesthetic judgment while evoking familiarity and comfort through the statistical characteristics of natural scenes [18-20] PSA provides a straightforward framework for understanding visual comfort, as the human visual system is adapted to process scenes aligned with natural spectra. Deviations from these often result in discomfort due to inefficient neural processing and increased metabolic costs [21,22]. Conversely, scenes that align with natural image statistics are perceived as more comfortable and aesthetically pleasing, fostering familiarity and a calming effect, as seen in both natural environments and artworks that replicate scale-invariant properties. Spatial frequency analysis thus serves as both a diagnostic tool for assessing aesthetic quality and a predictive metric for designing biophilic and visually engaging environments. As a predictor, PSA can guide design generation, informing the development of environments that align with human visual perception and comfort [23,24].

This study will test how passive solar shading geometries—ranging from simple to highly irregular configurations—affect occupant-centric visual comfort by integrating three complementary evaluation methods: Daylight Glare Probability (DGP), image-based view content analysis, and spatial frequency analysis. By simulating interior first-person perspectives, the research aims to quantify how different shading patterns influence glare mitigation, access to outdoor views, and alignment with natural image statistics. Through this multi-objective, view-based approach, the study seeks to validate a novel evaluation framework for optimizing passive façade shading systems that support visual comfort, perceptual well-being, and biophilic design.

### 1.2 Research gap and objective

While façade optimization has made significant progress, critical gaps persist in the integration of advanced methodologies and comprehensive metrics that account for occupant-centered comfort. Although numerous recent studies have investigated shading devices across diverse climates using a range of simulation tools, prioritize thermal and daylighting performance over the nuanced effects of visual complexity on occupant well-being, underscoring the need for a more comprehensive, interdisciplinary approach [25]. Visual comfort is mainly considered in terms of daylight availability and glare mitigation [26-28]. Also, visual comfort metrics—such as glare indices—are commonly applied in simulation-based analysis but are seldom integrated into automated optimization processes, limiting their impact on algorithm-driven façade design. Beyond energy efficiency, factors such as external view quality and content have been incorporated into comprehensive frameworks for assessing window views [29]. Yet, view evaluation remains fragmented, with existing standards such as LEED and BREEAM focusing on visual access but overlooking the aesthetic and psychological benefits of complex geometries. While research consistently demonstrates that perceptual dimensions such as aesthetic complexity and visual naturalness significantly influence psychological comfort and occupant well-being, these aspects are often insufficiently addressed in standard façade evaluation methodologies, with relatively few studies engaging with them in a substantive way [30]. From an occupant perspective, novel approaches, such as implementing virtual reality simulations, have been proposed to analyze subjective responses to views [31], but techniques for quantifying naturalness, aesthetic preference, and visual comfort often lack objective numerical metrics. Spatial frequency metrics have already been successfully applied as predictive tools in generating aesthetically optimized computer-generated textures using evolutionary algorithms [32], suggesting their potential relevance for façade design—the most immediate interface between buildings and occupants. Traditional methods for façade design optimization seldom use such objective measures for view content or spatial composition, leaving deeper insights into human visual perception untapped. Parametric and evolutionary optimization techniques provide a means to incorporate multiple objectives in the design and analysis of façade shading devices [33,34], yet they remain underutilized in integrating view-based glare probability, view content, and spatial frequency metrics. This study seeks to address these gaps by offering a numerical assessment framework that guides the design and optimization of shading devices from an occupant-centric perspective.

In our previous research, we explored the integration of spatial frequency analysis with structural safety assessments in a façade design pattern optimization workflow [35]. This approach demonstrated that structural feasibility and perceptual quality can be addressed simultaneously, producing façade geometries that are both structurally sound and visually aligned with the statistical characteristics of natural patterns. Through a series of single- and multi-objective optimization experiments, the method yielded configurations that balance structural efficiency with visual complexity, highlighting the potential of spectral analysis as a performance-driven alternative to traditional biomorphic design. Subsequently, we developed a generative design framework for adaptive tensegrity façade systems that integrates structural optimization, solar performance analysis, view access evaluation, and spatial frequency-based visual analysis [36]. As part of a multi-step optimization strategy, façade pattern generation was combined with the multiple integrated performance evaluations. The resulting modules demonstrated improvements in structural efficiency, shading performance, external view access, and spatial frequency distribution. While this approach marked a step forward, it remained limited in its ability to assess visual comfort from the occupant's perspective. Both previous studies were based on flat orthogonal façade projections and did not incorporate interior viewpoints or simulate perceptual experience from within the space. As a result, key aspects such as interior light distribution, visual scene composition, and the quality of external views from typical occupant positions—particularly seated perspectives—were not captured. These limitations revealed a critical gap in the evaluation of façade designs. Building on these findings, the current study shifts focus to an immersive, first-person view analysis that simulates how occupants perceive light and visual content through passive solar shading systems. Our goal is to develop and validate an analytical framework that integrates spatial frequency analysis from a first-person view—rather than flat 2D orthogonal façade projections—and to combine it with established visual comfort evaluation methods, including glare and view content analysis. This integrated approach aims to provide a holistic understanding of how specific design variables of irregular shading—such as panel size variations, rotation angles, and distribution patterns—affect occupant-centric visual comfort metrics, including glare probability, view quality, and spatial frequency distributions. Ultimately, by incorporating natural image statistics into façade design, this research provides architects and engineers with analytical tools that enhance visual comfort, balance functional performance with aesthetic and psychological considerations, and advance passive solar shading devices toward biophilic building envelopes that promote occupant well-being.

## 2. METHODOLOGY

### 2.1. Computational framework and practical implementation

The methodology employed in this study integrates advanced computational techniques to evaluate and optimize irregular passive solar shading devices for their impact on visual comfort. The framework encompasses three primary components: 3D modeling and parametrization, simulated image-based analyses,

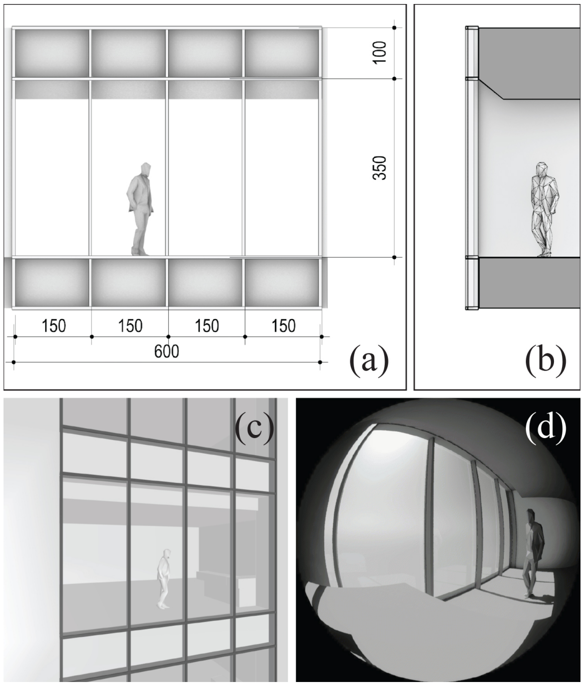


**Fig. 1.** Base study model: (a) Front projection, (b) Section, (c) Exterior perspective view, (d) Interior first-person view.

and MOO strategies —interlinked to refine the façade design from an occupant-centric perspective. A basic 3D building model was developed in 3D design software (Rhinoceros) to serve as the foundation for studying and evaluating various façade options. A parametric design approach in the computational design environment (Grasshopper) was employed to generate and manipulate shading geometries, providing precise control over design parameters such as shape, size, and distribution. Simulated image-based analyses for the three set objectives of glare, view content, and spatial frequency distribution were combined into a robust framework for evaluating the visual and environmental performance of the parametrically generated façade shading devices in the context of the base building model. This framework supports both manual and automated optimization, allowing designers to fine-tune critical parameters or employ iterative algorithms that refine shading patterns based on visual comfort metrics. By validating configurations in more complex problem spaces, such as highly irregular geometries, these algorithms demonstrate the framework's robustness while preserving computational efficiency and creative flexibility. This dual approach helps bridge the gap between performance-driven design and occupant-centric considerations, offering a flexible pathway for advanced shading optimization.

Parametric façade patterns [37] have proven effective for influencing daylight performance and occupant comfort, while advanced simulation workflows enable the dynamic form-finding of shading devices [38]. Combining multiple objectives can support automated or semi-automated shading device generation within MOO frameworks [39,40]. In this study, the integration of daylight simulations, image segmentation, and spatial frequency analysis provides a comprehensive approach for both evaluating and optimizing shading device designs. Specifically, for evaluating multiple design variations, these methods collectively offer a robust mechanism to quantify glare probability, external view quality, and spatial frequency characteristics associated with each configuration. In the optimization of parameterized shading designs, they enable a systematic approach to refining performance by iteratively adjusting design parameters. Simulated image-based analysis functions as a feedback loop, allowing automatic optimization algorithms to progressively improve shading configurations based on three key performance metrics: DGP, percentage of unobstructed view to the outside, and spectral distance from a natural scene reference. The trade-off between glare reduction and view preservation, complemented by spatial frequency analysis, ensures that optimized designs achieve balanced and visually comfortable light distributions. This dual application—evaluation and optimization—establishes the foundation for the experimental studies detailed in subsequent sections.

## 2.2. Study model, simulation parameters and objectives

The base building model developed for the purposes of this study represents a public or multi-use building located in the Greater Tokyo area, designed to reflect the demands of dense urban environments. The analyzed floor is situated at an elevation of 45 meters, reflecting the average height for the area and corresponding to a low- to mid-rise building configuration. The façade is modeled as a south-facing glazed system with the option to incorporate a double-skin façade, enabling the evaluation of various passive shading geometries aimed at improving visual comfort while maintaining energy efficiency and design adaptability. To evaluate the designs from a first-person view perspective, the model assumes a fixed workstation, such as a built-in cash register or reception desk, with the viewpoint set at a seated eye level (1.25 m) to align with occupant-centric criteria, including adequate "view out," as guided by international standards such as BREEAM. The proportions and dimensions of the study model are illustrated in Fig. 1, establishing a realistic and adaptable basis for analyzing shading device performance. Subsequent sections detail the simulation methodologies and specific parameters used in this study.

### 2.2.1. DGP calculation

Daylight Glare Probability (DGP) is a widely recognized metric which quantifies the likelihood of discomfort glare in daylit spaces. It incorporates several variables—vertical eye illuminance (Ev), luminance contrast (Ls), solid angle of glare sources (ω), and their position index relative to the field of view—to model glare response from the user's perspective [12]. DGP values are categorized into four standard thresholds: imperceptible glare (DGP < 0.35), perceptible glare (0.35–0.40), disturbing glare (0.40–0.45), and intolerable glare (DGP > 0.45). These thresholds

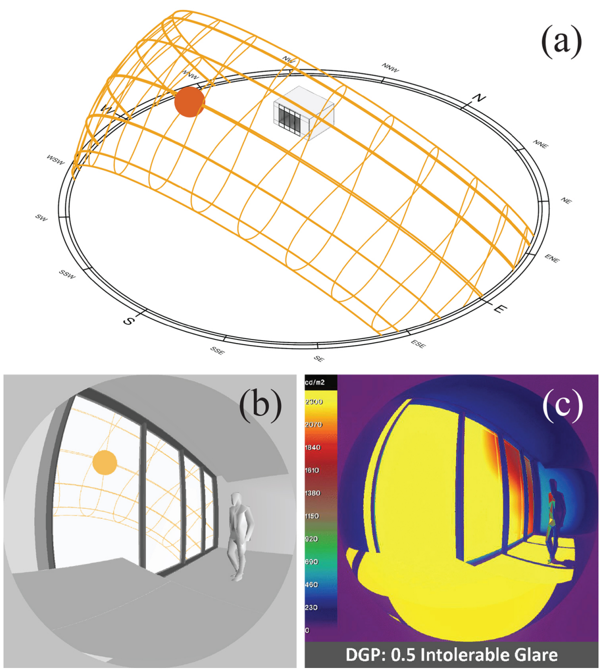


**Fig. 2.** (a) Sunpath diagram with Sun location for the studied point in time; (b) Interior first-person view with Sun location for the studied point in time, (c) DGP analysis result for the studied point in time.

allow researchers and designers to determine whether a given lighting condition will cause discomfort. Recent research has demonstrated that DGP can be effectively integrated into MOO workflows for static shading systems, particularly in combination with daylighting performance metrics [41]. However, while DGP is widely used in annual glare simulations, it is rarely coupled with perceptual metrics such as view content and spatial light distribution—factors essential to occupant visual experience. Annual glare simulations offer a broad overview of long-term performance but tend to generalize local conditions and overlook detailed spatial variation. Even though it is much more computationally intensive, point-in-time simulation provides higher visual fidelity, capturing moment-specific luminance distributions that more accurately reflect perceptual glare and comfort. For this reason, the present study adopts point-in-time simulation to enable a more nuanced evaluation of glare alongside view-based and spatial composition metrics within a MOO framework.

The study employs the DGP metric to assess visual discomfort by quantifying the likelihood of glare under specific daylighting conditions. The analysis is conducted using the Honeybee plugin for Grasshopper, which integrates Radiance for daylight simulations and OpenStudio for energy modeling. DGP is calculated based on vertical illuminance at the eye, luminance, solid angle, and positional index of glare sources, following established algorithms to model light behavior with precision. Climate data from the Tokyo Hyakuri EPW file is used to ensure local relevance, with the analysis focused on noon during the Autumn Equinox (September 23rd, 12:00). This point in time was selected based on solar geometry that balances between summer and winter extremes, representing a standardized baseline for glare assessment. The moment, characterized by intermediate solar elevation and high direct solar intensity, represents a critical scenario for evaluating glare potential, as identified by the sunpath diagram. The applied DGP threshold of 0.35 corresponds to the onset of perceptible glare, ensuring alignment with user comfort standards and industry benchmarks. This integrated approach provides a robust framework for evaluating and optimizing passive solar shading devices in the specified building model. Figure 2 illustrates the sunpath diagram with sun position set at the studied point in time, the sun position from the first-person view perspective and the glare analysis result for the base condition.

### 2.2.2. Image-segmentation

View access analysis is a critical aspect of occupant-centric building design, focusing on quantifying the extent of visual connection between interior spaces and the external environment. Quantitative approaches typically measure the percentage of visible sky or ground from a fixed vantage point, offering a basic metric of openness and visual connection to the external environment [42]. Detailed studies also reveal that geometric variables, such as window size and placement, can significantly influence occupant satisfaction and perceived quality of view access [43]. To capture the qualitative aspects of a view—such as the presence of natural features or urban elements, which are known to significantly influence occupant well-being—recent studies have highlighted that not only the quantity, but also the quality of views plays a crucial role in visual comfort and psychological satisfaction. Views that include natural elements like vegetation or water have been shown to contribute positively to occupant health and satisfaction, and simulation tools for early-stage design evaluation increasingly integrate occupant preferences to predict satisfaction levels [44,45]. These findings emphasize the importance of combining both quantitative and qualitative metrics in comprehensive view analysis, a goal that can be further advanced through semantic segmentation—a technique that enhances view analysis by classifying each pixel in an image into predefined categories such as sky, vegetation, buildings, or roads. This technique has been successfully applied in façade analysis, for example, to quantify the distribution of different façade materials [46]. From an occupant's perspective, semantic segmentation enables a more detailed understanding of view composition. It has been used to decompose dynamic window views, allowing for the assessment of compositional ratios of various urban elements, with input data derived not only from photographs but also from simulated models [47]. By leveraging these detailed classifications, designers can evaluate not just the extent but also the content of views, offering valuable insights into their potential psychological and physiological impacts on occupants.

In this study, image segmentation is employed to quantitatively assess the visual composition from an occupant's perspective

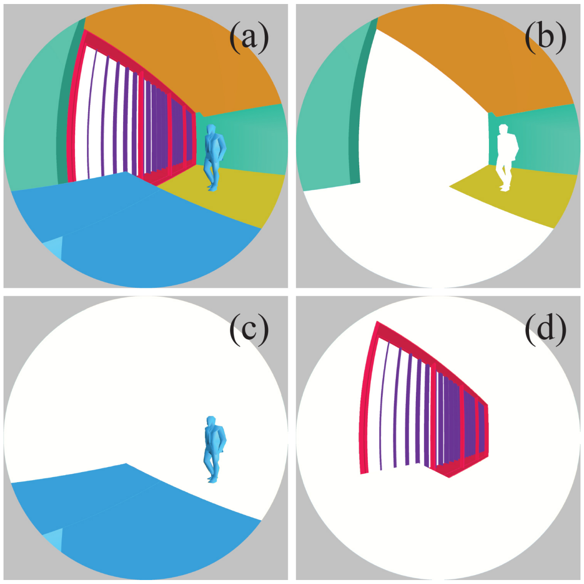


**Fig. 3.** Image segmentation: (a) Full semantically colored model view; (b) Segmented building surfaces; (c) Segmented interior context models; (d) Segmented primary and secondary façade structure models.

within a parametrically developed building model. It was developed through a set of custom-coded components inside the Grasshopper environment. The model geometries are organized and color coded semantically. A hemispherical image from the first-person viewpoint of the color-coded geometries is captured and the proportion of each category within the field of view is analyzed. By assigning distinct color codes to various architectural and contextual elements, the workflow categorizes the scene into structural components such as walls, floors, ceilings, primary façade structures (frames), and secondary façade structures (shading elements); glazing elements representing transparent or translucent surfaces facilitating external views; interior objects including furniture, fixed workstations, and human figures for scale; and external view components such as the sky and ground (earth). The key focus is determining the percentage of unobstructed views to the exterior, specifically calculating the combined pixel ratio of sky and ground visible through the glazing. This metric serves as an indicator of visual openness and engagement with the outdoor environment, which are critical factors in occupant comfort and satisfaction. While the current study concentrates on quantifying the extent of external visibility, further analysis could involve classifying external scene content, such as natural landscapes, adjacent buildings, or infrastructure, using the proposed modeling and segmentation technique. However, such detailed external content evaluation remains beyond the scope of this research. Figure 3 illustrates the semantic image segmentation by color coding.

### 2.2.3. Spatial frequency analysis

This study employs spatial frequency analysis from a first-person perspective to assess the visual and perceptual impact of shading designs by examining light and shadow patterns on interior surfaces. Rather than focusing solely on the 2D projection of the façade pattern geometry, the analysis evaluates rendered interior views to capture lighting interactions within the environment. The process is conducted using ghKomorebi, an open-source Grasshopper plugin we are developing specifically for spatial frequency analysis in the context of structural design and optimization. The core functionality includes a 2D Fast Fourier Transform (2D FFT) algorithm, which is automatically applied to the rendered first-person view image, followed by the calculation of the Azimuthally Averaged Power Spectral Density (AAPSD) of the resulting power spectrum. The AAPSD is computed in real-time by averaging spectral frequencies at a specified resolution (set at 100 azimuthal bins in this study), and the resulting frequency curve is benchmarked against that of a natural environment image with the same resolution. To compare AAPSD curves, the Bhattacharyya distance metric [48] was selected due to its advantages over traditional measures such as the L1 norm (Manhattan distance), L2 norm (Euclidean distance), and Kullback-Leibler (KL) divergence. While L1 and L2 norms measure absolute differences and can be overly sensitive to local variations, the Bhattacharyya distance quantifies the overlap between probability distributions, providing a more robust assessment of similarity. KL divergence, though commonly used for relative entropy, is asymmetric and can be undefined when one distribution assigns zero probability to regions where the other has nonzero values, making it less suitable for empirical spectral data. In contrast, the Bhattacharyya distance is symmetric and effectively captures the overall similarity between spectral shapes by focusing on distribution overlap. Figure 4 illustrates the rendered interior image, its 2D power spectrum, and the 1D AAPSD curve benchmarked against a natural image spectrum.

## 3. CASE STUDY 1: EVALUATION OF MULTIPLE GENERATED DESIGNS

As an initial experiment, five distinct shading device patterns were evaluated using the proposed framework, integrating simulated image-based analysis, image segmentation, and spatial frequency analysis to assess their impact on visual comfort and environmental quality. Each pattern was parametrically generated to explore variations in geometry, arrangement, and density, allowing for a comparative assessment of their effectiveness in controlling glare, maintaining external visibility, and distributing light.

Pattern A consists of vertical louvers with a depth of 400mm and a horizontal spacing of 380mm, designed to mitigate low-angle sunlight while preserving lateral visibility. Pattern B features horizontal louvers with a depth of 400mm and a vertical spacing of 350mm, primarily targeting overhead sunlight control while allowing unobstructed views along the horizon. Pattern C arranges 1000mm-wide panels with 1000mm horizontal spacing, creating a rhythmic alternation between solid and open areas that filter daylight while maintaining a structured visual connection to the exterior. Pattern D arranges panels of 1000mm width and 1500mm

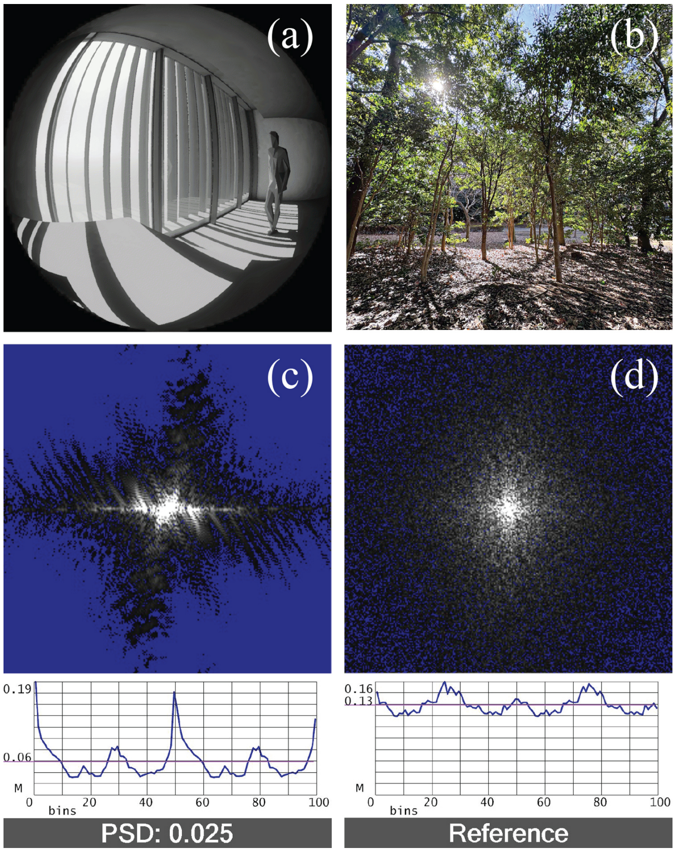


**Fig. 4.** Spatial frequency analysis: (a) Rendered first-person projection image; (b) Natural image reference, (c) Rendered image 2D PSA, AAPSD curve and spectral distance (PSD) from the natural image reference; (d) Natural image reference image 2D PSA and AAPSD curve.

height in a checkered pattern, introducing dynamic light modulation while providing intermittent openness. Pattern E follows a similar checkered configuration but with smaller panels (500mm × 500mm), offering an alternative balance between shading density and visual connectivity.

Figure 5 illustrates the geometry and dimensions of the shading device patterns.

Figure 6 presents the parallel analyses conducted for each shading configuration, integrating multiple evaluation methods to provide a comprehensive assessment. The analysis includes hemispherical renderings for glare assessment, image segmentation to quantify the proportion of unobstructed external views, and spatial frequency analysis to examine both the shading patterns and their projected interior light distributions. Together, these methods offer an objective comparison of how each design interacts with daylight and shapes the interior environment. The results, summarized in Table 1, highlight the performance of each configuration across key metrics, including glare probability, external view accessibility, and spatial frequency characteristics. This systematic evaluation establishes a quantitative foundation for comparing shading strategies and informs the subsequent optimization process, refining shading performance based on the most favorable design characteristics identified in this analysis.

The results indicate that Pattern B provides the highest glare reduction while maintaining the best external view. However, it also exhibits the least favorable spatial frequency distribution among the evaluated options. In contrast, Pattern E, with its small, checkered pattern panels, achieves the most even distribution of power spectrum density across orientations, closely aligning with the natural image benchmark. Additionally, it preserves a significant portion of unobstructed external view while maintaining an imperceptible daylight glare probability value.

## 4. CASE STUDY 2: AUTOMATIC OPTIMIZATION

As a second experiment, a flexible parametric study model featuring a highly irregular shading geometry was developed to test the applicability of the proposed evaluation strategy within an automatic MOO workflow. This experiment builds on the previous analysis by incorporating an iterative optimization process, enabling the refinement of shading configurations based on performance-driven criteria. Insights from the first case study informed the decision to further investigate a checkered panel pattern to enhance spatial frequency properties. To improve glare mitigation and maintain controlled visibility to the outside, panel rotation was introduced as a design variable. This rotational flexibility not only allows for optimized shading performance but also enables overlapping configurations without causing intersections. Additionally, variations in panel size were introduced to maximize adaptability and variability in the resulting light patterns. Each panel is a quadrilateral with rounded corners, two of which can be inscribed within a rectangular panel to minimize material waste and reduce excess cutouts. The experiment focuses on identifying the optimal geometric configuration of the panels, considering material choices that range from widely used 6 mm aluminum composite panels (ACPs)—for which recycling technologies are advancing and newer products increasingly incorporate recycled aluminum—to advanced bio-composite alternatives such as 8–10 mm flax fiber and bio-resin panels, which offer a lower environmental footprint through the use of renewable, bio-based resources. The panels are attached to the secondary façade structure using thin vertical metal rods that pierce through their center points, facilitating controlled rotation and positional adjustments. Arranged in a checkered pattern with a horizontal spacing of 500 mm and a vertical spacing of 500 mm, the panels maintain a structured yet adaptable configuration. The system allows for rotation during assembly, with the angle in both the XY and YZ planes adjustable through the central connector and fixed in place once the desired position is selected. This solution remains mechanically simple, and a detailed design of the connector mechanism could be readily developed and adapted in a practical application of the proposed design. The geometry of the base parametric shading panel model is illustrated in Fig. 7.

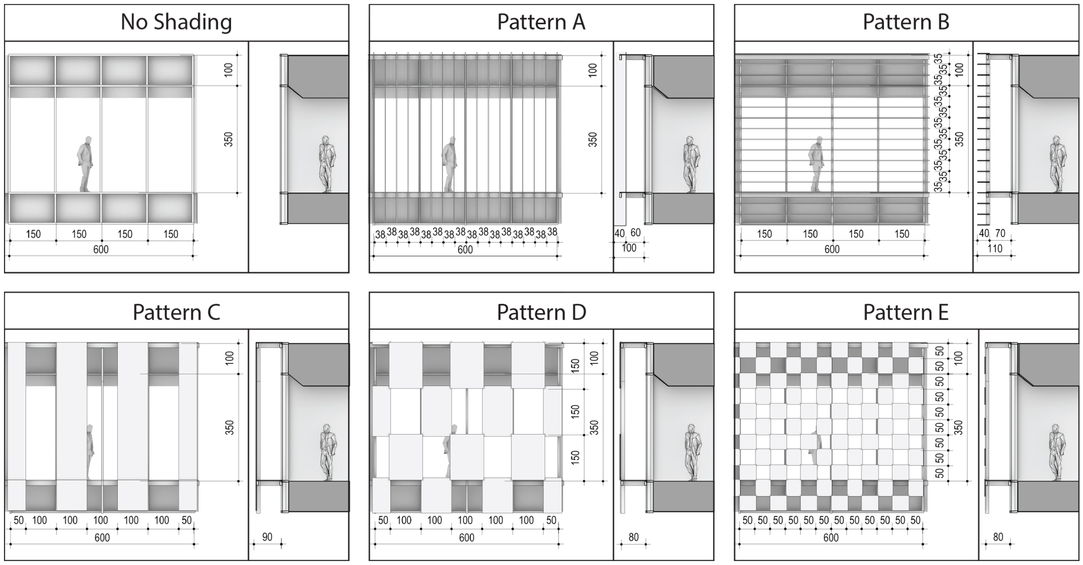


**Fig. 5.** Shading device patterns front projections and sections.

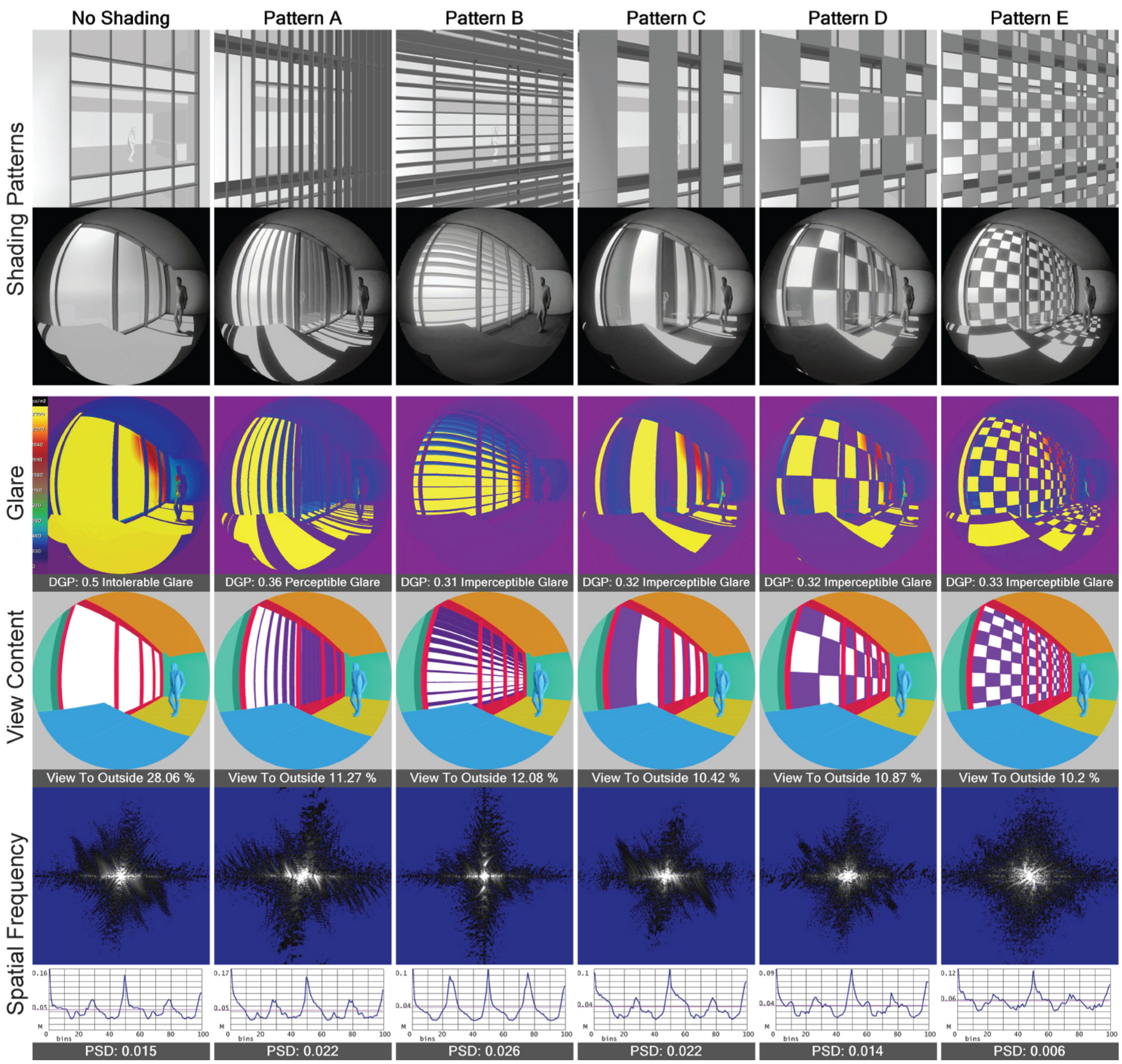


**Fig. 6.** Multi-objective analysis of the base model and the proposed shading device patterns.

**Table 1.** Results from the multi-objective analysis of the base model and the proposed shading device patterns.

| | | Shading Patterns | | | | | |
|---|---|---|---|---|---|---|---|
| | | No Shaders | Pattern A | Pattern B | Pattern C | Pattern D | Pattern E |
| Analyses | DGP | 0.5 | 0.36 | 0.31 | 0.32 | 0.32 | 0.33 |
| | View to Outside (%) | 28.06 | 11.27 | 12.08 | 10.42 | 10.87 | 10.2 |
| | PSD | 0.015 | 0.022 | 0.026 | 0.022 | 0.014 | 0.006 |

The optimization experiment is structured around the three key adjustable parameters for each panel: panel size, rotation in the XY plane, and rotation in the YZ plane. The panel size is categorized into three predefined types: Type 1 - 400 mm × 400 mm, Type 2 - 600 mm × 600 mm, and Type 3 - 800 mm × 800 mm. The rotation in the side (YZ) plane is constrained within a range of -45 to +45 degrees, while the rotation in the frontal (XZ) plane is free to 360 degrees. These three parameters are optimized for the 100 panels positioned directly in front of the studied model, influencing the field of view and interior lighting conditions. The analysis objectives follow the same framework as in the previous experiment, incorporating glare assessment, view content, and spatial frequency analysis.

The optimization process operates through an iterative algorithm that generates new shading configurations by adjusting the three design parameters, producing variations that are subsequently analyzed. The results of each iteration are automatically computed and serve as objective values for the optimization process. The optimization algorithm selected for this experiment is RBFopt, executed through the Opposum plugin in Grasshopper. RBFOpt is a model-based, derivative-free optimization method that builds on radial basis function (RBF) surrogates to handle black-box, high-dimensional problems in both engineering and design contexts [49]. It combines a global exploration step—focusing on parts of the parametric space with limited information—with a local refinement step for systematically improving the current best solution [50]. By adaptively choosing among different RBF types via cross-validation, RBFOpt maintains a balanced search strategy without incurring excessive computational overhead, making it well-suited for architectural design tasks where direct gradient information is often unavailable [51]. A limit of 200 iterations was set, ensuring a robust exploration of the design space while balancing computational efficiency. To ensure repeatability, the experiment was conducted five times, producing consistent results across each cycle. The consistency of the outcomes reinforces the reliability of the optimization process and the robustness of the proposed evaluation framework. The results presented in this study are derived from the fifth run of the experiment, which serves as a representative case for analysis and discussion.

Over the 200 iterations generated a range of solutions with varying performance outcomes was produced. The best-performing results are illustrated in Fig. 8, where individual iterations are compared based on key performance indicators. Iteration 30 achieved the highest percentage of unobstructed view at 13.25%, iteration 117 generated the lowest spectral difference at 0.002, and iteration 143 produced the lowest DGP value at 0.31. The overall best-performing shading configuration emerged in iteration 164, resulting in a PSD of 0.004, 12.7% unobstroctuded view to the outside, and satisfying the need for imperceptible glare at 0.34 (Table 2). These results highlight the effectiveness of integrating automated optimization with the proposed evaluation framework, demonstrating its potential for refining complex shading designs to enhance both visual comfort and environmental performance.

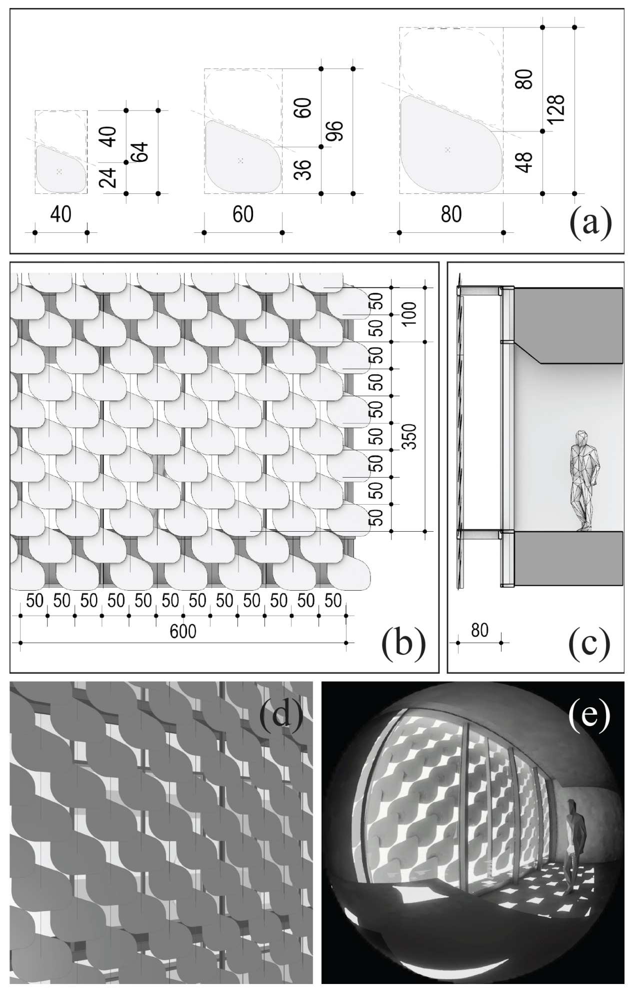


**Fig. 7.** Base optimization study model: (a) Predefined panel types inscribed in rectangular sheets, (b) Front projection, (c) Section, (d) Exterior perspective view, (e) Interior first-person view.

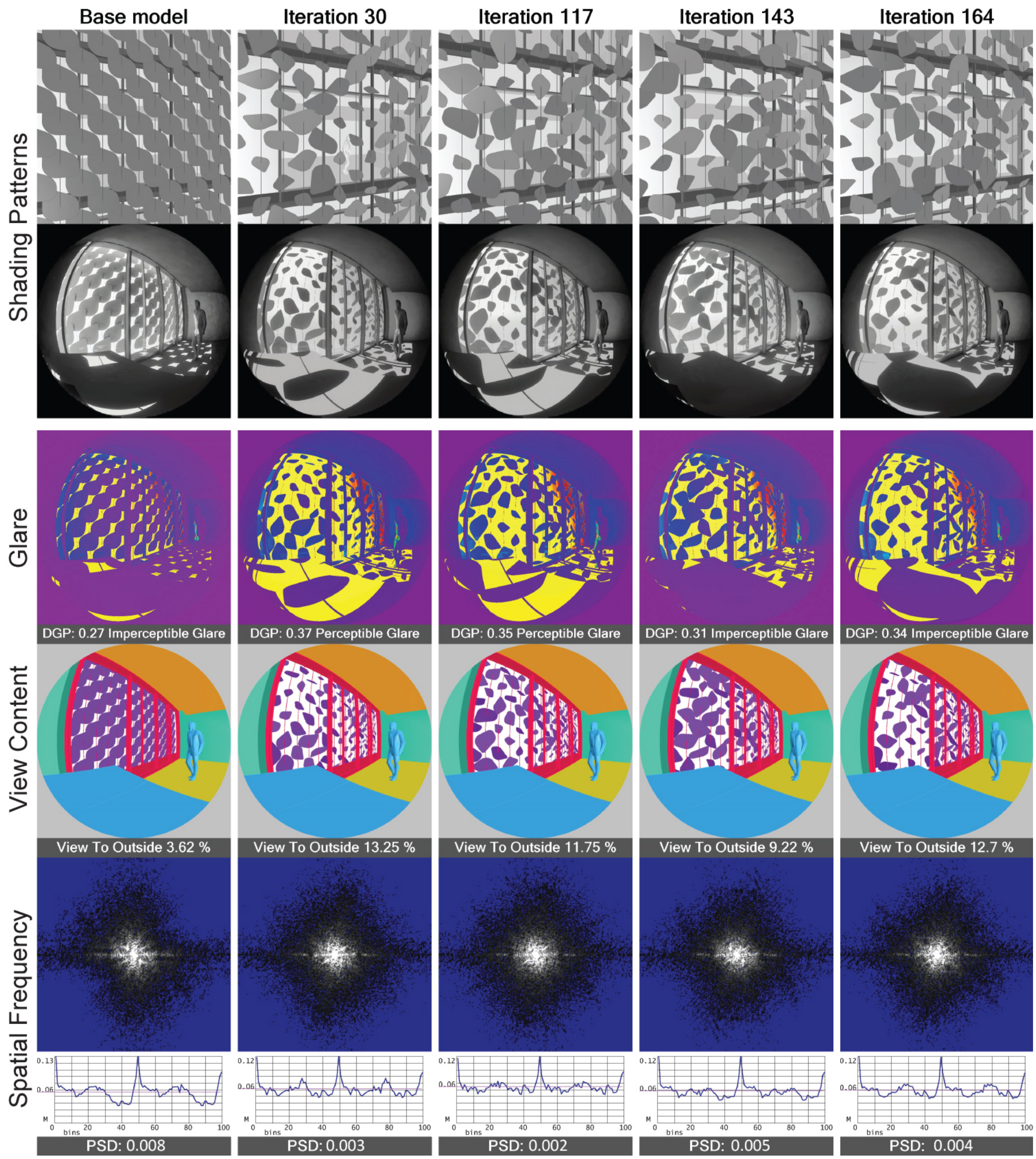


**Fig. 8.** Multi-objective analysis of the base optimization study model and selected shading device patterns resulting from the optimization experiment.

**Table 2.** Results from the optimization experiment.

| | | Parametric Shading Pattern Iterations | | | | |
|---|---|---|---|---|---|---|
| | | **Base model** | **Iteration 30 Best View** | **Iteration 117 Best PSD** | **Iteration 143 Best DGP** | **Iteration 164 Best Overall** |
| **Analyses** | **DGP** | 0.27 | 0.37 | 0.35 | 0.31 | 0.34 |
| | **View to Outside (%)** | 3.62 | 13.25 | 11.75 | 9.22 | 12.7 |
| | **PSD** | 0.008 | 0.003 | 0.002 | 0.005 | 0.004 |

## 5. DISCUSSION

The novelty of this study lies in its integration of three complementary evaluation metrics—Daylight Glare Probability (DGP), view content, and spatial frequency analysis—into a unified, occupant-centric optimization framework. While earlier studies have primarily focused on optimizing façade openings and shading devices based on daylight availability, energy performance, or singular visual comfort indices [4–8,14,15], few have incorporated detailed view analysis [45,47] or metrics of spatial composition [35,36]. Previous research has shown that visual comfort metrics can inform the generation of façade and shading designs [52] and has emphasized the importance of combining DGP with energy and psychological factors [53], as well as the need to evaluate view access in relation to complex geometries [42]. The proposed method expands the occupant-centric evaluative lens by addressing not only how much light enters a space or how much of the exterior is visible, but also how natural and perceptually comfortable the resulting spatial light distribution appears to occupants.

The two experiments illustrate the effectiveness of the proposed analysis framework for evaluating and optimizing passive solar shading devices with respect to visual comfort and environmental performance. The first experiment demonstrated how multiple shading configurations can be systematically assessed using glare analysis, image segmentation and spatial frequency analysis. By comparing five distinct shading patterns, it was possible to quantify their impact on glare probability, unobstructed external view, and spatial frequency distribution, establishing an objective basis for evaluating shading performance. The results highlighted how different geometric configurations influence interior lighting conditions and occupant visual perception, emphasizing the importance of a comprehensive assessment approach that integrates multiple analytical methods. The second experiment extended this evaluation by implementing an automated optimization process, demonstrating the feasibility of refining shading designs through iterative algorithmic adjustments. A flexible parametric shading model with irregular geometries was optimized based on key geometric parameters. The optimization results confirmed that, through systematic parameter adjustments, significant improvements in shading effectiveness can be achieved while maintaining a balance between daylight control and occupant-centric considerations. In the first experiment, five different shading patterns were evaluated against a no-shading baseline across three key metrics. Pattern B offered the best trade-off between glare control and view access, achieving the lowest DGP value (0.31) and the highest view percentage (12.08%), though its spatial frequency composition showed a substantial deviation from the natural reference. In contrast, Pattern E demonstrated the greatest visual naturalness with a PSD value 77% lower than that of Pattern B, and its DGP (0.33) remained below the discomfort threshold; however, its view access was significantly more limited (10.2%). None of the five predefined patterns presented a particularly balanced result across all metrics, illustrating the inherent trade-offs in static shading design. When comparing the optimized shading pattern from cycle 164 of the second experiment to the best-performing designs from the first experiment, it is evident that the optimization process led to a significant improvement in both PSD and unobstructed view. The optimized pattern achieved a 1.5-fold improvement in PSD performance compared to Pattern E, which had the best PSD performance in Experiment 1, with a BD of 0.004 as opposed to 0.006. Simultaneously, it resulted in a higher percentage of unobstructed view to the outside than Pattern B, the best-performing pattern in terms of unobstructed view in Experiment 1, with an unobstructed view percentage of 12.7% compared to 12.08%. These results demonstrate that the optimization process successfully balanced multiple performance criteria, achieving both improved light distribution and enhanced visibility. These findings are consistent with recent research advocating generative design methods that emphasize occupant-centric optimization criteria. The ability to generate a shading configuration that outperforms predefined design variations highlights the strength of integrating automated optimization with the proposed evaluation framework, reinforcing its potential for refining complex shading strategies in real-world applications.

The findings of this study provide a strong foundation for the future development of adaptive or kinetic façade systems. While the current framework evaluates and optimizes static configurations of passive solar shading devices, the use of parametric rotation and geometric variability in the optimization process simulates a wide range of potential physical arrangements. The rotation parameters fixed during evaluation emulate the range of motion characteristics of kinetic systems. Thus, the analytical framework developed in this study could be readily adapted to inform the design of a dynamic, responsive shading system. In such a future application, real-time data inputs (e.g., sun position, user presence, or luminance thresholds) could drive actuator-based adjustments to module orientation, enabling temporal optimization of shading configurations throughout the day or across seasons. This would extend the current research from static optimization to responsive environmental control, further enhancing visual comfort and energy performance while maintaining the aesthetic and structural benefits identified in the passive configurations. Future work could also extend this research by assessing the temporal variation of spatial spectral properties, which would provide deeper insight into how shading patterns evolve throughout the day and across different seasons, offering a more comprehensive understanding of their long-term impact on interior visual comfort. Additionally, incorporating the analysis of color and material reflectance properties would enhance the framework's ability to evaluate complex light interactions, particularly regarding spectral distribution and contrast variations within the visual field. These advancements would further refine the analytical capabilities of the proposed methodology, enabling more responsive and adaptive shading solutions that align with evolving architectural and environmental demands.

## 6. CONCLUSION

This study proposed and validated a computational framework for the evaluation and optimization of passive solar façade shading systems based on a multi-objective occupant-centric approach. By integrating DGP, view content analysis, and spatial frequency distribution from a first-person perspective, the method bridges existing gaps in façade performance evaluation. Two experiments demonstrated how predefined and optimized configurations can be comparatively assessed and refined using the proposed metrics. The results showed that highly irregular static geometries can outperform standard patterns in terms of both perceptual quality and glare mitigation. The study provides a foundation for future extensions, including kinetic façade systems and time-based analysis, and contributes a novel methodology that can inform biophilic, energy-efficient, and occupant-responsive façade design practices. Overall, the results of this study demonstrate that the proposed analysis and optimization framework provides a powerful tool for evaluating and refining shading devices. By leveraging computational design and performance simulation techniques, the methodology offers a systematic and scalable approach for optimizing shading solutions, bridging the gap between design flexibility and occupant comfort in passive solar control strategies.

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## CONTRIBUTIONS

Martin Ivanov and Jun Sato contributed to Conceptualization and Methodology. Martin Ivanov contributed to Software, Formal analysis, Investigation, Data curation, Writing – original draft, and Visualization. Jun Sato contributed to Validation, Resources, Writing – review and editing, and Supervision.

## DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

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