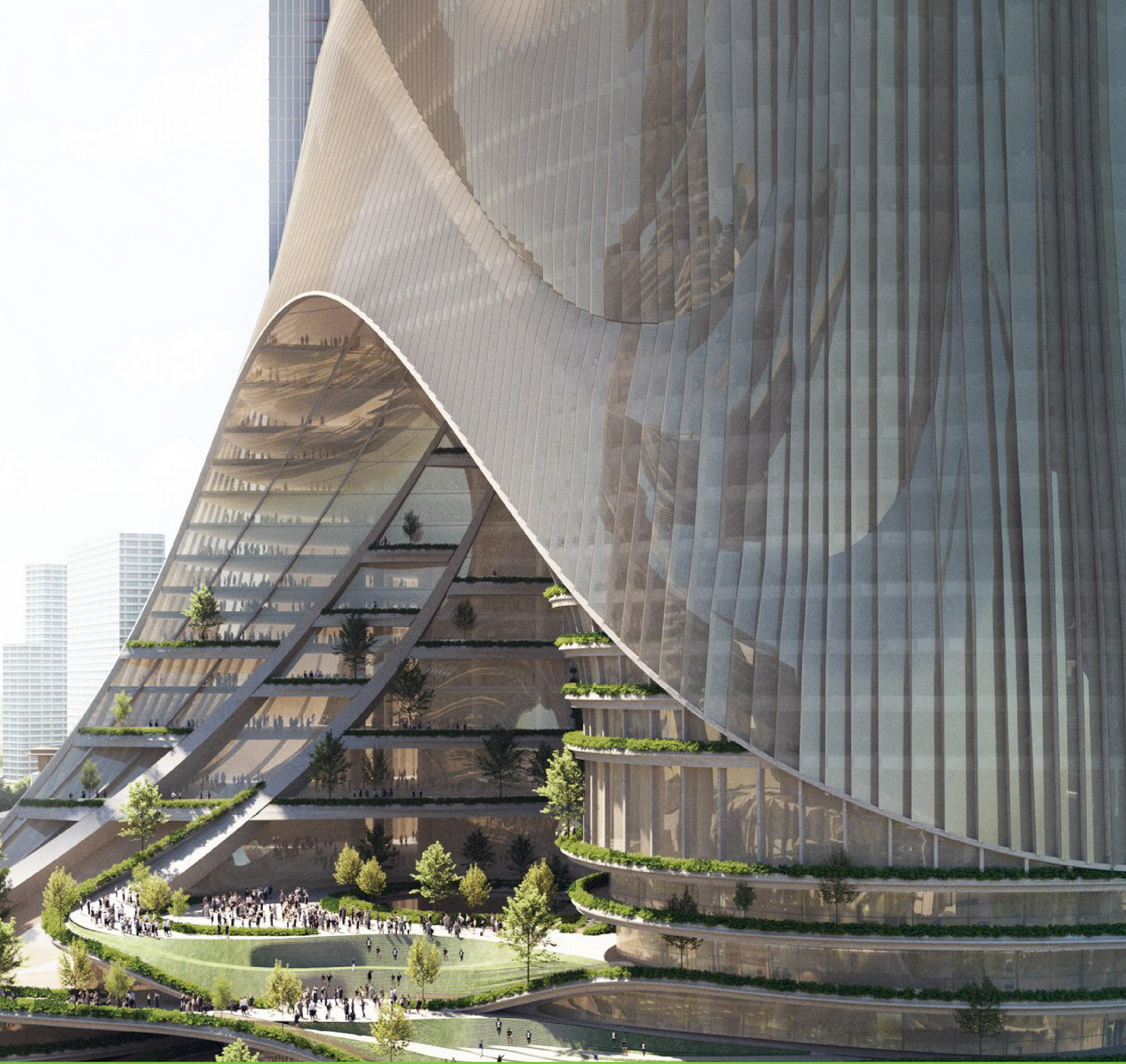

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From olive groves to urban buildings: Olea europaea-inspired adaptive photovoltaic façades for balancing energy efficiency and visual comfort

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Abstract

In response to the growing global energy demand, this paper presents an innovative biomimetic approach to designing adaptive Building Integrated Photovoltaics (BIPV) façades. Our method enhances solar energy efficiency while ensuring indoor visual comfort. Inspired by the morphological and functional characteristics of olive leaves, the façade is divided into two control zones, defined by the points where sunlight intersects with human sightlines on the façade. This approach uses Catmull-Rom curves for smooth control, driven by shape memory alloy (SMA) springs. The performance of the design is evaluated through three key indicators: PV irradiance, Illuminance Bias within the workspace, and indoor illuminance uniformity. Employing a multi-objective evolutionary algorithm, we explore viable solutions for the façade partition radius and varying degrees of aperture. In Beijing, a city representative of China's climatic zones, the façade's efficacy is evaluated through simulations at 12 distinct times during the equinoxes and solstices. Compared to static photovoltaic shading systems, our proposed façade achieves an improvement of at least 15.6% in PV Irradiance, Illuminance Bias, and Uniformity, marking a significant advancement in visually comfortable BIPV design based on biomimetic principles.

Keywords: Biomimetic design, adaptive photovoltaic façade, multi-objective optimization, visual comfort, energy efficiency, computational design.

1. Introduction

According to the “2022 China Building Energy Consumption and Carbon Emission Research Report” by the China Association of Building Energy Efficiency, the total energy consumption of buildings throughout their entire lifecycle in 2020 was 2.27 billion tons of coal equivalent (tce), accounting for 45.5% of the national total. Given the significant impact of the building sector on overall energy consumption and carbon emissions, promoting sustainable architectural practices is crucial. Building Integrated Photovoltaics (BIPV) are increasingly being adopted in modern architecture to enhance energy efficiency and support sustainable building practices. In high-density urban areas, building façades, with their larger surface area compared to rooftops, provide a more suitable location for BIPV installations, offering greater potential for energy capture. However, this shift from rooftop to façade-based BIPV may affect the indoor light environment, which is essential for the visual comfort of building occupants.

Traditional Photovoltaic (PV) façades often prioritize energy generation over user comfort, resulting in suboptimal energy efficiency. To enhance the overall benefits of BIPV façades, the concept of adaptive photovoltaic façades has emerged. Compared to traditional BIPV façades, adaptive photovoltaic façades have gained considerable attention in recent years due to their movable structural components and advanced control methods, which better balance energy yield and occupant comfort. Biloria et al. explored real-time adaptive BIPV shading systems optimized with a Multi-Objective Evolutionary Algorithm [1]. Conducted in a high-rise building in Sydney, the study shows that these systems can adjust BIPV panel positions throughout the day and with changing solar angles, leading to enhanced energy efficiency and improved visual comfort for occupants. Valitabar et al. presented a novel metric for evaluating dynamic vertical shading that enhances view, visual comfort, and operational energy [2]. Their method achieves a fourfold increase in view, year-round sky visibility, about 50% lower energy consumption, and minimal daylight glare probability.

Although recent studies have attempted to balance user comfort with energy efficiency, challenges remain. Some studies, due to their simplistic façade designs, yield results that are not particularly impactful. Others, while innovative in form, fail to optimize the façade's design or control logic to accommodate the diverse lighting needs of indoor activities, leading to discrepancies between simulation outcomes and real-world performance. Harnessing nature's proven designs and strategies, biomimicry offers a potent solution for addressing these engineering challenges. The natural world is characterized by photosynthesis and adaptability; thus, biological strategies that have evolved over millions of years can offer profound inspiration for photovoltaic adaptive façades. Anzaniyan et al. explored a kinetic façade for high-rise buildings, inspired by the Lupinus Succulentus plant, which dynamically adjusts to solar angles [3]. This innovative approach significantly reduces energy consumption, demonstrating the efficacy of nature-inspired designs in enhancing building energy efficiency.

This paper introduces an innovative biomimetic method for designing adaptive photovoltaic façades that seeks to optimize solar energy utilization while ensuring the visual comfort of office workers. Focusing on the most common building type in high-density urban areas—office buildings—we demonstrate the potential of this method to balance façade energy consumption and occupant visual comfort through comparative experiments with static PV shading forms.

2. Method

The leaves of *Olea europaea* exhibit different phenotypes depending on their position within the tree canopy, optimizing their adaptation to specific solar radiation and environmental conditions (Fig. 1). Leaves in the outer canopy, or sun leaves, are shaped to optimize both direct and diffuse solar radiation. In contrast, shade leaves, found deeper within the canopy, are adapted primarily to capture diffuse solar radiation, which is more consistent in those areas [4]. In designing the biomimetic adaptive photovoltaic façade, we draw inspiration from these adaptive strategies of Olea europaea leaves and propose a novel approach to enhance adaptive photovoltaic façades.

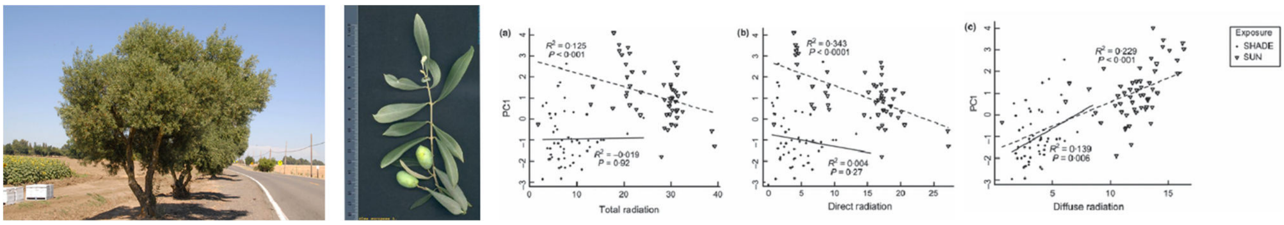

Figure 1: Photos of Olea europaea and the relationship between the leaf phenotype and solar radiation References from left to right: https://plants.ces.ncsu.edu/plants/olea-europaea/; http://herbarivirtual.uib.es/en/general/614/especie/olea-europaea-l-; Reference [4].

The objective of the proposed design is to emulate the biological logic of olive leaves, particularly the variations in morphology and internal anatomical structures of leaves at different canopy positions, which enable them to utilize various types of solar radiation efficiently. This concept is integrated into the morphology and control logic of photovoltaic adaptive façades, segmenting the façade into specialized zones: energy zones aimed at maximizing solar energy capture and visual zones designed to optimize lighting conditions for occupant comfort. This division aims to achieve a balance between energy efficiency and visual comfort.

2.1 Biomimetic design

2.1.1 Morphology

In terms of morphological design, the intention is to emulate specific features of olive leaves. Olive leaves typically exhibit an elongated-elliptical and symmetrical shape, with a relatively tough texture, and primarily perform photosynthesis on their upper surface. They are characterized by an opposite phyllotaxis on the branches.

In the façade unit design, we translate the morphological and phyllotactic symmetry of individual leaves into a structure adapted within a rectangular boundary, optimizing it for office building façades as shown in (Fig.2). The façade units are hinged along the diagonal of the rectangle, enabling an inward opening from 0 to 90 degrees. Each triangular “leaf” unit is individually controlled by a pivot, allowing for more precise modulation. Additionally, the exterior of each façade unit is equipped with photovoltaic panels. When closed, the façade mimics a 'sun leaf,' maximizing direct sunlight absorption while reducing glare. As a “shade leaf” when open, it provides expansive outdoor views and natural illumination, effectively utilizing diffuse light.

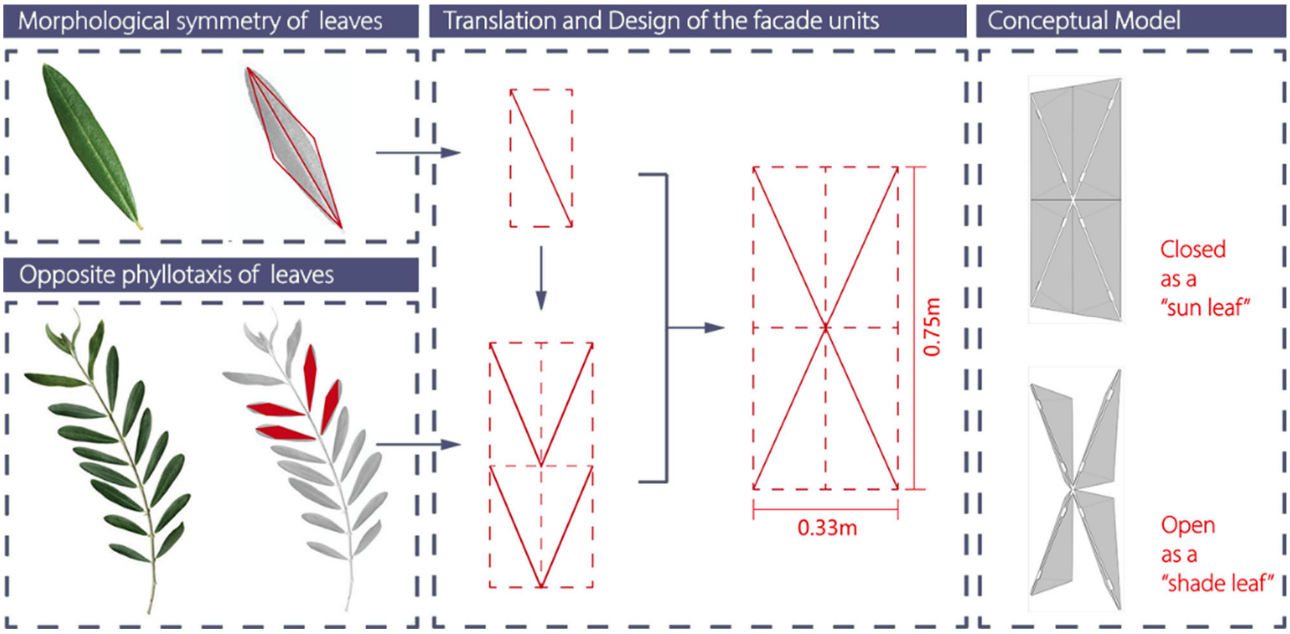

Figure 2: Biomimetic morphology design

2.1.2 Mechanism

Incorporating biomimetic principles, we have partitioned the façade units into two functional zones based on the layering mechanism observed in olive leaves, each tailored for distinct functionalities. The zones on the façade are determined by the intersection point where the line from the current position of the sun to the viewer's line of sight meets the façade surface. This is attributed to the fact that, on the façade, the periphery of this position is correlated with user visual engagement, while the areas formed beyond a given radius are designated as another functional zone (Fig.3(b)).

To ensure a smooth transition between the two zones while precisely controlling the transition forms of the façade units for a more even distribution of internal lighting, we have adopted the Catmull-Rom spline. This spline is an interpolating curve designed to create smooth transitions through a set of control points, offering G1 continuity and C1 continuity. This means the curve maintains continuous tangents and curvature at the junctions, ensuring smoothness and a natural progression of the line. Mathematically, the Catmull-Rom spline can be expressed as:

$$P(t) = 1/2\,[(2P_2 - P_1 + P_3)\cdot t^3 + (-3P_2 + 2P_1 + P_3)\cdot t^2 + (P_2 - P_1)\cdot t + 2P_2]$$

In this expression, P_1, P_2, P_3, P_4, are the control points, and t is the parameter that changes within the interval

$[0, 1]$. By adjusting the value of the parameter, different points can be obtained on the curve, thereby creating smooth transitions. In our study, the function graph depicting the diffusion trend (Fig.3(a)) defines the ordinate as a set of values representing the ratio of the projection length of the free vertex on the frame edge to the frame edge length during the rotation of the triangular leaf (Fig.3(c)). The abscissa of the function graph represents the distance from the center of the façade unit on the skin to the intersection point of the current sunlight path and the viewer's line of sight on the façade plane, which, during the computation of the function, is mapped to the parameter's range of values. In the graph, the position of the control points is related to point R, and the expression for points R, P_1, P_2, P_3, P_4 is as follows:

$$R\ (x_R, y_R), P_1\ (0, P_{1y}), P_2\ (x_{R2}, y_{R2}), P_3\ (x_{R3}, y_{R3}), P_4\ (5, P_{4y})$$

Given these coordinates, the relationships between the points are defined as:

$$x_{R2} = x_R - 0.3,\ x_{R3} = x_R + 0.3,\ y_R = 1/2\,(P_{1y} + P_{4y})$$

$$y_{R2} = y_R \pm 0.7 \times (P_{1y} - y_{R2}),\ y_{R3} = y_R \pm 0.7 \times (y_{R3} - P_{4y})$$

Among them, P_{1y}, x_R, P_{4y} are variable.

In the transmission mechanism of the façade unit, this study designs a drive unit using one-way thermally-induced shape memory alloy (SMA) springs made of nickel-titanium alloy (Fig.3(d)). The drive unit consists of two sets of SMA springs (Set 1 and Set 2). By selectively heating each set of springs, the antagonistic action between the two sets enables the drive unit to achieve continuous rotational movement of the shading panel. Heating Set 1 causes the springs to contract, driving the connected bearing and panel to rotate; heating Set 2 causes the springs to contract, returning the panel to its original position. By precisely controlling the heating time and current, the rotational angle of the panel can be accurately adjusted.

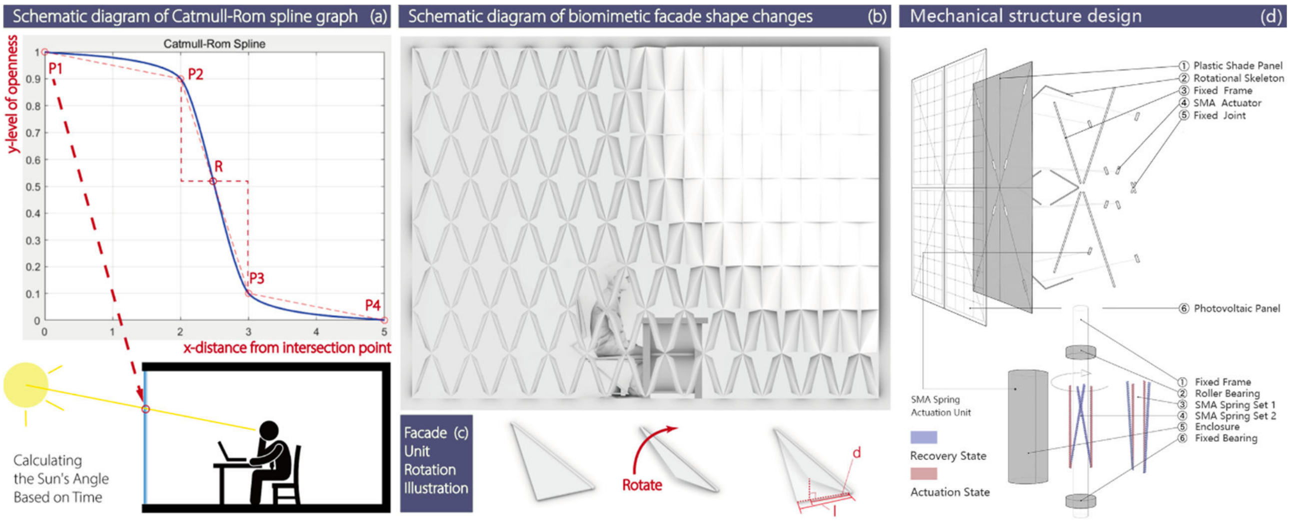

Figure 3: Biomimetic mechanism design

2.2 Validation experiment

2.2.1 Boundary conditions

In the context of China, climate zoning is determined based on annual average total illuminance, measured in kilolux. This study is centered on a contemporary single-occupant office in Beijing, positioned in the third of the five lighting climate zones, which represents a median and therefore a particularly representative region for daylight analysis. The south-facing office, featuring a glass curtain wall, includes a centrally located workstation. Simulations were strategically scheduled on dates reflective of the four seasons: March 21, June 22, September 23, and December 22. These were conducted at 8:00 a.m., 12:00 p.m., and 4:00 p.m., aligning with standard office hours. This timing choice, as indicated by Wang et al. [5], is instrumental for accurately assessing the façade's daylight performance.

2.2.2 Evaluation dimensions

This study optimized parameters using three evaluation dimensions:

(1) Uniformity: This metric calculates the standard deviation of illuminance values across the entire office space, aiming to ensure even lighting distribution and avoid discomfort caused by excessive illuminance gradients to users. Therefore, this value will be optimized with the goal of minimizing.

(2) Illuminance Bias: This metric calculates the deviation of daylight illuminance received at the work surface and its vicinity from the comfortable visual illuminance range. The comfort range for visual illuminance, as suggested by Wang et al. [5], is between 450-2000lx. If the illuminance exceeds this range, the absolute value of the difference is calculated and accumulated. This metric measures the comfort level of visual illuminance for users facing the work surface. To ensure that the illumination in the work area is within the range as much as possible, optimization will aim to minimize this value.

(3) PV Irradiance: This refers to the total solar irradiance received by the façade per unit of time, used to measure the energy gain produced by the photovoltaic panels on the façade's exterior. In optimization, the larger the value, the more it meets our expectations.

In assessing the first and second dimensions of evaluation, the office space was divided into a 0.2m grid to perform detailed calculations of the illumination levels. We utilized Rhino in conjunction with the Ladybug and Honeybee plugins to conduct this analysis. The chosen platform is widely recognized and has been rigorously validated, providing us with a reliable foundation for conducting our architectural and environmental simulations.

2.2.3 Optimization algorithm

This study utilizes Wallacei V 2.7 to perform optimization across three evaluative dimensions, showcasing its capabilities in multi-objective optimization (MOO) for real-time adaptive photovoltaic façade systems. MOO integrates multiple fitness functions to balance conflicting objectives, thereby enhancing both system efficiency and visual comfort. Wallacei simplifies this process by automating the optimization of objectives, driving innovation in the field, and significantly improving the energy efficiency of adaptive photovoltaic façade systems while minimizing visual discomfort.

2.2.4 Control group

In this research, the control group utilized a static PV shading system, consisting of 12 louvers on the façade with 0.3m vertical gaps and a thickness of 0.05m, positioned at a 60-degree angle to the xz-plane (Fig.4). This setup served as a reference point to evaluate the adaptive façade's effectiveness in optimizing energy capture and visual comfort. The comparison with the static PV shading system highlights the significant advantages of the biomimetic adaptive photovoltaic façade in optimizing energy efficiency and enhancing visual comfort.

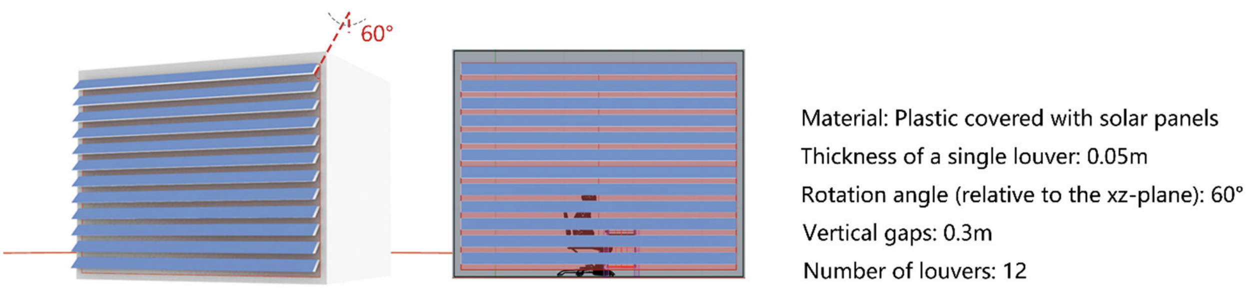

Figure 4: Appearance and parameters of the control group

3. Result and discussion

3.1 Experimental group data analysis

In this study, the biomimetic adaptive photovoltaic façade was developed using Rhino 7 and Grasshopper for three-dimensional and parametric modeling. The control of the Catmull-Rom curve was implemented through programming with the Python component built into Grasshopper. Daylight performance and visual comfort were assessed using Ladybug 1.7.0 and Honeybee 1.7.0, with weather data sourced from EnergyPlus in EPW file format. The model underwent multi-objective optimization using Wallacei V 2.7, focusing on selected genes P_{1y}, x_R, P_{4y}.

Fitness objectives included PV Irradiance, Illuminance Bias, and Uniformity. All computations, simulations, and optimizations were performed on a Windows computer equipped with an 11th Gen Intel Core i7-11800 CPU @ 2.30 GHz and 16.0 GB RAM. The optimization process required approximately 17 hours and 10 iterations to converge to a stable state, yielding 200 solutions, of which 32 were identified as Pareto optimal.

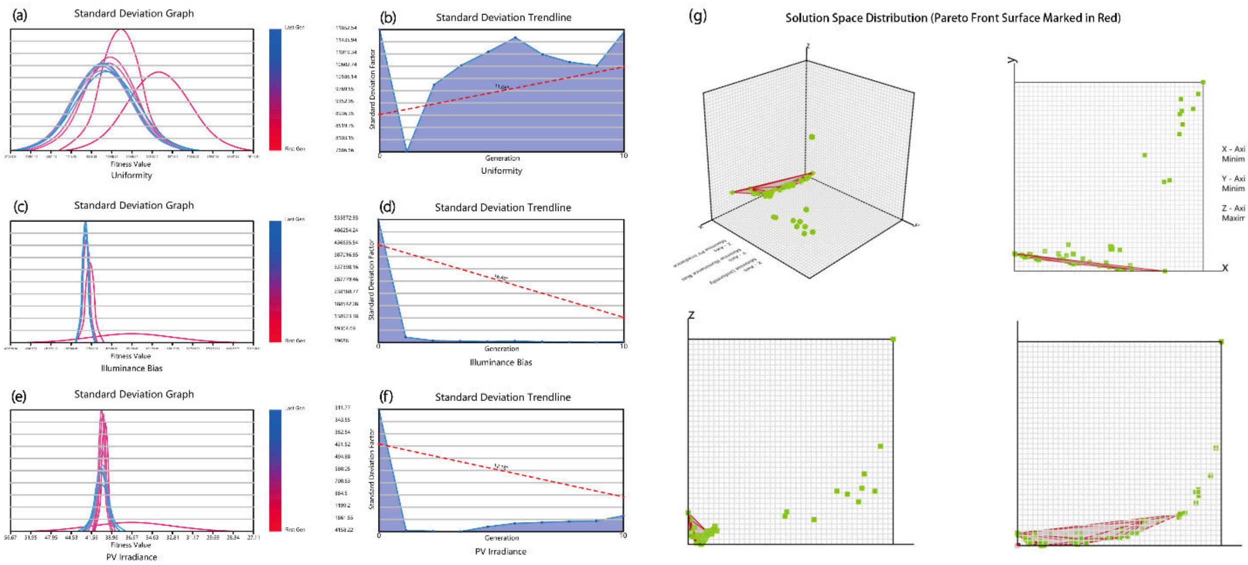

Figure 5: Trends of change of different objectives in the optimization process and the global distribution of solution space

Fig.5(a) illustrates that Uniformity generally increased over the optimization iterations until convergence. The broader range and gentler slope of the blue curve indicate greater dispersion in Uniformity in later iterations, deviating further from the mean. Moreover, Fig.5(b) reveals a significant reduction in Uniformity from 11852.54 to 7686.56 between the zeroth and first generations. During the subsequent eight generations, Uniformity gradually increased, stabilizing around 11000. Fig.5(c) shows a leftward shift and narrowing of the curve, suggesting a more concentrated distribution of target values over iterations. Additionally, Fig.5(d) demonstrates a rapid decline in Illuminance Bias from the zeroth to the first generation, followed by stable fluctuations below 40000. Fig.5(e) portrays a virtually unchanged curve position and transverse span with a decreased slope, indicating more dispersed PV Irradiance distribution in later iterations. Finally, Fig.5(f) clearly shows a rapid increase in PV Irradiance from the zeroth to the first generation, stabilizing around 2000 between the seventh and tenth generations. The distribution of Pareto solutions in Fig. 5(g) indicates that feasible solutions have been explored, and these solutions are located at the boundaries of the solution space.

The optimization process revealed substantial improvements across all three objectives, eventually stabilizing in the later iterations. This indicates successful convergence of the optimization algorithm, rational parameter configuration, and reliability of the results obtained.

Shading type	Uniformity (lx)	Illuminance Bias (lx)	PV Irradiance (kWh)
Static PV Shading	25883.82	318467.27	35.48
Minimize Uniformity	0.004198	151199.96	39.75
Minimize Illuminance Bias	40177.35	12789.53	37.67
Maximize PV Irradiance	5823.17	108846.19	41.24
Average solution	2726.62	120924.01	41.01

Table 1: Representative data of the experimental group and the control group

In the analysis of the Pareto front solutions, we pinpointed the most optimal solutions for each of the three objectives, as well as those offering a balanced trade-off among the trio of performance metrics, as depicted in the accompanying figures and tables. The data distinctly indicates that in these Pareto optimal solutions, the upper thresholds of all three optimization objectives have been effectively pushed, marking substantial enhancements compared to the static photovoltaic shading system. Notably, the Uniformity metric experienced a remarkable boost, with a reduction exceeding 99.9% relative to the static system, and Illuminance Bias saw a 96.0% decrease. The gains in photovoltaic efficiency, although notable, were comparatively moderate, with an increase of 16.2%.

Nevertheless, excelling in a single performance metric doesn't always equate to a superior overall design, as it may entail significant trade-offs in other areas, thereby diminishing its practical application value. Therefore, from the range of Pareto optimal solutions, we selected one that demonstrated balanced excellence across all metrics—the average solution. This solution provides a comprehensive overview of the Pareto optimal outcomes and possesses greater applicability in real-world scenarios. In contrast to the static photovoltaic shading system, this balanced solution showed improvements of 89.5% in Illuminance Bias, 62.0% in Uniformity, and 15.6% in PV irradiance.

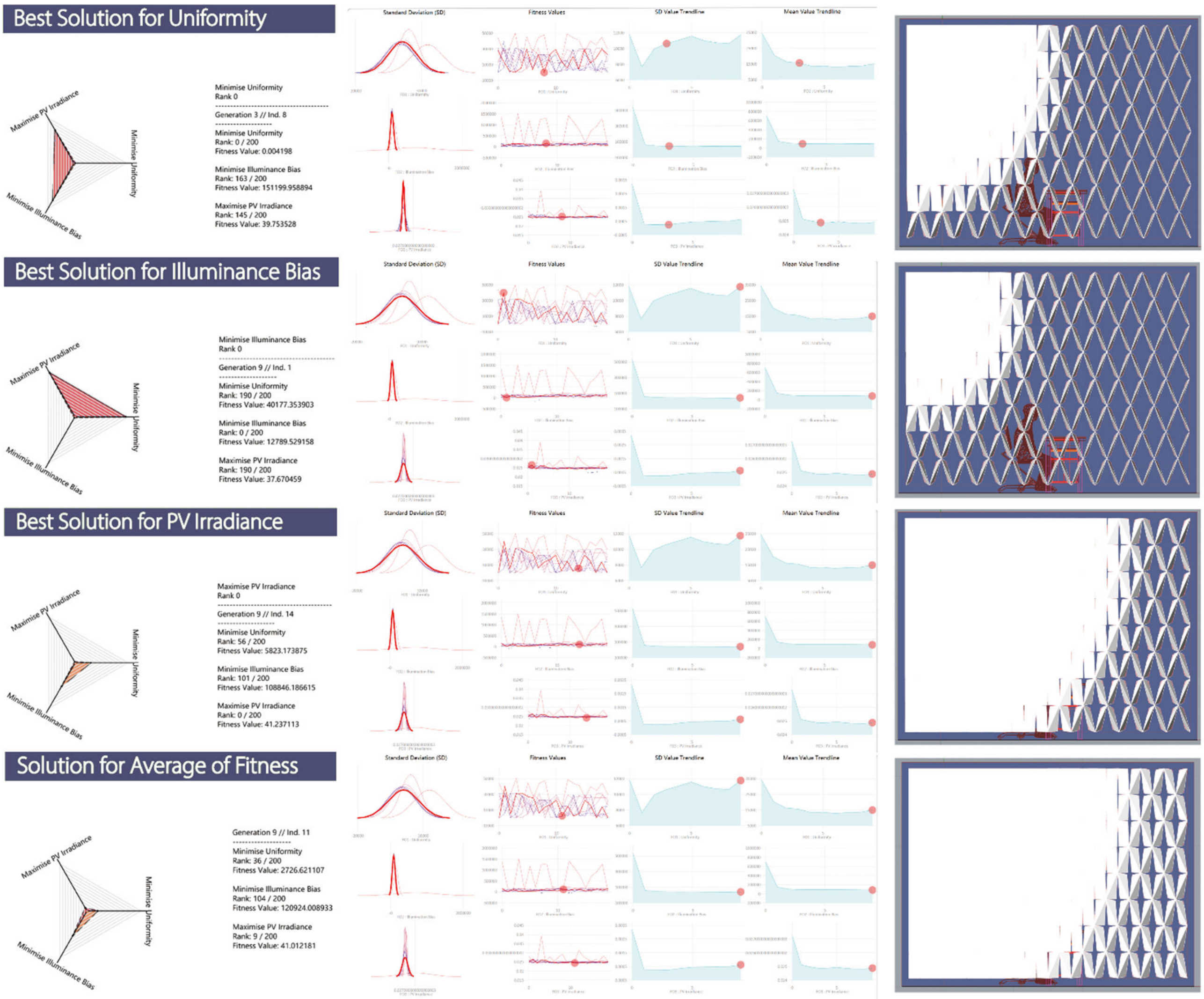

Figure 6: Representative solutions and corresponding façade appearance (e.g., 9/23, 16:00)

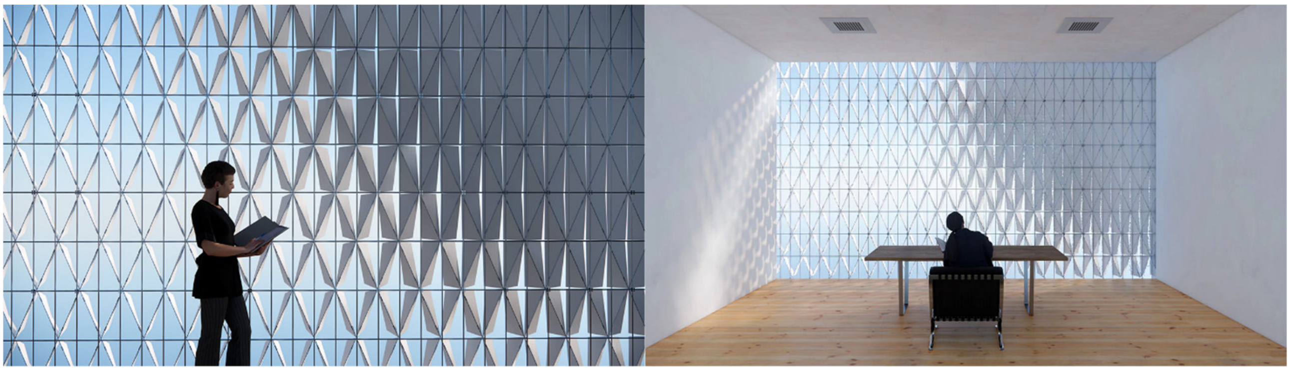

Figure 7: Interior perspective renderings (the average solution)

Interior perspective renderings highlight the effectiveness of the biomimetic façade, clearly showcasing its enhanced performance in optimizing light comfort post-optimization (Fig.7). They also highlight the aesthetic enhancement brought by the biomimetic design, indicating that it not only offers functional improvements but also greater visual appeal.

3.2 Discussion

Compared to static PV Shadings, the adaptive PV façade proposed in this study demonstrates significant advantages across all evaluated performance metrics, highlighting the integral role of biomimetic principles. Notably, the parts of the façade that are most visually impactful for occupants often concentrate on specific areas, where natural light characteristics play a central role, while other regions have a relatively weaker connection to visual comfort. Therefore, as suggested by the parameter settings of the mean solution, a partition control strategy that assigns a higher weight to photovoltaic efficiency in areas with lower relevance to visual metrics enhances the façade's multi-objective optimization capability. The variations in optimization results with parameter adjustments also underscore the importance of partition methods and varying aperture degrees for partitioned façades, demonstrating the positive impact of biomimicry applied in this study.

Another key finding is that PV Irradiance remains the most stable performance metric for BIPV façades, whereas indoor light environment indicators related to comfort show significant variability. This suggests that in addition to focusing on energy efficiency, BIPV façade designs should prioritize their impact on the indoor physical environment. Especially for adaptive BIPV designs with a vast solution space of design parameters, it is crucial to consider indoor light environment indicators and explore a wide range of design parameters.

Overall, the exploration of biomimetic practices in adaptive BIPV façades, inspired by the biological traits of olive leaves, offers new insights into the field. Compared to previous studies, our introduction of functional partitioning and smooth spline curves for façade control contributes valuable knowledge to research on adaptive façade control.

For future research, some limitations need to be addressed. Although this study examined certain aspects of the indoor light environment, many factors related to occupant visual comfort, such as glare, and field of view, remain to be investigated. Moreover, while our study is based on simulation results, the effectiveness of the proposed biomimetic approach should be validated through physical prototypes to translate these biomimetic strategies into practical applications.

4. Conclusion

Traditional BIPV systems face limitations in balancing energy consumption with occupant demands due to their design and control constraints. Although biomimetic approaches have proven effective in enhancing adaptive façades, their application in BIPV remains underutilized. In the design of adaptive photovoltaic façades considering energy consumption and visual comfort, additional work is needed to explore how mature natural designs and strategies can be effectively applied to the system.

In this paper, drawing inspiration from the morphological and functional characteristics of olive leaves, we propose a corresponding façade form and control logic based on biomimetic principles, incorporating user positioning. During the validation phase, using Illuminance Bias, Uniformity, and PV Irradiance as performance metrics, we explored feasible solutions for façade partition radius and variable aperture degrees using a multi-objective evolutionary algorithm. The conclusions of this study are as follows:

(1) Optimizing the parameters of functional partition radius and the aperture degrees of two zones, the NAGA-II algorithm with a generation size of 20 successfully identified 32 Pareto optimal solutions in 10 generations, proving the effectiveness of the optimization design process.

(2) The optimized façade morphologies in the Pareto optimal solutions showed at least a 13% improvement in Uniformity, Illuminance Bias, and PV Irradiation compared to the initial solutions.

(3) Compared to traditional fixed PV shading system, the proposed façade's average solution of fitness achieved improvements of 89.5%, 62.0%, and 15.6% in Illuminance Bias, Uniformity, and PV Irradiance, respectively, demonstrating its significant benefits in indoor visual comfort and photovoltaic efficiency.

Overall, the biomimetic adaptive photovoltaic façade approach proposed in this study, in comparison to the traditional fixed PV shading system, further expands the potential of biomimetic methods in balancing energy efficiency and light comfort in adaptive photovoltaic façades. The workflow presented here is not limited to specific conditions but can benefit occupants, investors, and the climate in various scenarios. Future work will focus on developing façade optimization strategies tailored to different times and weather conditions. Additionally, we propose exploring more advanced façade morphologies and intelligent materials to enable a wider range of adaptive movements.

5. References

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