JES, Vol. 54, No. 5, Sept 2026 DOI: 10.21608/JESAUN.2025.393563.1550 Part E: Architectural Engineering

Journal of
Engineering Sciences
Faculty of Engineering
Assiut University

مجلة
العلوم الهندسية
كلية الهندسة
جامعة أسيوط

journal homepage: http://jesaun.journals.ekb.eg

Multi-objective Optimization Approach of Enhancing Visual Comfort in Educational Buildings: A Case study-MSA University Classrooms, Egypt

Received 12 June 2025; Revised 19 December 2025; Accepted 19 December 2025

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Keywords
Responsive Façade, Multi-objective optimization, Visual comfort, educational buildings.

Abstract: The design of shade devices and the window-to-wall ratio are crucial factors in enhancing visual comfort, productivity, and overall well-being in buildings. By managing the design and configuration of shade systems, it is possible to achieve ideal levels of Useful Daylight Illuminance (UDI) while reducing thermal discomfort from overheating and visual discomfort from glare. This research presents a multi-objective optimization (MOO) strategy for existing educational buildings that utilizes different geometric shapes to enhance the efficiency of daylight and visual performance. Using a parametric approach and evolutionary multi-objective computation via Wallacei-x plug-in for Grasshopper, various shading device opening ratios, shading geometry, and window material in existing educational buildings in West Cairo, Egypt, are implemented by implementing responsive façade systems. The study evaluates the impact of various fixed shading designs, including horizontal and vertical angled blinds, on daylight performance metrics such as Daylight Factor (DF), Useful Daylight Illuminance (UDI), and glare risk (DGP). While no shading allows for maximum sun penetration, it also causes severe over-illumination and glare. In contrast, inclined horizontal shade at 15° provides maximum visual comfort and equal illumination distribution, albeit with diminished daylight availability. Vertical blinds at 0° and 15° provide a balance of daylight reduction and glare control, giving realistic options. Building on these findings, the study investigates the performance of a responsive shading system with five different polygonal geometries in a controlled classroom setting. The simulation study shows that responsive shading provides a flexible, efficient daylighting strategy, surpassing static designs. Geometric diversity and adaptation are essential for enhancing indoor environmental quality in hot, arid regions. Solutions for existing buildings are explored, providing recommendations for shading devices geometry in university buildings in a hot and dry climate.

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https://doi.org/ 10.21608/jesaun.2025.393563.1550

1. Introduction

Designing educational buildings with good visual conditions can enhance the performance of students by enhancing the visual and physical features of the learning environment [1]. Daylighting is the process of using daylight to produce desired lighting effects in buildings, like highlighting objects and task areas. Well-lit environments are difficult to achieve because of functional requirements and subjective perceptions.[2], [3]. However, oversupply of daylight can lead to negative effects such as glare risks, room overheating, and lack of privacy [2]. The facade of a building serves as a thermal barrier or shading system, ensuring thermal comfort and limiting solar exposure. Sometimes the functionalities of shading devices can be incompatible. Adequate daylighting is crucial for occupants' visual comfort, as it improves mental and physical health, increases work efficiency, and enhances psychological feelings [5]. In production, work, and study spaces, a comfortable light environment can lift spirits and enhance work efficiency. Therefore, the design of the facade is essential for a well-designed building [4], [5]. Optimizing solar protection can decrease daylight penetration, which affects the visual comfort of occupants and raises the need for artificial lighting. Factors like façade orientation, screen type, material, color, geometric form, depth, and perforation percentage influence the effectiveness of shading screens [6]. To balance these variables and improve building performance, parametric design and multi-objective optimization methods have been frequently employed. The goal of these tools is to find solutions that balance multiple objectives among comparable solutions with similar environmental performance [7], [8]. The internal environmental quality of over 40% of educational buildings worldwide is inadequate, with existing buildings playing a significant role. Additionally, 60-70% necessitate additional heating, chilling, and air conditioning systems[9]. Conventional façade designs often lead to excessive heat build-up, inadequate daylight, and artificial lighting, negatively impacting students' academic performance and well-being. The combination of architectural and artistic skills to create a responsive environment has led to blurred professional boundaries [10]. The study investigates improving visual comfort in university classrooms through the evaluation of responsive façade systems and their shading geometries. It focuses on optimizing multi-objective parameters to address challenges related to daylight performance in hot-arid environments. The central research question explores how polygon-based responsive façade shading systems can be optimized parametrically for better visual comfort in these educational spaces.

To answer this question, the study examines three hypotheses:

- Increasing the geometric complexity of responsive shading (from 3 to 5 polygons) leads to measurable improvements in daylight distribution.
- Multi-objective optimization (MOO) can identify façade layouts that exceed the visual comfort performance of conventional shading methods.
- Among the tested configurations, the five-polygon system will yield the most optimal balance between daylight availability and glare mitigation.

This paper introduces a novel approach to multi-objective daylighting optimization in hot, dry educational buildings that combines field validation, parametric simulation, and evolutionary optimization. It assesses responsive polygonal façades (triangular, quadrilateral, and pentagonal) and demonstrates how the five-polygon configuration achieves balanced daylight distribution, glare management, and view quality. The technique introduces a scalable and verified approach that goes beyond traditional static shading methods, filling a gap in current MOO research.

2. Background

2.1 Role of building envelopes in improving indoor quality and occupant comfort:

Globally, building envelopes must act as a filter between internal and external environments, enabling internal environment control through engagement, mediation, and adaptation. The external environment is not only governed by climate alone but also by a number of issues related to adjacencies, such as urban development, vegetation, and bodies of water. As diagram 1 shows, an urban microclimate generally [11]. The building sector accounts for over 40% of global emissions, making it a key factor in sustainability. Sustainable design, sometimes known as eco-architecture, is an attempt to respond worldwide. The building and housing business contributes to environmental issues such as resource depletion, CO_2 emissions, and other greenhouse gases. [12]. Human quest begins by unravelling the intricate threads that weave together architecture, nature, and innovation. People spend over 80% of their time within buildings, and it directly affects happiness, health, and a sense of well-being. One of the most important elements that affects building performance is the façade (envelope) [13].

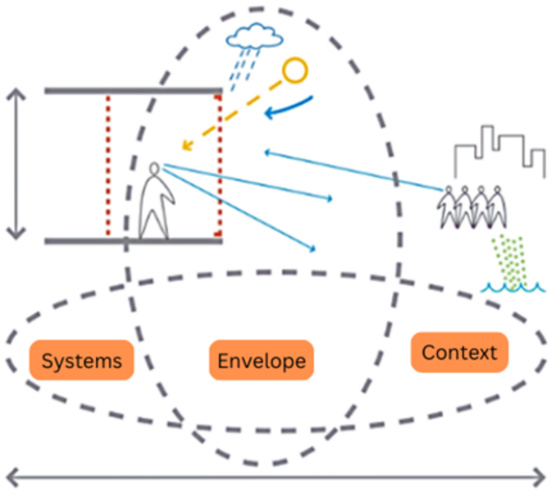

Figure (1): building fabric type chart and the building envelope balances performance and form, considering various factors from the building program, users, climate, and context, ensuring a practical and elegant envelope. Source: the building envelope book- Section Feedback loops of form and performance [11]**.**

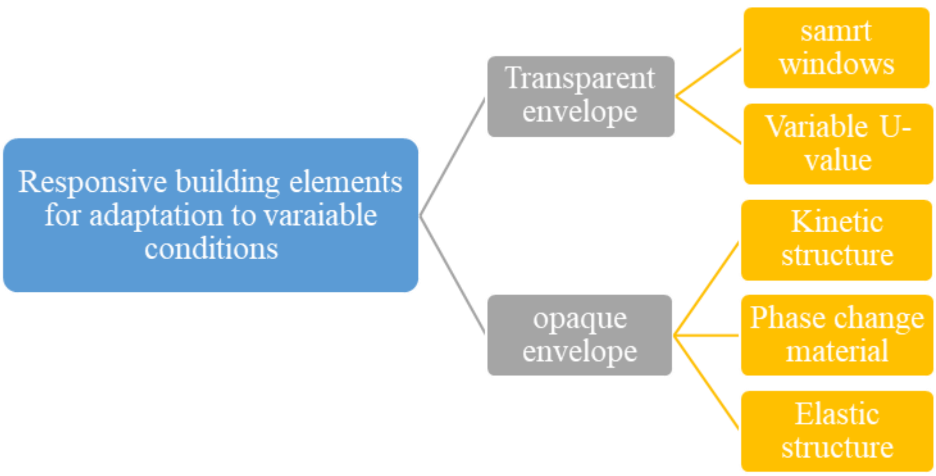

Figure (2): Responsive and adaptive elements in buildings. Source: enhanced by author, referring to [18]

The building envelope acts as a physical barrier between indoor and outdoor environments, as shown in Figure 2, providing thermal resistance and preventing heat waves from propagating inside. However, due to global warming, conventional building envelopes are unable to adapt to the rising temperature, making it crucial to adapt to the changing climate [14]. The building envelope serves to separate the interior from the exterior, providing climate protection, structural support, and aesthetic appeal. It consists of three key players: the outer layer for weather protection, the middle layer for insulation, and the inner layer for sealing and vapour control[15]. Physical states and force effects like sun, wind, and rain are utilized in building components and environments to create sustainable architecture and environments [16], [17]. Responsive architecture design adapts to changing environmental conditions, incorporating technological and environmental possibilities.
It focuses on improvisation and adaptability, evolving from functionality to intelligence. [19], [20]. As shown in Figure 2, Responsive and adaptive elements in buildings adapt their properties over time to meet occupants' needs and external conditions, improving comfort and energy efficiency by controlling indoor parameters [18]. Responsive facades (RFs) represent a transformative shift in architectural design, merging environmental consciousness with technological adaptability. These systems not only respond dynamically to changing environmental conditions but also contribute significantly to improving energy efficiency, indoor comfort, and sustainability. As demonstrated by global case studies, their implementation supports long-term energy reduction goals and enhances the overall performance and liveability of buildings. As illustrated in Figure 3, Climate-responsive façades offer a dynamic alternative to traditional static barriers, adjusting to changes in outdoor conditions. The design and features of these façades influence the extent of indoor environmental changes, providing a flexible response to fluctuating outdoor conditions. [21]. To meet indoor environmental quality and energy efficiency goals, climate-responsive façades adapt to both internal and external changes, offering a flexible solution. [22].

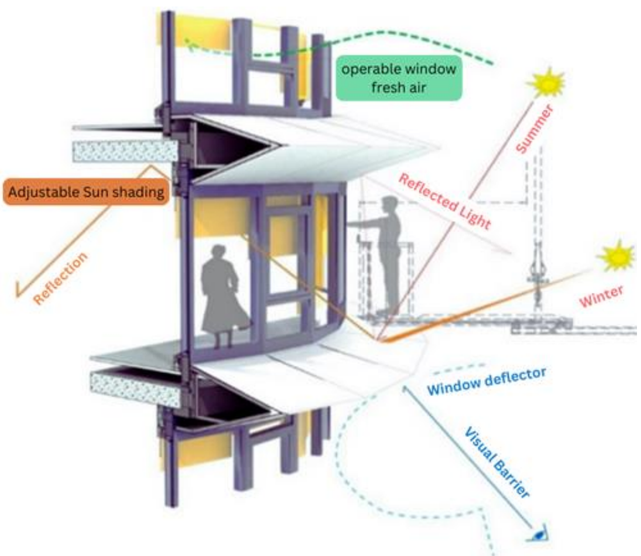

Figure (3): climate-responsive façade section with kinetic shading device. Source: [23]

The responsive and adaptive façade approach, though complex and energy-intensive, can be improved by enhancing embedded responsiveness to outdoor thermal variations, ensuring indoor comfort without additional energy supply [24], [25], [26]. Responsive facades enable buildings to respond in a receptive or sensitive way to changing form, materials, colours, and natural features by incorporating technological and environmental possibilities [27]. Responsive Architecture is necessary to enable integration between the building and the surrounding environment [28], [29].

Architectural responsiveness involves adapting to user interactions or environmental conditions through changes in facade patterns or material properties [30], [31].

2.1- Performance Metrics:

There are many performance metrics, as illustrated in Table 1. The following are important metrics for evaluating the environmental performance of buildings: Cooling Load shows the energy required to maintain indoor thermal comfort in a given climate, EUI measures the annual energy consumption per unit area, DGP measures visual discomfort from glare, and UDI assesses daylight sufficiency. These measurements inform design choices to maximize energy efficiency, comfort, and daylighting [32] [33] [34].

Table (1): Definition of some performance metrics:

Metric	Definition	Typical Threshold / Goal	Ref.
Useful Daylight Illuminance (UDI)	The percentage of occupied time when daylight levels at a workplace are within a useful range (typically 100–2000 lux).	UDI 100–2000 lux ≥ 80% (recommended)	[32]
Daylight Glare Probability (DGP)	A metric for evaluating visual discomfort from glare caused by daylight, combining luminance contrast and direct sunlight exposure.	DGP ≤ 0.35 (imperceptible), 0.35–0.40 (perceptible), >0.45 (intolerable)	[33]
Energy Use Intensity (EUI)	The annual energy consumption per unit area of a building, expressed in kWh/m²/year.	Target depends on climate & building type; lower is better	[34]
Cooling Load	The amount of energy required to maintain acceptable indoor thermal comfort is affected by solar gain through windows and façades.	Depends on the climate; aim to minimize with effective shading	[34]

As shown in Table 2, Daylight Glare Probability (DGP) is a crucial metric for evaluating indoor visual comfort. A value below 0.35 indicates imperceptible glare, between 0.35 and 0.40 signifies perceptible glare, from 0.40 to 0.45 indicates disturbing glare, and exceeding 0.45 results in intolerable glare, significantly affecting visual performance [33].

Table (2): Daylight glare probability comfort criteria and ranges, Source: [33], [35]

Daylight Glare Probability Range	Glare Comfort
DGP < 0.35	Imperceptible glare
0.35 < DGP < 0.40	Perceptible glare
0.40 < DGP < 0.45	Disturbing glare
0.45 < DGP	Intolerable glare

2.2- Multi-objective optimization approach using Genetic Algorithms:

The Multi-Objective Genetic Algorithm (MOGA) is a powerful approach for solving problems with conflicting performance goals, generating optimal trade-off solutions known as the Pareto front, based on project priorities [36]. In the context of responsive façade design in educational buildings, this approach is highly valuable. Responsive façades featuring kinetic elements or adaptive shading must balance daylight access for visual comfort with reduced cooling loads for energy efficiency. Using MOGA, architects can simulate and evaluate various façade configurations, optimizing parameters like shading angles, material properties, and actuation strategies. This ensures that the façade dynamically adapts to environmental conditions while meeting the dual goals of improved indoor comfort and lower energy consumption. Thus, MOO provides a structured, data-driven method to inform responsive design decisions in complex building environments [37]. A parametric approach to facade optimization, like genetic algorithms and parametric modelling, can enhance daylight and indoor conditions in educational buildings, improving student concentration, comfort, and academic performance [38], [39].

3. Literature Review

Recent studies have highlighted the necessity of optimizing building envelope design to improve daylighting performance, visual comfort, and energy efficiency in educational and office settings. For example, [38] applied multi-objective optimization to balance daylighting, thermal comfort, and energy use in middle school classrooms located in hot and dry regions. Similarly, [40] used the NSGA-II algorithm through Wallacei to optimize UDI, DGP, and EUI in educational buildings across different climatic zones in China, demonstrating the critical trade-offs between daylight sufficiency and energy consumption. In the context of arid climates, [41] investigated the effectiveness of various shading strategies using sDA, ASE, and EUI to identify climate-specific facade solutions. The impact of glazing ratio and window configuration was examined by [42], who explored their influence on energy demand and comfort in a Turkish school building. In Tehran, [43] optimized shading depth, angle, position, and energy usage intensity for office space to improve UDI and reduce DGP and energy use. For primary schools, [44] used genetic algorithms to optimize orientation, wall angle, and glazing type for improving both visual and thermal comfort. A more material-specific study by [45] focused on thermochromic glazing, employing LINMAP decision-making to evaluate daylight and energy performance. Furthermore, [31] conducted a parametric analysis of oriental-inspired sun-responsive skins, assessing metrics such as sDA, ASE, UDI, and DGP to optimize visual comfort. The research [46] examines adaptive façades, or AF, to improve building energy efficiency, indoor environmental quality, and user comfort. However, the performance evaluation of AF is still scattered because most studies focus on static facades and the early phases of design. Broader approaches to shape and envelope optimization were demonstrated by [47], who used genetic algorithms to reduce annual energy demand and simulation complexity. In the local context of Egypt, [48] evaluated right-angled triangular responsive façades in Cairo's climate, highlighting reductions in solar radiation and improvements in indoor comfort through parametric and comparative simulations. Moreover, Responsive façades, featuring dynamic shading and glare control, dramatically minimize environmental impact by lowering energy consumption, decreasing HVAC system emissions, and prolonging daylight hours, while simultaneously improving occupant productivity and well-being [49]. It prevents heat gain and daylight without glare in hot, dry regions like Egypt [50]. Table 3 below summarizes these studies, highlighting the diversity of methods, design parameters, and performance indicators employed in multi-objective optimization for sustainable and responsive educational buildings.

Table (3): summary of Research Background with research methods, parameters, software, and objectives of the study, Source: By the Authors, referring to the literature review sources.

Reference	Research Methods	Design Parameter	Performance Indicators	Software	Objectives
[38]	Multi-objective optimization	WWR Glass type Wall Material Shading Devices	-Daylighting -Thermal comfort -Energy consumption	Grasshopper Octopus	Optimization of daylighting, thermal comfort, and energy consumption in a middle school classroom.

Reference	Research Methods	Design Parameter	Performance Indicators	Software	Objectives
[31]	Optimization	Time parameters Louver material Rosette material Louver depth sDA, ASE, DA, UDI, DGP	Daylight metrics Visual comfort (Glare reduction/ Glare Probability/ LEED v4 measure Optimization	-Grasshopper -Ladybug -DIVA -Radiance DaySim -Galapagos	The study evaluates the visual comfort of an oriental-style solar skin on a south-facing office unit through parametric analysis, aiming to create an adaptive shading system.
[40]	Multi-objective optimization using Wallacei, based on the NSGA-II (Non-dominated Sorting Genetic Algorithm II).	Classroom orientation: 5° east or west. Dimensions: deflection angle, length, width, height (converging to 3.2 m). WWR: 0.5–0.7.	- Energy Use Intensity (EUI). - Daylight Glare Probability (DGP). - Useful Daylight Illuminance (UDI).	Grasshopper Ladybug& Honeybee Wallacei	- Maximize UDI at eye level for better daylight quality and students' eye health. - Minimize EUI for energy efficiency and carbon reduction. - Minimize DGP for visual comfort.
[42]	-Optimization -Energy simulation	Window Transparency Window contribution	-Energy Consumption -Visual and Thermal Comfort.	DIALux Design Builder EnergyPlus	Study the impact of different Transparency window combinations on classrooms.
[44]	Multi-Objective Optimization, Genetic algorithm	Building orientation Wall angle WWR Glazing Material	Thermal and Visual comfort	Grasshopper Ladybug& Honeybee	Optimizing architectural design features in primary schools to minimize energy consumption and improve comfort.
➢ **Proceed with the completion of the table.**					
[41]	- Pareto Frontier and Weighted-Sum methods for multi-objective optimization. - Building energy performance simulation validated by ASHRAE 140-2020.	- Shading strategies: vertical louver, horizontal louver, light shelf, overhang, and egg-crate. - Window-to-Wall Ratio (WWR).	(sDA) Evaluates the percentage of occupied hours with sufficient daylight. (ASE) Assesses potential glare risk from excessive sunlight. (EUI) Measures energy consumption.	Grasshopper Ladybug& Honeybee Octopus	- Identify climate-specific strategies for reducing energy consumption (EUI) and improving daylight control (sDA and ASE). - Explore optimum solutions for educational buildings in diverse climates.

Reference	Research Methods	Design Parameter	Performance Indicators	Software	Objectives
[43]	- Multi-objective optimization using Wallacei in the Grasshopper environment. - Weighted Sum Method (WSM) for selecting optimal solutions.	-Depth of Shading: 0.4 -Facade Offset - Location of Shading: Horizontal - (WWR): 80 - Count of Shading: 5 - Angle of Shading: 30 - Height of Window: 0.5	- **(EUI):** - **(sDA):** Evaluates daylight sufficiency. - **(DGP):** glare reduction. - **Thermal Comfort:** Evaluates temperature comfort.	Grasshopper with the Wallacei algorithm for optimization.	- Optimize shading design to improve EUI, sDA, and DGP. - Reduce glare levels in winter and summer. - Improve Useful Daylight Illuminance (UDI) from 25.8 to 68.4.
[45]	- Multi-objective optimization. - Pareto Frontier analysis using the Linear Programming Technique for Multi-dimensional Analysis of Preference (LINMAP).	- Transition temperature. - Solar and Luminous transmittance.	- Building energy consumption. - Useful Daylight Illuminance (UDI 300–3000).	Grasshopper Ladybug& Honeybee Multi-objective optimization tools LINMAP for decision-making.	Optimize thermochromic glazing for daylight and energy performance.
[48]	Simulation and Comparative Analysis	WWR Building Material Shade's angle of movement	Solar Radiation for an Office Room	Rhino, Grasshopper, Honeybee	The study examines right-angled triangular façade design in Cairo's hot climate to enhance indoor thermal comfort, reduce solar radiation, offering architects guidelines.
➢ Proceed with the completion of the table.					
[47]	- Multi-objective optimization using a genetic algorithm. - Open-access software for analysis and simulation. - Case study approach to demonstrate efficacy.	- Geometry variables for architectural variability. - Envelope variables, including passive and active strategies.	- Annual energy demand. - Annual energy cost. - Number of energy simulations required.	Open-access software (not specified but used for multi-objective optimization and simulations).	- Reduce annual energy demand by 60% through geometry optimization. - Reduce annual energy cost by 23% through passive and active strategies. - Minimize simulation complexity and computational requirements.

Reference	Research Methods	Design Parameter	Performance Indicators	Software	Objectives
[46]	The study involved a focused literature review (50+ publications, 13 deeply reviewed), expert interviews, focus group discussions, and stakeholder mapping.	Environmental and energy efficiency, comfort, interaction between occupants, control systems, and maintenance and lifespan expenses are all crucial aspects to consider.	Long-term performance and durability are ensured by the product's consideration of energy, environmental impact, thermal and visual comfort, user experience, operational reliability, and cost-effectiveness.	The proposed use of AI and predictive models is not mentioned by name, but rather through simulation methods and monitoring systems.	The proposal aims to address current gaps in AF performance assessment, propose a comprehensive KPI framework, enable user-centric, data-informed evaluation, and facilitate standardization and market integration.
[51]	Literature review of current BIPV products and technologies, data collection on product performance, and evaluation of international standards and classifications.	Product type (foil, tile, module, and glazing) and PV material (mono/poly-silicon, thin-film, organic) are crucial factors in determining the integration type (roof, façade, and glazing) and ensuring transparency, color, size, and flexibility.	The study evaluates the electrical efficiency, durability, and weather tightness, aesthetics, and energy payback time of various cell/modules under climate exposure.	The study relied on manufacturer data, certification reports, and testing standards, such as IEC/EN/UL series, without using specific simulation software.	In addition to highlighting testing and data availability gaps, this work reviews BIPV devices, assesses performance, and makes recommendations for future research approaches. Provide concepts for novel materials and retrofitting techniques.

- **Summary and Gaps of the Literature:**

A considerable gap still exists in addressing the integration of responsive façade systems designed especially for educational buildings in hot, arid regions, even though multiple studies have shown how effective multi-objective optimization is at improving daylight, thermal comfort, and energy efficiency across various climates [38] [40] [41]. For instance, although [40] and [43] considered optimization of façade geometries and shading configurations, they largely focused on fixed systems and did not incorporate dynamic or adaptive responses to real-time solar conditions. Likewise, [42] [44], and [45] investigated material properties and basic geometry variables, but did not evaluate climate-adaptive shading geometries such as polygonal or folding modules that respond to varying daylight angles. Future initiatives include establishing a European standard and emphasizing data collection and user-centric evaluation [46]. Furthermore, the majority of studies focused on daylighting and energy conservation, but [56] they provided little study of visual comfort using thorough glare control criteria like DGP or higher UDI levels in high-irradiance zones, two important factors in Egypt's hot desert climate. While [31] analysed sun-responsive skins, its scope was limited to office spaces and cultural motifs, lacking relevance to classroom design and student comfort. The study reviews the advantages and disadvantages of each technology, identifies shifts in design approaches, and recommends combining different technologies for more effective and adaptable facade systems, supported by case studies of 29 responsive facades.

In [48]**, an** attempt was made at a locally contextual study in Cairo, but its scope did not extend to comparative performance across multiple Egyptian climatic regions nor did it use adaptive polygonal shading systems or multi-region analysis using standardized daylight metrics like DA, UDI, and DGP. Nevertheless, many papers highlighted the importance of replacing traditional building components as glazing and construction materials. This paper [51], highlights the Building Integrated Photovoltaic (BIPV) systems, classifying products into foils, tiles, modules, and solar glazing. It examines their standards, applications, material usage, and efficiency, highlighting the potential for sustainable energy as they replace traditional building components. The study indicates a strong retrofit market and the need for new testing procedures and international standards. It emphasizes the evaluation of smart technologies in building systems, including adaptive and responsive façade systems, supported by a comparative analysis in Table 4. The research also explores multi-objective optimization of daylighting and visual comfort across various Egyptian climates, addressing significant gaps in energy consumption strategies, particularly for university buildings, while aiming to enhance occupant comfort and minimize environmental impact.

Table (4): Comparative analysis based on relevant investigations of several smart façade design systems

Criteria	BIPV (Building-Integrated Photovoltaic)	Electro-chromic Glazing	Responsive Façade Systems (RFS)
Main Function	Energy generation + Shading	Dynamic tinting for solar control	Adaptive control of light, shade, and view
Energy Efficiency	High (on-site electricity production)	Medium (reduces HVAC + lighting loads)	Medium-High (reduces HVAC + lighting)
Daylight Control	Moderate (fixed transmission unless integrated with shading)	High (dynamic control of visible light transmittance, 3-60%)	High (geometry, material, orientation adaptability)
Visual Comfort	Moderate (can cause glare or deep shading)	High (adaptive glare control)	High (customized solutions using UDI, DGP control)
Aesthetic Flexibility	Low-Medium	Low	High (variety of patterns, kinetic forms)
System Complexity	Medium (integration with building envelope)	High (electrical + glazing systems)	High (actuators, sensors, control systems)
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Initial Cost	High	High	Medium-High
Maintenance	Medium (periodic cleaning, inverter checks)	High (glass maintenance + electronics)	High (moving parts, sensors)
Best Suited Climate	Sunny (for energy yield)	Varies; effective in hot sunny regions	Hot-dry, variable light conditions.
Integration Potential in Egypt	High potential in new developments	Suitable for office/classroom buildings with glass façades	High adaptability for hot, dry regions (Egypt, Algeria, Saudi Arabia, etc.)
References	[51]	[46]	[29], [52], [53]

Previous studies on multi-objective optimization in buildings predominantly concentrated on static façades, mainly overlooking adaptive shading techniques and intricate visual comfort factors such as glare and excessive illumination. This is particularly significant in hot arid climates like Egypt, revealing a gap in optimizing responsive façades for daylighting and visual comfort in Egyptian educational buildings, especially through climate-based daylight metrics across various regions.

- Comparative Analysis (different smart systems of façade design) based on related studies: Building-Integrated Photovoltaic (BIPV), Electro-chromic Glazing, and Responsive Façade Systems (RFS) were compared with an emphasis on how well they perform in terms of energy efficiency, daylight management, visual comfort, and suitability for hot, dry conditions like Egypt's. This synopsis highlights the connections between these systems and provides pertinent citations from the literature to back up each argument [29], [52], [53],[46], [51].

4. Methods and Tools:

A mixed-methods approach combining field measurements, qualitative feedback, and simulation-based parametric optimization was used to analyze and improve daylight performance and visual comfort in educational classrooms in West Cairo's hot, arid climate.

4.1- Field Study and Qualitative Assessment:

A field study was conducted at the project site to validate the values generated by EPW files and climate data from monitoring stations using a weather checker device. Qualitative casual interviews with faculty members, teaching assistants, and students revealed issues such as overheating, frequent glare and reflection issues, and the tendency to block natural light with curtains, increasing dependency on artificial lighting, and diminishing concentration and comfort. This reduces concentration, as natural lighting enhances students' performance and concentration due to the connection between the indoor and outdoor environments, as shown in Figure 4.

Figure (4): weather checker, issues such as overheating, glare, and reflection of daylight on screens, boards, and seats, and the tendency to block natural light with curtains, increasing dependency on artificial lighting. Source: Author, 2025

This qualitative and quantitative feedback was crucial in calibrating the simulation inputs and contextualizing the model outputs, thereby reducing model-based uncertainty, this study aims to achieve with the specified methodology.

4.2- Simulation Tools:

The simulation workflow was developed using Rhino 8, Grasshopper 1.007, Ladybug 1.7.0, Honeybee 1.8.0, and Wallacei-X. As shown in Figure 8, the workflow consisted of three major stages:

1. Parametric Modelling of Responsive Façade Options: Responsive shading geometries of 3-, 4-, and 5-segment modules were created through an explicit Grasshopper script. The existing classroom was then modelled, where Honeybee zones, program schedules, HVAC systems, and construction materials were specified in accordance with ASHRAE 90.1-2019.

2. Daylight and Glare Performance Simulation: This approach enabled the performance evaluation of shading depth, rotation angle, geometry shape, and perforation ratio under the climatic conditions of West Cairo.
3. Multi-Objective Optimization: Wallacei-X was used to run evolutionary multi-objective optimization.The Pareto front was analyzed to identify the optimal façade solutions that balance all performance criteria. Three fitness functions were defined: maximizing daylight autonomy, minimizing glare (DGP), and maximizing UDI.

4.3- Methodological Phases: The optimized workflow consists of three main phases (Tables 6,7,8): Methodology for Multi-objective Optimization of Energy Efficiency and Visual Comfort in Educational Buildings through Responsive Façade Design in West Cairo, Egypt.

- **Phase 1: Parametric Modelling & Objective Definition:**

Includes parametric model development, simulation integration, objective formulation, and optimization through Wallacei-X as shown in table (5).

Table (5): Parametric Modelling and Objective Formulation

Step	Title	Description
1	**Parametric Design Modelling**	A parametric model of the existing educational building façade is developed using Rhino/Grasshopper. The model incorporates responsive shading parameters, including module geometry (triangular, rectangular, and hexagonal), shading depth, rotation angle, and perforation ratio.
2	**Performance Simulation & Objective Definition**	Ladybug and Honeybee are integrated to simulate daylight performance. Metrics include Useful Daylight Illuminance (UDI 300–2000 lux), Daylight Glare Probability (DGP < 0.35), and daylight autonomy. Performance objectives (fitness functions) are defined as: (1) maximizing daylight autonomy, (2) minimizing glare, and (3) maximizing UDI.
3	**Multi-Objective Optimization**	Wallacei-X is used to run evolutionary optimization. Multiple façade design iterations are generated and evaluated. Pareto-front analysis is applied to identify the most balanced and optimal shading configurations.

- **Phase 2: Case Study Validation:**

Applies the workflow to a real educational building in West Cairo (MSA University).
The existing classroom façade is modelled, simulated, and used as a baseline for comparison. Base Case Simulation, as shown in table (6).

Table (6): Case Study Validation

Step	Title	Description
Base Case Simulation	**Validation of Existing Classroom Performance**	The methodology involves modeling an educational building façade and classroom in West Cairo (MSA University), simulating baseline daylight and glare performance to validate model behavior and establish benchmarks for comparison.

- **Phase 3: Implementation of Optimized Responsive Façade:**

Optimal solutions are applied to the case study façade, and comparative analysis is conducted to assess improvements in daylight distribution and glare mitigation, as shown in table (7).

Table (7): Implementation of Optimized Responsive Facade Configurations

Step	Title	Description
Optimized Façade Application	**Performance Comparison and Robustness Testing**	The shading solutions from Phase 1 are implemented on the classroom façade, with a comparative analysis of the base case against the optimized design to evaluate improvements in daylight distribution and glare control. The optimized designs undergo testing in extreme summer conditions to assess their robustness and applicability, with a focus on their impact on occupant visual comfort and Indoor Environmental Quality.

4.4- Objective of the Methodology:

The overarching objective is to optimize shading configurations and daylighting strategies to enhance visual comfort in educational lecture rooms, with consideration of sun position, façade geometry, shading materials, and Window-to-Wall Ratio (WWR). This integrated, performance-based methodology demonstrates an automated workflow capable of developing climate-responsive façade systems suited for hot-arid regions such as West Cairo, ultimately enhancing visual comfort. The approach leverages parametric modelling and multi-objective optimization techniques to explore and identify optimal shading geometries under the hot and dry climatic conditions of West Cairo, Egypt. This methodology demonstrates a holistic and automated workflow that integrates parametric modelling, climate-based simulation, and evolutionary optimization. It enables the development of climate-responsive educational buildings that simultaneously enhance visual comfort and reduce energy consumption, as shown in Figure 5. This study uses a performance-based simulation and optimization approach to improve visual comfort and daylighting in educational classrooms through responsive façade shading design.

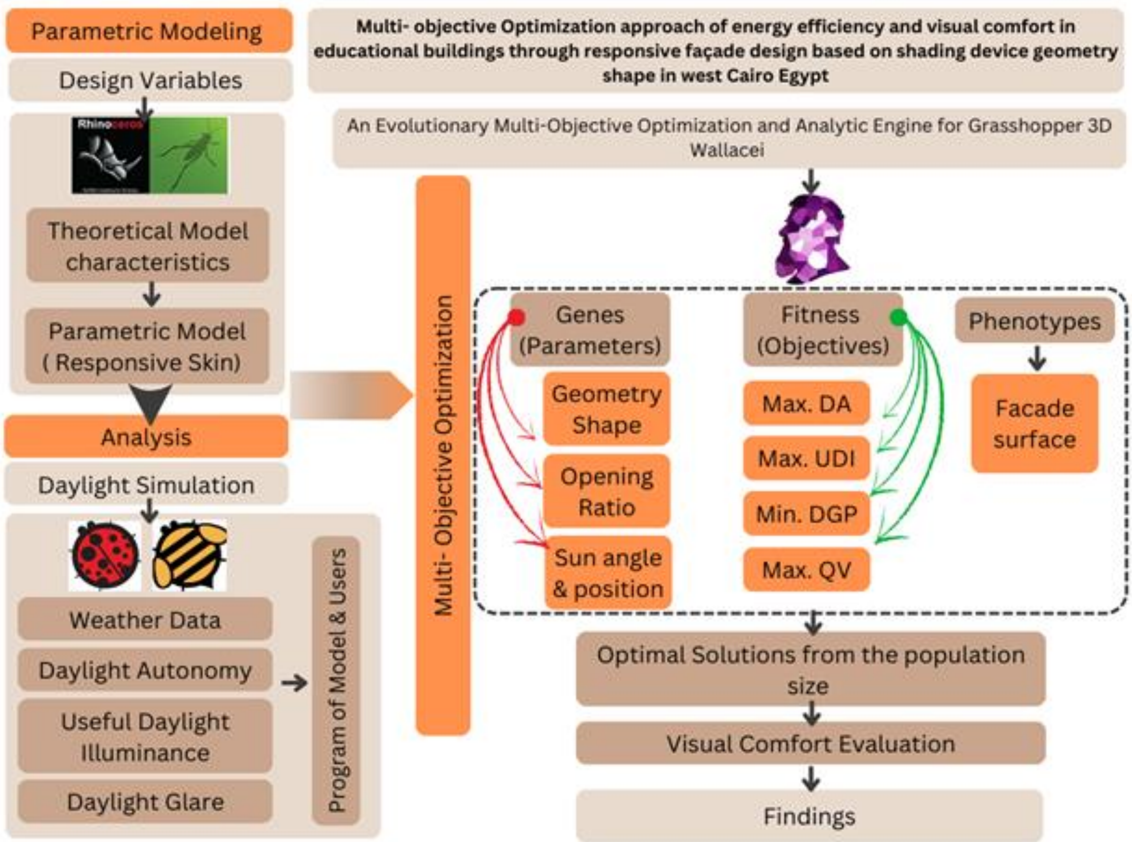


Figure (5): Research methodology and the simulation, Source: by author 2025

- Case Study Selection :

The case study was conducted in two phases: the first phase involved the investigation of several rooms in the southern section of building G, the second phase entailed a simulated analysis of one room, serving as a reference for the lecture halls and classrooms in the same orientation inside the building (Coordinates: 29°57'19"N 30°57'20"E; altitude 205 m), which in 6 October city at the southwest of Cairo. Based on the Koppen climate, Egypt is classified as a hot and dry climate [54]. As shown in Figure 6.

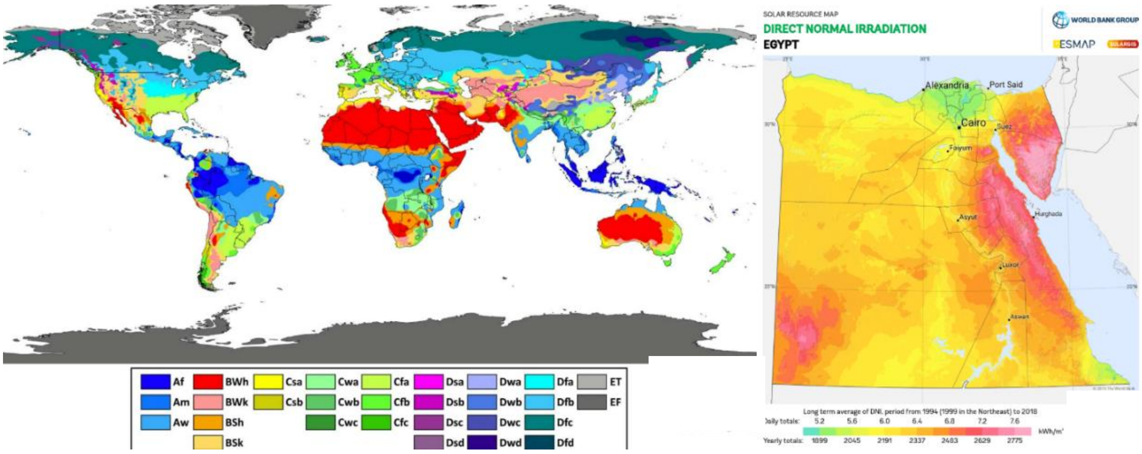


Figure (6): climate classification, Egypt. Source: Köppen's climate classification

As shown in Figure 7, MSA University is located in 6th of October City, Giza. The university is strategically positioned to provide a calm yet accessible environment, with easy connectivity to Cairo. It's proximity to major highways and residential districts.

The weather patterns in 6th of October city in Table 8, Cairo experiences extreme hot and dry desert weather with uniform daylight distribution and excessive heat gain due to direct solar radiation. The clear sky conditions can help utilize daylighting, but may cause visual discomfort or excessive heat gain, clear skies year-round [55], as shown in tables 8 & 9.

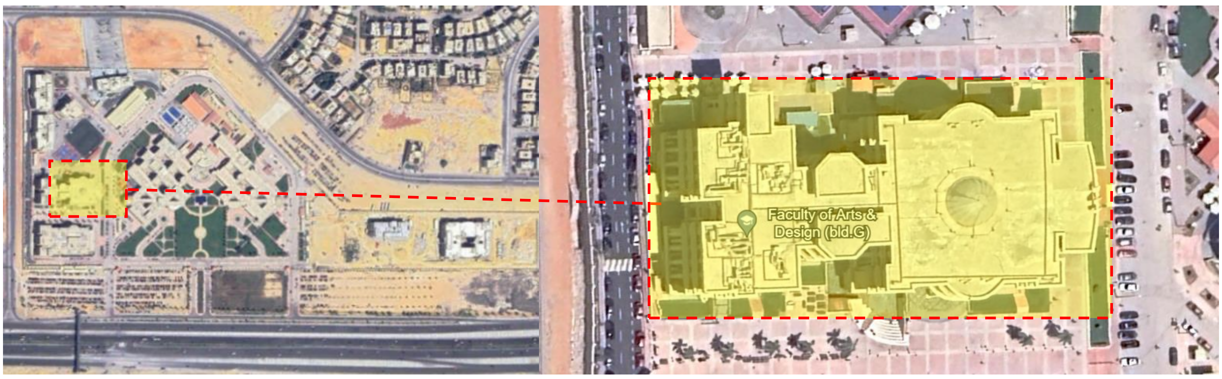
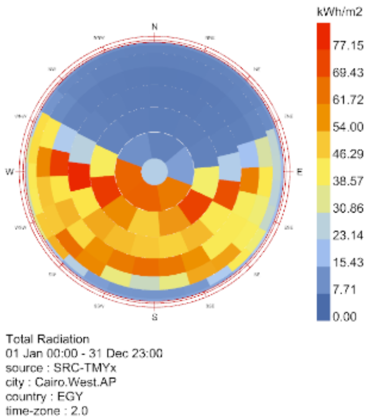
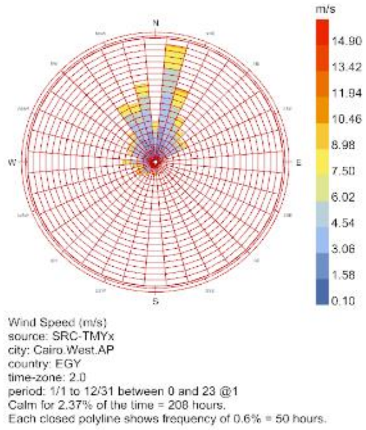
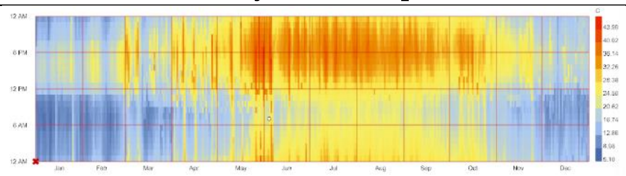
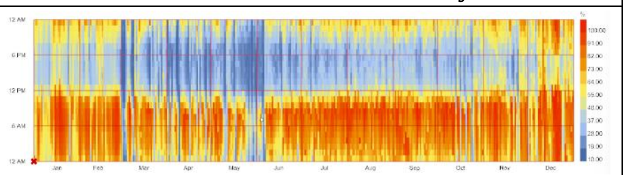
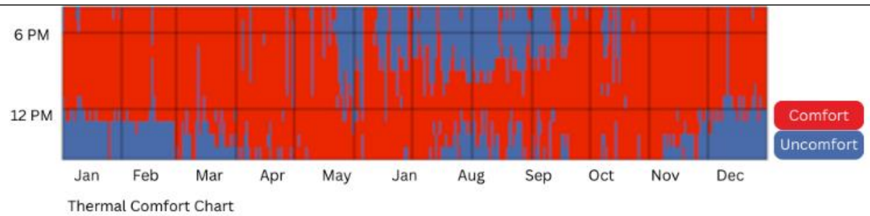
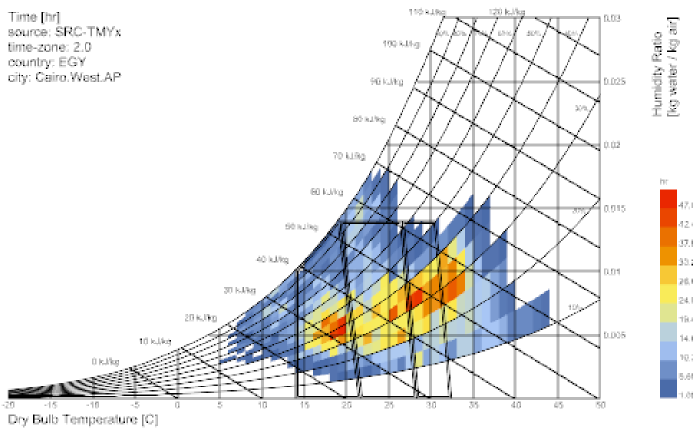


Figure (7): Maps of the location of the case study- MSA University in 6 October city, and the specific building (G). Source: Google Earth

Table (8): weather patterns in 6th of October city. By the author in 2025, referring to EPW

West Cairo (Giza)	Climate	Temperature (Summer)	Temperature (Winter)	Humidity	Key Psychometric Considerations
	Hot desert	40°C - 43°C	10-22°C	Relatively low (except near the Nile)	High dry bulb temperature with low humidity, requiring cooling in summer

Table (9): Using Ladybug in Grasshopper shows Annual solar radiation, Wind speed, relative humidity, and Total thermal comfort rates and detailed percent for each zone in the climates of West Cairo, by the author 2025.

<table>
<tr><th colspan="2">West Cairo (Giza)</th></tr>
<tr><th>Annual Solar Radiation</th><th>Annual Wind Speed</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><th>Annual Dry Bulb Temperature</th><th>Annual Relative Humidity</th></tr>
<tr><td>
Min. 8-12 °C Mean 28°C Max. 44°C</td><td>
Average 60% Maximum 91%</td></tr>
<tr><th colspan="2">Thermal comfort</th></tr>
<tr><td colspan="2">
</td></tr>
<tr><td colspan="2">➢ Proceed with the completion of the table.</td></tr>
<tr><th colspan="2">Psychometric chart</th></tr>
<tr><td colspan="2">
</td></tr>
</table>

As illustrated in Figures 8 &9, Part of the plan of the ground floor of the specific building and Direct Sun hours are shown by using different software.

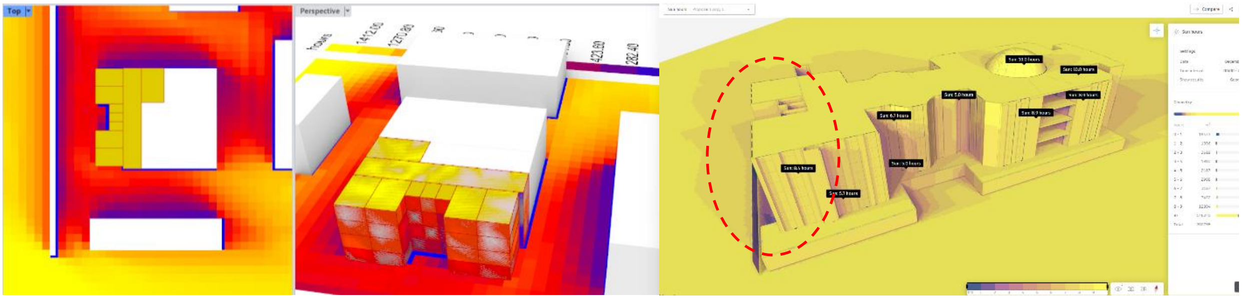


Figure (8): Direct Sun hours by using Ladybug in Grasshopper and other studies by using Insight 360 to test the sun hours on building surfaces. Source: Author 2025 using Grasshopper, Ladybug, and Revit with Autodesk Forma.

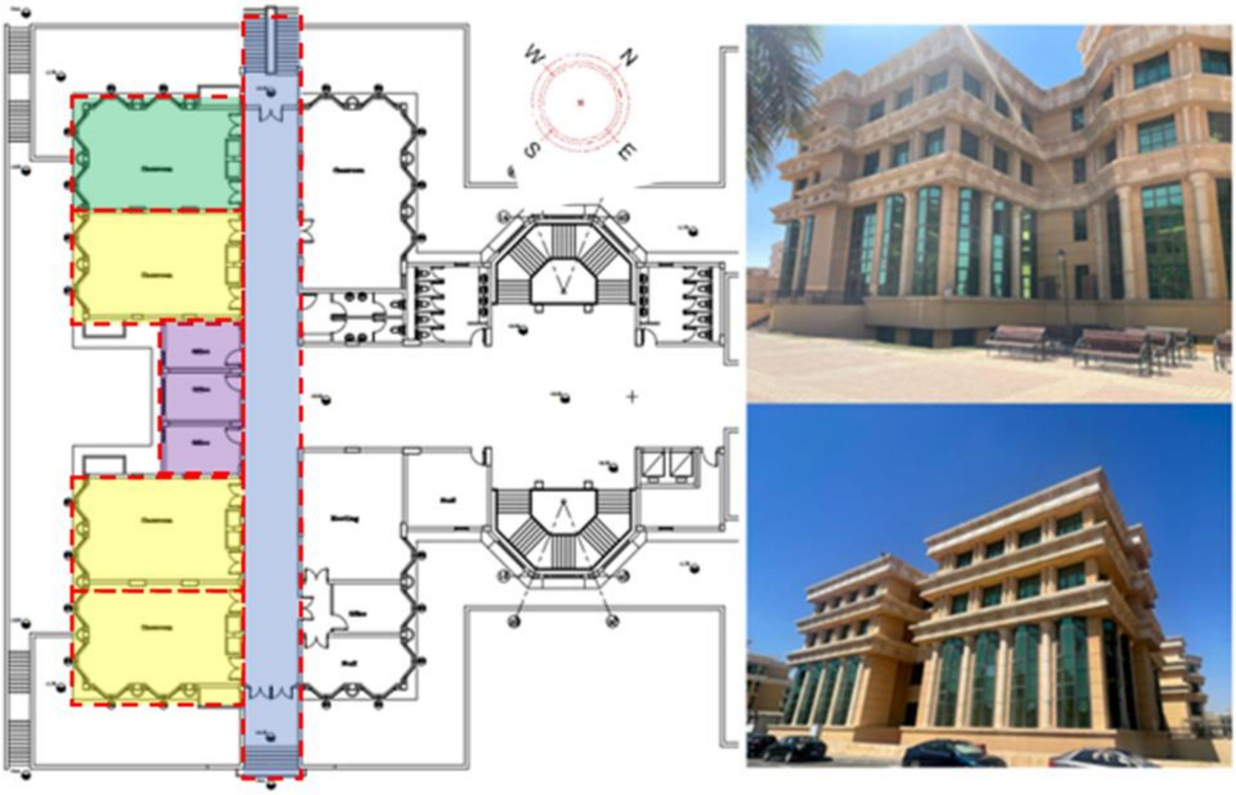


Figure (9): Part of the building of the ground floor (specific building for the study will be building G). Source: Author, 2025

Classrooms   Staff Office   Computer Lab

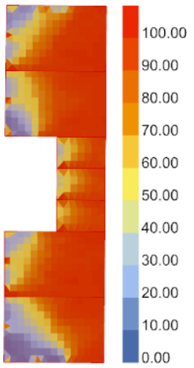
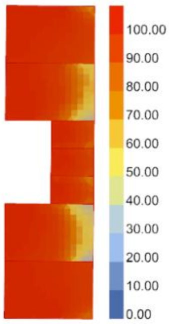
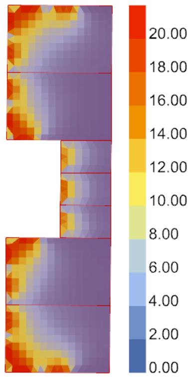
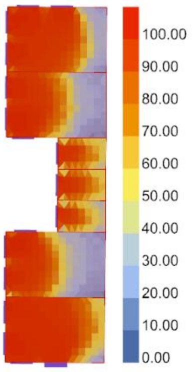
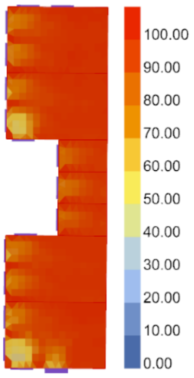
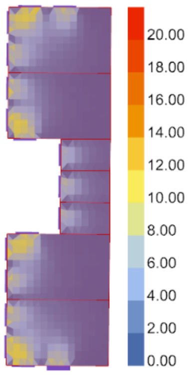
5. Discussion and Results

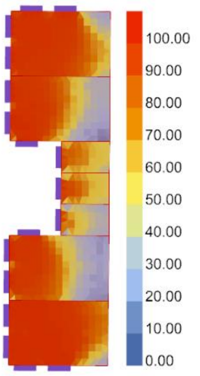
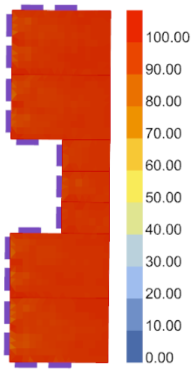
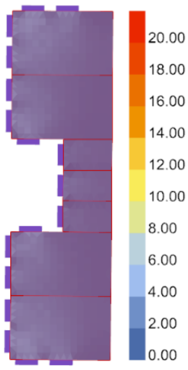
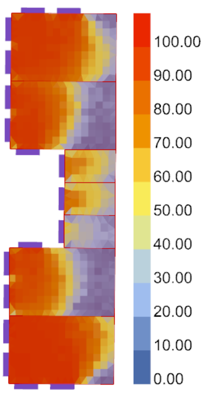
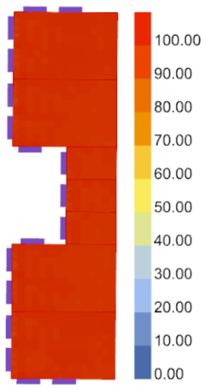
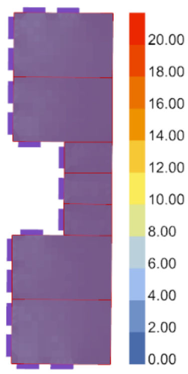
This section presents the performance evaluation results of a case study on daylighting and visual comfort in a university classroom in arid Egypt. The findings illustrate the effectiveness of the proposed method, which enhances visual comfort metrics such as UDI, DA, and DGP using a responsive façade system compared to the base case.

5.1- Analysis of part of the case study selected:

To demonstrate the evaluation of various shading device configurations specifically vertical and horizontal types, at differing angles to determine their individual advantages and limitations, as well as their efficacy in improving daylighting conditions and visual comfort in this part of the building which in include 3 classrooms, one computer lab and 3 staff offices, as shown in previous Figure 9 and analysed in table 10.

Table (10): Analysis of part of the building when using different shading devices at different angles to evaluate the advantages and disadvantages of each type and the effectiveness of each on the educational classrooms

Shading System	Daylight Factor (DF)	Useful Daylight Illuminance (UDI)	Daylight Autonomy (DA)	Problems
Without shade	 Very high near windows; over-lit zones.	 Lower UDI near openings due to glare; high UDI at the back.	 Maximum DA, especially in the front zones.	Very high near windows; causes over-lit zones and potential glare. Lower near openings due to excessive glare; high UDI only at the back. Maximum DA, especially at the front zones, but may not represent visual comfort.
vertical shade angle 0, distance 0.5, depth 0.6	 Reduced DF at the front; improved balance.	 Better distribution, still slightly uneven	 Improved at back, still high front DA	Reduced DF in front zones; better distribution, but still high contrast. More uniform UDI, but some underlit zones at the back. Reduced DA in rear zones; front still performs well.

Shading System	**Daylight Factor (DF)**	**Useful Daylight Illuminance (UDI)**	**Daylight Autonomy (DA)**	**Problems**
Horizontal shade angle 0, distance 0.5, depth 0.6	 Controlled DF near windows	 More uniform across the room	 Better than no shade	DF is significantly reduced, especially in the upper parts of the room. Better UDI balance; reduced glare, but shadows dominate deeper zones. Noticeable drop in DA in central and rear areas—risk of insufficient daylight.
➢ Proceed with the completion of the table.				
Horizontal shade angle 15, distance 0.5, depth 0.6	 Lowest DF of all options; significant reduction.	 Well-balanced UDI	 DA drops compared to others, but with enhanced visual Comfort.	DF further reduced; over-shading effect evident. UDI is improved, but more area falls below the minimum illuminance. DA suffers, especially deeper in the space, and a strong reliance on artificial lighting is expected.

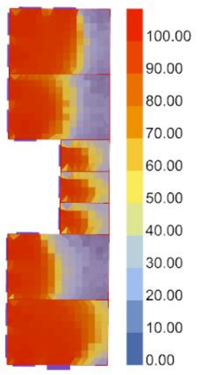
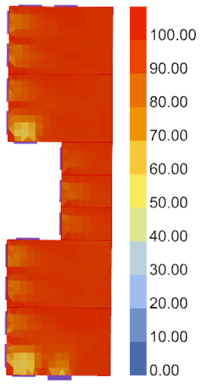
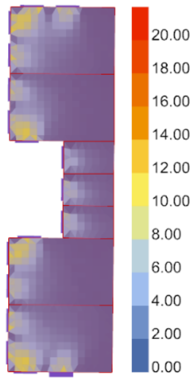
Shading System	Daylight Factor (DF)	Useful Daylight Illuminance (UDI)	Daylight Autonomy (DA)	Problems
Vertical shade angle 15, distance 0.5, depth 0.6	 DF is higher than horizontal 15°, but lower than 0° vertical.	 UDI is good and fairly balanced.	 DA improved compared to horizontal 15°, but still lower than no shade.	DF moderately low; more balanced than angled horizontal shade. Some improvement in UDI, but shading reduces exposure too much at the back. Moderate DA; not optimal for rear zones without support from side or top lighting.

Table (11): Characteristics of the University Classroom model: Modeled base case configuration:

Location	West Cairo- Giza, Egypt
Type of Building	Classroom/ Educational Building
Space Dimensions (L*W*H)	10*7.25*3.5
WWR	74%
Number of Windows	1
Window dimension	5.8*3.2 South
Windows Orientation	South west
Façade treatment Orientation	South west
Single glass: Transmittance of glass	0.68
Number of Occupancy	40 persons
Occupancy Schedules	8:00 AM – 5:00 PM
Sun Exposure Angle	Giza: sun's altitude in midday (12:00- 1:00 PM) Range: 37-41

Key findings from the previous analysis in Table 10 show that while no shading maximizes light, it also increases the risk of glare and over-illumination. Although it reduces overall sunshine levels, angled horizontal shade at 15°provides the best visual comfort and even dispersion of daylight. Vertical angled blinds 15° strike a balance between improving UDI and reducing daylight. The best shades for comfort and glare reduction are angled horizontal ones. There's a trade-off between daylight availability and glare reduction. All problems cannot be entirely resolved by a single solution. Angled blinds are effective at reducing glare and improving comfort, but deeper areas may require additional lighting. Based on the previous analysis from Table 9, the next phase will test one module of the classroom. The result of putting a responsive shading device with different geometries to test it will provide a balanced, adaptive, and efficient daylighting strategy, outperforming any fixed shading configuration or not, as show in Table 11 & Figure 10.

5.2- Shape of geometric shape: Justification for Selected Shading Geometries:

According to the study [56], 30% of building facades feature hexagonal designs, making them the most popular pattern kind. Other designs that draw inspiration from Islamic geometric patterns are the triangular, star, and Rosetta patterns. While Voronoi exhibits sophisticated computational or biologically inspired structures, Simple Geometry, Folded, and Voronoi reflect minimalist or parametric methods.
Conventional geometries prioritize culture and aesthetics, but contemporary geometries enable digital manufacture and flexible usefulness. Studies focusing on hot, arid climates do not adequately represent educational buildings, the illustration of this studies explained in Table 12. According to a parametric analysis of [31], dynamic facades performed better than static ones, increasing DA and reducing visual discomfort by 10%.

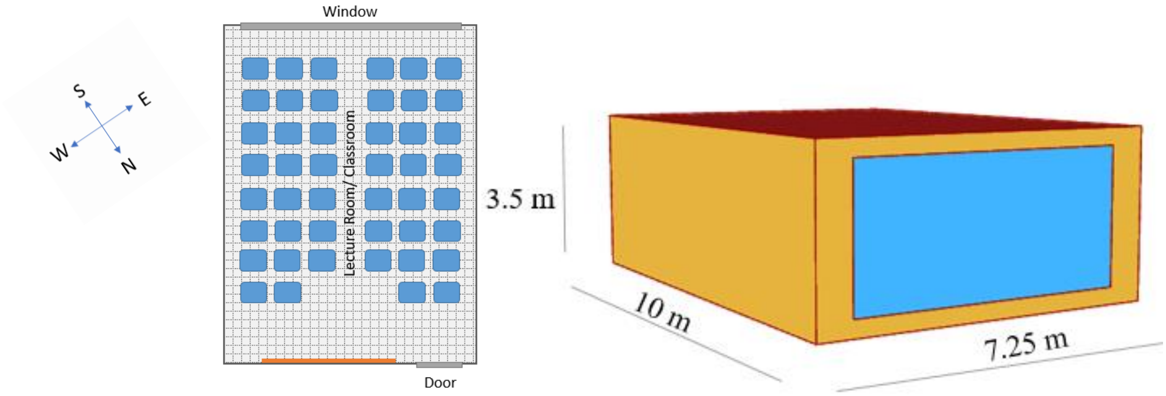


Figure (10): Classroom model and north arrow direction, Source: Grasshopper Model created by the Author

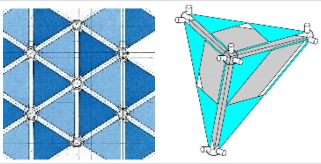
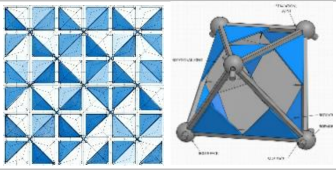
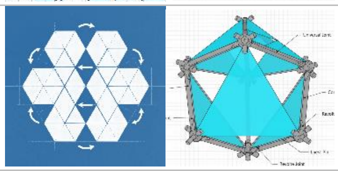
The suggested approach was determined to be a practical way to determine the annual daylighting performance and provide visual comfort. The movements and geometrical characteristics of horizontal louvers and Rosette modules were taken from field data and used in simulations.

Table (12): Summary of the importance of Geometric shapes. source: [56]

Pattern	% of Use	Remarks
Hexagonal	30%	Most frequently applied: efficient tiling with uniform light diffusion.
Star	18%	Aesthetically pleasing; rooted in Islamic architectural motifs.
Rosetta	14%	Culturally rich; derived from traditional Islamic geometries.
Simple Geometry	12%	Includes squares, circles; easy to manufacture and apply.
Folded	12%	Enables depth and modulated daylight; often used in origami-inspired designs.
Triangular	10%	Structurally stable; creates a strong visual rhythm.
Voronoi	4%	Biomimetic, irregular; underutilized but highly adaptive.

Due to their distinct advantages in daylight control and shading performance, such as increased daylight diffusion, simplicity of fabrication, and adaptability to triangle, quadrilateral, and pentagon shapes were chosen for responsive façade systems, as explained in Table 13.

Table (13): Explanation for Selecting Geometric Shapes in Responsive Façade Design, source: author referring to [31], [56]**.**

Geometry	Shapes	Reason for Selection for Testing
Triangle (3-sided)		A minimal surface effectively creates sharp patterns of shadow with a sharp angular variation. It works well for managing daylight at severe angles.
➢ Proceed with the completion of the table.		
Quadrilateral (4-sided)		Prevalent in louvers and modular panels; simpler to manufacture and incorporate into architectural grids (façade modules).
Pentagon (5-sided)		Enhances glare management and daylight diffusion by offering more angular complexity and erratic shadow patterns.

5.3- Importance of using responsive facades in educational buildings (classrooms):

Classrooms can benefit from dynamic shading systems because they can adapt to changes in lighting caused by sun angle, cloud cover, occupancy schedules, and real-time glare sensors. Automation, energy efficiency, thermal control, adaptive daylighting, and user-focused design are all features of these systems [57]. The electro-chromic glazing in Future Classroom Lab, the dynamic skin of Al Bahr Towers, and the kinetic louvers at MIT Media Lab are a few examples. Because visual comfort cannot be measured by daylight factor, usable daylight illuminance, annual sunshine exposure, or spatial daylight autonomy, it is essential when planning structures [46]. Dynamic shading systems can also boost sunshine factor by 4.3%, ASE by 45%, and daylight efficiency by 58% in university classrooms. The daylight factor is increased by 4.3%, ASE by 45%, and UDI efficiency by 58%, according to the study in Beni Suef, Egypt [58]. Additionally, these technologies can move activities from whiteboards to data displays and computers. As illustrated in Table 14, the features of the façade arrangement based on the selection criteria of geometry shape

Table (14): Characteristics of façade configuration (Responsive Façade):

Shape of modules	**Polygon ٥ segments**	**Polygon 4 segments**	**Polygon 3 segments**
Number of modules	5*16 = 80	5*16 = 80	5*16 = 80
Dimensions of modules	0.40	0.37 *0.37	0.40
Angles of Geometry	0 -100		
Materials for shading and windows	Frame: light metal/shades: transparent Glass modifier transmittance 0.68 simple class		
Distance between each Unit from center to center (0.55 cm) for the X axis Distance between each Unit from center to center (0.6 cm) for the Z axis			

5.4- Simulation process:

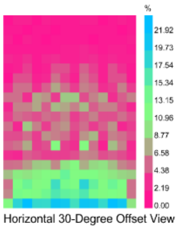
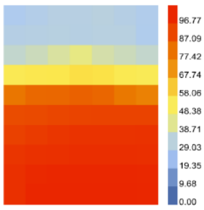
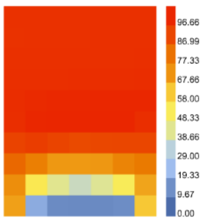
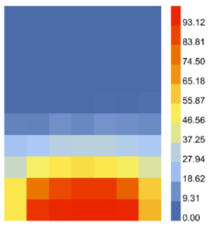
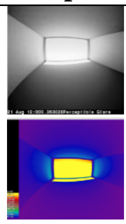
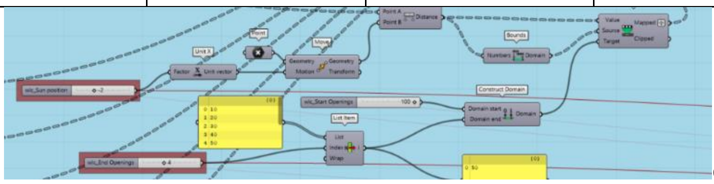
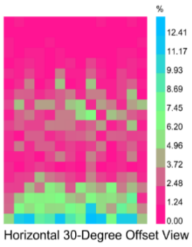
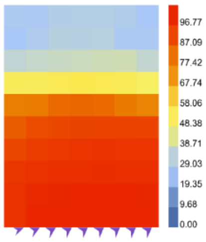
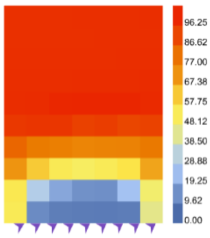
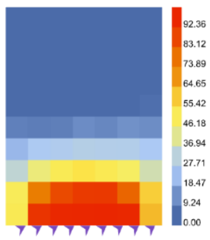
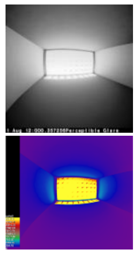
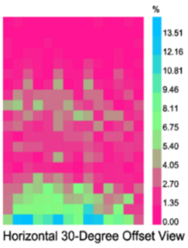
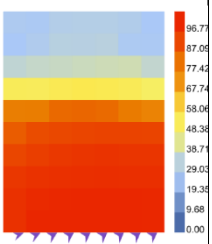
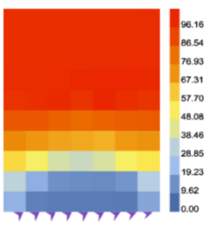
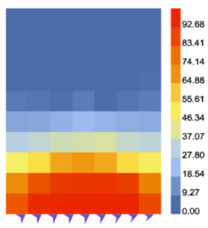
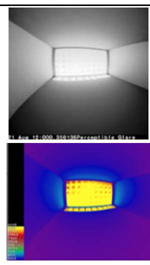
The simulation process begins with climate analysis using Ladybug to extract data from EPW files, focusing on Egypt's hot and dry climate. By optimizing responsive façade shading geometries, the simulation technique sought to improve visual comfort in West Cairo's educational buildings. Several polygonal shading devices (3, 4, and 5-sided) were modeled and tested using Rhinoceros, Grasshopper, Ladybug, and Honeybee. Daylight Autonomy (DA), Useful Daylight Illuminance

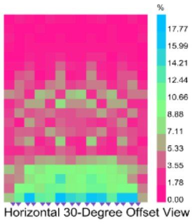
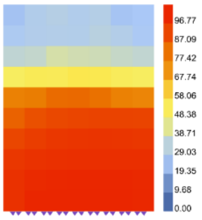
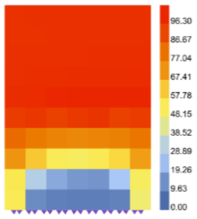
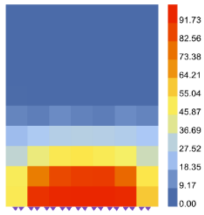
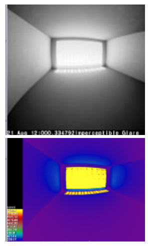
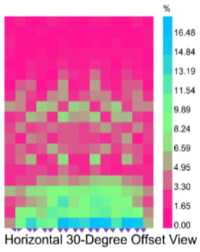
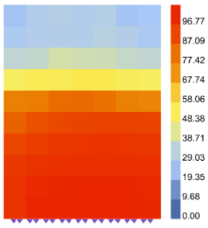
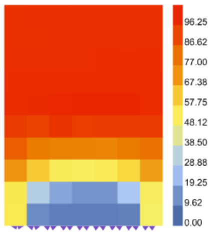
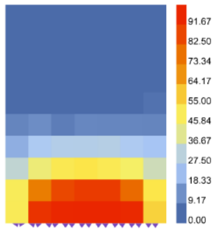
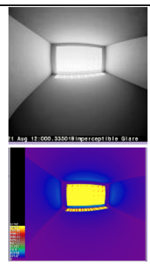
(UDI), Daylight Glare Probability (DGP), and View Quality Index (VQI) were among the key performance indicators. Real climate data with a constant 50% and 80% shading ratio was used to run the simulations. Study shows that the most successful geometry was a 5-polygon, which balanced visual quality, glare reduction, and daylight access, as explained in the findings.

The subsequent phase involves a comparative investigation of the 3, 4, and 5 polygon responsive shading geometries to determine which provides the ideal balance of daylight accessibility, glare mitigation, and visual comfort, as analyzed in Table 15. With evaluated Metrics:

- Quality View (QV) – Visual connection to the outside/ Daylight Autonomy (DA, 500 lux) – % of time daylight meets or exceeds 500 lux. / Useful Daylight Illuminance (UDI) Threshold Focuses on daylight within a useful range (500–2000 lux). / UDI up to 2000 lux – Avoids overexposure. / Daylight Glare Probability (DGP) – At 12 PM on August 21, values below 0.35 indicate acceptable glare.

Table (15): This study compares a base case with various shading device geometries to evaluate their impact on visual comfort, focusing on glare and luminance. It aims to identify the most effective design that optimizes both visual comfort and high environmental performance.

Different Scenarios of Shading Geometry	Quality View (VQ)	Daylight Autonomy (500)	Useful Daylight Illuminance, threshold (500)	Useful Daylight Illuminance, up to 2000	Daylight Glare Probability 21 August at 12 pm
Base case with No Shading					 0.363
 control point (sun position/ start and end domain)					
3 polygon Geometry Sun position on point -2 Opening 80% Start domain 100					 0.357
3 polygon Geometry Sun position on point -2 Opening 50% Start domain 100					 0.356

Different Scenarios of Shading Geometry	Quality View (VQ)	Daylight Autonomy (500)	Useful Daylight Illuminance, threshold (500)	Useful Daylight Illuminance, up to 2000	Daylight Glare Probability 21 August at 12 pm
4 polygon Geometry Sun position on point -2 Opening 80% Start domain 100					 0.347
4 polygon Geometry Sun position on point -2 Opening 50% Start domain 100					 0.341
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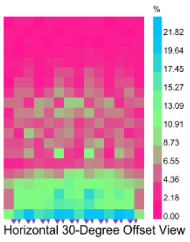
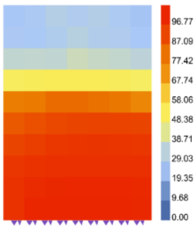
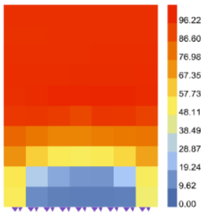
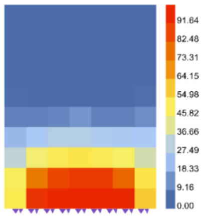
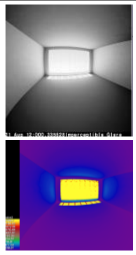
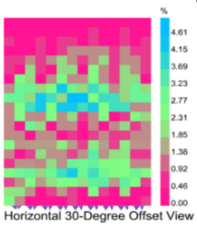
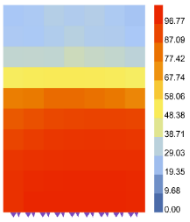
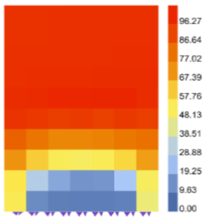
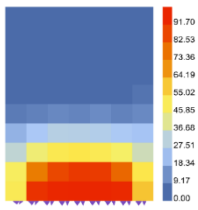
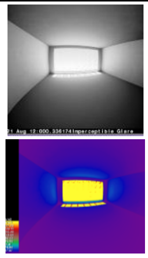
5 polygons Geometry Sun position on point -2 Opening 80% Start domain 100					 0.336
5 polygons Geometry Sun position on point -2 Opening 50% Start domain 100					 0.334

5.5- Explanation of Environmental Modeling Assumptions, Error Margins, and Validation Methods:
The study assesses the effectiveness of responsive façade geometries in improving visual comfort within educational spaces in West Cairo, Egypt, using a performance-driven simulation and optimization approach. It employs multi-objective optimization alongside structured modeling and empirical validation, supported by a field investigation that included air temperature and humidity measurements, as well as interviews with staff and students. Observed issues included overheating, glare, and reliance on artificial lighting. According to previous standards and research, mesh resolution, radiance parameters, and climate data quality can cause a ±10–15% difference in daylight metrics (UDI, DA). With possible inaccuracies of up to ±0.05 in DGP ratings, glare analysis (DGP) is sensitive to user viewpoint, reflectance settings, and simplified geometry. The results are reliable despite simulation uncertainties, as they are used comparatively rather than as absolute values. This hybrid approach

utilizes evolutionary optimization, climate-based simulations, and empirical field verification. The findings provide design recommendations for educational structures in hot, dry regions such as West Cairo, emphasizing the importance of sun exposure and visual comfort for sustainability and learning effectiveness. Based on the analysis of the previous Table 16, the most efficient Geometry is 5 Polygon Geometry with 50% Opening, which offers the most optimal trade-off among all tested scenarios: Balanced daylight levels (high UDI) - Acceptable glare (lowest DGP = 0.334) - Moderate yet sufficient view quality (QV). This geometry enhances visual comfort while reducing daylight loss, rendering it appropriate for educational settings in hot, sunny areas like Egypt. The following table 15 compares the simulation-based assessment of different polygonal responsive shading geometries (triangular, quadrilateral, and pentagonal polygons) to a base scenario that does not have shading.

Table (16): comparison of various polygonal responsive shading geometries with a baseline scenario

Geometry Type	Opening (%)	QV	DA	UDI (500)	UDI (2000)	DGP (↓ best)	Interpretation
Base Case (No Shading)	–	High QV	Highest DA	Low UDI (500)	High overexposure	0.363	Excessive daylight/glare; poor comfort despite high DA
3 Polygon	80%	Low QV	Moderate DA	Improved UDI	Balanced UDI 2000	0.357	Reduces glare but limited QV
3 Polygon	50%	Low QV	Lower DA	Higher UDI (500)	Less UDI 2000	0.356	Balanced, glare-controlled
4 Polygon	80%	Moderate QV	Moderate DA	Good UDI	Moderate overexposure	0.347	Better balance of light and view
4 Polygon	50%	Low QV	Moderate DA	Good UDI	Better UDI 2000	0.341	Improved visual comfort
5 Polygon	80%	Moderate QV	Moderate DA	Highest UDI	Balanced exposure	0.336	Most balanced design light/view/glare
5 Polygon	50%	Moderate QV	Lower DA	Highest UDI	Lower overexposure	0.334	Most optimal: glare-controlled, visually comfortable

6. Multi-objective optimization utilizing Wallacei to evaluate outcomes from various geometric configurations of shading devices:

As illustrated in Table 17, optimal solutions are indicated by peak clusters on four graphs that depict fitness objectives from FO1 to FO4. The visualizations display the top exporting solutions based on fitness values, with the best-performing ones indicated by black lines. They help users weigh trade-offs by displaying distribution, correlation, and influence. The best solutions typically have mid-to-low FO1 UDI up and FO2 DA values, and higher FO3 DGP/FO4 QV values. The phenotypic preview shows visual diversity and geometric results, indicating that the best solutions are both geometrically and spatially diverse.

Table (17): Summary of Wallacei Multi-Objective Optimization: Chosen Solutions and Fitness Assessment. Source: By Author

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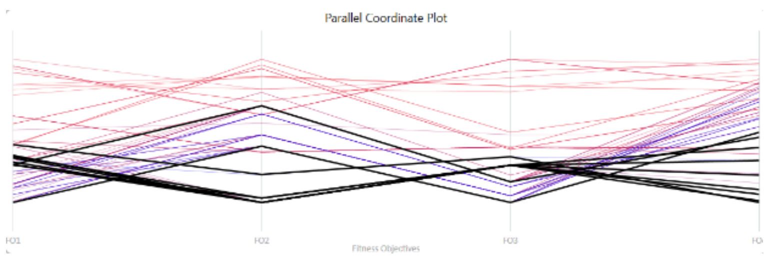

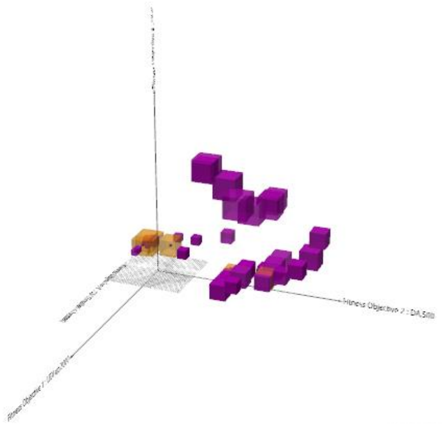
The clusters of purple cubes indicate higher values in that region, while the smaller and differently colored cubes represent lower or different data groups. The plot helps identify patterns, distribution, and relationships between the three dimensions.
All values and highlighted black values in graph showed the best values exported/ sample size 100
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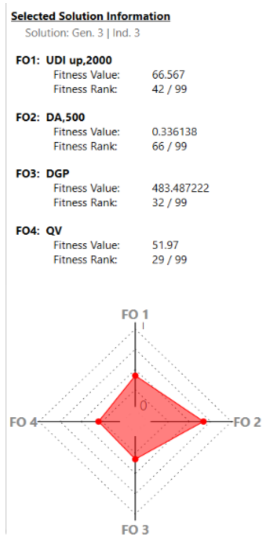

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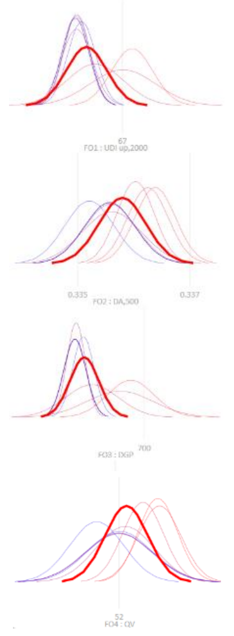
<td></td>
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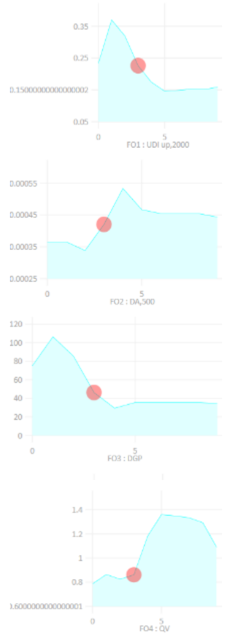
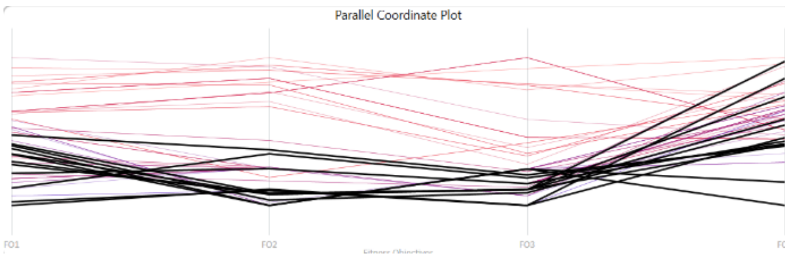
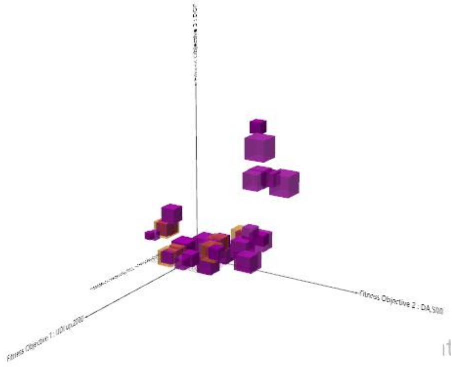
<td></td>
<td></td></tr>
<tr><td colspan="2">Multiple colored lines compare different test cases or design options across the same scale. Red lines indicate higher-performing cases, while purple and blue lines represent lower ones. The charts make it easy to see trends, variation, and which options perform better or worse for each objective.</td>
<td colspan="2">The filled blue area represents how the objective value changes across different solutions. The red dot highlights the selected or optimal solution on each graph. The plots make it easy to see how performance decreases or increases across the range and where the chosen point sits within the overall trend.</td></tr>
</table>

Multi-objective optimization using Wallacei-x to evaluate the efficiency of 4 polygon shapes





All values and highlighted black values in the graph showed the best values exported / sample size 100

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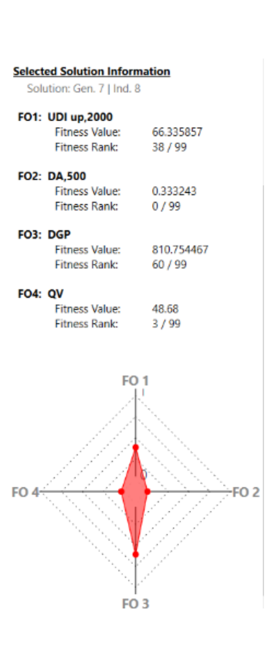
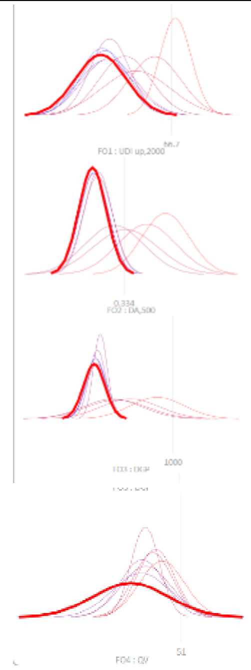
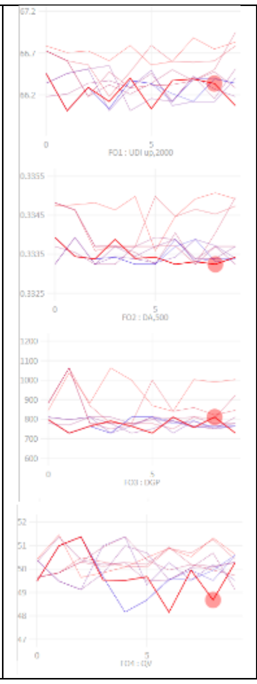
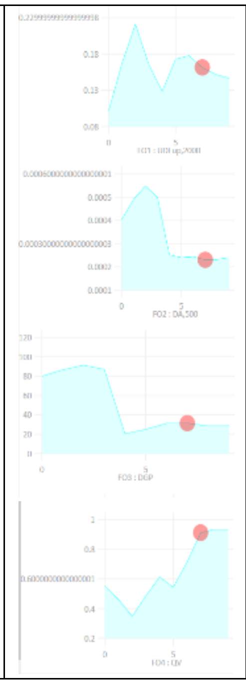
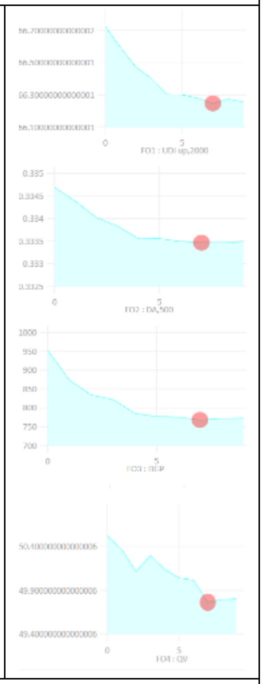


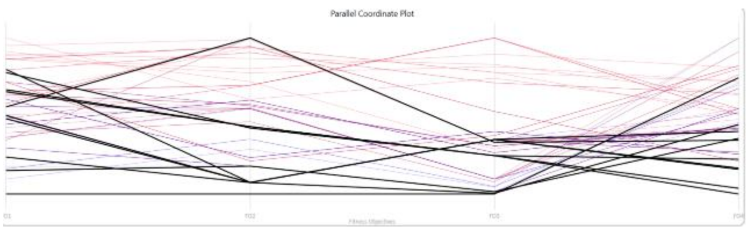


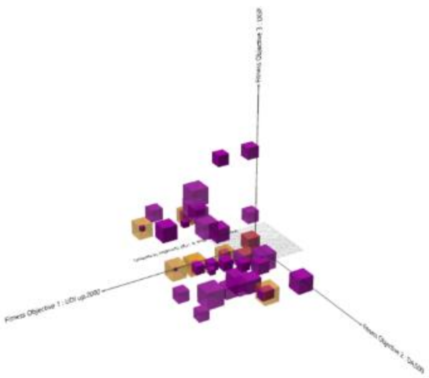






Multi-objective optimization using Wallacei to evaluate the efficiency of 5 polygonal shapes





All values and highlighted black values in graph showed the best values exported/ sample size 100

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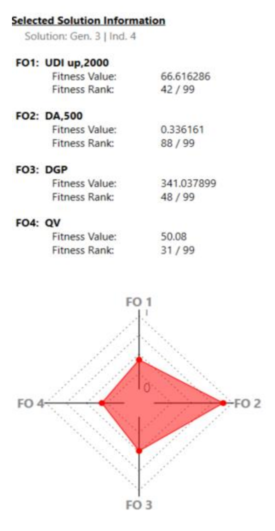

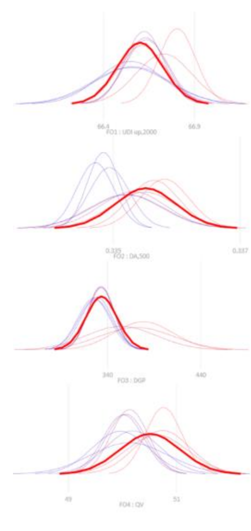
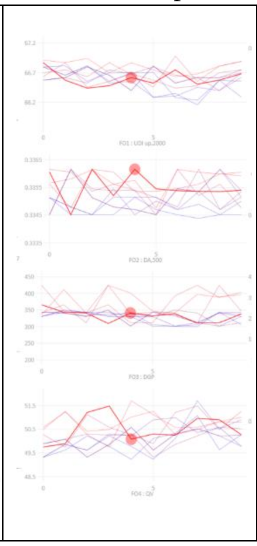
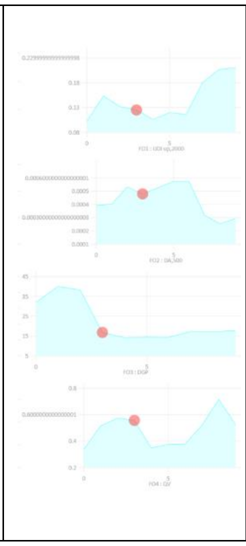
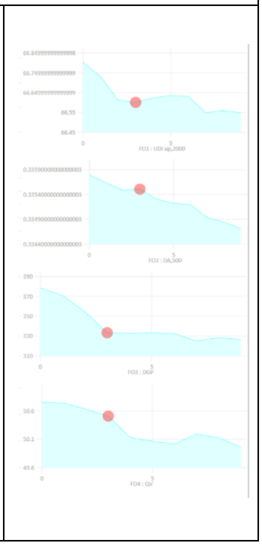

From the previous analysis in Table 17, Glare reduction, adequate daylighting, and visual connection to the outside are all balanced by the multi-objective optimization technique. The best solutions according to the phenotype's exports (9 in 3polygons /12 in 4polygons/10 in 5polygons=31 out of 100), illustrated in Table 18.

Table (18): Table of Performance Comparisons between different geometries

Metric	3 Polygon	4 Polygon	5 Polygon
Population Size	100		
Exported Best Solutions	31		
DA (Daylight Autonomy)%	63.5 – 66.0	64.5 – 66.8	66.5 – 66.98
UDI (Useful daylight Illuminance) %	290 – 380	300 – 410	410 – 424.33
DGP (lower is better)	0.357 – 0.355	0.347 – 0.345	0.334 – 0.336
Qv (Quality View)%	47.5 – 50.5	48.5 – 51.0	49.2 – 51.7

With the best trade-offs between the main goals, the 5-polygon geometry is the most well-balanced approach. More evenly distributed daylight in interior zones is shown by its smoother heat maps, which maximize UDI between 100 and 2000 lux and better manage excessive brightness than designs with three or four polygons. Best values and generations of 5 polygon shading: The system reliably ensures optimal daylight accessibility and comfort, minimizes glare, and exhibits a high Qv, signifying strong performance across various configurations and superior, balanced trade-offs. It is illustrated in the Parallel Coordinate Plot graphs 11 and 12 and Solutions with the repeated fitness value.

The top half of (DA) is dominated by blue lines, and it ranges from 66.16 to 66.98%. Higher glare denotes less comfort, whereas lower glare is preferable. Top-performing solutions are concentrated near the upper end of the useful daylight illumination (UDI) range, which is 299.79 to 424.33. Red lines remain lower, signifying greater obstruction, while blue lines peak close to 51.7. Quality of View (Qv) varies from 49.23 to 51.7 %.

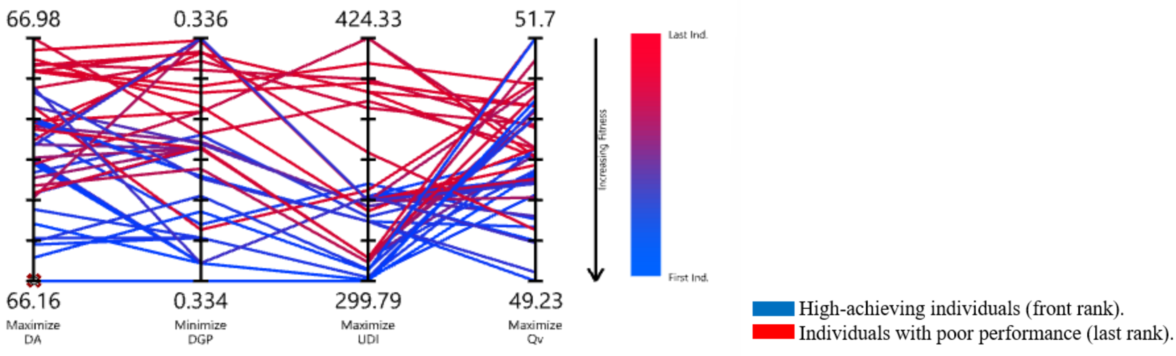

Figure (11): Parallel Coordinate Plot analysis, Source: Author using Wallacei-X

Using various trade-offs between daylight autonomy, glare probability, useful daylight illuminance, and view quality, Figure 12 displays clusters of solutions with similar fitness values for every objective.

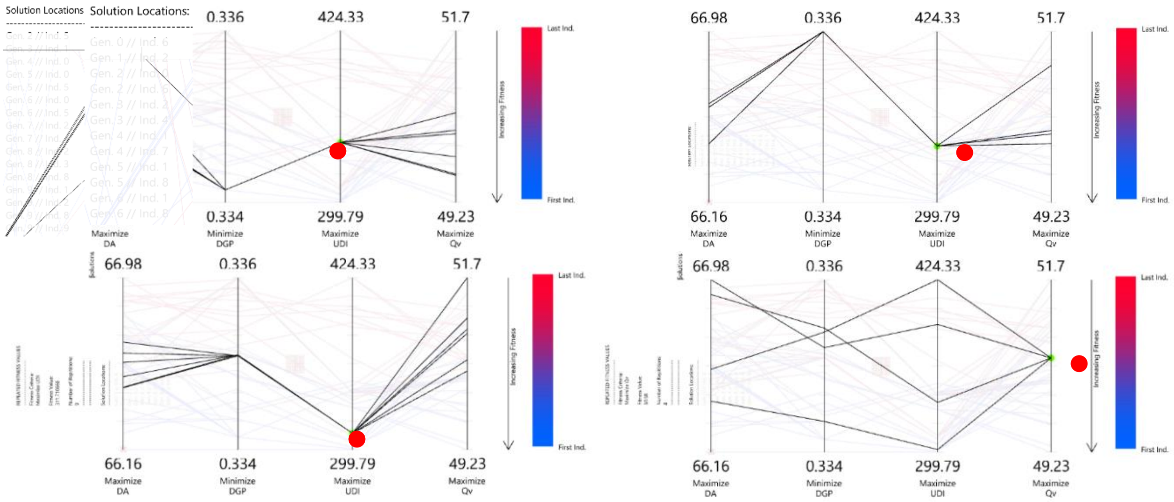

Figure (12): Solutions with the repeated fitness value, Source: Author using Wallacei-X

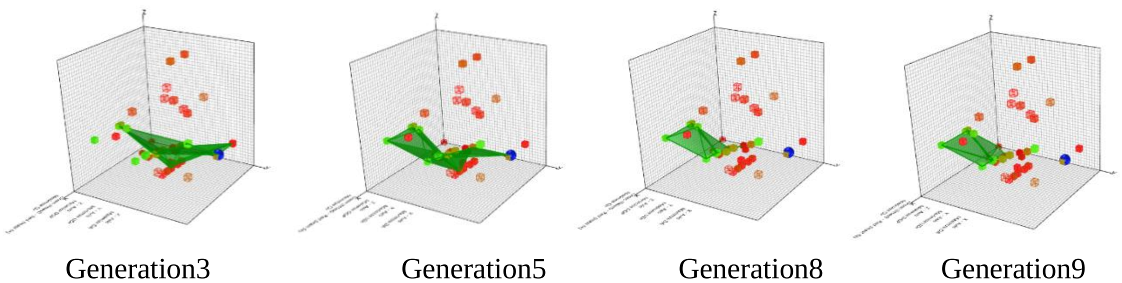

Figure (13): objective space & Pareto front for best values in selected generation. Source: Author, 2025, using Wallacei

The Wallacei Objective Space charts show candidate solutions in different generations, with orange dots representing candidates and green surfaces representing optimal trade-offs. The chart breaks down the solution space by generation, with Generation 3 showing random or poorly optimized solutions. Generation 5 shows tighter clustering of orange points, indicating convergence as shown in Figure 13.
Generation 8 shows a slight improvement in Pareto shape, with most orange points clustering near the Pareto front. Generation 9 shows minimal change from Generation 8, with blue dots still on the Pareto front with high fitness. The 5-polygon shading device likely appears around Generation 5 and remains on the Pareto front through Generations 8 and 9. It provides robust, high-performance results

across key daylight metrics and is a dominant, stable solution in the trade-off space. Improvement plateaus after Generation 5, making it an efficient and early-optimal solution.

The most dependable and effective choice for classrooms is the five-polygon shading device. It guarantees sufficient natural light for a larger part of the day by achieving the highest average DA (66.7%), superior UDI (over 410 lux), lowest DGP (about 0.335), and the best Qv (around 50.5%). It also offers a higher and more consistent quality view (Qv) of approximately 50.5, indicating clearer, less obstructed outward vistas, and the lowest Daylight Glare Probability (DGP) of around 0.335, below the threshold for visual discomfort. Additionally, 206 out of 100 users export the "best" solutions, showing that the gadget performs reliably even with minor design changes. A dependable and effective choice for workspaces is the 5-polygon shading device.

7. Conclusions

In this study, the efficiency of polygonal responsive façade geometries in improving daylight performance and visual comfort in educational buildings situated in the arid and hot West Cairo, Egypt, climate was assessed. The study examined the effects of three different geometric shading modules: triangular (3-sided), quadrilateral (4-sided), and pentagonal (5-sided), using a performance-driven simulation framework that combined Rhinoceros, Grasshopper, Ladybug, Honeybee, and a multi-objective optimization process through Wallacei-X. The effectiveness of each arrangement was assessed using key performance measures, including Quality View Index (Qv), Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), and Daylight Glare Probability (DGP). By verifying simulation assumptions, field data collection decreased uncertainty and increased the accuracy of the model. By evaluating simulation assumptions, field data collection decreased uncertainty and increased the accuracy of the model. The responsive shading geometry of the five-sided polygon (pentagon) showed the best performance and the most balanced trade-offs:

Maximum DA: 66.7% on average- Greater than 410 lux, the superior UDI indicates excellent daylight sufficiency without overexposure - Lowest DGP: 0.335, much below thresholds for discomfort - Best Qv: 50.5%, which indicates excellent views with little obstruction. These results demonstrate how responsive façade systems may effectively control daylight fluctuation, reduce glare, and enhance occupant comfort in educational settings. Classroom visual quality and spatial daylight performance are effectively improved by integrating flexible geometry, especially the 5-polygon design. In summary, responsive façade solutions, especially when they employ optimal 5-polygon shading geometries, offer a dependable and adaptable means of improving daylight performance and visual comfort in educational buildings. In addition to addressing the climate concerns of hot, arid regions, this approach promotes sustainable, user-centered architectural design. The more geometric shapes in a shade system, the more efficient they are at reducing glare and maximizing natural light.

Modifications to shading depth, rotation angle, or polygon size may be needed for larger façades or higher windows. Conducting sensitivity analysis by adjusting the parametric model's room dimensions and window-to-wall ratios (WWR), then optimizing the geometry and re-simulating, can help validate adjustments. The parametric flexibility allows for repeated optimization across different room geometries without starting over, highlighting the need for a sensitivity analysis on various classroom geometries in future work to ensure scalability and robustness.

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