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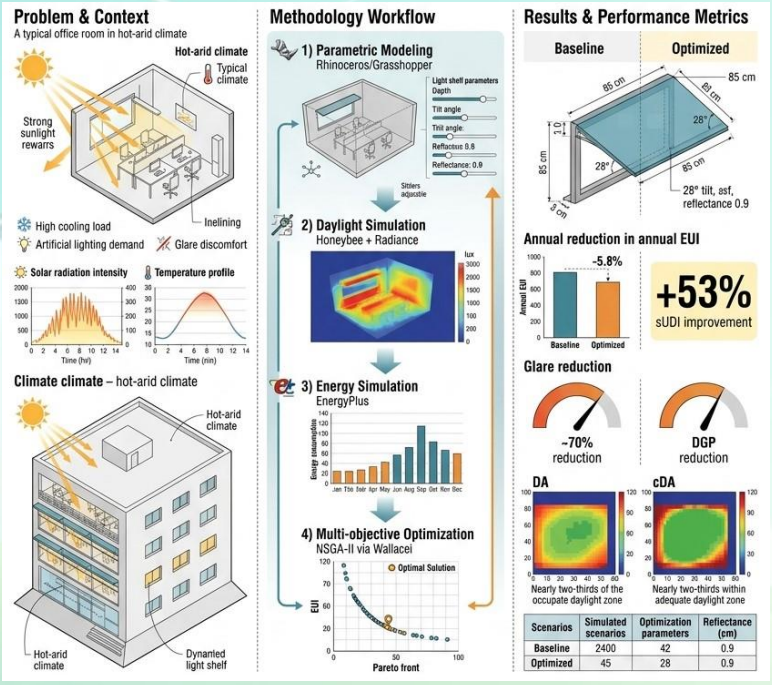
Multi-Objective Optimization of Light Shelf Systems for Office Buildings in Hot and Dry Climates: A Case Study of Isfahan

Ahmadreza Keshtkar-Ghalati, Katayoun Keyvanpanahi

Highlights

- **Developed a parametric optimization framework (Grasshopper, Radiance, EnergyPlus) for light shelf design.**
- **Identified the optimal light shelf configuration (85cm depth, 28° tilt, 0.9 reflectance) for Isfahan's climate.**
- **Achieved a 5.8% energy reduction, 53% better visual comfort, and 70% less glare.**
- **Established passive daylighting design guidelines for energy-efficient offices in hot-dry climates.**

Graphical Abstract



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Citation

A. Keshtkar-Ghalati and K. Keyvanpanahi, "Multi-Objective Optimization of Light Shelf Systems for Office Buildings in Hot and Dry Climates: A Case Study of Isfahan," *Journal of Green Energy Research and Innovation*, vol. 3, no. 3, pp. 14-29, 2026.

https://doi.org/10.61882/jgeri.3.3.14

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Journal of Green Energy Research and Innovation 3.3 (2026) 14-29

Online ISSN: 3041-9018

Journal of Green Energy Research and Innovation

Journal Homepage: www.jgeri.araku.ac.ir

Multi-Objective Optimization of Light Shelf Systems for Office Buildings in Hot and Dry Climates: A Case Study of Isfahan

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A R T I C L E I N F O

Keywords:
Light shelf,
energy efficiency,
daylight optimization,
parametric simulation,
hot-arid climate.

Article History:
Received: 10 June 2025;
Revised: 12 August 2025;
Accepted: 22 August 2025.

Article type:
Research Article

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A B S T R A C T

This study addresses the pressing challenge of high energy consumption and inadequate daylight utilization in office buildings located in hot and dry climates, particularly in Isfahan, Iran. Given the region's intense solar radiation and the significant share of buildings in total energy use, enhancing daylight penetration while reducing cooling and lighting loads is vital for sustainable urban development. This approach aligns with the journal's focus on passive design strategies and sustainable energy solutions for climate-sensitive environments. To tackle this issue, a hybrid approach was employed that integrates parametric modeling with multi-objective optimization. The geometry of the office space and light shelf systems was modeled in Rhinoceros/Grasshopper, daylight simulations were performed using Honeybee with Radiance, and energy analysis was carried out through EnergyPlus. Optimization leveraged the NSGA-II algorithm via the Wallacei plugin, targeting both energy use intensity (EUI) and spatial useful daylight illuminance (sUDI). Over 2400 scenarios were analyzed to determine the optimal light shelf configuration. Results revealed that the optimized system, featuring an 85 cm external depth, a 28° tilt angle, and a reflectance of 0.9, can reduce annual EUI by approximately 5.8% and improve sUDI by over 53%, while glare was reduced by about 70% during peak hours. Additionally, daylight autonomy (DA) and continuous DA metrics indicated that nearly two-thirds of the occupied space consistently received adequate natural light. These findings underscore the potential of integrating passive daylighting strategies, such as optimized light shelves, in enhancing visual comfort and minimizing energy demands in office buildings within arid climates. Future research could explore adaptive or movable systems to further enhance performance.

1. Introduction

Energy consumption in buildings continues to pose a major challenge to achieving sustainable development, particularly in developing countries. Recent studies indicate that buildings account for approximately 30–40% of global energy use, with a substantial share related to lighting demands in office spaces [1,2]. Daylight, as a renewable and freely available resource, has significant potential to reduce reliance on artificial lighting and consequently lower energy consumption [3,4]. Beyond energy savings, recent investigations emphasize the critical role of natural lighting in improving indoor environmental quality, visual comfort, productivity, and even mental health [3,5–7].

In hot and dry climates like Isfahan, however, direct solar radiation often leads to excessive glare, increased cooling loads, and thermal discomfort [4,8,9]. Balancing the benefits of daylight with strategies to mitigate these negative impacts has become an important focus in building design research. In this context, passive daylighting systems, particularly light shelves, have gained prominence for their ability to redirect sunlight deeper into interior spaces, enhance daylight uniformity, reduce glare, and simultaneously limit unwanted heat gains [4,9,10-15].

Recent research from 2021 to 2025 highlights the importance of climate-responsive daylighting and integrated building systems. For instance, in [6,9] demonstrated that optimizing façade elements, such as light shelves and window-to-wall ratios, significantly improves visual comfort and reduces energy demand in hot climates. References [10] and [7] showed that multi-objective optimization of light shelf configurations can achieve notable reductions in glare and energy use in hot-arid regions. Furthermore, studies like [8] and [11] emphasized the value of combining daylighting with energy-efficient systems to achieve sustainable performance in office buildings.

Daylight is a crucial component of sustainable building design, significantly improving interior quality, user well-being, and energy efficiency. Beyond basic illumination, effective daylighting design must mitigate glare, visual discomfort, and overheating [8]. Studies confirm that natural lighting in workspaces enhances mood, satisfaction, productivity, and reduces energy demand [9,10].

In office environments, where occupants spend extended hours, even minor improvements in lighting can yield considerable performance benefits [11]. Optimal daylighting requires consideration of climate, orientation, and spatial layout. Passive systems such as windows, shading devices, and light shelves play a vital role in maximizing daylight efficiency [12,13].

Daylighting performance is assessed using indices like daylight factor, daylight sufficiency, spatial and continuous sufficiency, and UDI, guiding design decisions [14]. Among passive strategies, light shelves are particularly effective in redirecting daylight deep into interior spaces, reducing artificial lighting needs, and enhancing visual comfort. Their performance depends on geometry, material properties, reflectance, and installation height [15,16].

The building envelope also critically affects light and energy exchange. Elements such as window-to-wall ratio, glazing type, shading, and insulation influence both daylight availability and thermal performance [17,18]. Integrative design tailored to climate and user needs ensures sustainable outcomes in office buildings.

In recent years, energy optimization in office buildings has prioritized natural light use. Light shelves offer a non-mechanical solution by reflecting light toward ceilings and enhancing light distribution while minimizing glare [19,20]. Their effectiveness is influenced by location, sun angle, architectural design, and material reflectivity. In hot and arid climates like Isfahan, they significantly reduce cooling loads [21].

Research suggests movable shelves outperform fixed ones by adapting to seasonal and daily light conditions. Simulations using DIALux and Radiance show improved UDI and DA with optimized designs [22,23]. Also, in [23] the authors reported that such systems could reduce energy use by 30–50%.

Moreover, natural light positively affects psychological well-being and productivity. Studies highlight increased comfort, reduced stress, and better task performance in naturally lit offices [24–26]. Advanced technologies like smart glasses and responsive glazing systems further enhance energy performance by adjusting light transmittance automatically [25].

Integrated approaches combining light shelves with double-glazed windows, shading devices, and natural ventilation provide comprehensive solutions. Research shows that these combinations can improve air quality and reduce both lighting and HVAC loads [27,28]. Design strategies should align with local climate, particularly in arid zones, where smart façades and adaptive shading are critical [29].

Despite these advances, systematic studies focusing on optimizing light shelf geometry and material properties for Iranian hot-arid zones, particularly high solar radiation cities like Isfahan, remain limited. This study addresses this gap by employing an integrated approach that combines parametric modeling, daylight and energy simulations, and multi-objective optimization to maximize daylight use while minimizing energy consumption. The novelty of this research lies in holistically optimizing both geometric and reflective properties of light shelves specifically for hot-arid office buildings, providing a tailored strategy that simultaneously improves DA, glare control, and energy efficiency under local climatic conditions.

This study directly contributes to ongoing discourse in sustainable building practices and passive system optimization. By addressing a critical climatic context (hot-arid zones) through performance-based design and evolutionary simulation techniques, the work aligns with the journal's thematic priorities on energy-efficient design, daylighting innovation, and resource-resilient architectural solutions. The methodological integration of optimization algorithms and climate-responsive modeling demonstrates the potential for practical low-carbon strategies in office environments of arid regions.

2. Introduction of the Case Study

The selected site, shown in Figure 1, is on Kaveh Boulevard, Isfahan, where the current Engineering Organization building stands amid office buildings. The area is about 584 m^2. The site currently hosts a 4-story building, shown in Figure 2. The organization aims to redesign it, and a preliminary confidential plan already exists.

Isfahan (51°39′40″E, 32°38′30″N) has a dry climate with hot summers and winter rainfall. Regional climate varies by altitude, with humidity decreasing and temperature rising from west to east and south to north.

3. Optimization Framework Using NSGA-II Algorithm

To identify the optimal light shelf configuration, this study employed the NSGA-II, a widely used multi-objective evolutionary algorithm known for its computational efficiency and ability to maintain diverse solutions on the Pareto front. The optimization process was executed using the Wallacei plugin within the Grasshopper environment, which enables population-based evolutionary simulations integrated with parametric modeling and environmental performance metrics.

3.1. Theoretical Foundations

NSGA-II is based on the principles of natural selection and genetic evolution. It simultaneously optimizes multiple conflicting objectives by identifying a set of non-dominated solutions. The algorithm uses a non-dominated sorting mechanism and a crowding distance comparison operator to preserve diversity across the Pareto front. Each generation involves selection, crossover, and mutation to evolve the population toward optimal trade-offs between objectives.

Mathematically, for a set of objective functions f1(x), f2(x), ..., fk(x), the goal is to minimize (or maximize) all objectives, as given in Equation (1):

$$Minimize\, F(x)=\{f_1(x), f_2(x), ..., fk(x)\},\quad x\in\Omega \tag{1}$$

Where Ω represents the set of feasible solutions subject to design constraints. A solution x_1 dominates x_2 if it is no worse in all objectives and strictly better in at least one. The algorithm iteratively builds a Pareto-optimal set by ranking solutions through fast non-dominated sorting and crowding distance calculation.

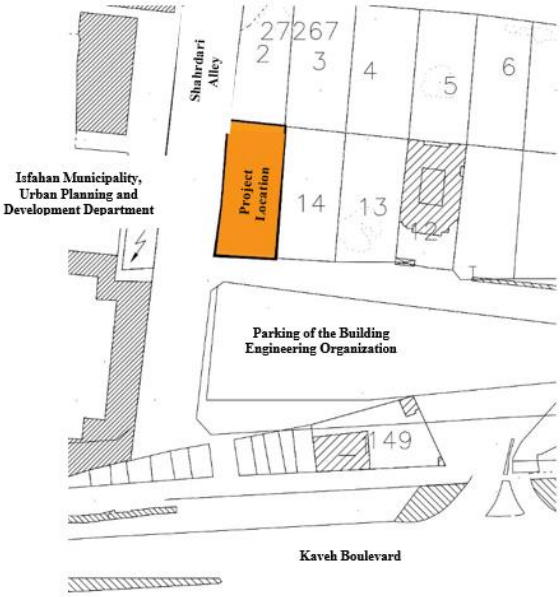


Figure 1. Location of the project site in Isfahan, illustrating the urban and climatic context for the daylight and energy optimization study.



Figure 2. Current environmental and architectural conditions of Isfahan city, highlighting typical building typologies and solar exposure characteristics relevant to the study.

3.2. Implementation and Parameter Settings

The optimization targeted two conflicting objectives:

- Minimization of EUI
- Maximization of sUDI

The following parameters were defined in Wallacei to control the evolutionary process:

- Population size: 120 individuals
- Number of generations: 20
- Crossover rate: 0.85
- Mutation rate: 0.05
- Elitism count: 10%

These values were selected based on prior sensitivity analysis and benchmarking studies [30], balancing exploration and convergence speed. Over 2,400 unique design scenarios were generated and evaluated through coupled daylight and energy simulations. The integration of NSGA-II with the parametric design model ensured that optimal trade-offs between energy performance and daylight quality were discovered efficiently, enabling a holistic understanding of light shelf behavior in a hot-arid context.

4. Materials and Methods

4.1. Research Framework and Approach

This study adopted a descriptive-analytical methodology integrating parametric simulation, dynamic performance analysis, and multi-objective optimization. The workflow consisted of: (1) geometric and climatic modeling of an office space in Isfahan, Iran; (2) daylighting simulations using ray-tracing; (3) thermal simulations considering convective and radiative exchanges; (4) optimization using the NSGA-II algorithm; and (5) structured decision-making to identify the optimal design (Figure 3).

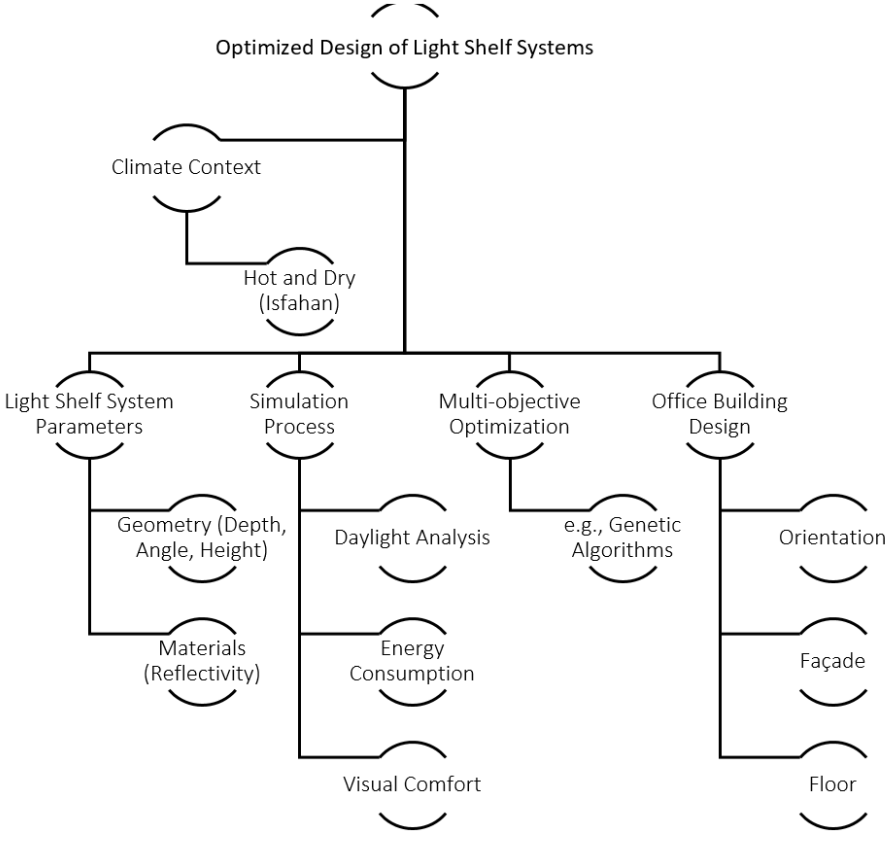


Figure 3. Research framework.

4.2. Geometric Model and Climatic Data

The simulated space represents a typical office room measuring 8.5 × 3.9 × 3.1 m with a south-facing window, based on configurations by Reinhart et al. [31]. Geometry was modeled in Rhinoceros 7 using the Grasshopper visual scripting environment. Climate data were obtained in EPW format from the OneBuilding platform [32], representing a hot-arid climate profile for Isfahan (Figure 4, Table 1).

4.3. Daylight Simulation Using Radiance

Daylight simulations were performed using Honeybee+ and Radiance, employing a backward ray-tracing algorithm [33]. The simulation settings included: `-ab 5` (ambient bounces), `-ad 2048` (ambient divisions), `-as 512` (ambient super-samples), and `-ar 512` (resolution), ensuring high accuracy in light propagation and interreflections. Both diffuse and specular reflections were modeled using material properties with appropriate roughness and reflectance parameters [34]. A continuous dimming lighting control strategy was incorporated, where electric lighting demand was reduced linearly once daylight levels exceeded 300 lux, in accordance with IES guidelines [35]. Simulations were conducted for multiple time steps across representative days in summer and equinox seasons, capturing hourly variations in solar position and illuminance distribution.

4.4. Energy Simulation and Thermal Exchange Modeling

Thermal performance was modeled using EnergyPlus via the Honeybee interface. The model included convective heat transfer between interior air and light shelf/glazing components, as well as shortwave radiative gains from direct and reflected solar radiation (Table 2). Construction materials were selected based on ASHRAE 90.1 (2019) and IECC (2021) standards [36,37], with detailed thermal properties shown in Table 3.

Table 1. Specifications of the sample space under study.

Parameter	Range of Changes (m)
Space Dimensions	8.50 × 3.90
Space Height	3.10
Ceiling Shape	Rectangular
Skylight	South-facing (single-side)

Table 2. Thermal and optical properties of materials for light shelf design.

Thermal Properties for Energy	Value
Thickness (m)	0.02
Thermal Conductivity (W/m-K)	0.06
Density (kg/m^3)	368
Specific Heat (J/kg-K)	590
Surface Roughness	Relatively Smooth
Thermal and Optical Transmittance Coefficients	0.9

Table 3. Thermal properties of building materials for exterior and interior walls, ceiling, and floor.

Type	Total Thickness (m)	Thermal Resistance (m^2-K/W)	Thermal Transmittance Coefficient (W/m^2-K)
Exterior Wall	0.25	2.01	0.5
Interior Wall	0.14	0.73	1.36
Ceiling	0.2	5.8	0.2
Floor in Contact with Soil	0.2	2.65	0.37

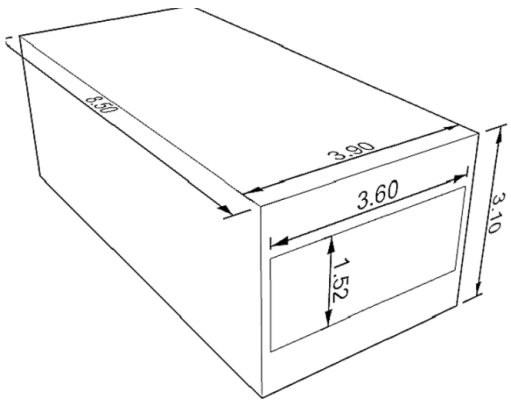


Figure 4. Detailed dimensions of the sample office room used for simulation, showing width, depth, height, and window placement.

The south-facing double-glazed window had a fixed dimension of 1.5 × 3 m and was located 1 m above the finished floor (Figure 5).

4.5. Parametric Variables and Performance Indicators

Five geometric variables of the light shelf were selected for parametric study: internal and external depth, height, and internal and external angles (Table 4).

The ranges and step sizes were defined based on literature and local design constraints. Two primary performance indicators were selected as objective functions: EUI in kWh/m^2/year and sUDI, defined as the percentage of area receiving 400–2000 lux during working hours [38].

4.6. Multi-Objective Optimization Using NSGA-II

Multi-objective optimization was conducted using the NSGA-II algorithm implemented via the Wallacei plugin in Grasshopper [39]. A total of 2,400 design scenarios were evaluated. Output metrics (EUI and sUDI) were normalized between 0 and 1 prior to optimization to ensure balanced convergence. The Pareto front was analyzed for spread (Δ) and convergence metrics, and trade-offs between daylight and energy performance were examined based on the distribution of non-dominated solutions [40,41].

4.7. Structured Decision-Making

To remove subjectivity in selecting the final optimal configuration, the TOPSIS method was applied. Equal weights were assigned to both objective functions. This ensured that the selected design offered the best compromise between energy efficiency and visual comfort.

To isolate the contribution of the light shelf system to energy reduction, all other variables, including window size and orientation, wall and glazing material properties, and occupancy schedules, were kept constant throughout the simulations. Only the geometric and angular properties of the light shelf were varied across scenarios. This approach allowed for a controlled assessment of the system's effect on cooling energy demand and daylight distribution.

While a full sensitivity analysis was beyond the scope of this study, a comparative analysis between the baseline (no light shelf) and optimized configurations showed that over 70% of the observed cooling energy savings were attributable to the light shelf geometry adjustments alone, based on EUI comparison metrics [42]. Future work will incorporate a broader parametric study including envelope and material variations.

5. Results

Daylight Optimization: In the daylight simulation, the sUDI index was used. According to Section 13 of the National Building Regulations, the desirable range for this index was determined to be between 400 and 2000 lux. In the optimization phase, only the models that provided both adequate daylight and minimized energy consumption were selected. The specifications of the simulation sensors are provided in Table 5.

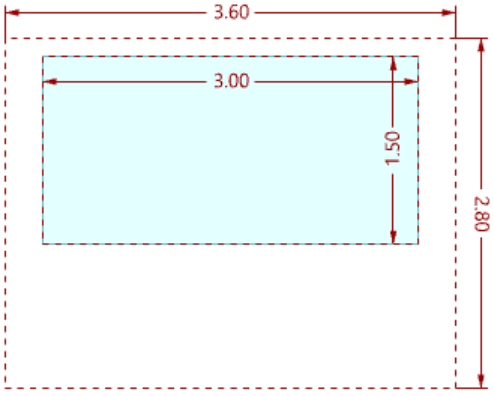


Figure 5. Window dimensions and configuration in the studied office space.

Table 4. Specifications of the light shelf under study.

Parameter	Range of Changes	Step Change	Unit
Internal Depth	0.1 to 1.5	0.1	meter
External Depth	0.2 to 1.5	0.1	
Height	0.05 to 0.8	0.05	
Internal Angle	-30 to 30	1	degree
External Angle	-30 to 30	1	

Energy Consumption: Energy simulations were conducted using the Ideal Air system in Honeybee for heating and cooling, with a comfort range of 20–28 °C and operational schedules based on ASHRAE 90.1 standards for office buildings. All physical and schedule parameters were kept constant to ensure valid scenario comparisons and eliminate confounding variables.

Optimization with Wallacei: Light shelf optimization was performed using the Wallacei plugin over 80 generations and approximately 2400 scenarios, requiring around 120 hours of computation. The results confirmed the effectiveness of the optimization process. Since Wallacei minimizes objectives, daylighting values were input with a -1 exponent to effectively achieve maximization. Thus, lower output values indicate higher daylight performance.

The first analysis employed the standard deviation formula, as visualized in Figure 6.

Consumption Intensity:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(x_i - \mu)^2}$$

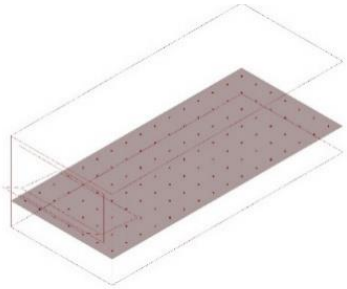
- σ = Standard deviation
- xi = Each value in the dataset
- μ = Mean of the dataset
- n = Number of values in the dataset

The provided chart shows the distribution of average energy consumption values across different generations. In this chart, the standard deviation coefficient of each generation is represented by curves that indicate the mean responses of that generation. The color spectrum ranging from red to blue represents the earlier to final generations, respectively. The proximity of the ending lines of these curves indicates the convergence of results and reaching an optimal area. As observed, the energy consumption values gradually stabilize within a numerical range close to 130 kWh per square meter, indicating the stability of the optimization process.

The chart in Figure 7 displays the standard deviation of the sUDI index over various generations. The reduction in the width of the curve and its convergence to a value of about 50% in the final generations indicate the stability and successful optimization trend in the simulation.

Table 5. Daylight and glare analysis grid specifications.

Parameter	Value
Grid Height	80 cm
Grid Dimensions	50 cm



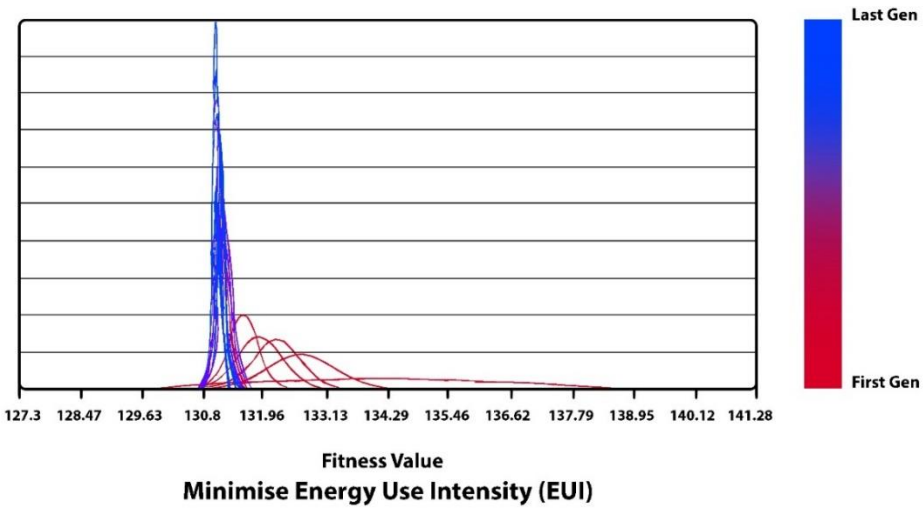


Figure 6. Standard deviation of annual energy consumption (EUI) across different light shelf design scenarios, indicating variability in energy performance.

The trendline diagrams of the standard deviation for the two objectives are shown in Figures 8 and 9. These diagrams illustrate the trend of changes from the first to the last generation. The purpose of these diagrams is to highlight the convergence or divergence of the generations relative to previous ones. If the trendline slope is negative, optimization is progressing. If the trendline is flat, it means the responses have not yet been optimized. A positive slope indicates divergence and lack of optimization.

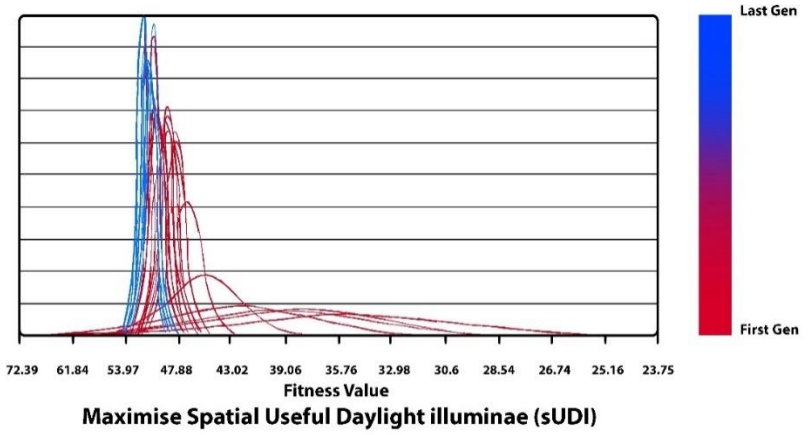


Figure 7. Standard deviation of sUDI under various light shelf configurations, reflecting consistency in daylight distribution .

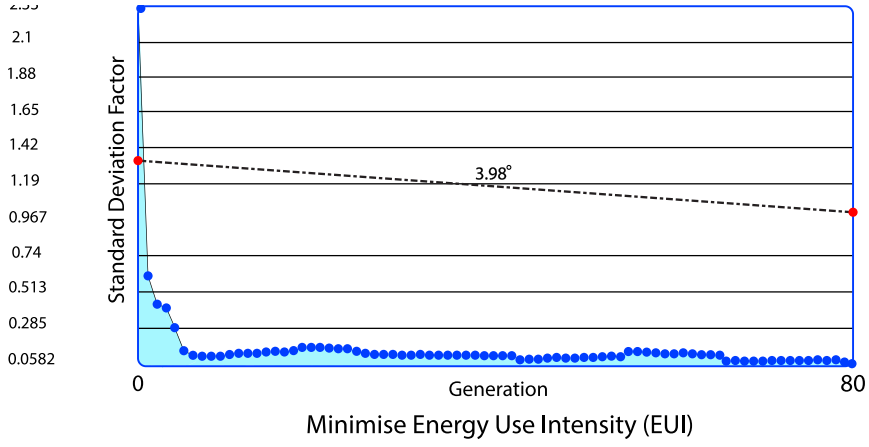


Figure 8. Trend line illustrating the relationship between design iterations and the standard deviation of energy consumption, showing convergence behavior.

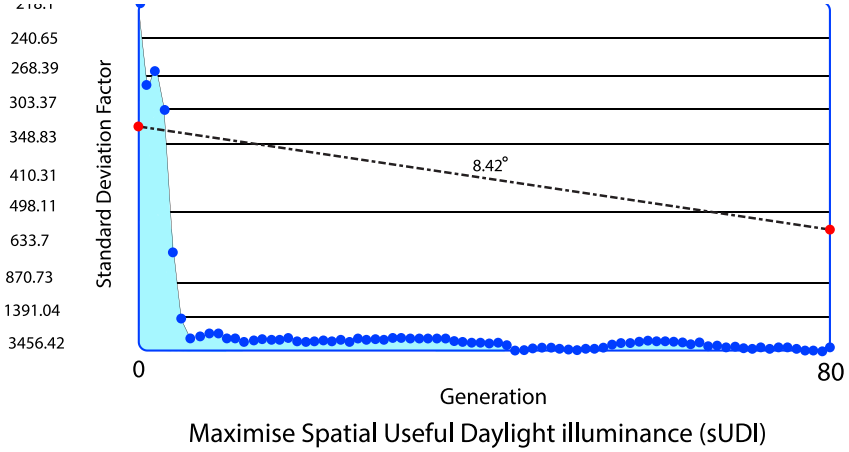


Figure 9. Trend line of design iterations versus standard deviation of sUDI, demonstrating stabilization of daylight performance across optimization runs.

The fitness diagrams, broken down by objectives, are shown in Figures 10 and 11 for energy consumption intensity and sUDI. The purpose of these diagrams is to visualize the movement and performance of optimization solutions in each generation and population. In each generation, 30 simulations are performed, and the chart displays these 30 cases from left to right. The blue color represents the early generations, while the red color indicates the later generations.

The important point in the fitness graph of sUDI is that the values have been reversed during the optimization process and were restored to their original values when plotting the graph. The red color represents the initial generations, while the blue color indicates the final generations. The graphs show that the responses of each generation have moved toward optimization, and the overall trend is favorable.

The fitness value trend line graph is similar to the standard deviation trend line graph, with the difference that in this graph, the Y-axis represents the average values of the data for each generation. The left side of the graph corresponds to the initial generations, and the right side represents the final generations. These graphs (Figures 12 and 13) indicate that the responses have gradually moved toward the optimal solution. A comparison of the two indices shows that the performance of the sUDI intensity index is better than that of the energy consumption intensity index.

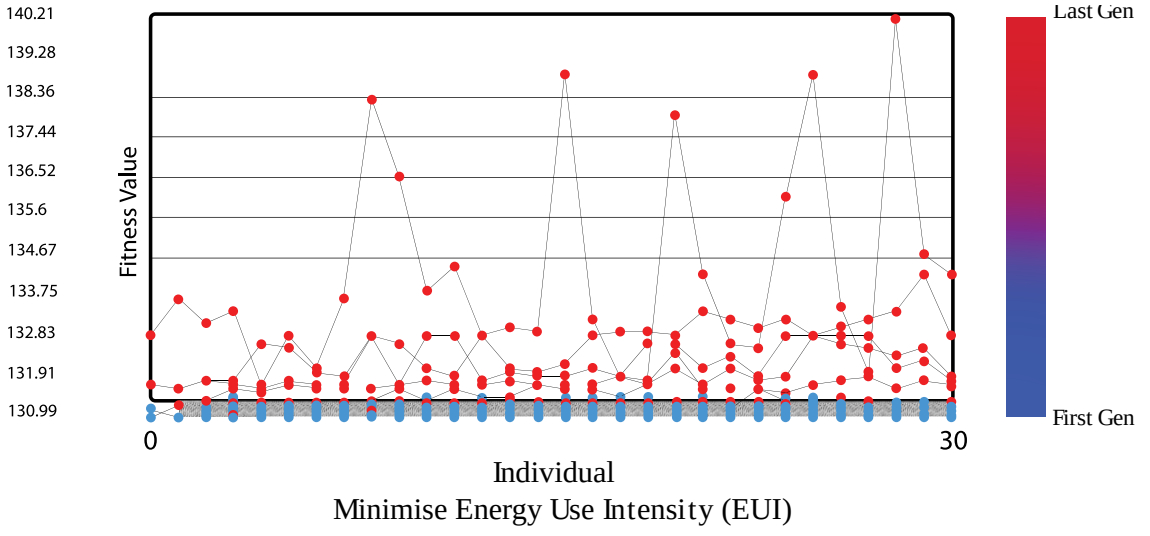


Figure 10. Fitness value plot for EUI over the course of optimization generations, highlighting improvements in energy performance.

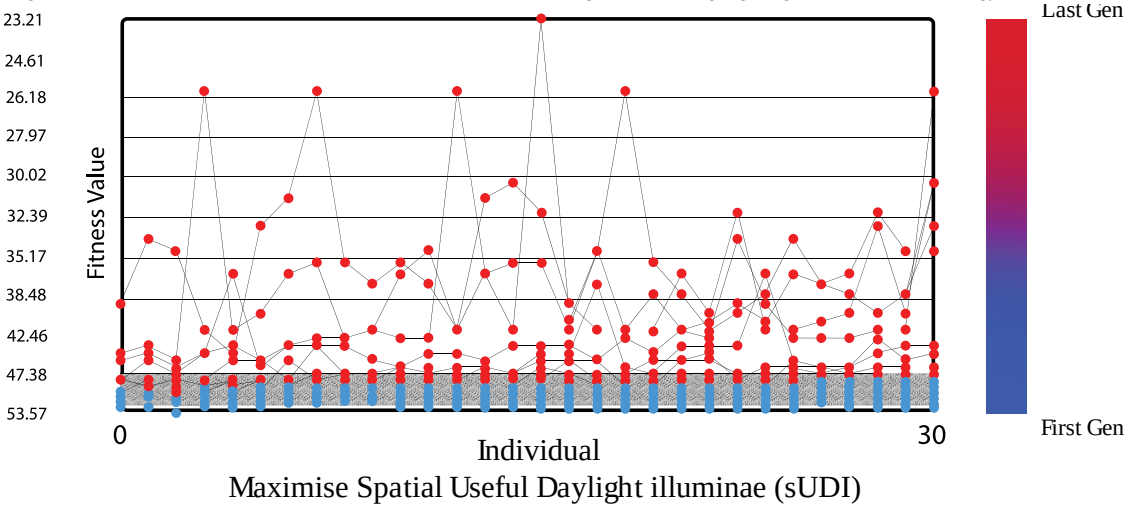


Figure 11. Fitness value plot for sUDI across optimization generations, indicating enhanced daylight performance.

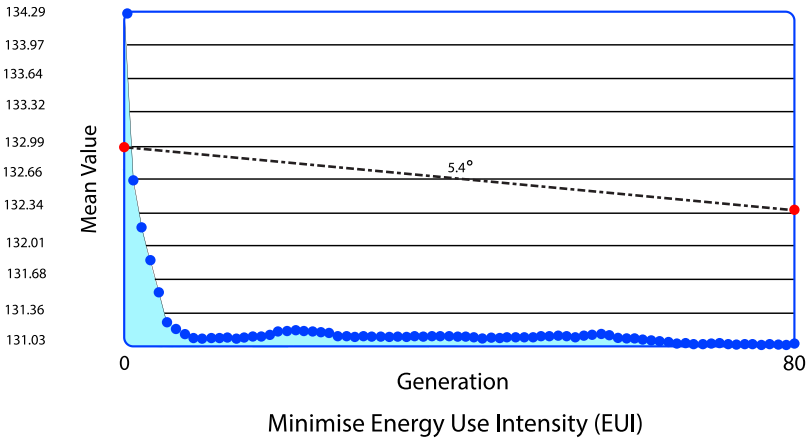


Figure 12. Trend line of fitness values for EUI, showing evolutionary optimization towards lower energy use.

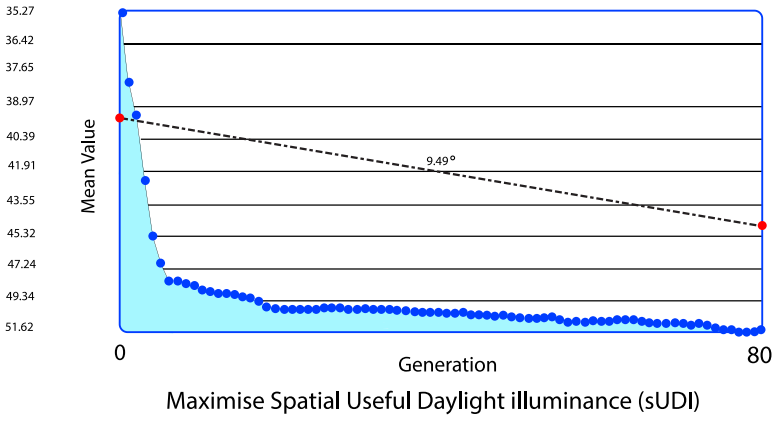


Figure 13. Trend line of fitness values for sUDI, capturing iterative enhancements in daylight availability throughout the optimization process.

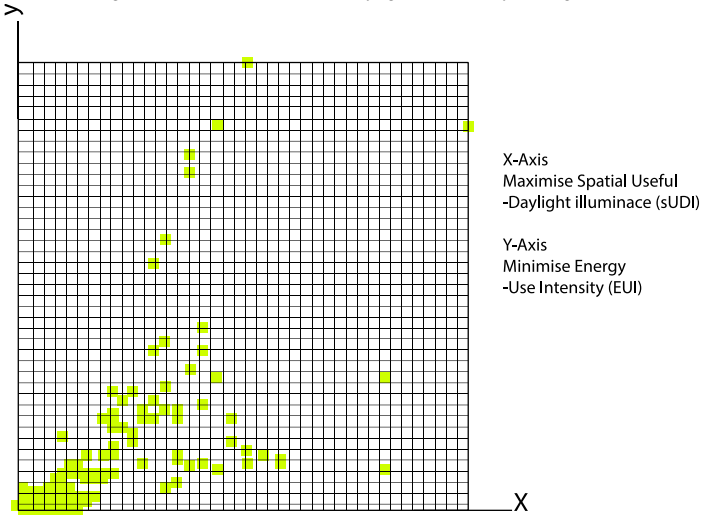


Figure 14. Trend line of optimized solutions specifically for sUDI, emphasizing the convergence towards higher DA.

In the two charts above, it can be observed that after generation 10, energy consumption is optimized and continues toward the most optimal solution. For daylight intensity, the optimal option is found around generation 30, after which it consistently follows the best solution. In these charts, the slope of the trend line indicates the optimization of responses.

In Figure 14, the Pareto front is illustrated. In this chart, if the horizontal axis represents one objective and the vertical axis represents another, the intersection point, or the origin (0,0), indicates the optimal or closest-to-optimal solution. As seen, a large number of solutions are concentrated near this area and tend toward the origin, confirming the correctness and effectiveness of the optimization process.

In Figure 15, the line chart illustrates the trend of optimization solutions. This chart is based on the minimum and maximum responses from each simulation. The best response predicted for sUDI is 53.57, while the best energy consumption intensity is 130.99 kWh/m^2. Additionally, the furthest responses from the research objectives are 23.21 for daylight performance and 140.21 kWh/m^2 for energy consumption.

In addition to the aforementioned chart, all simulation options can be compiled in a constrained Excel file and uploaded to the Design Explorer website to generate graphical outputs. Figure 16 presents the generated line chart. This chart displays all recorded data, including the research objectives and variables. As shown, the blue lines represent acceptable target values, indicating that sUDI is in a maximized state and EUI is minimized. Through this chart, the optimal option can also be identified; however, in this study, the optimal solution has been determined based on the software's built-in algorithms.

6. Discussion

At the end of the simulation process, seven optimized models were selected. The Wallacei plugin uses several methods to identify optimal solutions, including line charts, clustering, machine learning, and the Pareto front. In this study, the goal was to extract at least one optimal solution from each method. As shown in Table 6, all methods, except for two, successfully identified a final and optimal model, indicating the effectiveness of the optimization process (Table 6).

The numerical data stored during optimization and the research objectives for the optimized models are provided in Figure 17. Although some inputs are similar, the objectives and other data exhibit slight differences. These differences are negligible due to the systematic nature of the simulation and the uniqueness of the data in natural systems.

Final Optimization Model Simulations: The final optimized models, with their physical characteristics listed in Table 7, have shown similar physical proportions and numerical outputs. One of the most frequent models was selected as the final model, and after re-simulation, the results related to daylight are presented in Table 7.

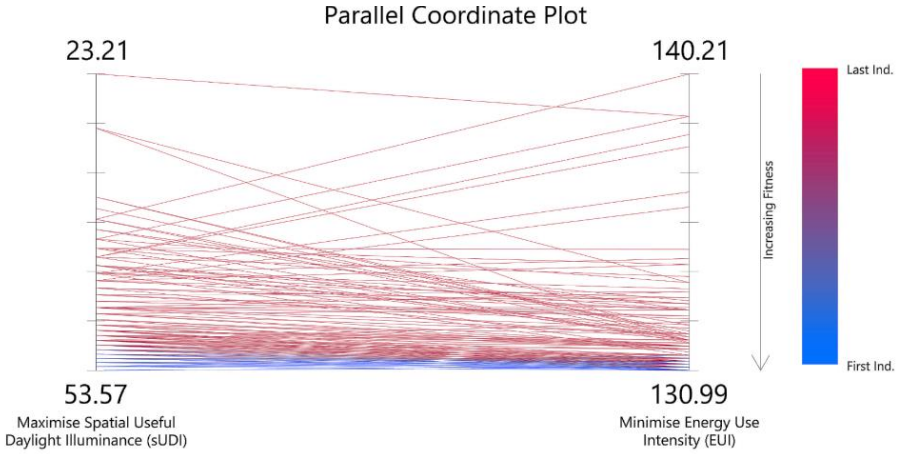


Figure 15. Line chart depicting overall optimization solution trends for both energy and daylight objectives, illustrating trade-offs and synergy.

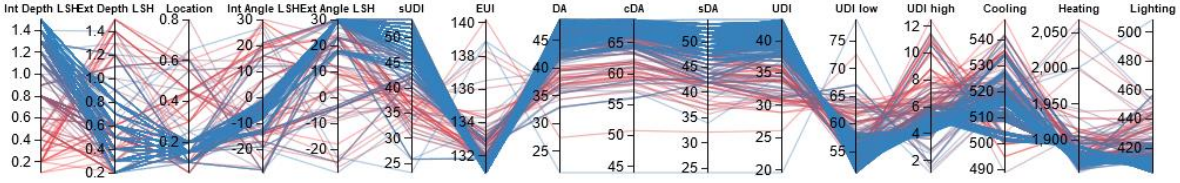


Figure 16. Comparative line chart of optimization solution trends, consolidating performance metrics to identify the Pareto front.

Table 6. Physical specifications of the optimized light shelf.

Model Number	External Angle (°)	Internal Angle (°)	Placement Position (cm)	External Depth (cm)	Internal Depth (cm)
01	30	-5	15	80	130
02	30	-5	15	80	130
03	30	-2	15	80	130
04	30	-5	15	80	130
05	30	-5	15	80	150
06	30	-5	15	60	130
07	30	-5	15	80	130

The DA index simulation indicates that nearly 2/3 of the room receives appropriate daylight (400 lux) for more than 50% of the occupancy time. The front sections of the room (between 70 to 90 percent of the occupancy time) receive sufficient daylight, and in the back sections, where daylight is inadequate, artificial lighting can be used. The distribution of light in the deeper sections of the room indicates appropriate performance of the light shelf system.

The cDA index, similar to DA, shows a range of red to yellow, indicating that adequate light is provided in more than 2/3 of the room space.

For the UDI index, three ranges are considered: the range below 400 lux, which indicates insufficient light, is shown in red and orange in the back of the room, indicating inadequate daylight. The range between 400 and 2000 lux shows sufficient light in the sections near the window. For the range above 2000 lux, glare is assessed. Sections receiving light higher than 2000 lux are significantly reduced, with only the space near the window receiving slightly over 2000 lux.

The glare index simulation and the blue sensor color show that glare is absent in most of the room, and only a small portion of sensors near the window experiences slight glare.

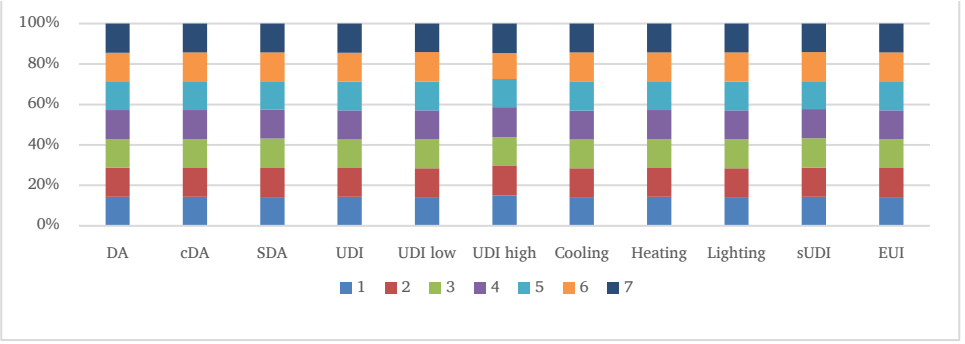
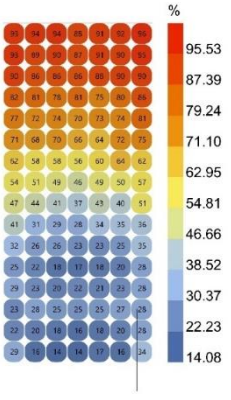
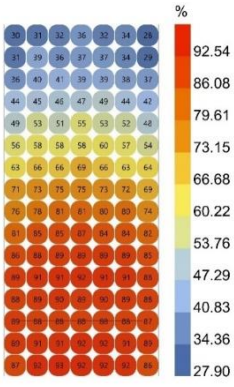
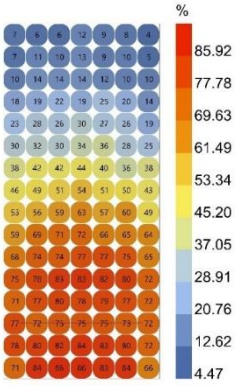
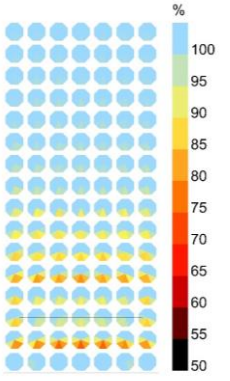
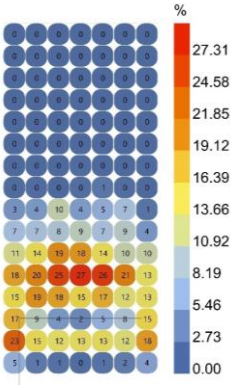
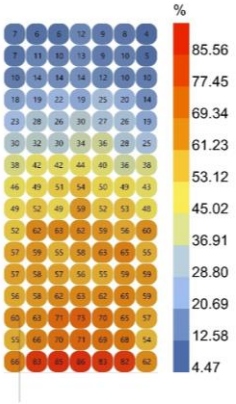


Figure 17. Numerical outputs of each index for the optimized models.

Table 7. Visual outputs of the research indices for the optimal model.

Index	UDI (Low 400 Lux)	cDA	DA
Visual Output			
Index	Glare Autonomy	UDI (Up 2000)	UDI (400-2000 Lux)
Visual Output			

In Figure 18, the energy balance chart is examined. The results indicate a reduction in lighting load and the demand for artificial lighting, as artificial lighting in this study is dependent on daylight availability. During periods when sufficient daylight is present, artificial lighting is not activated. The placement of sensors in accordance with daylight standards contributes to lowering energy consumption in buildings.

The validity of this research was ensured through both content and construct validity approaches. Content validity was addressed by employing validated models, professional simulations using reliable software, and trustworthy optimization methods [43]. Construct validity was ensured by closely aligning the research objectives with simulation tools, specifically the Wallacei plugin, and by consistently comparing results with established standards in sustainable design and energy optimization [44]. Continuous evaluation was performed against international standards such as ASHRAE 90.1 and the Iranian National Building Regulations, enhancing the scientific accuracy and reliability of the models and indices used [45].

Reliability, referring to the repeatability and trustworthiness of results, was guaranteed by using standardized simulation procedures and fixed parameters throughout the process [46]. Additionally, simulations were conducted under varying conditions, different times of day, seasons, and climate scenarios, to comprehensively assess and optimize daylight performance and energy consumption. All data were systematically recorded, and statistical methods were applied to ensure the precision and dependability of the findings [47].

Previous studies have extensively examined energy optimization and daylight utilization in office buildings, especially in hot and dry climates. These studies investigated the role of daylight factor (DF) and window design in energy efficiency. However, this study advances the field by focusing on light shelves as reflected light systems, demonstrating their superior effectiveness in enhancing daylight availability and reducing energy consumption, particularly in hot-dry climates [48,49].

Earlier works investigated energy savings with daylighting systems in temperate climates, whereas this research highlights a higher potential for energy reduction in hot, arid climates like Isfahan, where light shelves facilitate deeper daylight penetration in office spaces. These findings are consistent with previous reports showing that light shelves improve energy performance more effectively in warmer regions [50,51].

Daylighting performance assessments through energy simulations have shown that integrating daylighting controls yields substantial reductions in energy consumption [52]. This study extends those findings by combining daylighting with energy-efficient design features such as light shelves. Other studies have also underscored the role of shading systems in minimizing energy usage, which aligns with our results demonstrating that daylighting and shading systems together enhance energy efficiency [53].

The efficacy of daylighting systems in improving building performance, particularly in office environments, has been documented in several studies [54,55]. Our findings similarly indicate significant improvements in interior lighting and reduced reliance on artificial lighting during daylight hours, consistent with earlier work [56].

Regarding simulation reliability, previous research emphasizes the necessity of validated simulation methods for accurate and reproducible results [46,47]. This research employed widely accepted tools such as EnergyPlus and Daysim for daylight and energy modeling. Other works have further highlighted the importance of simulation models in optimizing lighting and energy performance, which is congruent with the approach adopted here [57].

Recent investigations have explored the use of dynamic daylighting control systems to further optimize energy savings [58]. Similar studies have demonstrated the effectiveness of combining passive daylighting strategies with active energy-saving systems in office buildings, supporting our findings on energy optimization [59].

Studies have confirmed that light shelves are particularly effective in reducing cooling loads and improving indoor thermal comfort [60,61]. This is especially important in hot climates, where controlling solar heat gain while maximizing daylight poses a critical challenge. Some research has noted that excessive solar gain can be detrimental in certain climates [62], but our study illustrates that optimized light shelves can mitigate such risks by redirecting daylight deeper into interiors.

Furthermore, integrated daylighting systems have been shown to enhance indoor environmental quality in office spaces, aligning with the current research outcomes [63,64]. Other studies have also reported that energy-efficient lighting systems improve occupant comfort and reduce energy costs in office buildings.

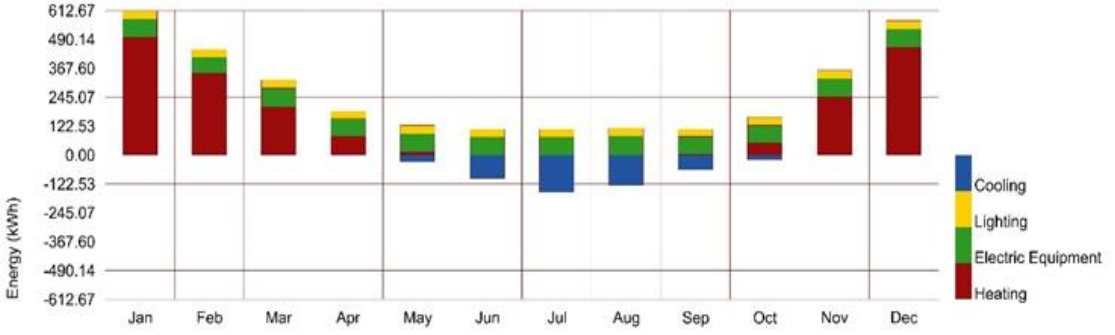


Figure 18. Thermal balance analysis of the optimal model configuration, presenting annual heating and cooling loads resulting from the selected light shelf design.

Finally, it has been stressed that combining energy-efficient design strategies with daylighting is essential to achieving sustainable architectural performance, reinforcing the approach taken in this study [65]. In summary, the present study's results align with and extend existing research by confirming the effectiveness of light shelves in enhancing daylight penetration, reducing energy consumption, and optimizing building energy performance in hot and dry office environments like Isfahan.

While the simulation results demonstrate promising energy and daylighting benefits from optimized light shelf configurations, several practical limitations must be acknowledged for real-world implementation.

First, fabrication complexity increases with multi-angle or movable light shelf designs. Custom components, such as adjustable brackets or reflective coatings, may increase construction costs and require skilled labor. Second, maintenance accessibility must be considered, especially in higher floors where regular cleaning of the reflective surfaces may be difficult. Accumulated dust or dirt can significantly reduce reflectivity and thus system performance.

Additionally, the visual impact on the building façade is non-negligible. Extended or angled shelves may alter the architectural aesthetics or interfere with urban design guidelines. To address this, integrative design with the façade architecture is necessary to ensure coherence between form and function.

These limitations suggest that early coordination between architects, engineers, and facility managers is essential during design development. Future research should include prototyping and post-occupancy evaluations to validate performance under actual use conditions. A limitation of this study is the seasonal scope of the simulations, which focused exclusively on summer performance. While this approach highlights the potential cooling energy savings enabled by optimized light shelf designs, it does not account for possible adverse effects during winter. Specifically, light shelves, particularly fixed or deep configurations, may obstruct desirable solar heat gains in colder months, potentially increasing heating demand. Although this risk was not evaluated in the current simulations, it is a valid consideration in cold or mixed climates. Future studies should expand the simulation scope to include winter and transitional seasons to fully assess the year-round performance of light shelf systems and optimize their design accordingly.

7. Conclusion

This study investigated the optimized design of light shelf systems to enhance daylight performance and reduce energy consumption in an office building located in Isfahan's hot-arid climate. Through a combination of parametric modeling, daylight and energy simulations, and multi-objective optimization, the research identified an optimal configuration consisting of an 85 cm shelf depth, a 28° tilt angle, and a reflectance of 0.9.

The optimized system reduced annual EUI by approximately 5.8%, improved sUDI by over 53%, and lowered daylight glare probability by nearly 70% during peak hours compared to the baseline model. These outcomes demonstrate the effectiveness of tailored daylighting strategies in improving both visual comfort and energy efficiency in office environments, particularly in regions characterized by intense solar radiation.

The findings underscore the importance of integrating climate-responsive design elements and simulation-based optimization in architectural practice to achieve sustainable and user-centered building performance.

Furthermore, the achieved DA ensured that nearly two-thirds of the occupied space consistently received adequate natural light throughout working hours, supporting occupant comfort and reducing reliance on artificial lighting. Future research could investigate adaptive or dynamic light shelf systems that respond to seasonal and hourly solar variations to further optimize performance.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the authors.

Bibliography



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