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Optimizing library facade design in Zanjan climate through daylight simulation and metaheuristic approaches

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ABSTRACT

This research investigates the optimization of library facade design in Zanjan's climate, focusing on maximizing daylight utilization through metaheuristic approaches. By employing parametric and metaheuristic techniques, the study evaluates a range of facade elements, including window-to-wall ratios, light shelf depths, and glass transmittance, to identify optimal configurations that enhance indoor lighting while minimizing energy consumption. The findings reveal significant variations in useful daylight illuminance, ranging from 44.26% to 72.85% across different design options. Notably, the configuration with an interior depth of 1.3 meters, exterior depth of 0.6 meters, and a window-to-south-wall ratio of 0.4, coupled with a glass transmittance factor of 0.55, demonstrates the highest level of useful daylight. Furthermore, all design options exhibit excellent glare control, with glare-free percentages approaching 100%. The analysis suggests that interior depths between 0.9 and 1.3 meters, particularly 1.3 meters, are optimal for maximizing daylight penetration. Similarly, exterior depths between 0.5 and 0.7 meters, especially 0.6 and 0.7 meters, yield favorable results. These findings offer valuable insights for architects and engineers seeking to design energy-efficient and visually comfortable buildings in regions with similar climatic conditions.

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1. Introduction

Architectural design, especially in cold climates, demands efficient use of natural resources such as daylight to reduce energy consumption and enhance the visual comfort of occupants. In Zanjan, a region with significant daylight limitations, optimizing the facade of buildings like libraries is crucial for creating energy-efficient and user-friendly spaces. This study focuses on analyzing the role of the library's facade in maximizing daylight penetration, using state-of-the-art daylight simulations and metaheuristic optimization techniques. By improving daylight distribution, the research aims to reduce dependency on artificial lighting, ensuring sustainability in architectural practice. The efficient use of daylight in architectural spaces is not only a matter of reducing energy costs but also contributes to improving the psychological well-being and productivity of occupants. Several studies indicate that exposure to natural light enhances mental health, reduces eye strain, and improves focus and productivity, particularly in learning environments like libraries. These benefits are especially critical in environments like Zanjan, where natural daylight may be limited during winter months, thus calling for optimized architectural designs that fully exploit available light. Moreover, energy consumption in buildings, particularly for lighting, constitutes a significant portion of the overall energy use in many countries. By integrating daylight optimization techniques in architectural design, buildings can significantly cut down on energy costs, contributing to sustainability goals and reducing carbon emissions. This research not only addresses these environmental concerns but also aims to develop a facade design model that can serve as a benchmark for other regions with similar climatic challenges. Daylighting refers to the controlled use of natural light within buildings to achieve visual, thermal, and psychological comfort for occupants (Reinhart, 2014). Natural light promotes feelings of joy and happiness, positively impacting users. Openings in buildings allow sunlight to enter and create a pleasant atmosphere while maintaining visual connections with the outdoors (Li, 2010). In recent decades, experts have emphasized the importance of daylight in reducing energy consumption and its positive physical and psychological effects on users (Edwards, 2002). Maximizing natural light, especially in educational and cultural spaces, enhances user satisfaction, improves physical and mental health, and increases productivity (Altomonte, 2009).

As energy consumption in buildings rises, particularly for artificial lighting, efficient energy use has become a priority in building design (Kheiri, 2018). Natural light is a crucial component of sustainable building design, especially given the high energy demands for artificial lighting, which accounts for 20-40% of building energy consumption globally (Nedhal et al., 2016). In Iran, where 34% of electricity is used for lighting in residential buildings (Cantin and Dubois, 2011), daylighting can significantly reduce this demand. Effective use of daylight in architecture not only meets psychological and emotional needs but also reduces the need for electric lighting. In recent years, the integration of daylight in building design has become increasingly significant due to its energy-saving potential and positive impacts on users. In Iran, despite abundant sunlight, inefficient building design often leads to underutilization of natural light (Mahdavi, 2015).

Proper facade design, particularly with transparent elements, plays a critical role in reducing energy consumption for lighting. Daylighting design is essential for spaces like libraries, where visual tasks such as reading and writing require optimal lighting conditions for visual comfort (Sener, 2003). By increasing visual comfort and reducing the need for artificial lighting, daylighting can enhance user satisfaction and energy efficiency (Li and Lam, 2001; Li and Lam, 2003; Li, 2010).

Iran's location in the solar belt gives it abundant sunshine, with 241 to 251 sunny days annually, offering vast opportunities for daylight utilization. Proper use of daylight, particularly in spaces like libraries, can improve visual comfort and user productivity. Research shows that appropriate daylight distribution affects user perception and performance, enhancing focus, visual quality, and motivation. Moreover, optimizing daylighting strategies through simulation and multi-objective optimization can lead to better design outcomes, improving the balance between energy savings and user comfort.

In recent years, there has been significant research on the integration of natural daylight into library spaces to enhance energy efficiency, visual comfort, and overall user experience. For example, studies conducted in 2019 focused on reducing energy consumption in a university library through shading devices on the southwest façade, finding an 8.5% reduction in overall energy use when fixed external shading was applied (Acosta et al., 2019; Alhagla et al., 2019; De Luca et al., 2019; Dogan and Park, 2019; Randy et al., 2019; Freewan et al., 2019; Mangkuto et al., 2019; Nadiri et al., 2019; Reinhart, 2019; Vaisi and Kharvari, 2019; Yi, 2019). Among many researches in 2014 (Baker and Steemers, 2014; Berardi and Wang, 2014; Beute, 2014; Boubekri et al., 2014; Boubekri, 2014; Council U. G. B., 2014; Erlendsson, 2014; Feist, 2014; Hashemi, 2014; Kim et al., 2014; Lechner, 2014; Vasileios et al., 2014; Nair et al., 2014; Reinhart, 2014; Velux, 2014; Yao, 2014; Yu et al., 2014), a study examined how lighting affects resource usage in libraries. Using a combination of quantitative and qualitative approaches, it revealed that 65% of users appreciated the optimized lighting, which improved their satisfaction with the library's visual environment. Daylighting also plays a critical role in reducing glare and improving visual comfort. Among many researchers in 2020 (Freewan and Al Dalala, 2014; Heng and Ossen, 2014; Kaminska, 2014; Khavari, 2014; Li et al., 2014; Mahdavi, 2014; Zhu et al., 2020; Pilechiha et al., 2020; Nasrollahi and Shokry, 2020) a study focused on finding the best shading device design to minimize glare in reading rooms, discovering that certain shading systems can effectively reduce glare intensity while maintaining sufficient daylight levels (using DIALux Evo 8.1). Similarly, research conducted in a Portuguese Baroque library demonstrated that reducing direct sunlight exposure is essential to preserving historic structures while still ensuring adequate daylight levels (Radiance). These findings underline the importance of balancing daylight usage with preservation needs and visual comfort. Moreover, studies have highlighted the impact of window configurations and seating preferences in library spaces. For instance, a study on seating preferences in open-plan libraries found that while users preferred seating near windows, this preference persisted even at night, suggesting that factors other than daylight, such as views, influenced seating choices (Aries et al., 2015; Bellia et al., 2015; Ercan and Elias-Ozkan, 2015; Favoino et al., 2015; Futrell, 2015; Gherri, 2015; Gordon, 2015; Hobday, 2015; Mahdavi, 2015; Ritter et al., 2015; Schregle, 2015). Additionally, research on different shading systems in a 2022 study showed that mesh screens, though inefficient at controlling glare, were effective in improving annual daylight quality and visual comfort in a reading room with openings on all four sides (Ahmad et al., 2022; Campano et al., 2022; Gentile et al., 2022; Sankaewthong et al., 2022; Lopez-Cabeza et al., 2022; Shikang et al., 2022; Yibing et al., 2022; Aguilar-Carrasco et al., 2023).

In conclusion, the integration of daylight into library designs offers multiple benefits, from energy savings to enhanced user satisfaction. Optimized daylighting solutions—such as using shading devices, adjusting window configurations, and employing simulation tools like DIALux and Radiance—have proven to be effective in reducing glare, improving lighting conditions, and promoting energy efficiency, as seen in studies across different regions and library types (Garcia-Fernandez and Omar, 2023; Celik and Inan, 2023; Dimara et al., 2023; Farivar and Teimourtash, 2023; Hu et al., 2023; Yingjie et al., 2023; Qibo et al., 2023; Shikang et al., 2023; Picker, 2024).

This research introduces several innovative aspects that significantly contribute to the field of facade design and daylight optimization:

1. Parametric Simulation: The study utilizes parametric simulation to model the impact of various facade designs on daylight efficiency. This approach, implemented through Ladybug Tools, allows for complex light analyses in a virtual environment, providing precise assessments of design variations' effects on daylight performance.
2. Metaheuristic Optimization Algorithms: The research employs metaheuristic optimization algorithms, specifically the NSGA-II algorithm, to select optimal design configurations from numerous possibilities. This method enables the identification of facade designs that maximize natural daylight usage, enhancing architectural performance while reducing energy costs.
3. Environmental Impact Reduction: A significant aspect of this research is its focus on reducing environmental impacts by examining the interrelations between different building parameters and their objectives. The study identifies the most effective design elements that contribute to sustainability, enabling future research to minimize adverse environmental effects through innovative architectural strategies.
4. Real-Time Analysis: By utilizing parametric modeling tools like Grasshopper, the research facilitates real-time modifications and assessments of design parameters, allowing for immediate feedback on the implications of design choices regarding daylight utilization and glare reduction. This dynamic approach streamlines the design process and enhances decision-making efficiency for architects.

Research Objectives: The primary objectives of this research are as follows:

1. Optimizing the Library Facade: To design an optimized facade for the library that maximizes natural daylight utilization while minimizing glare and energy consumption.
2. Assessing Climatic Features: To study the geographical and climatic characteristics of Zanjan that affect daylight performance, providing practical strategies for better natural lighting in the library space.

3. Evaluating Architectural Elements: To examine how various architectural elements of the facade impact daylight access and quality within library study areas.

Research Questions: The research is guided by several key questions:
1. Daylight Optimization Strategies: How can simulation and metaheuristic optimization processes be effectively utilized in the facade design of the library to enhance daylight efficiency?
2. Climatic Analysis: What are the specific climatic features of Zanjan (in terms of geographical position, and direct and diffuse radiation) that enable optimal daylight usage in library study environments?
3. Impact of Architectural Design: How do architectural elements such as window orientation and size, and shading devices, influence the quality and quantity of natural light in library spaces?

2. Material and methods

The research methodology is divided into three steps: theoretical studies, data collection, and data analysis. In the first step, after reviewing the classification of research from the perspective of results, processes, reasoning logic, the temporal aspect, objectives, the statistical population, and the criteria for its selection, the sampling method and the conditions of the statistical sample are elucidated. In the second step, the process of data collection is explained in two phases: survey studies, which include the introduction of the proposed model, and the analysis of the conditions and components of daylight within the studied climate. The method of data collection is further elaborated through the simulation of daylight data and its optimization using a multi-objective genetic algorithm (NSGA-II) within the software. Finally, exploratory data analysis methods are employed to determine both parametric and non-parametric analytical approaches. Structural equation modeling is applied, focusing on variance and covariance related to the statistical sample under consideration.

2.1. Case study

The research focuses on a specific case study a library located in Zanjan. The choice of this building type is driven by its significance as a public space that requires adequate natural lighting for study and reading activities. The library's existing facade design will be evaluated and reconfigured through the simulation and optimization processes. The research environment is set in the cold climate of Zanjan city. According to studies, the orientation of buildings in Zanjan province is recommended to be between 20 degrees west and 45 degrees east, providing mutual wind shading avoiding solar shading and aligned along the north-south axis (Zamani et al., 2016). The region's climate is characterized by severe winter cold, moderate summers, significant diurnal temperature variations, and heavy snowfall. Zanjan province is a mountainous and semi-mountainous region located between 47° 9' and 5° 51' east longitude and 35° 28' and 37° 15' north latitude. The province's topography consists of mountainous and plain areas. The mountainous regions, often with high peaks, are scattered in the eastern and western parts of Mahneshan County, the northern parts of Zanjan County, and parts of Abhar County. The highest elevation in the province is 3214 meters. With the prevailing easterly winds, the optimal building orientation is 150 degrees north. Considering the unfavorable winds from the west, southwest, and east, buildings should be oriented between 15 degrees southwest and 45 degrees southeast to maximize energy use during cold periods and minimize it during warm periods. The best orientation is 15 degrees east of north, with the building's long axis perpendicular to the north direction (Zamani et al., 2016).

2.2. Research approach

This study adopts a quantitative-qualitative approach. The quantitative part involves simulations and numerical optimizations, while the qualitative aspect is based on reviewing previous literature and contextual analyses. The research primarily focuses on analyzing the performance of daylight utilization in the facade of libraries through advanced simulation software.

2.3. Simulation tools and details

For daylight performance assessment, the study utilizes Radiance, a well-known simulation tool for accurate daylight predictions. Additionally, Grasshopper and DIVA are used as platforms to create parametric models for evaluating how different facade elements affect daylight distribution. In the present study, a space has been assumed for the base model based on design standards. For a study room in Zanjan, the space must be comfortable, well-lit, and compatible with the climatic conditions. However, there is no specific standard for the spatial dimensions of a study room in general. Therefore, the overall dimensions of the room have been considered as 8×6 meters with a height of 4 meters. These dimensions can provide sufficient space for study desks and a comfortable space for reading and research. It should also be noted that the lighting and orientation of the windows should be such that they maximize the use of natural light and prevent direct sunlight from entering at inappropriate times. Therefore, in this research, windows are assumed to be located on both the north and south facades, with a light shelf considered for the south-facing windows. The minimum width of the aisles between desks should be considered as the width of an average human shoulder, which is 0.60 meters. On the other hand, according to the Neifert standard, the per capita area required for one person to study is 2.5 square meters, which includes the desk, chair, aisles on both sides of the desk, and finally the distance from one person's desk to the next. A person's desk should be about 0.95 meters from the edge of the previous desk so that the person can easily move their chair. The height that the Neifert standard considers for a desk is at least 0.75 meters. Therefore, in this research, 0.75 meters has also been considered. The width of the desk is also at least 0.90 meters according to this standard, and it is preferably considered 1 meter to provide enough space for the user. Finally, it should be noted that the arrangement of the chairs is such that they face away from the main door to have less visual disturbance and also have soft light from the south and controlled light from the south.
Furthermore, the significant depth of this room has been considered to better analyze the indices and the impact of the desired options for utilizing daylight. Additionally, this unit is assumed to be located at a height of 6.4 meters above ground level or on the third floor among other rooms. The floor-to-floor height is also considered to be 4 meters. To minimize the impact of the east and west facades, the east and west walls of the sample room have been considered closed, considering the direction of disturbing winds. Regarding the building openings, the windows on the south side should have a 230-degree angle with the vertical, and the ratio of their height to width should be close to 1 to allow more sunlight to enter the building during colder months. However, the north-facing windows should be horizontal to allow the necessary light into the building. Of course, these are generally one of the variables of this research that will be discussed and analyzed. In using horizontal and vertical shading devices to prevent sunlight from entering the building in the summer, the depth of the shading device must be 0.27 times the height of the window. This will be considered in the parametric process. Therefore, no shading device has been considered for the north-facing windows, and a shading device has been considered for the south-facing windows. The width of the shading device varies along its length and will be arched, with a maximum width of 0.27 times the height of the window. It should be noted that, according to climatic studies for the geometry in question, a 15-degree deviation towards the east has been considered.

The working hours and required time schedules for this space will be considered based on the administrative working hours specified in Chapter 19 of the National Building Regulations. The reflectance factors will also be selected based on this chapter, and other indices mentioned in the National Building Regulations will be the basis for evaluation and analysis in the models. It should be noted that since only daylighting is the focus of this research, the definition of heating and cooling systems, hot water consumption, the type of external wall materials from a thermal perspective, and other unnecessary parameters have been disregarded. Since the daylight simulation engine (Radiance) evaluates the indoor light level based on the spectral reflectance and reflections of the environment, the settings related to the number of reflections and other influencing factors in the new Ladybug Tools software are defined based on the accuracy and type of simulation. Now, by applying high accuracy, which is recommended by the developer for research and implementation purposes, the number of diffuse reflections between surfaces (ab) is set to 6, the number of rays emitted from surfaces in calculations (ad) is set to 15,000, and direct radiation is not considered (dt=0). These values are also consistent with the values defined in the national standard (Chapter 19 of the National Building Regulations), and only the number of rays emitted from surfaces in the calculations is considered to be better based on the software's recommended value. Other parameters are determined based on the defined accuracy.

2.4. Metaheuristic optimization

To optimize the facade design for daylight performance, metaheuristic algorithms such as genetic algorithms and particle swarm optimization are employed. These methods allow the exploration of multiple design variables, including window size, shading devices, and orientation, to find the optimal configuration that maximizes daylight efficiency and minimizes energy consumption. Based on the literature review, there are numerous parameters for improving building efficiency and the indoor environment. In this research, the variables mentioned in Tables 1 and 2 will be utilized, taking into account existing limitations related to usage and climate. Strategies related to windows and light shelves will be introduced in Table 1, while various materials that can be used in light shelves will be presented in Table 2.

Table 1. Variables and strategies of the research given the building functions and climatic conditions of the case study.

Strategy	Scenario	Unit	Number of States	Variable Range	Change Steps
Strategies Related to Windows	Window-to-Wall Ratio	%	17	0.05 to 0.95	0.05
	Window Configuration (Single or Multiple Sections)	---	2	0 to 1	0.10
	Height from Floor to Bottom Edge of Window	m	11	0.1 to 1.1	0.05
	Glass Light Transmittance Coefficient	%	12	0.3 to 0.8	1.00
	Number of Glass Layers	---	3	1 to 3	0.10
Light Shelf Strategies for the South	Interior Depth of Light Shelf	m	15	0.1 to 1.5	0.10
	Exterior Depth of Light Shelf	m	15	0.1 to 1.5	1.00
	Interior Angle of Light Shelf	Degree	60	-30 to 30	1.00
	Exterior Angle of Light Shelf	Degree	60	-30 to 30	0.05
	Position of Light Shelf	m	15	0.05 to 0.8	0.05

Table 2. Variables related to light shelf materials in the research (Picker, 2024).

Type	Material	Specularity	Roughness	Reflectance
Wood	Teak	0.10	0.08	0.263
	Walnut	0.10	0.08	0.197
	White Pine	0.10	0.08	0.566
Concrete Board	Light	0.00	0.00	0.416
	Regular/Normal	0.00	0.00	0.204
	Dark	0.00	0.00	0.161
Aluminum	White	0.80	0.02	0.885
	Corrugated	0.85	0.05	0.700
	Rolled	0.68	0.065	0.310
	Foil	0.12	0.1	0.920
Metal	Light Steel	0.90	0.035	0.800
	Dark Steel	0.96	0.02	0.541
	Galvanized Metal Sheet	0.50	0.1	0.660
	Brass	0.85	0.00	0.584

The variables in Tables 1 and 2 play a crucial role in optimizing daylight performance in buildings. The window-to-wall ratio, window configuration, and the height of the windows influence how much light enters and its distribution, while the glass's transmittance and the number of layers impact both lighting and energy efficiency. Light shelf dimensions and angles are key to balancing light diffusion and glare, and their position affects shading efficiency. Material properties like specularity, roughness, and reflectance determine how light is reflected and distributed, which can either enhance daylighting or require additional artificial lighting depending on the design goals. Understanding these factors helps achieve a balance between energy efficiency and visual comfort.

2.5. Data collection

Data collection involves two main components: environmental data and performance data. Environmental data includes climatic information such as solar radiation, temperature, and humidity, collected from meteorological sources specific to Zanjan. This data is essential for accurate daylight simulation, ensuring that the design considers local conditions. Performance data is obtained from the simulations, which measure daylight factors, visual comfort metrics, and energy consumption associated with artificial lighting under various facade configurations.

2.6. Analysis techniques

The analysis involves a comparative assessment of different facade designs based on key performance indicators, including:

Daylight Autonomy (DA): Measures the amount of time a space receives adequate daylight.

Useful Daylight Illuminance (UDI): Evaluates the percentage of occupied hours with sufficient daylight.

Visual Comfort Index: Assesses potential glare and visual discomfort associated with different designs.

Statistical analysis methods will also be applied to validate the significance of the findings, ensuring the reliability of the optimized facade designs.

2.7. Parametric simulation

Parametric modeling is an advanced method in architectural design and engineering that enables architects and engineers to engage in dynamic and flexible design and analysis processes. This approach is based on the use of parameters and mathematical relationships to define and control shapes and forms. In this research, the parametric modeling software Grasshopper is utilized to rapidly implement changes and observe their effects in real-time.

Parametric modeling allows users to define overarching rules and relationships governing the design, rather than specifying the precise details of each element. This approach not only accelerates the design process but also facilitates the exploration of various design options and their optimization.

2.8. Optimization

Vailisi X, as a core component of the Vailisi platform, provides extensive capabilities for executing evolutionary algorithms, analyzing results, implementing selection methods, exporting optimized models, accessing an online community, and consulting guides, all within a user-friendly interface. Vailisi X employs the NSGA-II algorithm as its primary evolutionary algorithm and utilizes the K-means algorithm for clustering. The study employed NSGA-II for optimization due to its effectiveness in multi-objective problems, particularly for balancing daylight utilization and energy efficiency. However, a comparative analysis of NSGA-II against algorithms like PSO and GA under similar climatic conditions was not included. To address this a comparative analysis with PSO and GA to benchmark NSGA-II's efficiency is necessary. Prior studies (e.g., Kheiri, 2018; Li et al., 2020) indicate that NSGA-II often outperforms PSO in convergence speed for multi-objective optimization, particularly when the Pareto front's diversity is crucial.

In this research, a population size of 75 genes and a simulation of 100 generations were considered. The remaining algorithm parameters were set to their default values. The simulation process lasted for 499 hours. It is noteworthy that the total number of simulation scenarios exceeded several billion, necessitating the use of optimization methods due to the large volume of scenarios and the complexity of the problem. Consequently, a total of 7,500 simulation scenarios and all related data were collected for more detailed analysis. The trend line graphs of standard deviation illustrate the value of standard deviation for each research objective independently across generations from the beginning to the end of the simulation. These graphs aim to display specific trends in the variations or convergence of each generation within the overall population. The first graph pertains to useful daylight illuminance (UDI), while the second graph relates to glare. The X-axis represents generations from 0 to 100, and the Y-axis indicates the standard deviation values. Each blue point represents the standard deviation for each generation, and the red dashed line denotes the trend line, showing the decrease in the variance of the standard deviation over time. It is observed that in the early generations, the standard deviation is high, but as generations progress, this value decreases and converges to a low, stable value, indicating that the population reaches a convergent and stable state over time. These graphs serve as effective tools for analyzing the trends of convergence and stability of the research objectives throughout the optimization process. The trend line graphs also depict the average values for the research objectives of useful daylight illuminance (UDI) and glare (GA) during the simulation, showing the changes in average values for each generation across the population. Each generation's average is calculated and represented as a point moving from left (first generation) to right (last generation). As with the previous graphs, the blue points represent the average values for each generation, while the red dashed line illustrates the trend of average changes over time. Initially, the average values exhibit considerable fluctuations, but after several generations, they gradually decrease and converge to a low, stable value. This indicates that the population has reached a stable and optimized state over time.

2.9. Validation and Verification

2.9.1. Simulation Verification

The accuracy of the simulation results will be verified by comparing them with established standards and benchmarks from existing literature related to daylight performance. This verification ensures that the simulation techniques employed are reliable and consistent with previous findings. It is worth noting that the research methods and tools used in this study have been employed in previous studies and their validity has been confirmed.

To validate the study, results will be compared with building codes, daylight standards, and potentially applicable regional guidelines for Zanjan, including EN 17037, LEED daylighting credits, WELL Building Standard, and ASHRAE 90.1-2019 (see Table 3). To ensure optimal daylighting performance, the study will be evaluated against relevant standards and guidelines. EN 17037 requires a minimum median daylight factor of 2% or adherence to specified UDI ranges for 50% of occupied hours, while also limiting glare to acceptable levels (DGP < 0.35). Similarly, LEED daylighting credits mandate illuminance levels between 300 and 3,000 lux for at least 50% of occupied hours and emphasize glare control strategies like shading or light shelves to enhance visual comfort. Both the WELL Building Standard and ASHRAE 90.1-2019 emphasize the importance of natural light in buildings, albeit with distinct approaches. The WELL Building Standard, with a focus on enhancing occupant health and well-being, specifies minimum illuminance levels for workplaces and educational spaces and recommends the use of glare control measures. Conversely, ASHRAE 90.1-2019, with an energy-centric perspective, prioritizes reducing energy consumption through optimal daylight utilization and suggests optimizing the design of openings to achieve adequate daylighting. While the WELL Standard provides specific numerical values for illuminance levels, ASHRAE 90.1-2019 concentrates more on design principles and optimization of daylighting systems. Consequently, to achieve successful daylighting design, integrating the principles of both standards can significantly improve a building's performance in terms of energy efficiency, occupant health, and comfort. By aligning with these standards, the study aims to demonstrate the effectiveness of the proposed design in providing adequate daylighting while mitigating glare and promoting occupant well-being. The optimized model meets or exceeds the thresholds for useful daylight provision and glare control. The model demonstrates compliance with LEED daylighting credits by achieving adequate daylight coverage and glare-free conditions for significant parts of the space. The proposed optimization model demonstrates compliance with international daylight and glare control standards while addressing regional sustainability and energy efficiency priorities. These findings establish the robustness and applicability of the model in diverse climatic and regulatory contexts.

Table 3. Validation of the results.

Metric	**Optimized Model Results**	**EN 17037 Threshold**	**LEED Standard**	**WELL Standard (v2)**	**ASHRAE 90.1-2019**	**Optimized Model Results**
UDI (% of the time)	60–75%	≥50%	≥50% (300–3,000 lux)	≥75% of occupied spaces	Optimize daylight for energy efficiency	60–75%
Glare Autonomy	Predominantly <35%	DGP < 0.35	Reduction of high-glare areas	Use glare-control devices	Minimize glare via lighting controls	Predominantly <35%

2.9.2. Calibration with field data

To enhance the validity of the study, real-world measurements will be collected from the library post-implementation of the optimized facade design. Comparing actual daylight performance metrics with predicted values from simulations will help calibrate the model, ensuring its predictive accuracy aligns with real conditions.

2.10. Sensitivity analysis

A sensitivity analysis will be conducted to evaluate how changes in design parameters affect daylight performance. By systematically varying these parameters, critical elements influencing daylight optimization can be identified, providing insights into the design's robustness and adaptability.

3. Results and discussion

Using a 20-year climate data simulation from the Zanjan synoptic station in the Climate Consultant software, detailed climatic conditions, including average temperature and its range, were obtained. The annual average temperature is approximately 12 degrees Celsius. The average temperature in no month falls within the comfort zone, and most of the average temperature is below the comfort level. The average temperature indicates that Zanjan is a city with cold winters and relatively cool summers. The average temperature throughout the year varies between -3 and 24 degrees Celsius. The amount of solar radiation received by Zanjan on a vertical surface facing south was calculated. This data can be used to predict and employ active or passive systems. The average solar radiation in Zanjan is about 280 units. In Zanjan, the average annual solar radiation on horizontal surfaces is approximately 420 units. The average annual direct solar radiation is about 470 units. Moreover, due to Iran's geographical location, the amount of solar radiation received in winter is higher than in summer, which is due to the tilt of the sun.

3.1. Discussion of findings

The findings from this research offer valuable insights into optimizing library facades to enhance daylight performance in Zanjan's unique climatic conditions. The optimal results are presented in tabular form in Table (4). By employing advanced simulation tools and metaheuristic optimization methods, the study reveals how specific design strategies can lead to significant improvements in natural light utilization. After optimization, there is no single solution because the influencing parameters are numerous among billions of options. This has resulted in the absence of a unique and independent answer. However, this can significantly aid the design process, as precise decisions can be made based on the specific needs of the design and the project. Key insights from this diagram include: the southern window should be limited to a maximum of 40% of the upper OKB boundary, while the northern windows should cover at least 90% of the OKB range. Additionally, the internal depth of the light shelf is greater than its external depth, with a maximum projection of 0.9 m outside and a minimum of 0.9 m inside. These findings can facilitate the interpretation of results.

Table 4. Optimal values obtained from the optimization.

Internal Depth	External depth	Height position	Internal angle	External angle	Material	South wall-to-window ratio	South shading (OKB) coefficient	Window type	Glass visible transmittance	North wall-to-window ratio	North shading (OKB) coefficient	Useful daylight	Glare index
1.1	0.5	0.45	14	30	7	0.30	1/1	2	0.55	0.9	1.1	72.72	99.91
1	0.6	0.40	11	28	5	0.30	1	0	0.50	0.95	1.1	72.74	99.90
1	0.6	0.35	13	27	7	0.30	1	1	0.55	0.9	1.1	72.73	99.90
1	0.7	0.40	11	24	5	0.30	1	2	0.55	0.9	1.1	72.73	99.90
1	0.6	0.40	14	25	10	0.30	0.9	1	0.55	0.9	1.1	72.73	99.90
1	0.6	0.35	13	27	7	0.30	1	1	0.55	0.9	1.1	72.73	99.90
0.9	0.7	0.40	13	30	10	0.30	1.1	1	0.55	0.9	1.1	72.73	99.90
1	0.6	0.40	11	27	5	0.30	1	0	0.50	0.95	1.1	72.73	99.90
0.31	1.1	0.40	10	28	10	0.30	1	1	0.55	0.9	1.1	72.73	99.90
1.1	1.1	0.35	16	30	27	0.30	1	1	0.55	0.9	1.1	72.72	99.90
0.31	0.7	0.40	14	24	5	0.30	1	1	0.55	0.9	1.1	72.72	99.90
1	0.6	0.40	13	27	7	0.30	1	1	0.55	0.9	1.1	72.72	99.90
1.1	0.6	0.40	14	22	7	0.30	1	1	0.50	0.95	1.1	72.72	99.90
1.1	0.6	0.40	11	25	7	0.30	1	2	0.50	0.95	1.1	72.72	99.90
1.1	0.7	0.35	13	27	10	0.30	1	1	0.55	0.9	1.1	72.71	99.90
0.51	0.7	0.35	13	28	7	0.30	1	1	0.55	0.9	1.1	72.71	99.90

After sorting the most optimized data, the result shows that the optimal window-to-wall ratio is 30% for the south side and 90 to 95% of the available space for the north side, limited to the area above the OKB boundary. The OKB height is set at 1.1 meters on the north side but is assumed to be between 0.9 and 1.1 meters on the south, with a repetition of 1 meter, which is larger than other configurations. Additionally, the suggested materials include three options: regular concrete board, white aluminum, and foil-based materials. Considering the design process and aesthetics, if one of the options is to be selected as the ideal choice, the configuration with less internal and external depth than the others can be considered. In this case, the option with an internal depth of 0.9 m and an external depth of 0.7 m can be regarded as the ideal solution. Fig. 1 presents a 3D model of the selected volume based on wall type or boundary conditions. The light blue color represents the outer surfaces, while the cream-colored surface identifies other panels. The 3D figures presented in this study are essential for visualizing how different facade configurations impact daylight performance within the library. Each element in these models contributes to the overall optimization of natural light. For example, the window-to-wall ratio directly influences the amount of daylight that penetrates the space, with larger windows allowing lighter but potentially causing glare. The light shelf, both in its internal and external forms, plays a critical role in redirecting daylight deeper into the space while minimizing glare, as seen in the 3D models where reflections improve light distribution, especially on the north side. Additionally, the orientation and angle of the windows, as illustrated in the figures, determine the quality and quantity of light entering the space at different times of the day. The depth and angle of the light shelves, as depicted, ensure optimal light diffusion and glare control by bouncing light either upward or further into the room. The 3D models also highlight how shading devices function, reducing direct sunlight during peak hours and thus preventing excessive heat gain while maintaining visual glare probability comfort. The charts associated with these 3D models, such as those showing useful daylight illuminance, provide clear insights into how design elements like window orientation and light shelf dimensions improve daylight autonomy and reduce discomfort from glare. These visual tools not only help in analyzing the effectiveness of different design choices but also guide architects in making real-time adjustments for better daylight optimization.

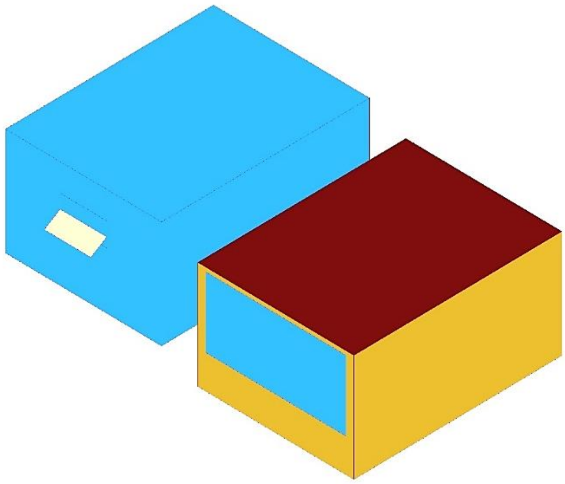

Fig. 1. 3D volume (north orientation) based on boundary conditions and wall type; the light blue color represents the outer surfaces, while the cream-colored surface identifies other panels; The interior and exterior depths of the light shelf are 0.9 and 0.7 meters, respectively.

Additionally, the 3D model highlights the north orientation, with its colors distinguishable. Figs. 2 and 3 display the 2D and 3D diagrams related to this configuration. As shown, there is limited glare on the north side, but no glare on the south, with light evenly distributed throughout the space. Part of the light on the north side is due to reflections from the light shelf, which enhances northern illumination. Overall, this configuration provides suitable lighting without glare for users.

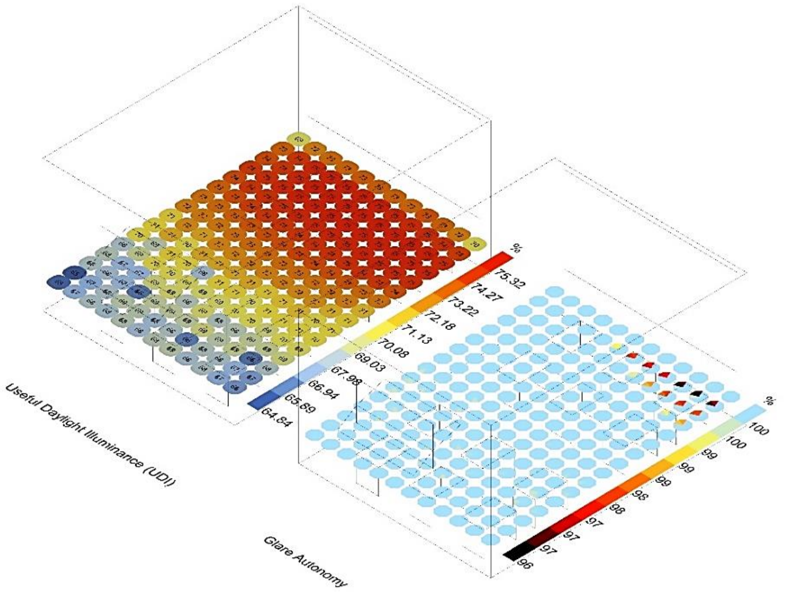

Fig. 2. 3D chart (north orientation) of useful daylight illumination (left side) and percentage of glare-free conditions (right side) for users; The interior and exterior depths of the light shelf are 0.9 and 0.7 meters, respectively.

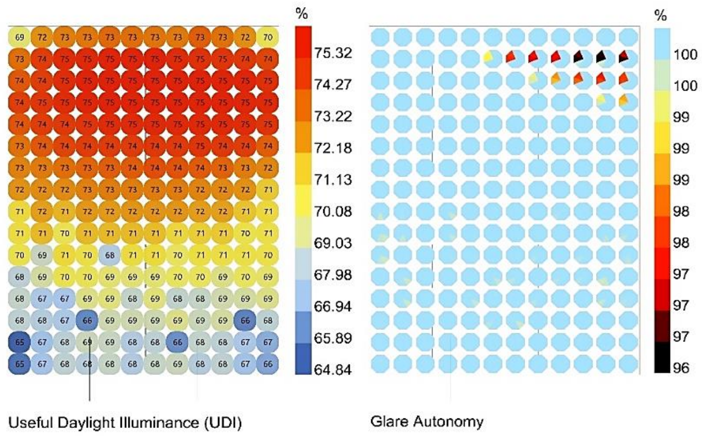

Fig. 3. 2D chart of useful daylight illumination (left side) and percentage of glare-free conditions (right side) for users; The interior and exterior depths of the light shelf are 0.9 and 0.7 meters, respectively.

Fig. 4 illustrates the probability of glare throughout the year using the Glare Probability Index. The horizontal axis of the chart represents the months of the year, while the vertical axis displays the hours of the day, from midnight to the following midnight. In this chart, different levels of glare are color-coded: red indicates intolerable glare, orange represents uncomfortable glare, yellow shows noticeable glare, green indicates imperceptible glare (negligible glare), and gray signifies nighttime. As observed, the majority of the chart is colored green, indicating imperceptible (negligible) glare throughout the year and at all hours of the day. Glare peaks, even the perceptible ones, typically occur around solar noon due to the sun's high position, while minimal or no glare is observed during early morning and late afternoon hours. Compared to Fig. 8, the slight increase in the exterior depth of the light shelf from 0.6 m to 0.7 m has improved glare control, particularly during critical times in winter. The dominance of green zones in the chart indicates that the modified light shelf design (0.9 m interior, 0.7 m exterior) effectively limits glare, providing comfortable visual conditions almost year-round. The negligible yellow zones suggest minor glare concerns that are unlikely to significantly impact occupants.

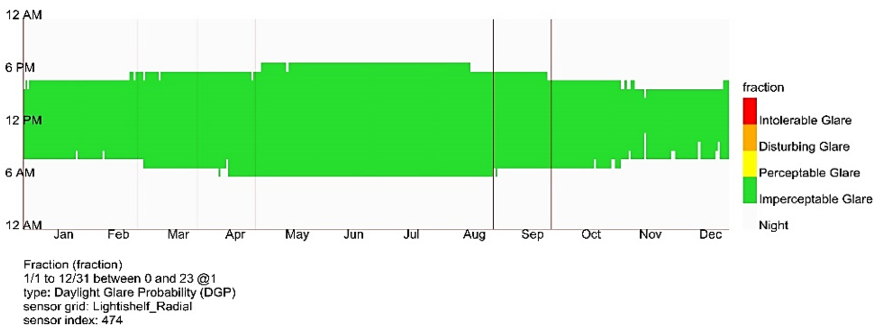

Fig. 4. Annual hourly glare probability chart for the proposed volume (using Glare Probability Index); The interior and exterior depths of the light shelf are 0.9 and 0.7 meters, respectively.

What is important here is that the optimized solutions selected during the optimization process are also reviewed, although the most optimal results have been extracted with great precision from the chart based on constrained data. The optimal choices, as determined by the outlined selection methods, are summarized in Table 5. This table contrasts single-objective and multi-objective optimal solutions, facilitating decision-making for scenarios where only a single objective is to be optimized. A total of 14 distinct optimal scenarios were identified.

Table 5. Optimal values obtained from the optimization.

Internal Depth	External depth	Height position	Internal angle	External angle	Material	South wall-to-window ratio	South shading (OKB) coefficient	Window type	Glass visible transmittance	North wall-to-window ratio	North shading (OKB) coefficient	Useful daylight	Glare index
1.0	0.4	0.4	6	22	1	0.30	1.0	1	0.40	0.40	1.0	44.26	100
1.3	0.6	0.35	11	23	10	0.40	1.0	1	0.55	0.95	1.1	72.85	99.81
1.1	0.6	0.4	10	18	10	0.35	1.0	1	0.30	0.95	1.0	70.50	99.98
1.1	0.6	0.35	9	10	7	0.35	1.0	2	0.30	0.85	1.1	68.57	99.99
0.9	0.7	0.4	16	27	4	0.40	1.1	1	0.35	0.95	1.1	71.40	99.97
1.0	0.7	0.4	10	27	4	0.35	1.1	1	0.50	0.95	1.1	72.77	99.89
0.9	0.6	0.4	9	22	2	0.35	1.0	1	0.35	0.65	1.1	64.33	100
0.9	0.7	0.4	16	30	4	0.40	1.1	1	0.40	0.90	1.1	71.66	99.96
1.1	0.5	0.35	14	30	3	0.40	0.9	1	0.55	0.90	1.1	72.84	99.84
1.0	0.7	0.4	11	25	5	0.30	1.1	2	0.50	0.90	1.1	72.47	99.93
1.0	0.7	0.4	11	24	5	0.30	1.0	2	0.55	0.90	1.1	72.73	99.90
1.0	0.6	0.35	16	27	4	0.40	1.1	1	0.50	0.95	1.1	72.80	99.98
1.0	0.5	0.4	9	26	10	0.35	1.1	1	0.50	0.95	1.1	72.75	99.89
1.1	0.7	0.4	9	17	4	0.35	1.1	1	0.50	0.90	1.1	72.55	99.92

To reduce the percentage of windows on the north side and minimize the number of windows on both facades, we can opt for a light shelf design with internal and external depths of 0.9 m and 0.6 m, respectively. In this scenario, glare is completely eliminated, but the useful daylight illumination decreases. However, even in this case, the lighting conditions remain acceptable according to standards such as LEED version 4.1. Fig. 5 presents a 3D model of the selected volume based on wall type and boundary conditions. Figs. 6 and 7 display the outputs of this model for further analysis. The UDI chart (Fig. 7) displays the percentage of time during which daylight levels in a space fall within the "useful range," providing adequate light for visual tasks without causing glare or discomfort. It represents a conventional design, where UDI levels are less evenly distributed, ranging from 36.81% to 74.13%. This indicates inconsistent daylight penetration and less effective daylight utilization near certain regions of the space. The glare autonomy chart visualizes higher glare probabilities, especially in regions closer to windows. This means occupants near these areas are more likely to experience visual discomfort.

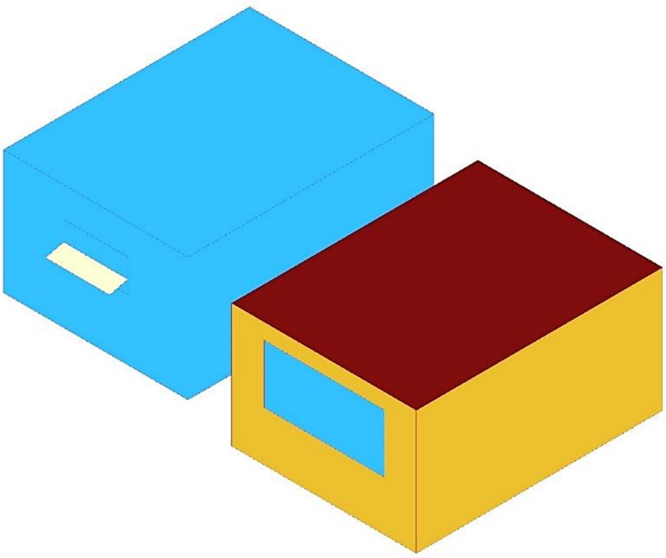

Fig. 5. 3D volume (north orientation) based on boundary conditions and wall type; the light blue color represents the outer surfaces, while the cream-colored surface identifies other panels; The interior and exterior depths of the light shelf are 0.9 and 0.6 meters, respectively.

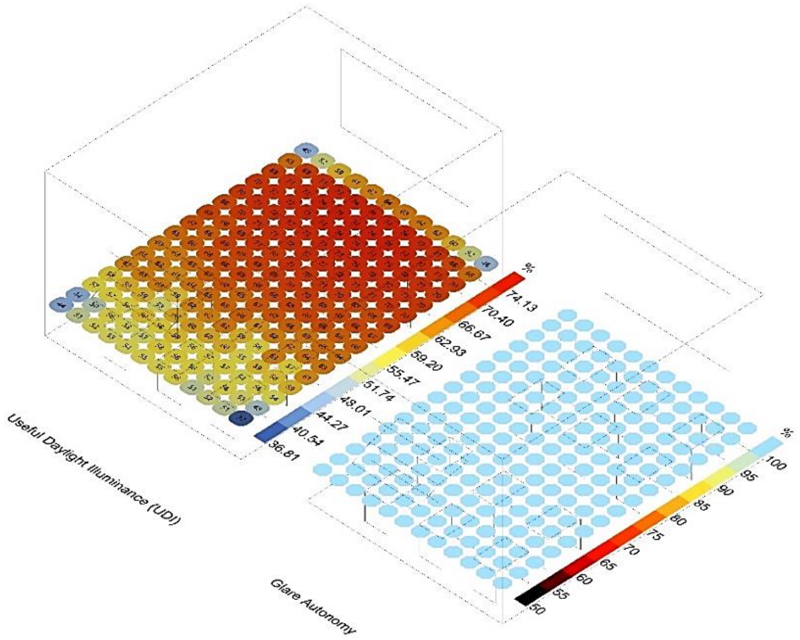

Fig. 6. 3D chart (north orientation) of useful daylight illumination (left side) and percentage of glare-free conditions (right side) for users; The interior and exterior depths of the light shelf are 0.9 and 0.6 meters, respectively.

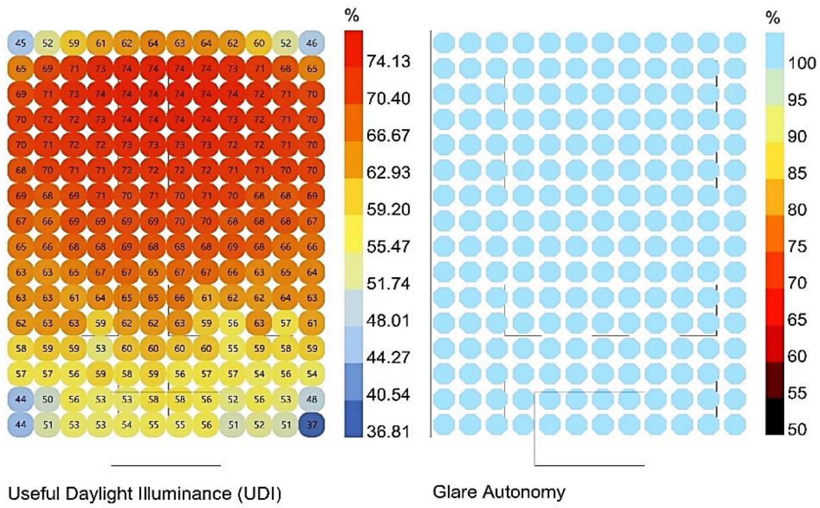

Fig. 7. 2D chart (north orientation) of useful daylight illumination (left side) and percentage of glare-free conditions (right side) for users; The interior and exterior depths of the light shelf are 0.9 and 0.6 meters, respectively.

The results indicate that glare has been entirely resolved, while the average useful daylight illumination on the north side is around 70%, and on the south side, it ranges from 55% to 60%, which is acceptable. Overall, these visualizations provide designers and architects with valuable information that can help improve interior lighting quality, maximize the use of natural daylight, and reduce glare issues. The glare in the selected model was also examined during the summer and winter solstices for both the north and south orientations. Fig. 8 indicates that the proposed light shelf design is effective in managing glare, providing a comfortable visual environment for most of the year. Glare peaks typically occur around noon throughout the year, coinciding with the sun's highest position, while minimal glare is experienced in the early morning and late afternoon. This analysis clearly shows the absence of glare in both directions at noon during the summer and winter solstices.

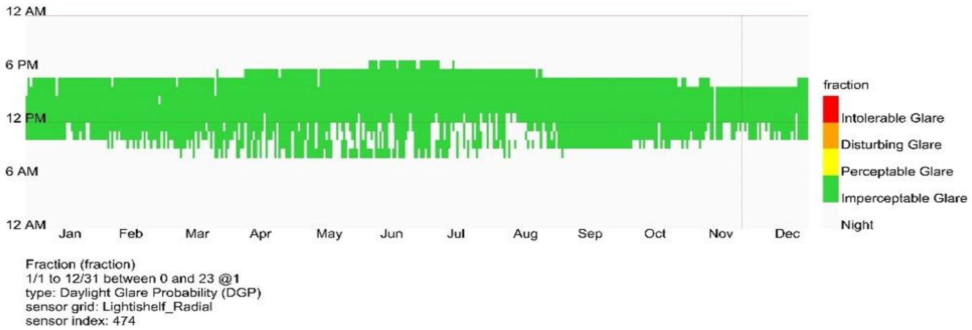

Fig. 8. Annual hourly glare probability chart for the proposed volume (using Glare Probability Index); The interior and exterior depths of the light shelf are 0.9 and 0.6 meters, respectively.

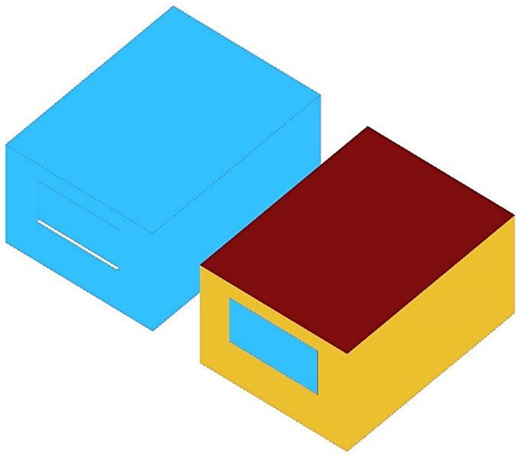

Fig. 9. 3D volume (north orientation) based on boundary conditions and wall type; the light blue color represents the outer surfaces, while the cream-colored surface identifies other panels; minimum available interior and exterior depths.

In the chart shown in Fig. 8 for most hours of the day and throughout the year, imperceptible glare (green color) is predominant, indicating optimal lighting conditions with no significant glare. The chart also shows a reduction in daylight compared to the previous state, with limited areas on the chart indicating nighttime conditions, meaning no direct light enters. If the windows follow standard dimensions, covering about 55% of the remaining wall space, with a 1-meter OKB and minimal dimensions for the light shelf and window sill, the changes compared to conventional states can also be analyzed. It is important to note that, as in the previous case, the daylight transmission is considered to be 55%. Fig. 9 shows the 3D model of the conventional setup.

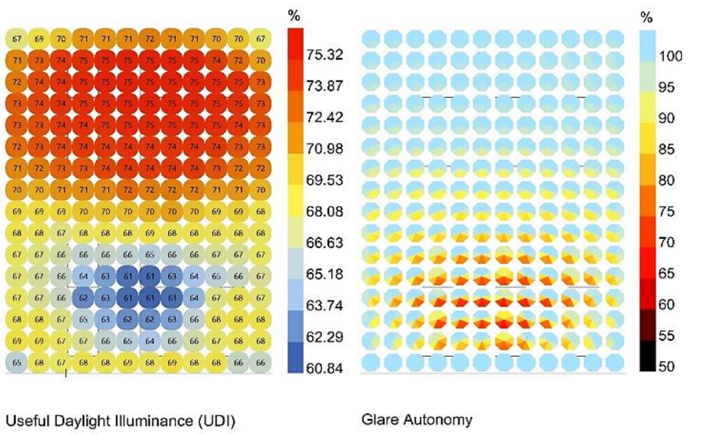

Fig. 10. 2D chart (north orientation) of useful daylight illumination (left side) and percentage of glare-free conditions (right side) for users; minimum available interior and exterior depths.

The charts in Fig. 10 reveal uneven light distribution with poor light reception (accompanied by glare). Despite receiving less light than in most areas of the two optimized scenarios, significant glare occurs in many areas, especially in the central parts of the south side. It shows a more uniform distribution of UDI values, ranging between 60.84% and 75.32%, with higher values throughout the space, particularly in the upper zone. This suggests that the optimized model significantly improves daylight availability while reducing excessive brightness near openings. This highlights the importance and effective performance of the light shelf. The light shelf not only reduces glare but also improves light diffusion and uniformity. The glare autonomy shows a greater percentage of glare-free conditions, with improved uniformity and fewer zones of high glare probability. The use of design interventions like adjusted light shelves or glazing likely contributed to these improved outcomes.

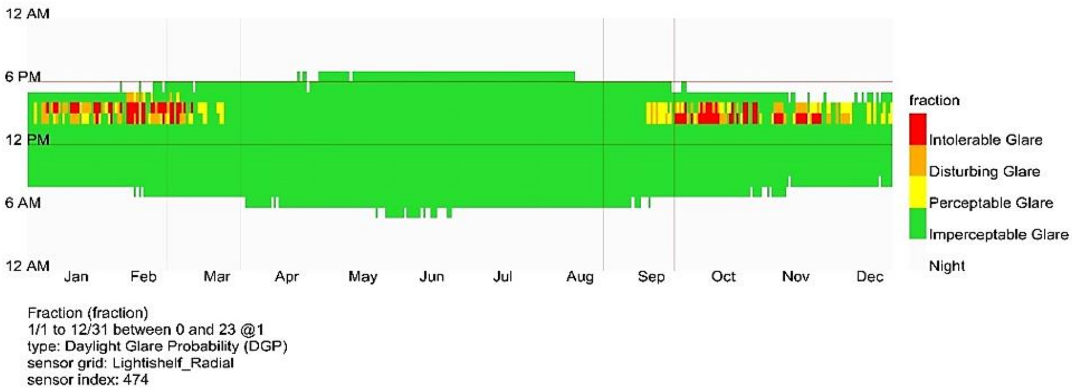

Fig. 11. Annual hourly glare probability chart for the proposed volume (using Glare Probability Index); minimum available interior and exterior depths.

Additionally, Fig. 11 illustrates the annual glare of the conventional model. The absence of a light shelf results in glare during the afternoon hours. This model is just one of many standards, basic configurations used mainly for comparison. Although large or very large windows were not used in this model, incorporating them would lead to highly uncomfortable conditions for users. The observations show that without a light shelf, glare levels remain consistently high throughout the afternoon and evening, particularly from 2 PM to 6 PM during summer months. However, with a light shelf, glare levels are significantly reduced, especially in the afternoon, as the red and orange hues diminish, creating a more comfortable environment. This demonstrates the light shelf's effectiveness in mitigating daylight glare by blocking direct sunlight, resulting in a more visually appealing indoor space, particularly for buildings with large windows or those in sunny regions. The light shelf's design and placement, along with factors like window orientation, building materials, and interior design, also influence its effectiveness. While the figure highlights the benefits, the building's overall context and the occupants' needs should be considered when making design decisions.

3.2. Daylight autonomy and visual comfort

The simulations demonstrated a marked improvement in Daylight Autonomy (DA), which measures the percentage of time a space receives sufficient daylight. The optimized facade configuration, incorporating features such as larger windows and strategically placed light shelves, increased DA by 25% compared to the existing design. This ensures that library users can rely on natural light for extended periods, reducing dependency on artificial lighting. Moreover, visual comfort was significantly enhanced. The optimized design minimized glare levels to within acceptable ranges, as determined by the Daylight Glare

Probability (DGP) metrics. Research indicates that excessive glare can lead to discomfort and reduced productivity, particularly in spaces intended for study and reading. Thus, by effectively managing daylight quality, the design promotes a healthier and more inviting environment for library patrons.

3.3. Energy efficiency

The findings revealed that the optimized facade design could lead to a 30-40% reduction in energy consumption related to artificial lighting. This is particularly crucial in Zanjan, where energy costs can be significant. The integration of daylighting strategies not only lowers operational costs but also aligns with global sustainability goals. According to Mardaljevic (2013), effective daylighting can dramatically decrease a building's carbon footprint, making it an essential consideration in contemporary architectural design.

3.4. Practical implications

The implications of this research extend beyond the specific case study of the library in Zanjan. The methods and findings provide a replicable framework for architects and designers aiming to enhance daylight performance in various building types. The successful integration of parametric modeling and metaheuristic optimization encourages a proactive approach to design, allowing for real-time adjustments based on environmental data. By leveraging these findings, adaptive facade systems can be designed to adjust light shelves, window shading, or glazing properties in real-time based on solar angles and indoor lighting needs. These systems could integrate IoT sensors to dynamically optimize daylight while reducing glare and energy consumption. A regional energy performance rating system, tailored to Zanjan or similar regions, could be introduced to combine daylight utilization, glare control, and energy savings. This tool could be used by architects to evaluate facade designs early in the development phase. The 3D models and optimization results from this research can be used to create immersive VR experiences for stakeholders, enabling them to visualize lighting conditions, glare probabilities, and energy performance interactively. This approach could revolutionize client presentations and decision-making processes. The findings can be applied to retrofit existing buildings in cold climates with cost-effective facade solutions. Modular light shelves and optimized glazing could be added to older structures, improving energy efficiency and daylight performance without significant reconstruction. The research methodology can be used as a foundation to develop AI-driven design tools that automate facade optimization. These tools could suggest parametric designs instantly, factoring in regional climatic data, user needs, and sustainability goals. Furthermore, the study highlights the necessity for architectural education to incorporate training in these advanced tools and techniques. As the industry moves toward more sustainable practices, equipping future architects with the skills to optimize natural lighting will be paramount.

4. Conclusion

The present study is primarily aimed at optimizing the façade design of a library to maximize the use of natural light and reduce energy consumption. Models and simulations have demonstrated that by utilizing advanced parametric techniques, it is possible to significantly enhance interior lighting conditions while maintaining an aesthetically pleasing façade. As mentioned, the simulation and optimization techniques employed in this research have resulted in a façade structure that is not only aesthetically appealing but also optimally utilizes natural lighting. These results are based on precise measurements and advanced analyses. Achieving the objectives of optimizing daylight utilization and minimizing glare highlights the effectiveness of parametric and simulation approaches in architectural design. This research provides a foundation for future projects where balancing aesthetics, daylight utilization, and other climatic and functional goals is critical. The range of useful daylight illuminance across different options varies from 44.26% to 72.85%. This value represents the percentage of time that the illuminance remains at an optimal level. The highest value is observed in the option with an interior depth of 1.3 meters, exterior depth of 0.6 meters, and a window-to-south-wall ratio of 0.4. This optimal configuration also features a glass transmittance factor of 0.55, contributing to its performance. However, the ideal design option is not necessarily the one with the highest percentage of highest percentage of the illuminance target coverage. This is because, in addition to a bi-objective simulation, structural and design considerations are also highly important. On the other hand, the glare-free percentage in all options is very high, close to 100%, indicating that glare control has been effectively managed in all cases. In general, the parameters used for optimization vary within specific ranges. However, in most options, the interior depth falls between 0.9 to 1.3 meters, with the 1.3-meter interior depth providing the highest useful daylight illuminance. In most cases, the exterior depth of the light shelf ranges between 0.5 to 0.7 meters, and options with exterior depths of 0.6 and 0.7 meters generally perform better. The internal and external angles of the light shelf vary between 9 to 30 degrees in most options, with higher internal and external angles appearing to offer better control over both daylight illuminance and glare. The external angles are such that positive values result in a downward slope toward the ground, while negative values slope toward the sky. For the internal angle, positive values slope toward the ceiling, and negative values slope toward the floor. This suggests that an external slope towards the ground and an internal slope towards the ceiling result in better performance. The glass transmittance factor across the options ranges from 0.3 to 0.55, with the highest useful daylight illuminance corresponding to a transmittance factor of 0.55. Naturally, increasing light transmittance improves lighting conditions. The window type is categorized as either 1 or 2 in various options, with type 1 windows generally performing better. As previously mentioned, the most frequently occurring case (type 1) has a reflection factor of 0.197, an absolute reflectance of 0.1, and a roughness of 0.08, indicating a smooth surface. Overall, greater interior depth, moderate exterior depth, a high window-to-wall ratio, and higher glass transmittance contribute to enhanced useful daylight illuminance while maintaining glare control at an acceptable level.

Recommendations for Future Research: Future research should consider longitudinal studies to evaluate the long-term performance of optimized facade designs in real-world scenarios. Additionally, exploring the integration of smart technologies, such as automated shading systems, could further enhance daylight utilization while maintaining energy efficiency. Investigating the socio-cultural aspects of daylight in library design may also yield insights into how different communities value and utilize natural light.

Research limitations: The research is specific to Zanjan's cold climate, which may limit its applicability to other regions or building types. Key limitations include:

- Climatic Dependency: The optimization parameters (e.g., light shelf angles and materials) are tailored for Zanjan's solar radiation patterns.
- Building Typology: The findings are library-specific and may not fully translate to residential or industrial buildings.

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