

Original Research Article

Optimal and Efficient Daylight-Oriented Design of the Library Building Façade Structure Using Simulation

(Case Study: Zanjan City)*

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Abstract | Architectural design faces the ongoing challenge of improving building performance through the optimization of daylight utilization in façades, particularly in cold climates such as that of Zanjan, which nonetheless exhibits a high potential for effective use of natural daylight during periods of high solar radiation. With the overarching objective of designing a library façade structure through daylight simulation and metaheuristic optimization processes to identify optimal models with the highest level of daylight illuminance efficiency, this study addresses the following question: How can simulation and metaheuristic optimization processes be employed in the design of a library façade structure to enhance daylight performance? The Grasshopper parametric modeling environment and the Ladybug Tools plugin were employed for modeling and simulation. Grasshopper's parametric framework enables rapid implementation of design variations and real-time observation of their impacts. In the descriptive-analytical phase, SPSS software was used alongside the Kolmogorov-Smirnov test, Pearson correlation analysis, and Partial Least Squares (PLS) modeling. The findings indicate that an optimal daylighting model with the highest daylight performance and the most appropriate illuminance distribution was achieved using an internal light shelf depth of 1.3 m, an external light shelf depth of 0.6 m, and a glazing light transmittance of 0.55.

Keywords | *Daylight performance, Façade structure, Simulation, Zanjan City, Library.*

Introduction | Optimizing building performance and the effective utilization of daylight, particularly in administrative and public spaces, plays a crucial role in enhancing occupant comfort. The building façade is a key determinant in harnessing natural light, and given the significant daylight potential of Zanjan, this research can contribute to improving façade design quality and daylight performance.

The main hypothesis of this study posits that, by employing simulation and metaheuristic optimization processes based on daylight parameters, the façade structure of a library in the climatic context of Zanjan can be systematically

evaluated and an optimal design pattern can be achieved. Accordingly, and in line with the overarching objective of “designing a library façade structure using daylight simulation and metaheuristic optimization processes to identify optimal models with the highest daylight illuminance efficiency”, the following question is raised: How can simulation and metaheuristic optimization processes be utilized in the design process of a library façade structure to enhance daylight performance? Furthermore, in pursuit of the secondary objective, “studying the geographical characteristics of Zanjan to propose practical and optimal strategies for utilizing natural daylight and achieving appropriate illuminance distribution to enhance daylight performance in libraries”, this study seeks to answer the question: What climatic characteristics of Zanjan (in terms of geographical location and direct and diffuse solar radiation) influence the optimal use of

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daylight in library reading spaces? In addition, to address the secondary objective of “examining the manner and extent to which architectural elements in the design of the library façade structure affect the optimal use of daylight in reading spaces”, the following question is raised: How do the architectural elements of transparent building envelopes influence the quality and quantity of illuminance in library reading spaces?

Literature Background

Nasrollahi & Shokry (2020) presented a study aimed at identifying practical solutions for enhancing daylight utilization in library spaces, examining the role of architectural elements such as window position and dimensions, material reflectance, surface configuration, and spatial proportions. In recent years, the importance of daylighting in building design has increased due to the need to reduce energy consumption and the documented positive effects of natural light on occupants (Freidooni et al., 2022, 2023; Edwards & Torcellini, 2002; Xue, Y., & Liu, 2021; Li, 2010). In library design, the development of appropriate lighting systems and the control of incoming daylight through the façade are essential considerations (Sadri et al., 2024). To address both quantitative and qualitative performance and visual comfort, Yi (2019) employed multi-objective optimization methods to achieve aesthetic improvements in façade design. Numerous studies have investigated the role of architectural elements such as window placement and size, material reflectance, and spatial configuration on daylight utilization (Nasrollahi & Shokry, 2020; Gherri, 2015). Gherri (2015) analyzed daylight performance in library spaces using the DIALux software. In a study on optimizing natural lighting in libraries, Fernandes et al. (2013) proposed three strategies: integrating solar systems, replacing interior and exterior materials with nanomaterials, and employing an Anidolic daylighting system to enhance indoor illumination. Liu et al. (2023) improved the lighting performance of a circular academic library in Shanghai using parametric design methods and the Ladybug plugin. Similarly, Çelik & nan (2023) utilized the Velux Daylight Visualizer to analyze daylight distribution in library environments.

Theoretical Framework

The term *Shākeleh* (façade) refers to the structure or identity of an entity (Amid, 1984). Accordingly, the façade structure of a library refers to the building's frontal configuration, specifically designed to support reading activities and directly influenced by external factors such as daylight. Optimization is defined as a problem with multiple feasible solutions, where the objective is to identify the best possible solution (Moraga et al., 2006; Talbi, 2008). Metaheuristic processes are generally inspired by natural phenomena. In these processes, the specific path toward the solution is not critical;

rather, identifying an optimal or near-optimal solution is sufficient. Although metaheuristic methods typically yield solutions of lower precision compared to exact algorithms, their significantly reduced computation time has led to their widespread adoption in complex optimization problems (Djannaty & Doostdar, 2008).

Research Methodology

The Grasshopper parametric environment and the Ladybug Tools plugin were employed in this study for modeling and simulation. Grasshopper parametric modeling enables rapid implementation of design variations by allowing designers to define governing rules and relationships rather than explicitly modeling every geometric detail. Accordingly, metaheuristic optimization techniques were adopted in this research. In the descriptive-analytical phase, data were initially examined using SPSS, and descriptive statistics for each variable, including mean, standard deviation, and value range, were recorded. Data normality was assessed using the Kolmogorov–Smirnov test; where normality was confirmed, Pearson correlation analysis was conducted. Subsequently, the regression model was analyzed using PLS4, and then the path coefficients, coefficients of determination (R^2), variance inflation factors (VIF), and the statistical significance of relationships were calculated. Finally, an importance–performance matrix of the variables was generated.

Baseline Glare Threshold Standard

Excessive luminance can cause visual discomfort or eye fatigue, and when illuminance exceeds 2000 lux, the probability of glare increases. The Daylight Glare Probability (DGP) index is used to evaluate daylight visual comfort with values interpreted as follows: $\geq 45\%$ intolerable, 40–45% disturbing, 35–40% perceptible, and $< 35\%$ imperceptible (Reinhart & Wienold, 2011).

Discussion

• Optimization variables

Numerous parameters can influence building performance and indoor environmental quality. In this study, considering functional and climatic constraints, the variables presented in Tables 1 & 2 were selected. Table 1 introduces window-related and light-shelf design strategies, while Table 2 presents various materials applicable to light shelves.

• Research context

The study area is located in the cold climate of Zanjan, a mountainous and semi-mountainous region situated between $47^{\circ}9' - 5^{\circ}51' E$ longitude and $35^{\circ}28' - 37^{\circ}15' N$ latitude. Based on prior studies, buildings in Zanjan Province are typically oriented along the north–south axis, with orientations ranging from 15° west to 45° east, positioned outside each other's solar shadows and within wind-shadow zones. The optimal orientation is 15° east (Zamani et al., 2013).

• **Climatic data analysis using climate consultant**

The annual average temperature in Zanjan is approximately 12 °C, and no month falls entirely within the thermal comfort range. The city experiences cold winters and relatively cool summers. Annual mean temperatures range from -3 °C to 24 °C, while the average solar radiation on vertical and horizontal surfaces is approximately 280 W/m²·h and 420 W/m²·h, respectively.

• **Baseline architectural wall and window section**

As illustrated in Fig. 1, with a standard ceiling height and conventional window design, daylight penetrates up to Table 1. Research variables and design strategies. Source: Sadri et al., 2025.

1.5 times the window head height from the floor. The inclusion of a light shelf increases this penetration depth to approximately twice the window head height, thereby enhancing daylight performance and reducing reliance on electric lighting.

• **Library space conditions**

A standard reading room in Zanjan measuring 8 × 6 m with a ceiling height of 4 m was designed as the reference model in this study. Windows were placed in the north and south directions to optimize daylight utilization, while the light shelf was applied

Strategy	Scenario	Unit	Number of States	Value Range	Step
Window-related strategies	Window-to-wall ratio	percent	17	0.05–0.95	0.05
	Single vs. segmented window	–	2	0 or 1	–
	Sill height	cm	11	0.1–1.1	0.1
	Glass visible transmittance	percent	12	0.3–0.8	0.05
	Number of glazing layers	–	3	1–3	1
South-facing light shelf	Internal depth light shelf	m	15	0.1–1.5	0.1
	External depth light shelf	m	15	1.5–0.1	0.1
	Internal angle light shelf	degree	60	-30 to +30	1
	External angle light shelf	degree	60	-30 to +30	1
	Vertical position light shelf	m	15	0.05–0.8	0.05

Table 2. Light shelf material properties. Source: Sadri et al., 2025.

Type	Material	Specularity Coefficient	Roughness Coefficient	Reflectance Coefficient
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
	Standard	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	0.10	0.920
Metal	Bright steel	0.90	0.035	0.800
	Dark steel	0.96	0.02	0.541
	Galvanized sheet	0.50	0.10	0.660
	Brass	0.85	0.00	0.584



Fig. 1. Standard daylight penetration depth for south-facing windows: 1.5 times the window head height for conventional windows and up to 2 times with a light shelf. Source: Luther, 2004.

only to the south-facing window. Spatial dimensions were defined according to Neufert standards (Table 3), with a per-capita area of 2.5 m². Desk spacing was approximately 95 cm, and desk height was at least 75 cm with a minimum width of 90 cm. Chairs were positioned with their backs to the entrance to minimize visual disturbance, while allowing occupants to benefit from both northern and southern daylight. The room's relatively large depth was intentionally selected to enable a more precise evaluation of daylight metrics and the effectiveness of different daylighting strategies.

The unit was assumed to be located 6.4 m above ground level or the third floor, above two office floors, and surrounded by adjacent rooms. Floor-to-floor height was 4 m.

To eliminate the influence of the east and west façades, these elevations were considered opaque. South-facing windows were designed with an azimuth of 230° and an aspect ratio close to 1 to maximize solar penetration during cold seasons (ibid.), and were equipped with curved horizontal overhangs with a depth equal to 0.27 of the window height. North-facing windows were designed as horizontal openings to provide uniform daylight distribution. The entire building was oriented with a 15° eastward deviation (Fig. 2).

Daylight simulation parameters were defined in accordance with Chapter 19 of the Iranian National Building Regulations and Ladybug Tools settings. The simulation employed six diffuse reflections, 15,000 calculation rays, and zero direct sunlight contribution, consistent with national standards.

Wallacei X, the core component of the Wallacei platform, was used to perform evolutionary optimization using the NSGA-II algorithm and K-means clustering for result analysis. A population of 75 individuals over 100 generations was simulated using predefined parameters (crossover probability 0.9, mutation probability 1/n, distribution index 20, and random seed 1). The simulation required approximately 499 hours. Given the billions of possible configurations and the high complexity of the problem, optimization techniques were essential. In total, 7,500 simulation cases and their associated datasets were collected for analysis. Multiple optimization methods, clustering techniques (K-means and hierarchical), and Pareto front analysis were applied in this study to select and evaluate optimal solutions.

Visualization tools such as parallel coordinate plots and standard deviation trend charts (Fig. 3) were used to compare solutions and assess generational convergence.

The charts indicate that the standard deviation of Useful Daylight Illuminance (UDI) and glare was high in early generations but decreased progressively, eventually converging to a small, stable value. This demonstrates population stability and convergence over time (Fig. 4). Mean values also fluctuated initially but gradually stabilized, which indicates convergence toward an optimal solution. Simulation outputs were stored in three categories: light shelf

Table 3. Specifications of the reference reading room. Source: Neufert & Neufert, 2012.

Parameter	Dimension (m)
Study Room width	6.00
Study Room length	8.00
Study Room height	4.00
Entrance height	2.10
Desk length	1.00
Desk width	0.70
Window height	1.50
Entrance Width	2.00
Desk height	0.75
Chair height	0.45

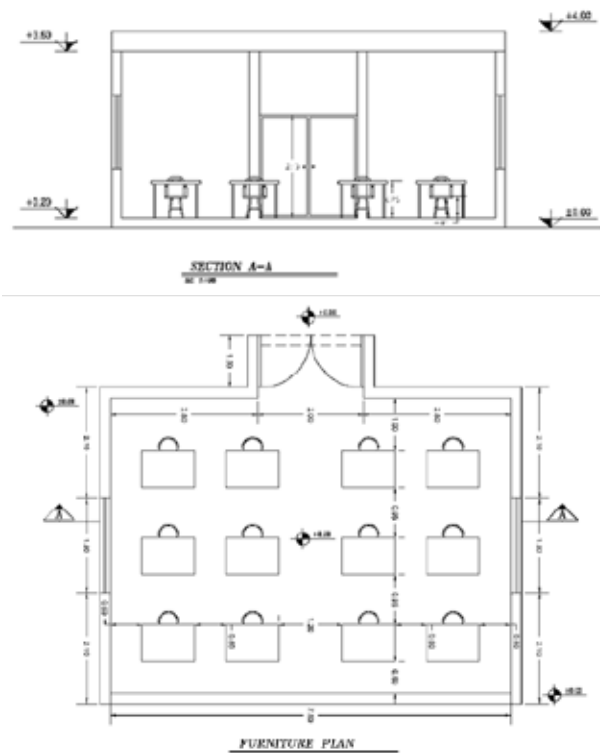


Fig. 2. Plan and geometric section of the reference reading room. Source: Authors.

design parameters, window position and characteristics, and material types.

The second category of objective parameters included UDI and the average percentage of points perceived as glare-free by occupants. Other daylight metrics, such as Daylight Autonomy (DA), Continuous Daylight Autonomy (CDA), Spatial Daylight Autonomy (sDA), and lower and upper UDI thresholds, did not directly influence the optimization process and were used solely for evaluation and data mining. All constrained data were visualized in linear charts (Fig. 5), which can assist designers in manually selecting optimal solutions after optimization by extracting recommended input values. In

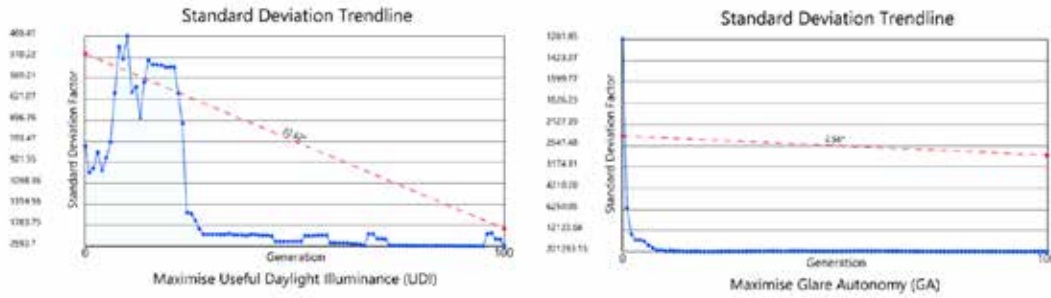


Fig. 3. Standard deviation trend line plots of the objective functions across generations. Source: Authors.

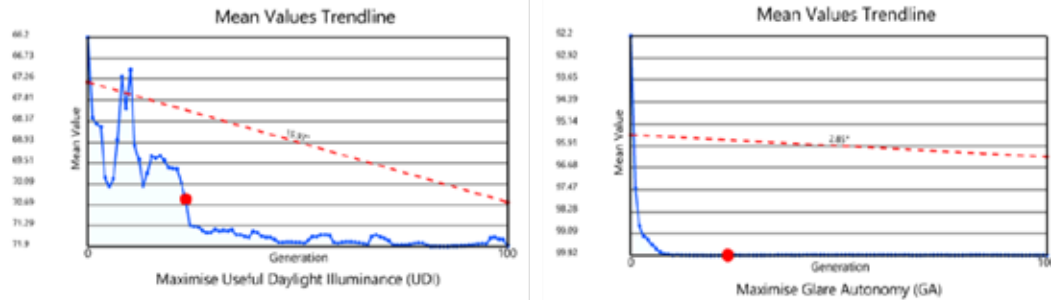


Fig. 4. Mean value trend line plots of the objective functions across generations. Source: Authors.

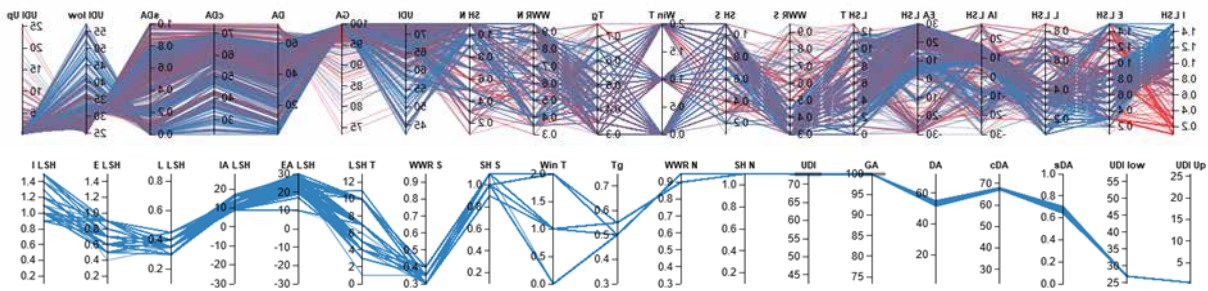


Fig. 5. Line chart of simulation data (top); optimized chart based on maximum useful daylight illuminance and glare-free condition (bottom). Source: Authors.

Fig. 5, data points are distinguished by red and blue colors based on iteration count.

The above chart indicates that the optimization process does not lead to a single unique solution. This is due to the large number of influential parameters among billions of possible configurations, which makes a singular optimal solution unattainable. However, this characteristic can be considered an advantage in the design process, as it enables informed, project-specific decision-making. Based on the results, the following key design guidelines were extracted:

1. For south-facing windows, a maximum of 40% of the window area should be allocated above the sill level.
2. For north-facing windows, at least 90% of the window area should be located above the sill level.
3. The internal depth of the light shelf should exceed the external depth; the maximum external projection should be 90 cm, while the minimum internal projection should also be 90 cm.

Adhering to these criteria enhances result interpretability and significantly improves the accuracy and efficiency of the architectural design process.

Following data processing and optimization, the optimal

window-to-wall ratio was determined to be 30% for the south façade and 90–95% for the north façade. The northern sill height was fixed at 1.1 m, while the southern sill height varied between 0.9 and 1.1 m. Repetition of sill elements at 1 m intervals yielded the best performance.

Regarding materials, three options (concrete board, white aluminum, and foil) were evaluated. Considering both design and aesthetic criteria, the optimal configuration with minimal internal and external depths consisted of a 90 cm internal and 70 cm external light shelf (Fig. 6-a).

As shown in Fig. 6-b, glare on the north façade was limited, while no glare was observed on the south façade. Daylight distribution was uniform, with a portion of northern illumination supplied via reflection from the light shelf. Overall, adequate daylight levels without disturbing glare were achieved in both summer and winter conditions.

To reduce window area on the north façade and limit opening dimensions on both façades, an alternative configuration with internal and external light shelf depths of 90 cm and 60 cm, respectively, was selected. In this scenario, glare was completely eliminated (100%), although UDI decreased. Nevertheless,

daylight levels remained within acceptable standards, such as LEED v4.1 (Fig. 7).

The results indicate that glare is absent during most hours of the day throughout the year, confirming favorable visual comfort conditions free from disturbing glare. However, reduced daylight levels in some areas produced conditions similar to nighttime, reflecting the absence of direct sunlight.

Considering windows covering 55% of the wall area (with a sill height of 1 m) and a light shelf with minimal dimensions located at the sill level, a direct comparison with the conventional configuration becomes possible; the daylight transmittance was likewise maintained at 55%.

In the conventional model, daylight distribution was uneven, leading to glare and excessive brightness, particularly in the central southern zone. The light shelf significantly reduced glare, improved daylight diffusion, and enhanced illuminance uniformity (Fig. 8). In the absence of a light shelf in the conventional model, glare occurred during certain afternoon

hours. This reference model was intentionally designed without oversized windows to avoid excessively adverse lighting conditions.

• **Descriptive-analytical data assessment**

According to Table 4, the highest mean value corresponds to the “external light shelf angle” (21.11), which also exhibits the largest standard deviation (8.294). In the glare-related indicators, the highest mean value (99.779) and the highest standard deviation (99.900) are likewise associated with this variable.

therefore, the assumption of normality is not confirmed (Table 5). Nevertheless, normality was disregarded in this study for two reasons: (1) the sample size exceeds $n > 30$, and (2) the PLS method is not sensitive to deviations from normal distribution.

Given that the variables were measured on an interval scale, Pearson’s correlation coefficient was employed for analysis. The correlation matrix results show that all dependent variables, except “UDI”, exhibit statistically significant correlations with “internal light shelf depth”,

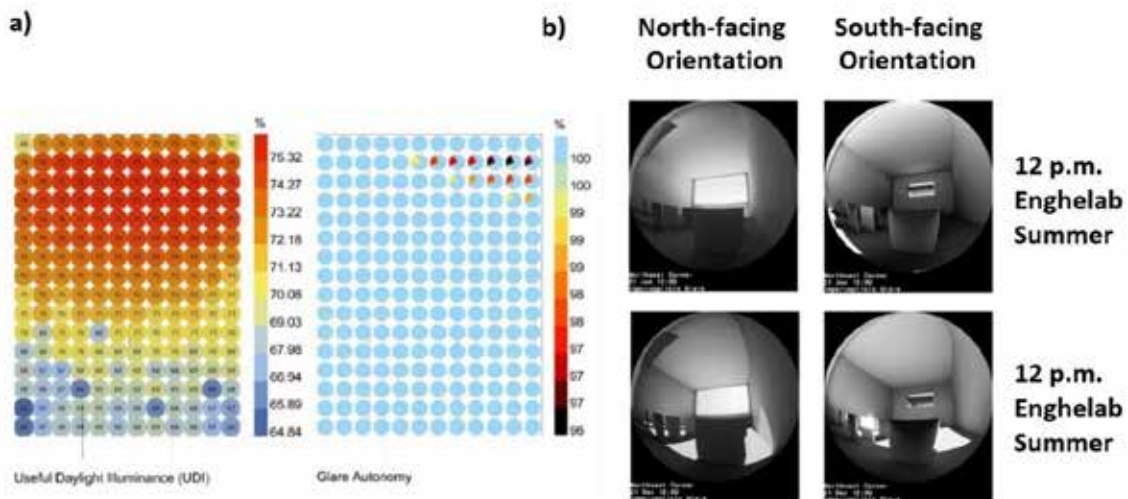


Fig. 6. (a) Two-dimensional plot of useful daylight illuminance and percentage of glare-free occupants; (b) glare conditions during the summer and winter solstices for the north- and south-facing orientations. Source: Authors.

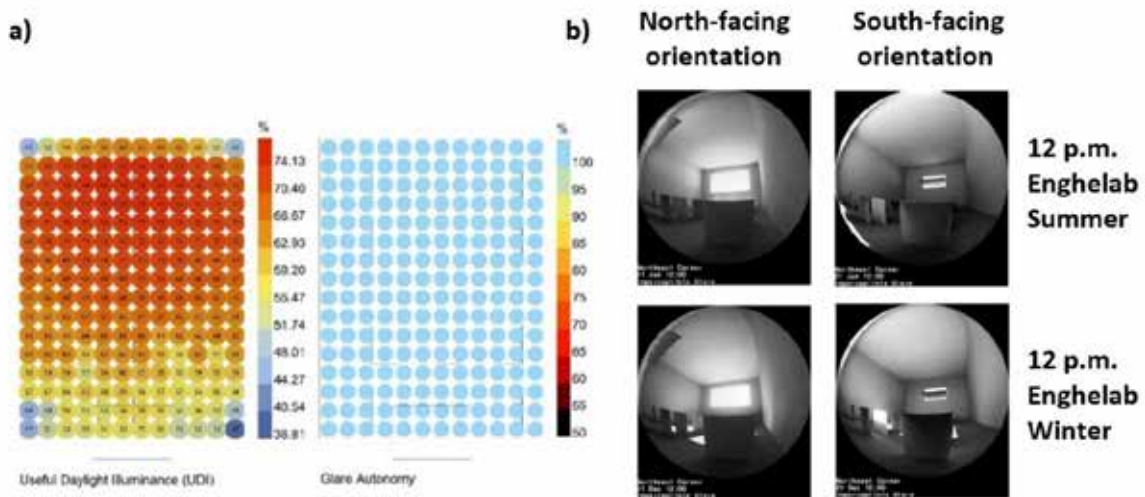


Fig. 7. (a) Two-dimensional plot of useful daylight illuminance and percentage of glare-free occupants; (b) glare conditions during the summer and winter solstices for the north- and south-facing orientations. Source: Authors.

with “glare” (GA) demonstrating the strongest positive correlation ($r = 0.168$). Additionally, all dependent variables, except “CDA” and “UDI_up”, show significant correlations with “external light shelf depth”, where glare presents a strong negative correlation ($r = -0.49$). The independent variable “light shelf position” shows significant negative correlations with “UDI” and “annual glare-free percentage”, while demonstrating a significant positive correlation with “UDI_up”. This variable reports a notable negative correlation ($r = -0.156$) for glare. No other dependent variables show significant relationships with “light shelf position”. The “internal light shelf angle” exhibits statistically significant correlations with all

dependent variables; notably, glare (GA) demonstrates a strong positive correlation ($r = 0.334$). Similarly, the “external light shelf angle” is significantly correlated with all dependent variables, with glare again showing a strong positive correlation ($r = 0.323$). The “light shelf material type” is significantly correlated with all dependent variables, with “spatial daylight autonomy (SDA)” reporting a strong positive correlation ($r = 0.364$).

The independent variable “south window-to-wall ratio (WWRs)” shows significant correlations with all dependent variables, and a strong negative correlation with glare ($r = -0.631$). “South sill height” is significantly correlated with all dependent variables except “DA” and “CDA”, with glare exhibiting a stronger positive correlation ($r = 0.460$) compared to other variables. The “number of glazing layers” also shows significant correlations with all dependent variables.

Although DA shows a negative relationship in some cases, it demonstrates the strongest positive effect overall ($r = 0.725$). Glass visible transmittance and north window-to-wall ratio (WWRN) are significantly correlated with all dependent variables, with the strongest effects observed for DA and UDI ($r = 0.819$). Moreover, “north sill height” is significantly correlated with all dependent variables, with the greatest positive effect reported for glare ($GA = 0.466$).

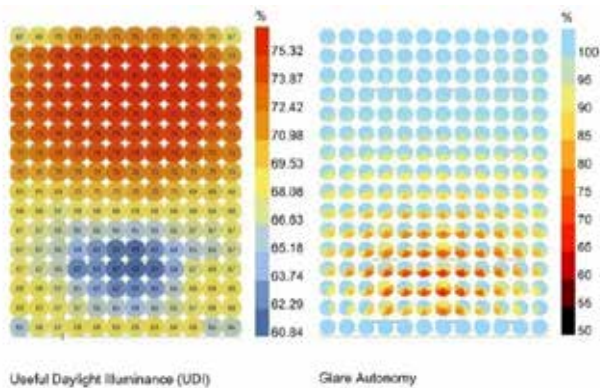


Fig. 8. Two-dimensional plot of useful daylight illuminance and percentage of glare-free occupants. Source: Authors.

Table 4. Distribution of mean values for independent variables. Source: Authors.

Variable	Mean	Standard Deviation	Minimum	Maximum
Internal light shelf depth	1.08	0.19	0.1	1.5
External light shelf depth	0.69	0.187	0.1	1.5
Light shelf position (relative to window height)	0.38	0.685	0.1	0.85
Internal light shelf angle (°)	11.04	4.824	-30.00	28
External light shelf angle (°)	21.11	8.294	30	30
Light shelf material type	6.562	2.578	0	13
South window-to-wall ratio (WWRs)	0.348	0.587	0.3	0.95
South sill height	0.96	0.114	0.1	1.1
Number of glazing layers	1.16	0.644	0	2
Glass visible transmittance coefficient	0.47	0.852	0.3	0.75
North window-to-wall ratio (WWRN)	0.88	0.112	0.3	0.95
North sill height	1.07	0.1	0.1	1.1

Table 5. Distribution of mean values for dependent variables. Source: Authors.

Variable / Index	Mean	Standard Deviation	Minimum	Maximum
Useful Daylight Illuminance (UDI)	71.27	72.748	42.55	72.85
Annual glare-free percentage	99.779	99.9	73.31	100
Daylight Autonomy (DA)	45.741	45.145	0.968	72.69
Continuous Daylight Autonomy (CDA)	63.23	64.088	23.318	74.46
Spatial Daylight Autonomy (sDA)	0.573	0.703	0	1
Lower UDI threshold (UDI_low)	28.35	27.7	24.67	57.36
Upper UDI threshold (UDI_up)	0.363	0.099	0.061	25.594

• **Path coefficient assessment in PLS**

The standardized conceptual model tested using the PLS algorithm and the associated path coefficients are presented in Fig. 9. The strongest path coefficients correspond to the following paths:

- WWRN → CDA = 0.805
- WWRN → UDI = 0.848
- WWRN → UDI_{low} = -0.877

The coefficient of determination (R²), defined as the square of the multiple correlation coefficient, indicates the proportion of variance explained by the independent variables. The R² values for CDA, DA, GA, SDA¹, UDI, UDI_{low}, and UDI_{up} are 0.944, 0.974, 0.944, 0.959, 0.779, 0.820, and 0.546, respectively.

In the importance–performance matrix analysis, DA was selected as the reference index due to its higher coefficient of determination value. Results show that the highest performance is associated with north sill height (SillHN = 97.331), while the highest importance is attributed to north window-to-wall ratio (WWRN = 90.161). Furthermore, glare (GA) demonstrates the highest importance for south sill height (SillHS), while UDI is most strongly influenced by WWRN.

• **Hypothesis evaluation**

The findings confirm that the primary hypothesis regarding the optimization of library façades in the climate of Zanjan using simulation-based and metaheuristic methods can be formalized into a theoretical framework. The results demonstrate that parametric models are capable of improving indoor daylight performance while simultaneously delivering an architecturally desirable façade. Ultimately, an optimal configuration characterized by an “internal light shelf depth” of 1.3 m, an “external

depth” of 0.6 m, and a “glass visible transmittance” of 0.55 is identified as the most effective façade design solution.

Conclusion

The “Useful Daylight Illuminance” (UDI) across the evaluated scenarios ranges from 44.26% to 72.85%, representing the proportion of time during which illuminance levels remain within the desirable range. The highest UDI corresponds to a configuration featuring an “internal light shelf depth” of 1.3 m, an “external depth” of 0.6 m, a “south window-to-wall ratio” of 0.4, and a “glass visible transmittance” of 0.55. However, the optimal design choice does not necessarily correspond to the maximum daylight coverage, as structural and architectural objectives must also be considered alongside the bi-objective simulation outcomes. At the same time, the “glare-free percentage” remains consistently high and close to 100% across all scenarios, indicating effective glare control in all evaluated configurations.

Overall, the results demonstrate that each optimization parameter varies within a specific range. In most cases, “internal light shelf depth” lies between 0.9 and 1.3 m, with 1.3 m yielding the highest “UDI”. Furthermore, “external light shelf depth” typically ranges between 0.5 and 0.7 m, with depths of 0.6 and 0.7 m exhibiting superior overall performance. “Internal and external light shelf angles” generally fall between 9° and 30°, with larger angles providing improved daylight regulation and glare mitigation.

The findings further indicate that a combination of an externally downward-sloping shelf and an internally upward-sloping shelf toward the ceiling produces the best overall performance. Moreover, windows with visible transmittance values between 0.3 and 0.55 and

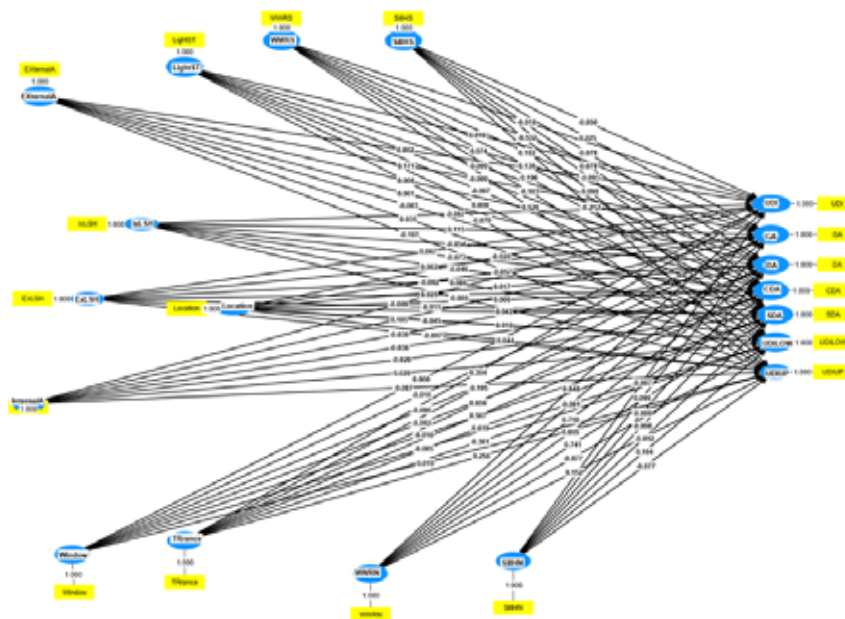


Fig. 9. Model and path coefficients. Source: Authors.

surface properties characterized by reflectance of 0.197, absolute reflectance of 0.1, and surface roughness of 0.08 are identified as the most suitable options. In general, increasing “internal depth”, maintaining a moderate “external depth”, adopting a “higher window-to-wall ratio”, and selecting a higher “glass transmittance” contribute to enhanced useful daylight availability and effective glare control.

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Declaration of No Conflict of Interest

The authors declare that they have no conflict of interest in conducting this research.

Endnotes

1. Spatial Daylight Autonomy (SDA) is a performance metric used to assess the level of access to natural daylight within an indoor space. It indicates the

percentage of a defined floor area that receives at least a specified minimum level of daylight for a given portion of the annual occupied hours.

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