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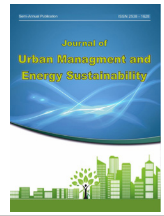

CASE STUDY RESEARCH PAPER

Enhancing Daylight and Energy Efficiency in the Architecture Studio by Designing Light Shelves and Windows with Sensitivity Analysis and Optimization

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ABSTRACT

Designing and implementing effective daylight systems and windows is crucial. When carefully chosen and constructed, they can significantly improve building energy performance and enhance occupants' visual comfort by reducing uncontrolled solar gains and excessive interior daylight. Moreover, a light shelf can potentially increase the light at the end of the space and provide uniform daylight distribution. To improve occupants' visual comfort and energy efficiency in various orientations and climates, it is crucial to solve the design and optimization process and combine optimal design parameters for window and light shelf systems. This study proposes a methodology that combines parametric design, sensitivity analysis, and Non-dominated Sorting Genetic Algorithm-II) NSGA-II (to optimize light shelf and window design across various parameters and ranges to provide optimal design solutions. Sensitivity analyses were performed to determine the influence of the parameters of light shelves and windows on energy performance and visual comfort. Based on the results of sensitivity analysis, WWR (among the window variables) and exterior angle and exterior depth (among the light shelf variables) are the most critical parameters for the objectives, and other parameters have different effects. Afterward, a multi-objective optimization was applied for the optimal design of windows and light shelves. According to the results, considering the light shelf on the base model, a 25% increase in energy efficiency, a 37% increase in useful daylight illuminance, and a 90% reduction in annoying glare in the space were achieved. It should be noted that these results are based on comparing the best non-dominant solutions' metrics with the base model's metrics. Further work is suggested to explore additional optimization objectives, including natural ventilation, cost, and thermal comfort in the presence of a light shelf, as well as attention to the aesthetic aspects of the presence of the light shelf on the window.

Running Title: Enhancing Daylight and Energy Efficiency in the Architecture Studio by Designing Light Shelves and Windows

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40	02	13

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INTRODUCTION

In recent years, daylight in buildings has developed as a design strategy for reducing energy consumption (Keshtkar Ghalati & Sharifzadeh, 2024), improving visual comfort, and enhancing user productivity. The presence of daylight in space can increase user satisfaction with visual and thermal comfort and significantly affect melatonin regulation, which is highly dependent on the received light (Acosta, Campano, Leslie, & Radetsky, 2019). The presence of daylight in educational spaces is crucial because it enhances students' physical and mental health, increases concentration, improves learning quality, and increases efficiency (Heschong, 2003), (Elmkhah & Eiraji, 2022). The highest level of energy consumption in government buildings belongs to educational spaces. This level of energy consumption is growing in developing countries, including Iran (Eiraji & Elmkhah, 2021), so finding suitable solutions to managing and controlling the issue is obvious when considering its importance. Architectural design studios require appropriate daylighting with optimal distribution, as students' activities vary (some work mainly on computers, while others do mainly paperwork), and each activity requires a different level of desired illuminance. Moreover, students spend long hours in these studios, and the age spectrum is diverse, with teachers and students present (Bellia, Musto, & Spada, 2011). Windows can provide daylight but quickly diminishes as the distance from the window increases. The lack of sufficient daylight in some interior areas is causing them to remain dark. To satisfy users with the quantity and quality of natural light, daylighting systems have been proposed to provide comfort conditions in the interior space for most hours of the day. A daylighting system should be chosen based on the space's usage and considering the possibility of combining it with windows and other daylight systems (Tabadkani, Roetzel, Li, & Tsangrassoulis, 2021).

Since the main objective of this research is to improve the visual comfort conditions in terms of the quantity and quality of daylight and energy efficiency in the architectural design studio of the Faculty of Architecture at the Isfahan branch (Khorasgan), a light shelf system was used in combination with window design (Window to Wall Ratio, Visual Transmittance, Solar Heat Gain Coefficient, U Value) as a corrective solution (in such a way that it is possible to change the variables that have a non-structural role on the facade), the light shelf is a passive design system that can be installed horizontally or obliquely at a high height of a window. It provides shade during hot seasons and reduces annoying glare inside the space. In addition, it increases the depth of light penetration into the central and deeper parts of the space, reducing energy consumption (Motazedian & Mahdavinejad, 2016). They do not obstruct the view outside the space; for these reasons, they are considered one of the most popular technologies. Given that this system operates most efficiently in clear and sunny weather conditions (Mohammadjavad, Mansooreh, & Mahnaz, 2016), this research aims to determine the optimal proportions and usage of this system in combination with windows in the city of Isfahan, which experiences a high number of sunny days, with an average of 3029 hours per year.

Upon reviewing previous studies on light shelves, some research has focused on classifying different types of light shelves and their variables for different spaces (Motazedian & Mahdavinejad, 2016), (Moazzeni & Ghiabaklou, 2016), (Zohreh & Mahnaz Mahmoody, 2023). Some other researchers have studied this field while paying attention to the climate by using parametric methods to find optimal solutions for designing light shelves (A. A. S. Bahdad, Fadzil, Onubi, & BenLasod, 2021), (Mahdavinejad, Tahbaz, & Dolatabadi, 2016), (Sabbagh, Mandourah, & Hareri, 2022), (Mangkuto, Feradi, Putra, Atmodipoero, & Favero, 2018), (Ebrahimi-Moghadam, Ildarabadi, Aliakbari, Arabkoohsar, & Fadaee, 2020b), (A. Bahdad, Syed Fadzil, & Taib, 2020), (Beykaei, Mozaffari Ghadikolaei, & Ebrahimi, 2022). Since this research is focused on the optimal design of the light shelf to achieve the intended objective, after reviewing the studies conducted on the light shelves' typology and their characteristics, the main focus was evaluating research related to multi-objective optimization of light shelf and window design. Table 1 outlines the key points of the studies, while the evaluation methods and results follow below.

Behdad and colleagues conducted a study to propose an optimized office workspace design that ensures an adequate supply of natural light while minimizing thermal energy consumption. This study's framework combines parametric design, energy and daylight performance simulation tools, and a genetic algorithm. The final optimal solutions for the best design parameters of a light shelf can significantly improve the overall average of useful daylight illuminance by 62.50%, 56.25%, 57.50%, and 68.13%, respectively, in March, June, September, and March. Additionally, the thermal energy performance can improve by +1.15%, -4.62%, -6.81%, and -3.05%, respectively, when compared to the single-objective solutions of light-shelf parameters (A. A. S. Bahdad et al., 2021). This research examined the impact of each variable on enhancing environmental quality, precisely energy efficiency and daylight, to identify the variables that significantly influence system efficiency. Another study by Ziaei and Vakilinejad investigates how sky cloudiness affects the optimal light-shelf properties of typical classrooms. The methodology comprises three steps: optimizing light shelf parameters for daylight, analyzing thermal comfort for selected solutions, and choosing the best option. The best options for light-shelf properties differ in each city due to the varying sky cloud cover. The efficiency of the light shelf in Tehran with less sky cloudiness is more effective than in Sari in terms of providing both daylight

Table 1: Classification of some recent publications related to LS in the field of energy and daylighting optimization.

Source	Objectives	Metric	parameters	Algorithm	Sensitivity
(Ziaee & Vakilinezhad, 2022)	Optimizing daylight performance and thermal comfort in classrooms with light shelves	sDA, ASE, UDI	Exterior and interior depth, and Pivot angle of the interior part.	SPEA-2 and HypE	-
(Mangkuto, Feradi, et al., 2018)	Daylight optimization based on the modification of light shelf design parameters.	sDA, ASE	Exterior and interior depth , External tilt angle, Specularity	SPEA-2 (Octopus program)	-
(A. A. S. Bahdad et al., 2021)	Design parameters of light shelves optimized for visual comfort and thermal energy performance.	sDA, UDI, EUI	Position Height, External and internal part angle, External to internal depth ratio.	SPEA-2 (Octopus program)	+
(Ebrahimi-Moghadam, Ildarabadi, Aliakbari, Arabkoohsar, & Fadaee, 2020a)	Multi-objective optimization of energy consumption and thermal comfort using internal light shelves.	EUI	Angle, depth and number of the light shelves.	SPEA-2 (Octopus program)	+
This study	Improving visual comfort and energy efficiency using light shelves.	UDI, sDGP, EUI	External and internal depth, angle of exterior part, material, clerestory height, Window specifications.	NSGAII	+

and thermal comfort, especially for cases with more WWR (Ziaee & Vakilinezhad, 2022). So, the present study was conducted in Isfahan on many sunny days. Moqaddam and others have studied the impact of a light shelf on improving visual and thermal comfort in residential buildings. An illuminance analysis has been carried out for the building with and without the LS to determine the optimal visual conditions for selecting space according to the highest and lowest light intensity in the investigated areas. The study compares the optimal LS's role in improving thermal comfort and energy indicators such as heating, cooling, and electricity with the base situation. The analysis results reveal that using the optimal LS leads to an average improvement of 18%, 11%, and 7% in the annual demand for heating, cooling, and electricity throughout the year (Ebrahimi-Moghadam, Ildarabadi, et al., 2020a). Another study created four different design options for light shelves and simulated their impact on the amount and quality of daylight in a classroom. After analyzing and scrutinizing the simulation outcomes, the experiment revealed that using light shelves was not very effective in this particular case. Nonetheless, they can assist in diminishing the impact of the variation in lighting levels between the regions adjacent to the windows and the areas situated further inside the classroom, as well as minimizing the overall contrast (Sabbagh et al., 2022). In this study, optimal models of the light shelf are obtained through the optimization of the variables of this system with the combination of some window parameters. Then, the optimal models are compared with the base model to determine the extent of improvement in environmental conditions.

Reviews reveal that numerous studies have explored the design of light shelves to enhance natural lighting and energy efficiency. However, nearly all research on light shelf design has not yet considered the impact of light shelf variables on specific objectives. It simply combines variables with many states to achieve objectives. In the design process, determining the number of states for each variable, considering their effectiveness in achieving the objectives of reaching efficient responses in the shortest time, is critical. Therefore, sensitivity analysis and multi-objective optimization methods were used during this research process to fill research gaps and design light shelves in combination with windows to achieve overall objectives. A literature review revealed some gaps in the existing knowledge. These gaps are listed below:

1. Light shelf design configurations are not investigated in different climates; there needs to be more knowledge.
2. Many studies on light shelf design do not thoroughly evaluate the effect of variables on the objective. This could be due to the complexity of the optimization process or the study's specific focus.
3. The design of window variables is usually not considered when studying light shelf design.
4. Consider the cost and ease of implementation when selecting a light-shelf design configuration. Examine all aspects to select the most suitable options. Knowledge is deficient regarding this particular item.

MATERIALS AND METHODS

Research process

This study's framework combined parametric design, integrated daylight and energy performance simulation tools, and GA. Thus, the research framework employs a parametric design method developed in the Rhino/Grasshopper, Ladybug, and Honeybee plugins. Incorporating these tools was necessary to achieve the objectives of this study: Rhino as a modeling tool; Grasshopper as a parametric interface; Ladybug and Honeybee tools for daylight and energy analysis based on the Radiance and Energy Plus engines. In this research, parametric design allows for modifying variables that can change to improve existing conditions. This research aims to propose a multi-objective optimization design for window and light shelves in an educational building. An architectural studio in Isfahan's semi-arid climate was selected and developed using Grasshopper parametric software to achieve this. Thus, the research framework employs a parametric design method developed in the Rhino/Grasshopper, Ladybug, and Honeybee plugins. The incorporation of these tools was necessary to achieve the objectives of this study: Rhino as a modeling tool, Grasshopper as a parametric interface, Honeybee and Energy plus tools for daylight and energy analysis, and finally, multi-objective optimization was conducted with the wallacei plugin (non-dominant genetic sorting algorithm (NSGA-II)) to optimize objectives defined as minimizing energy use intensity (EUI), spatial daylight glare probability (sDGP), and maximizing spatial functional daylight illumination (sUDI). Figure 1 shows the process of optimizing the building's performance with the necessary software.

The research process has five steps, as follows:

1. Identifying design variables based on previous studies helps define a suitable and reasonable range for each variable.
2. A parametric base model is created, and its dimensions are considered based on the current situation. In this stage, non-parametric variables such as building rotation, studio dimensions, and the climate of Isfahan are taken into account.
3. Consider specific values for all variables that cover their entire range when performing the simulation process. Then, regression analysis is used to determine the impact of variables on the objectives, known as sensitivity analysis.
4. The multi-objective optimization process is based on the sensitivity analysis results. The more susceptible variables have a broader range of states in the optimization process. Wallacei's genes link the design variables of the light shelf, and Wallacei's objectives link the outputs of the daylight, comfort, and energy simulation components.
5. Non-dominated solutions on the Pareto front are analyzed and compared with the base model to determine the impact of combinations of the window and light shelf parameters on the objectives.

Research Variables

In this research, with the help of metrics daylight, glare, and energy consumption (Spatial Useful Daylight Illuminance (sUDI), Spatial Daylight Glare Probability (sDGP), and Energy Use Intensity (EUI)), which are defined as dependent variables the impact of each of the independent variables (design variables of the light shelf and the window) on the intended objectives (providing the desired amount of daylight available and energy efficiency) is evaluated.

Dependent variables

Metrics (sUDI, sDGP, and EUI) were used as dependent variables to describe daylight availability, glare analysis, and energy demand of the defined space in the presence of a light shelf, changes in window variables, and the base model. The "Daylight and energy performance metrics" section briefly describes these indicators.

Independent variables

Light shelf variables

One of the critical challenges in effectively increasing the daylight performance of buildings using light shelves is the need for sufficient information about the influential variables of this system in improving environmental conditions. Optimal variables to ensure desirable efficiency are one of the most essential parts of light shelf design. The light shelf's design variables include internal and external depth, materials, system slope angle, and clerestory height. This study attempted to determine the range of each light shelf variable based on a review of previous research in this field and the features of the intended space. Recent research has discussed several light shelf variables, which Table 2 displays.

Internal and external depth: Adding depth to the light shelf reduces glare but proportionally decreases daylight entry. Therefore, the

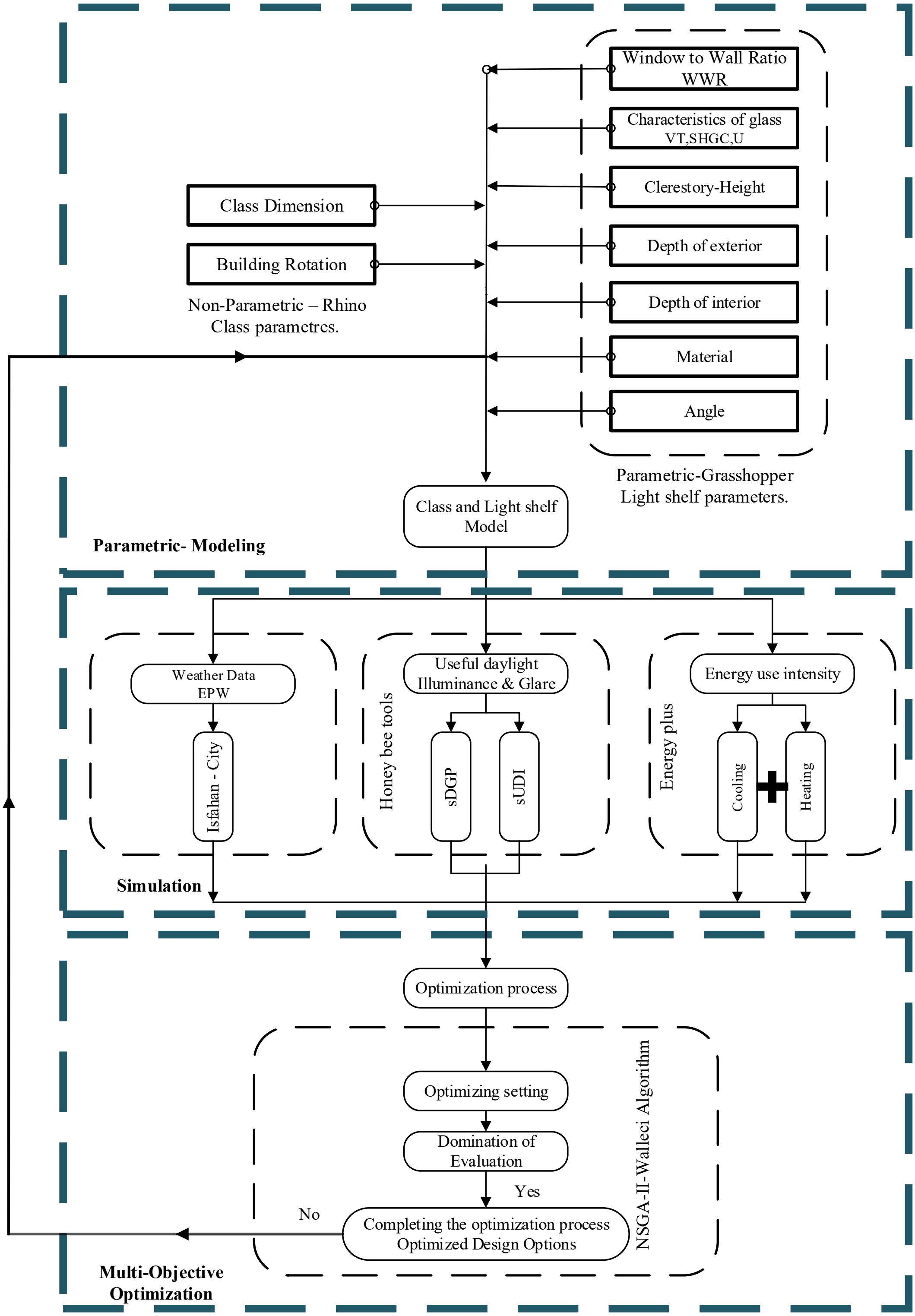


Figure1: Research workflow

appropriate depth should be determined by performing a simulation for each model. According to the current research (educational), the maximum internal depth was considered to be 50 centimeters to prevent users' visual distraction. The external depth ranged from 30 to a maximum of 90 cm, taking into account two factors: 1. The width of the horizontal shading proposed for the southeast front in the city of Isfahan is 70 cm, according to Topic 19 of Iran's National Construction Regulations. 2. The facade features non-structural vertical elements, each with a width of 40 cm. The determined range provides enough space to reflect the daylight but does not obstruct the users' view outside the space.

Angle: In a study, Lee (2019) examined the use of light shelves to reduce energy consumption, focusing on changing the angles of light shelves and their impact on natural light quality. This study emphasizes the importance of changing the angle of the light shelf according to the sun's radiation angle in different seasons in the climate under consideration. In this research, a range of 0° (horizontal) to 40° degrees was considered for the angle of the light shelf (positive with the horizontal surface). This range is based on the sun's radiation angle in Isfahan, which reaches a maximum of 80.95 (SA(Max) = 90°-L + 23.5°) on June 21 and a minimum of 34.05 (SA(Min) = 90°-L + 23.5°) on December 21. On the other hand, an angle for the light shelf towards the outside (negative) was not considered to prevent users from seeing outside the space. In this research, the inner shelf is in a horizontal position because, due to the limited width of the internal shelf, it is considered impractical to angle the inner shelf to the horizon. Therefore, no change was made in the angle of the interior light shelf.

Material: The choice of material for the light shelf significantly influences the level of daylight and glare in the space. Since semi-mirrored surfaces perform better than shiny and mirrored surfaces, aluminum materials were used for the light shelf in this research. Different types

Table 2: Examining the design variables of the light shelf that the mentioned researchers have worked on.

Light shelf variables					
Position and depth	Material	Angle	Height		Reference
Both/ exterior and interior			Window height	Clerestory height	
*					(Tabadkani et al., 2021)
	*	*			(Salahsoor & Zarandi, 2023)
*		*		*	(Mohammadjavad et al., 2016)
*	*	*	*	*	(Kontadakis, Tsangrassoulis, Doulos, & Zerefos, 2018)
*		*			(Ebrahimi-Moghadam, Ildarabadi, Aliakbari, & Fadaee, 2020)
*	*	*			(Sabbagh et al., 2022)
*		*	*		(Ziaee & Vakilinezhad, 2022)
*	*	*			(Mangkuto, Feradi, et al., 2018)
*		*	*		(A. A. S. Bahdad et al., 2021)
*		*			(Moazzeni & Ghiabaklou, 2016)
*	*	*	*	*	This study

of it have been considered to simulate energy and lighting, as presented in Table 3 separately for the Energy Plus and Radiance engines. The Radiance Color Picker is used to determine the reflective properties of the selected materials (R.C. Picker, 2017).

Window variables

This study selected several window parameters, such as VT, SHGC, U-value, and WWR, as variables to achieve the objectives alongside the light shelf system. The related variables were selected based on standards (Topic 19 of Iran's National Construction Regulations and ASHRAE standards). Table 4 presents the different types of windows and their corresponding variable values.

This study has installed light shelves on the south facade windows, with adjustable parameters. Figure 2 illustrates the design factors for the light shelves and windows considered in the study.

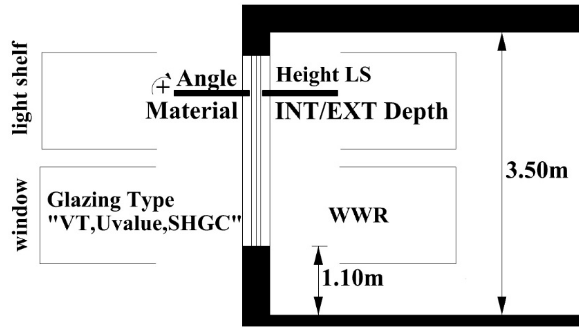


Figure 2: Design factors of light shelf and window that have been considered in the study.

Table 3: Characteristics of the selected materials of the optical shelf for simulating energy and daylight.

Radiance								Energy Plus	
Co.	Material	ρ	R-ref	G-ref	B-ref	Specularity	Roughness	Solar Reflectance	Visible Reflectance
0	Aluminum	0.885	0.90	0.80	0.88	0.80	0.02	0.883	0.883
1	Brushed Aluminum	0.70	0.70	0.70	0.70	0.85	0.05	0.75	0.752
2	Rolled Aluminum	0.31	0.310	0.31	0.31	0.68	0.65	0.405	0.405
3	Oxidized Aluminum	0.48	0.487	0.48	0.44	0.30	0.02	0.436	0.436

Table 4: Window properties and values of its variables.

Window type		U value (w/m2k	SHGC	VT
0	Starphine	2.69	0.82	0.84
1	clearsungate-400	1.80	0.63	0.76
2	Single low-E (e2=0.2)	4.35	0.72	0.81
3	Double Clear(a)	3.4	0.69	0.78
4	Double Clear(b)	2.8	0.72	0.77
5	Double low-E (e2=0.0.4)	2.70	0.44	0.70
6	Triple pane	2	0.68	0.74
7	Triple Low-E (e5=0.1)	1.30	0.58	0.70
*	Base model	5.82	0.85	0.75
In all windows, the glazing Visual Transmittance coefficient ratio to the solar heat gain coefficient (VT/SHGC) is more than 1.				

In the following, the range of values for each variable (light shelf and window) has been determined individually. This considers valid standards, acceptable field studies, and the design's limitations in the space under investigation. Table 5 presents this information.

Daylight and energy performance metrics

As materials are assigned to the building, light shelf, and window with corresponding weather files, the simulation proceeds for energy and daylight simulations. The performance of the defined space was demonstrated using metrics (sUDI, sDGP, and EUI) to describe the availability of daylight, glare analysis, and energy demand. Generally, these metrics exhibit the following characteristics:

1. A modified version of the UDI, known as the sUDI metric, evaluates the spatial domain. UDI is the proportion of the occupancy period over a year where the horizontal brightness at a specific point is within a particular range (300 to 3000 lux) (Shafavi, Tahsildoost, & Zomorodian, 2020). The sUDI considers both spatial and temporal features of daylight performance (Mangkuto, Siregar, Handina, & Faridah, 2018).
2. Daylight Glare Probability (DGP) is one of the glare metrics widely used for evaluating visual comfort in well-lit environments. The calculation of this metric depends on the luminance of the source and background, the amount of light entering the eye, and the observer's angle of view to the light source, with an acceptable range of 0.35 to 0.40 (Fadaii Ardestani, Nasseri Mobaaraki, Ayatollahi, & Zomorrodian, 2018). The HB Annual Glare component (GA) output was used to calculate glare in this research. Glare Autonomy (GA) indicates a percentage of points that do not experience glare during the occupied hours (with a DGP below the glare threshold, DGP<0.40). Then, by performing post-processing, the percentage of surface sensors that do not experience non-annoying glare for more than 75 percent of the hours of space occupancy was obtained, which connected the Wallacei X component as one of the genes.
3. By dividing the full annual energy loads by the building's floor area, the EUI metric (KWh/m2) calculates the total building energy consumption (Rafati, Sanaieian, & Faizi, 2021). It is important to note that in this research, the user's activities, the use of electrical appliances, and the heat emission from artificial lighting remain constant for all simulations and scenarios. This research calculates the annual cooling and heating load per square meter using the energy output for the simulation.

Table 5: The light shelf and window variables are defined along with their respective ranges.

Variables		Minimum	Maximum
Light shelf	Interior Depth(cm)	20	60
	Exterior Depth(cm)	30	90
	Light shelf material-Aluminum	For simulation purposes, Table 2 displays the calculated solar and visible reflectance values of aluminum.	
	Exterior light shelf Angle (∘)	0	40
	Clerestory height(cm)	30	60
window*	Window-to-wall ratio- WWR (%)	20	60
	Visual transmittance	70	85
	Thermal Transmittance ($W/m^2 \cdot K$)	1.30	5
	Solar Heat Gain Coefficient	0.40	0.8 (Based on the climatic classification of the city)
Eight window types were selected according to the specifications presented in Table 6, and the variables VT, SHGC, and Uvalue were considered within the desired range.			

DISCUSSION AND FINDINGS

Location and climate

The present project is located in Isfahan, with a geographic longitude of 51.862 east and a latitude of 32.751 north. According to the TMYx climate file extracted from the climate.one building website, Isfahan's climate classification is 3B (hot and dry) and BSk (Cold Semi-Arid) according to ASHRAE and Köppen-Geiger, respectively.

Study context

In this research, an architectural studio located in the Faculty of Architecture and Urban Planning of Khorasgan was considered for simulation due to its dimensions being close to the standard dimensions of architectural studios, with an area of 64.20 square meters. The WWR in this studio is about 25 percent, and the studio's height is 3.50 meters. This ceiling height, based on the study conducted by Hue about the light shelf, is suitable for implementing the system (Motazedian & Mahdavinejad, 2016).

Due to the window front on the southeast side, this studio was chosen for the optimization process. Nasiri and Zarandi researched to achieve the principles of designing high-efficiency light shelves in educational buildings. They found that when controlling the incoming daylight, the classroom's position and fronts facing south are considered the priority, with the north front being the second priority (Nassiri & Mahmoudi Zarandi, 2020). On this facade, no high-rise building would shadow the wall. According to the research approach, conducting this study in an existing architectural design studio necessitates presenting corrective solutions with minimal cost and design impact. The research approach led to eliminating certain vertical elements on the faculty's facade, which serve no structural purpose. The faculty site, Table 6, provides images and features of the intended class.

The architectural workshop class runs from 8:00 a.m. to 5:00 p.m. The base model's additional features for simulating daylight and energy are listed below, along with an explanation. Table 7 shows the interior surfaces' reflectance coefficient and the glazing visual transmittance for the base model simulation, considering the current class situation. Other surface reflectance coefficients, except for the window parameters, are considered the same for other processes.

Modeling simulation process

In the daylight modeling process, the building model is connected to the material component in the Radiance program to determine the amount of opaque reflectance and visual glazing transmittance. Table 7 lists the optical properties of the materials. Additionally, the settings of the radiance parameters are considered to have the highest level of precision. For instance, ambient bounces (ab), ambient divisions (ad), super ambient samples (as), limited reflectance (lr), and limited weight (lw) are set to 6, 25000, 4096, 8, and 4*10^-7, respectively.

In the energy modeling process, the building model is connected to the materials available in Energy Plus and then connected to a thermal zone that has four walls, a ceiling, and a floor. In the current model, all walls except the southeast are adiabatic. Adiabatic walls help to focus on the design of light shelves and windows. The thermal characteristics of the class materials were considered according to ASHRAE zoning (3B) by ASHRAE 90.1 2019 (standard) (American Society of Heating & Air Conditioning, 2019), shown in Table 8.

Sensitivity analysis

Sensitivity analysis is essential in building performance analysis. It helps identify the key variables that significantly impact each objective (Fang & Cho, 2019). Usually, this process occurs during the early stages of design, when each factor exhibits a wide range of values. Performing it before the optimization process allows for selecting the most influential design variables, simplifying the optimization problem, and significantly reducing time (Mangkuto, Rohmah, & Asri, 2016). Ideally, designers should perform a sensitivity analysis before optimization processes to find the value and appropriate range

Table 6: Pictures and physical characteristics of the class.

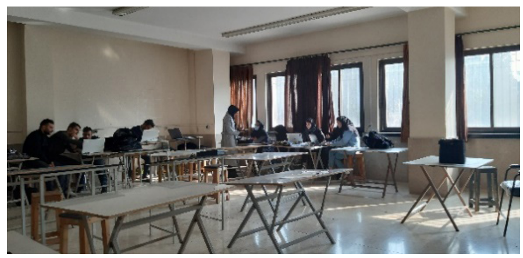
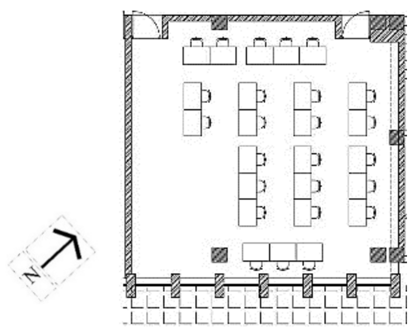
	
SouthEast Elevation of Studio.	The site of the Faculty of Architecture and Urban Planning.
	
The interior of the studio	The interior of the studio – view from the window
Class dimensions: 8.90 * 9.20 Class area: 67.45(M2)	
Specifications of the Studio.	Studio's plan

Table 7: Building material optical properties considered in the daylight simulation.

Material Type	Reflectance	Construction
Radiance opaque material	White color: 70%, stone plinth up to a height of 1 meter: 45%, brick façade: 10%	Interior wall
Radiance opaque material	White color: 60 percent	Interior Ceiling
Radiance opaque material	Cream colored stone: 45%	Interior Floor
Radiance glass material	VT=0.75, SHGC=0.85, Uvalue=5.82, WWR=25%	Widow Type

for each parameter (Naji, Aye, & Noguchi, 2021). A balanced distribution of variables is necessary for the data to perform a sensitivity analysis. Therefore, three values were considered for each variable from the selected range, which covers the full range of the optimization process with these values. The simulation process was then carried out using the Colibri plugin. The result is 2187 simulations with a uniform distribution of variable values. Table 9 displays the values taken into account for the sensitivity analysis.

Table 9: Values considered for variables for sensitivity analysis.

Variables		Variables and their ranges for Sensitivity analysis
Light shelf	Interior Depth(cm)	20-40-60
	Exterior Depth(cm)	30-60-90
	Light shelf material-Aluminum	Aluminum – Brushed Al – Rolled Al
	Exterior light shelf Angle (◦)	0-20-40
	Clerestory height(cm)	20-40-60
Window	Window-to-wall ratio- WWR (%)	20-40-60
	Visual transmittance	70-77.50-85

This study used SPSS software to conduct statistical analysis and sensitivity analysis, with regression serving as the most common method. In this study, the Standardized Regression Coefficient (SRC) serves as the indicator for sensitivity analysis. A high absolute value of the SRC factor indicates that a design variable significantly impacts the performance metric. A positive SRC indicates a positive effect on the performance metric, while a negative SRC indicates a negative impact. However, a positive or negative effect does not necessarily mean a more significant or smaller value is always better. This only shows a general trend for all design options (Rafati, Hazbei, & Eicker, 2023). Table 10 displays the SRC values for seven variables by metrics and the number of modes for each variable based on sensitivity analysis. These values are ranked based on the absolute SRC value.

In this ranking, the window wall ratio (WWR), the glazing visual transmittance, and the angle of the external light shelf have the most significant impact on receiving daylight. The WWR, the light shelf's exterior angle, and the glazing's visual transmittance significantly affect glare. On the other hand, the WWR, the glazing's visual transmittance, and the shelf's external depth have the most significant impact on energy consumption. As a result, based on the ranking of each variable in terms of its effectiveness on the objectives, 3–8 states were considered for the optimization process, as shown in Table 9. Despite WWR having the most substantial impact on the three objectives, certain limitations persist, such as the minimum height of window sills in studio spaces due to the presence of workshop tables. As a result, the maximum amount considered for this space was 60%. The range chosen for this variable was between 20 and 60%, with a consistent step length of 5. Then, the optimization process begins.

Table 8: Thermal properties of building material.

City	ASHRAE climatic zoning	Construction	U-Value (W/ m2.k)	Solar Heat Gain Coefficient
Isfahan	3B	Wall	0.701	N/A
		Ceiling	0.220	N/A
		Floor	0.420	N/A

Multi-objective optimization

Multi-objective decision-making optimizes objective functions based on constraints to find the most satisfactory and efficient solutions. To find an optimal answer, the desired optimization algorithm first generates several answers to determine which are closer to the optimal answer or, in other words, more appropriate. One of the most widely used evolutionary algorithms is the genetic algorithm, which employs the principles of natural selection to generate a group of solutions to achieve an optimal solution. In a recent study, the non-dominated Sorting Genetic Algorithm-II (NSGA-II) outperformed other multi-objective genetic algorithms in terms of results (Rafati et al., 2021). Therefore, it was chosen as the preferred genetic algorithm for this research. The NSGA-II improves the selection operation based on the genetic algorithm for solving multi-objective optimization problems. A response is pareto-optimal or dominant when no other possible solution optimizes one objective without undermining another objective (Pilechiha, Mahdavinejad, Pour Rahimian, Carnemolla, & Seyedzadeh, 2020). In this research, the variables were evaluated and optimized based on the number of states assigned to them after the sensitivity analysis (variable ranking results) by NSGA-II.

The best choices to achieve the minimum energy consumption and glare were selected based on EUI (the total energy required for cooling and heating), sDGP metrics, and maximum daylight based on the sUDI metric. This approach ensures that the selected solutions have balanced performance across all objectives, leading to more sustainable and efficient designs. After the optimization process, the results of the Pareto front and the last generation were examined, and the characteristics of the variables in each answer were evaluated based on their values. This research is based on the maximum number of generations in the optimization process. Therefore, for this algorithm, 50 generations and 20 populations per generation were considered. Many generations and a small population size help reach a reliable result faster. In this study, a crossover probability of 0.90 was considered. The crossover probability between 0.3 and 0.9 is a suitable selection, as numerous parents will have offspring (Naji et al., 2021). Mutation probability is usually kept low because a high mutation probability can cause an initial random search. 1/nv calculates the mutation probability, the number of variables (Rafati et al., 2023). Given the seven variables in this problem, the algorithm selects 0.143 as the mutation probability.

Table 10: Variables ranked by influence on sUDI, sDGP, and EUI metrics and the number of modes based on sensitivity analysis.

Variables	sUDI		sDGP		EUI		Number of modes.
	SRC	ranked	SRC	ranked	SRC	ranked	
Visual Transmittance	0.124	3	0.182	3	0.366	2	8
WWR	0.876	1	0.913	1	0.884	1	6
Exterior Depth	0.021	7	-0.123	4	-0.191	3	5
Clerestory height	0.055	5	-0.043	7	0.10	5	4
Interior Depth	-0.041	6	-0.067	6	0.00	7	5
Exterior Angle	0.145	2	0.183	2	0.114	4	8
Material	0.115	4	0.069	5	0.023	6	4
In all cases, sig<0.05. According to the effect of the visual transmittance coefficient of the glass, 8 types were selected for the window.							

Table 11 summarizes all the algorithm settings.

Table 11: NSGA-II setting

Parameters	NSGA-II
Population count	20
Generation size	50
Crossover probability	0.90
Mutation probability	0.147
Selection function	Tournament
No. of Fitness Objectives	3
No. of Genes	7
No. of Values	44
Size of Search Space	2.6e5

The multi-objective optimization process in this research has led to the presentation of various desirable solutions. Table 12 presents a set of optimal solutions, which are the most appropriate values of sUDI, sDGP, and EUI metrics.

Since the primary function of the light shelf is to increase the amount of available daylight, the most influential criterion in choosing solutions is to receive the desired daylight with minimum annoying glare, and the second priority is a lower percentage of energy consumption. Note that the Pareto front's responses did not significantly differ in the number of metrics, which did not influence the choice of the optimal outcomes. Table 13 presents some appropriate responses to the design of light shelves and windows, as well as the simulation of the base model.

RESULT AND CONCLUSION

Among daylighting systems, the light shelf, due to its physical compatibility compared to other fixed systems, has an extraordinary ability to meet visual comfort needs and increase energy efficiency (Tabadkani, Roetzel, Li, & Tsangrassoulis, 2020; Tabadkani et al., 2021). Therefore, after reviewing relevant studies and identifying research variables, the present study pursued an optimal design for the light shelf and window, focusing on visual comfort and energy efficiency

Table 12: The non-dominant solutions in receiving daylight, glare control, and energy consumption.

Pareto/last Gens	Type window	WWR	EXT.Depth	Clerestory height	INT.Depth	Angle	Material	sUDI	sDGP	EUI
15/6	1	0.2	0.9	0.4	0.6	0	3	0.742	0.045	4994.27
15/11	7	0.2	0.9	0.4	0.3	0	3	0.734	0.064	4925.39
16/2	7	0.2	0.9	0.4	0.6	5	3	0.719	0.045	4928.17
16/19	7	0.25	0.9	0.4	0.3	0	3	0.977	0.106	5003.1
21/5	7	0.2	0.9	0.4	0.3	0	1	0.844	0.068	4931.39
21/12	7	0.30	0.9	0.5	0.6	5	3	0.969	0.072	5045.22
21/19	7	0.2	0.9	0.4	0.4	0	3	0.688	0.057	4925.39
23/1	7	0.2	0.9	0.5	0.6	0	1	0.859	0.042	4982.72
23/4	6	0.2	0.9	0.5	0.6	0	1	0.977	0.057	5125.13
23/16	7	0.25	0.9	0.4	0.6	0	3	0.898	0.053	5003.1
26/13	7	0.25	0.9	0.4	0.2	0	3	0.984	0.114	5003.1

Pareto/last Gens	Type window	WWR	EXT.Depth	Clerestory height	INT.Depth	Angle	Material	sUDI	sDGP	EUI
27/12	7	0.2	0.9	0.4	0.4	5	3	0.734	0.057	4928.17
28/6	7	0.2	0.9	0.4	0.2	5	3	0.781	0.08	4928.17
29/1	7	0.2	0.9	0.5	0.6	0	2	0.602	0.038	4972.68
29/19	7	0.25	0.9	0.4	0.6	0	1	0.992	0.076	5014.68
31/15	7	0.2	0.9	0.4	0.2	0	3	0.742	0.072	4925.39
32/10	6	0.2	0.9	0.4	0.6	0	1	0.914	0.045	5067.84
32/18	7	0.2	0.75	0.4	0.4	0	3	0.719	0.061	4924.5
33/10	7	0.2	0.9	0.4	0.2	0	2	0.664	0.072	4924.42
34/1	7	0.2	0.9	0.5	0.6	0	3	0.711	0.038	4974.22
35/19	7	0.2	0.9	0.4	0.2	0	1	0.859	0.08	4931.39
36/9	7	0.2	0.75	0.4	0.2	0	1	0.844	0.087	4930.87
38/15	7	0.25	0.9	0.5	0.6	0	1	0.992	0.072	5050.36
39/16	6	0.2	0.9	0.4	0.6	5	1	0.969	0.049	5076.78
43/18	7	0.2	0.9	0.4	0.6	0	1	0.828	0.045	4931.39
43/19	7	0.2	0.9	0.5	0.6	5	1	0.953	0.057	4969.99
44/14	7	0.2	0.9	0.4	0.2	5	1	0.938	0.08	4937.87
45/0	7	0.2	0.75	0.4	0.5	0	2	0.633	0.045	4923.37
45/1	2	0.25	0.9	0.4	0.6	0	2	1.000	0.091	5509.812
45/12	7	0.2	0.75	0.4	0.4	0	2	0.641	0.061	4923.372
46/16	7	0.25	0.9	0.5	0.6	0	3	0.914	0.049	5037.875
Last gen	7	0.25	0.9	0.5	0.6	0	1	0.992188	0.07197	5050.363402
Last gen	7	0.25	0.9	0.4	0.2	0	3	1	0.117424	5003.103493
Last gen	2	0.25	0.9	0.4	0.6	0	2	1	0.090909	5509.812444
Last gen	7	0.20	0.9	0.4	0.2	5	3	0.78125	0.079545	4928.170917
Base model	**	0.25	-	-	-	-	-	0.728	0.366	6570.078

WIN COD 1: VT:0.84, SHGC:0.82, U_{VALUE}:2.69, WIN COD 2: VT:0.81, SHGC:0.72, U_{VALUE}:4.35
WIN COD 6: VT:0.75, SHGC:0.68, U_{VALUE}:2, WIN COD 7: VT:0.70, SHGC:0.58, U_{VALUE}:1.30

through sensitivity analysis and optimization. Both this study and Rafati et al. (2023) conducted the sensitivity analysis prior to the optimization process, setting them apart from other research methodologies (Fang & Cho, 2019) and (Godsiye Sadat, Yousef Gorji, & Peiman, 2023). This approach facilitates the identification of the most influential variables of the objectives, leading to a reduction in optimization time. Previous studies performed sensitivity analyses after optimization to examine the relationships between parameters and the resulting outputs. This study utilizes trade-off solution configurations to summarize the results in two steps:

1. Comparing a model with and without a light shelf in the studio to determine which scenario performs better. The best light shelf solutions found in the Pareto front and the last generation are selected to be compared with those without the light shelf.
2. The studio's optimization process involves examining the light shelf configuration parameters of the Pareto front and last-generation cases. Exploring the best-case parameters allows to differentiate between the dimensions and measures of influential parameters based on daylight and energy objectives.

The simulation results indicate that the presence of a light shelf on the south window significantly enhances visual comfort and energy efficiency, mirroring the findings of previous studies (Moazzeni & Ghiabaklou, 2016), (A. A. S. Bahdad et al., 2021), (Mangkuto, Siregar, et al., 2018), (Ziaee & Vakilinezhad, 2022), and (Rezaei, Sangin, Heiranipour, & Attia, 2024). Considering the light shelf on the base model, there is a 25% increase in energy efficiency, a 37% increase in helpful daylight brightness, and a 90% reduction in disturbing glare in the space. It should be noted that these results are based on comparing the best non-dominant solutions' metrics with the base model's metrics. This improvement in the amount of daylight is consistent with the results of studies (A. A. S. Bahdad et al., 2021; Bernardi & Anaraki, 2016; Rezaei et al., 2024). Still, it differs from the study's findings (Sabbagh et al., 2022), which show that the use of light shelves affects the quality and distribution of daylight in classrooms by 17% and has the most significant effect on reducing the contrast between the area near the window and the interior of the classroom.

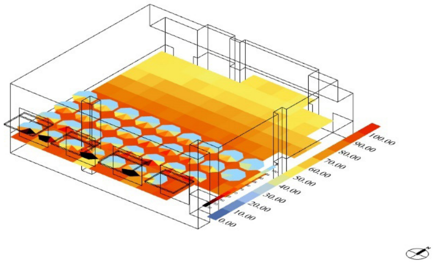
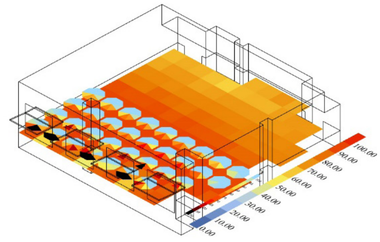
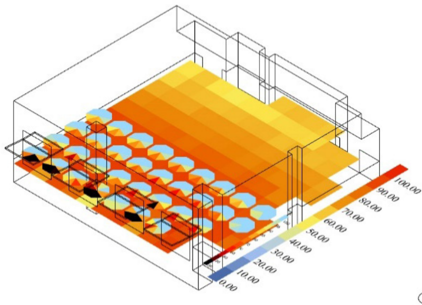
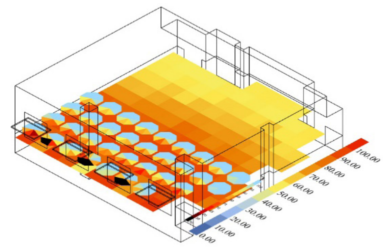
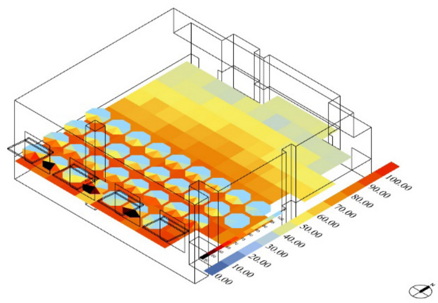
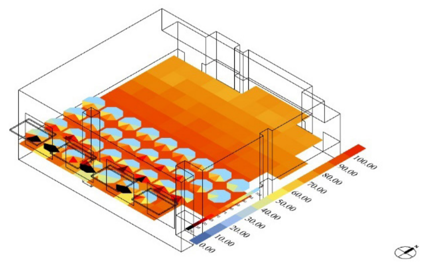
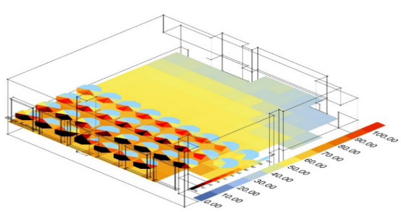
New policies must be developed to establish updated window and light shelf design standards suitable for all climates and locations. Current standards only consider a limited range of design variables. The significant impact of daylighting systems on occupants' comfort emphasizes the need for comprehensive studies on control strategies as critical design variables for optimizing windows and light shelves for lighting performance and controlling solar heat gain. This is essential in regions with abundant sunshine and buildings primarily used during the day.

The use of light shelves in this climate and front leads to an improvement in the quantity and quality of daylight and a reduction in energy consumption, as demonstrated by a comparison between the simulation results of the base model and some of the best optical variables from the Pareto front and the last generation. The addition of a light shelf resulted in an improvement in the sUDI metric in areas away from the window and a significant decrease in the annoying glare in areas near the window. Overall, the use of light shelves leads to an increase in the amount of uniform natural light in the interior space, as well as helping to reduce the total cooling and heating load of the space.

Based on the evaluation of different types of light shelves in the Pareto front and the last generation results, the following points can be summarized:

The most repeated type of window for achieving maximum daylight, the least amount of annoying glare, and energy consumption belong to Triple Low-E (e5=0.1), Triple pane, and Single Low-E (e2=0.2) windows, which have the specifications (VT:0.70, SHGC:0.58, UVALUE:1.30), (VT:0.75, SHGC:0.68, UVALUE:20), and (VT:0.81, SHGC:0.72, UVALUE:4.35), respectively.

Table 13: Simulation of some appropriate responses in the presence of a light shelf and simulation of the base model.

An appropriate scenario	An appropriate scenario
	
{16;19}: EUI=5003, sDGP=0.106, sUDI=0.977	{21;12},: EUI=5045, sDGP=0.072, sUDI=0.969
	
Last gen-2 EUI=5509, sDGP0.09=, sUDI=1	{36;9}: EUI=4930.90, sDGP=0.087, sUDI=0.844
	
Last gen-10 EUI=4928.20, sDGP=0.080, sUDI=0.78	{26;13}: EUI=5003.10, sDGP=0.114, sUDI=0.984
	
Base Model EUI=6570.10, sDGP=0.40, sUDI=0.70	

Based on the optimization results, the optimal WWR for windows facing the southeast is either 20%, 25%, or 30%. When considering responses that are constant in all variables except for the WWR, it is clear that as the WWR increases, the values in all metrics (sUDI, sDGP, and EUI) also increase. However, since the increase in sDGP and EUI metrics is not significant due to the increase in natural light in the space, it seems more appropriate to use either a 25% or 30% WWR.

As previously mentioned, the angle variable significantly influences the optimization process for optimal daylight receiving and energy consumption. Based on the Pareto front's responses, which are similar to each other in other variables except for the angle, the optimization results indicate that an angle of 5 degrees relative to the horizon improves the amount of light received. Increasing the angle of the light shelf in the considered range causes the amount of incoming light to the interior space to increase and, on the other hand, does not cause significant changes in the other two metrics. Given the educational use of the space, the reflection angle was considered to be upward (to avoid obstructing the view outside).

The external light shelf has a depth of 0.90 cm for 25% and 30% WWR and 0.75 and 0.90 cm for 20% WWR. However, depending on other conditions, the internal shelf's depth varies from 0.20 to 0.60. Similar to the other variables except for the inner depth, a balanced response shows that a greater internal depth within the defined range reduces glare annoyance. It was discovered that there was no significant difference in the amount of incoming light or energy consumption.

Aluminum with different reflective properties is chosen for balanced responses. According to the results, the material with a higher reflectance coefficient leads to more daylight reception.

Glass with a higher visible light transmission coefficient (VT) increases the amount of light received inside the space while also increasing energy consumption. Therefore, it is advisable to select glass that aligns with the priorities of the space's intended use.

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