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Multi-objective Optimization of Girih Tile Patterns and Colored Glass in Orosi Windows: A Case Study of Isfahan Architecture

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ABSTRACT

Efficient energy use is vital in architecture, and the building envelope plays a key role in aesthetics, thermal comfort, energy efficiency, and natural lighting. Traditional architecture has employed innovative solutions for building envelopes to address climatic challenges and ensure suitable indoor thermal conditions. One prominent example is the use of Girih tile patterns and colored Orosi windows, which have successfully met the functional and climatic needs of traditional buildings. This study investigates various Girih tile patterns and colored glass combinations in Orosi windows of traditional buildings in Isfahan. Their layout and wood-to-glass ratio were analyzed. Using a semi-experimental, quantitative approach with software simulations, 60 Girih tile patterns were assessed in Rhino7 with Honeybee and Ladybug, and 120 colored glass combinations were optimized via Octopus in Grasshopper. Results show that the optimal pattern (N50), a twelve-sided Safavid design with 58.14% wood density, achieved 88.51% useful daylight illuminance, 99.03% visual comfort, and 99.47% thermal comfort. This yielded the highest overall performance (95.67% average, SD = 6.20). Patterns with 51–57% wood density maintained high optimization, while densities above 59% reduced daylight penetration. For colored glass, combinations with higher yellow content reached up to 87.89% UDI, whereas patterns dominated by colorless and blue glass dropped to 4.58% UDI. These findings provide evidence-based guidelines for designing openings that balance daylighting, visual comfort, and thermal efficiency in Isfahan's cold semi-arid climate. It is noteworthy that the results of analyzing the performance level of single colors differ significantly from the arrangement of various colors alongside each other.

Keywords: multi-objective optimization, daylight illuminance, visual comfort, thermal comfort

1. INTRODUCTION

The building sector is currently a major energy consumer, and substantial population growth is expected to increase energy demand and resource consumption in the coming years. Numerous studies emphasize the importance of innovative design strategies and guidelines to improve energy performance and occupant comfort in buildings [1,2,3]. Traditional architectural solutions, proven to be effective in ensuring occupant comfort and addressing energy needs, can serve as a reliable source of inspiration [4]. Architectural components in traditional buildings are often multifunctional and incorporate valuable cultural principles, making them efficient models for contemporary architecture [5]. Building openings are pivotal elements that affect visual aesthetics, daylighting, thermal comfort, and energy use [6]. Thoughtful design of these features, using appropriate patterns, can significantly reduce energy consumption while enhancing visual and thermal comfort. However, designing an optimal opening that meets all criteria is challenging, as some variables may conflict [7]. In traditional Iranian architecture, this challenge has been addressed through Girih tile patterns and colored glass, known as Orosi windows. These windows, whether stationary or adjustable, serve multiple functions, including enhancing visual appeal, maintaining privacy, promoting mental well-being,

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NOMENCLATURE

LS	*Library Study*
FS	*Field Survey*
LM	*Laboratory Measurements*
NA	*Numerical Analysis*
A	*AutoCAD*
Rh	*Rhino*
D	*Diva*
DB	*Design Builder*
H-L	*Honeybee-Ladybug*
BSk	*Cold Semi-arid*
B	*Arid and Semi-arid*
V	*Vernacular*
DP	*Daylight Performance*
TP	*Thermal Performance*
G	*Geometry*
AG	*Albedo of Glass*
PD	*Proportion and Dimension*
WWR	*Window-to-wall Ratio*
P	*Pattern*
PsE	*Psychological effects*
CT	*Construction Technique*
GN	*Girih number*
UDI	*Useful daylight illuminance*
TC	*Thermal Comfort*
OT	*Operative temperature*
NG	*Number of glasses*
WGR	*Wood Glass ratio*
SD	*standard deviation*
CS	*Case Study*
SA	*Simulation Analysis*
DA	*Descriptive Analytics*
QM	*Qualitative Method*
E	*ECOTECT*
G	*Grasshopper*
R	*Radiance*
DA	*Daysim*
BWh	*Hot Desert*
BWk	*Cold Desert*
C	*contemporary*
M	*Modern*
DR	*Decoration Role*
AC	*Air condition*
O	*Orientation*
M	*Material*
BF	*Building Form*
C	*Color*
A	*Angle*
PhE	*Physiological Effects*
GT	*Girih type*
DA	*Daylight autonomy*
VC	*Visual Comfort*
R	*Radiance*
WD	*Wood density*
ASG	*Average size of glasses*
AV	*Average value*

regulating natural light, providing external views, facilitating airflow, reflecting cultural values, and deterring insects [8]. Previous studies have investigated the structural, functional, and environmental characteristics of Orosi windows [9]. Research has shown that colorful glass in Orosi windows serves multiple purposes, including light control, aesthetic enhancement, and insect repulsion [10], while positively impacting human personality and behavior [11,12]. Atrvash and Fayaz [13] studied the impact of Orosi windows on indoor airflow, considering orientation, proportion, and dimensions. They found that window positioning can modify airflow, with open designs promoting better circulation. Haghshenas and Ghiabaklou [14] analyzed the effect of tinted glazing on daylight and energy transmission in nine Orosi windows from vernacular houses. Simulations and experiments revealed that tinted glass reduces transmitted energy by nearly one-third compared to standard float glass by blocking high-frequency waves. Haghshenas et al. [15] measured light transmission through Safavid-era Orosi windows and found that yellow glass minimized harmful wavelengths without significantly reducing visible light, while blue glass allowed harmful wavelengths despite reducing visible light. Studies of twelve Qajar houses in Qazvin showed that these windows absorbed or reflected 28–52% of visible solar radiation, with higher light transmission through simple and yellow glass compared to blue, red, and green variants [16]. Mousavi et al. [17] examined the impact of skylight positioning, room geometry, and courtyard location on daylight in traditional Yazd houses. Their results highlighted correlations between window-to-wall ratios, window height, room depth, and sky visibility. Small frames with colored glass improved light distribution and reduced glare. Hosseini et al. [18] demonstrated that geometric patterns in Orosi windows affect daylight performance, with geometry and color interaction influencing light admission. Using simulations with Rhino, Grasshopper, and Diva, they emphasized the importance of window geometry and thickness. Hosseini et al. [4] also studied how colorful glass can control direct sunlight to enhance visual comfort, analyzing geometry, orientation, proportions, and window-to-wall ratio. Their results show that combining lattice frames with Iranian-Islamic patterns significantly improves visual comfort by optimizing daylight metrics and controlling glare, depending on function, climate, and occupant behavior.

Two additional studies by Hosseini et al. [8,18] investigated dynamic interactive façades inspired by butterfly wings. Using Rhino, Grasshopper, Honeybee-Ladybug, and Diva, they showed that adjusting façade position and colored glass transparency can enhance visual comfort and energy efficiency. Omidi et al. [19] integrated kinetic façades with colored glass inspired by Orosi windows. Simulations considering sun position and occupant location revealed that blue and red glasses mitigate glare, while yellow, green, and colorless glasses maximize daylight admission. Omidi et al. [19] also compared framed Orosi windows with colored glass to unframed or ordinary windows using Rhino, Grasshopper, Daysim, and ECOTECT. Their results confirmed that tinted glass manages light quality but increases lighting

Table 1. Summary of Literature Review.

Num.	Author	Year	Methodology	Software	Climate	Building Type	Function	parameters
1	Lu & Steinhardt	2007	QM/CS	-	-	V	DR	G/P
2	Haghshenas & Ghiabaklou	2008	LS/FS/CS/SA/LM	A	-	V	DP	AG/C
3	Nabavi et al.	2012	LS/CS	-	B	V	DP	BF/G
4	Atrvash & Fayaz	2015	LS/CS/SA	-	BWh	V	AC	O/ PD
5	Haghshenas et al	2016	LS/FS/LM	-	BWh	V	DP	AG/C
6	Jalili & Sefidi	2016	QM/CS	-	BWh	V	DP	C
7	Gorji Mahlabani & Boushehri	2017	LS/CS/FS	-	BSk	V	DP	C/AG
8	Wahdattalab & Nikmaram	2017	LS/CS/FS	-	BSk	V	DR	C/G/P
9	Hosseini et al	2018	LS/SA	Rh/G/D	BWh	C	DP	G/O/WWR/C
10	Mousavi et al	2018	LS/CS/NA	-	BWh	V	DP	G/PD/O/WWR
11	Hosseini et al	2020	LS/SA	Rh/G/D	B	M	DP	C/G/P
12	Hosseini et al	2020	LS/SA	Rh/G/D	BWh	C	DP	C/G/P/AG/A
13	Madhoushian & Fallahi	2021	LS/CS/NA	A/Rh	BSk	V	DR	C/G/P
14	Hosseini & Heidari	2022	LS/SA	Rh/G/H-L	BWh	V	DP	G/P/WWR/C/A
15	Omidi et al	2022	LS/CS/LM	Rh/G/DA/E	BWh	V	DP	C/G/P
16	Raisi et al. 2024	2024	LS/CS/SA	DB	BWh	V	DP/TP	G/O/C/P

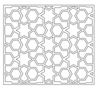
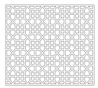
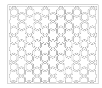
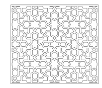
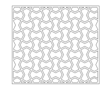
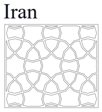
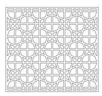
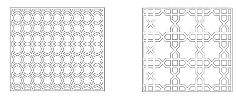
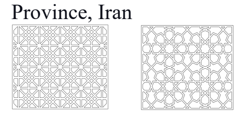
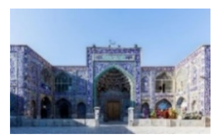
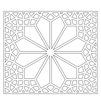
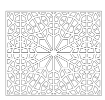
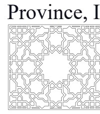
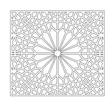
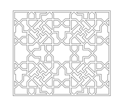
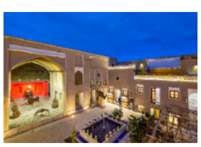
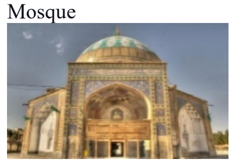
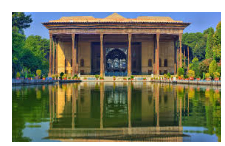
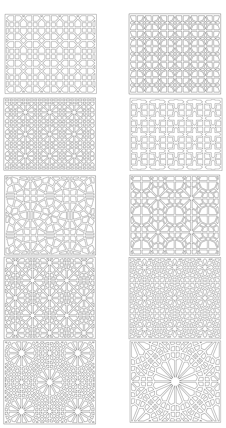
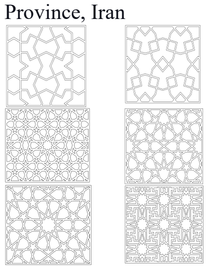
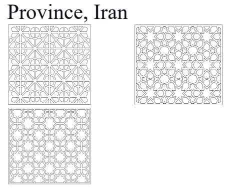
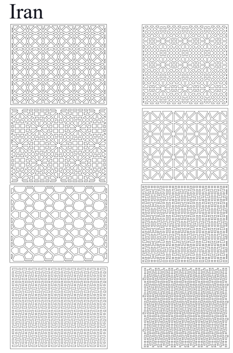
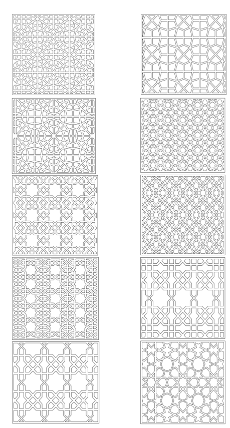
energy demand. The combination of glass types and frame shapes improved Useful Daylight Illuminance (UDI) and reduced illuminance variation across spaces, with glass color being the most influential factor. Raisi et al. [20] evaluated Orosi window-colored glass in Qajar House, Shiraz, using Design Builder simulations and experiments. Yellow glass improved thermal comfort by up to 22% and outperformed other colors in spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). Blue and green glass were the next most effective. A brief review of relevant studies is presented in Table 1.

While some studies address construction techniques and historical context, the majority of the literature focuses on the environmental and functional performance of Orosi windows, consistently identifying glass color and geometric pattern as the most influential variables. However, no prior research has systematically examined Orosi windows from the viewpoint of multi-objective optimization with clearly defined performance goals.

The design of windows in harsh climates frequently suffers from a lack of a logical and systematic approach, leading to shortcomings in meeting multiple critical requirements simultaneously [21]. In Isfahan's hot and dry climate, managing glare and high temperatures is essential for building efficiency. Integrating Girih tiles into colored windows can improve thermal comfort and natural ventilation [9,19,22]. A significant challenge arises from the inherent conflict among key design variables, such as energy efficiency, thermal comfort, and visual appeal, making it difficult to create a window that satisfies all these aspects comprehensively. While traditional architectural solutions have historically provided valuable insights, they are often neglected in contemporary design. Orosi windows, despite their proven benefits over time, are seldom integrated into modern designs, representing a missed opportunity for innovation and advancement in window design strategies [23,24].

This study performs a multi-obective optimization of Girih tile patterns and colored glass for buildings in Isfahan, with the aim of enhancing thermal comfort, visual comfort, and glare control. By analyzing traditional Girih patterns and exploring their integration into contemporary architectural designs, the research seeks to develop sustainable, climate-responsive solutions. These traditional girih patterns are chosen by studying 20 existing traditional building in Isfahan (Table 2). The primary objective is to establish design guidelines that enable architects to incorporate optimal combinations of Girih patterns and colored glass in modern buildings and achieving a balance between aesthetic, functional, and environmental performance. Specifically, the study first identifies the most effective geometric pattern without stained glass, followed by a detailed optimization analysis that includes the impact of colored glass.

Table 2. Case studies of several girih types in existing buildings.

Traditional building	Bakran Pulpit	Ali Qapu	Qotbiyya Mosque	Kooshk Gate	Jameh Mosque of Isfahan
Image					
Historical period	Seljuk	Safavid	Seljuk	Safavid	Seljuk
Location	Bakran, Isfahan Province, Iran	Isfahan, Iran	Isfahan, Iran	Isfahan, Iran	Isfahan, Iran
Girih					
Traditional building	Jameh Mosque of Natanz	Imamzadeh Omran ibn Ali	Abyaneh Isfahan	Hasht Behesht	Haft-Tan Mausoleum
Image					
Historical period	Seljuk	Safavid	Sasanid	Safavid	Seljuk
Location	Natanz, Isfahan Province, Iran	Isfahan, Iran	Natanz, Isfahan Province, Iran	Isfahan, Iran	Golpayegan, Isfahan Province, Iran
Girih					
Traditional building	Sadbazar school	Haruniyeh	Jameh Mosque of Safa, Shagird	Seyyed Mosque	Aqa Noor Mosque
Image					
Historical period	Safavid	Seljuk	Seljuk	Safavid	Safavid
Location	Isfahan, Iran	Isfahan, Iran	Shagird, Isfahan Province, Iran	Isfahan, Iran	Isfahan, Iran
Girih					
Traditional building	Safavi House	Jameh Mosque of Shahib	Golpayegan Jameh Mosque	Nain Jameh Mosque	Chehel Sotoun
Image					
Historical period	Safavid	Seljuk	Seljuk	Seljuk	Safavid
Location	Isfahan, Iran	Shahib, Isfahan Province, Iran	Golpayegan, Isfahan Province, Iran	Nain, Isfahan Province, Iran	Isfahan, Iran
Girih					

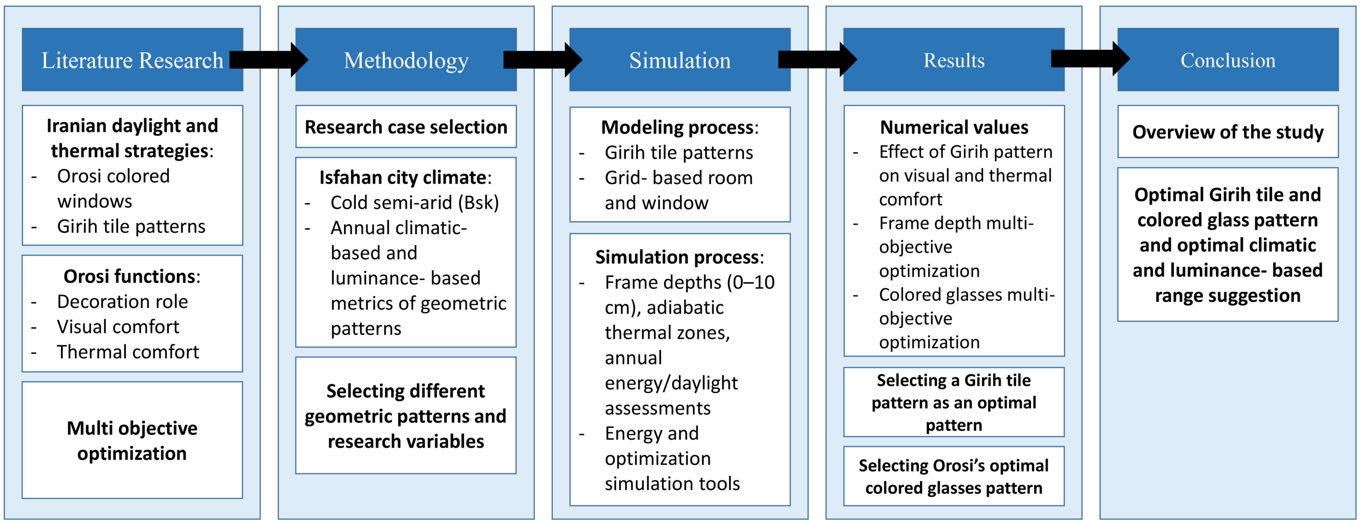


Fig. 1. Structure of the research.

While earlier research has examined individual aspects such as window geometry, colored glass, or daylight performance, few have investigated the integrated effects of Girih tile patterns, wood-to-glass ratios, and colored glass arrangements on both visual and thermal comfort. Although daylight, glare, and airflow have been studied separately, multi-objective optimization techniques have rarely been applied to identify the most effective combinations of patterns and glass colors. Therefore, this study addresses the gap by conducting numerical simulations and multi-objective optimizations to simultaneously evaluate daylight performance, visual comfort, and thermal behavior, providing evidence-based guidelines for selecting optimal Orosi window designs. It provides a comprehensive analysis of Girih tile patterns and colored glass variations in Isfahan, focusing on physical characteristics that influence thermal and visual comfort in stained glass openings areas largely overlooked in previous studies.

The research consists of 5 Sections. Section 2 focuses on methodology, The Methodology section includes case selection in Isfahan's climate, employing a quantitative, semi-experimental methodology and combining numerical simulations and optimization to assess Girih tile patterns in Isfahan's traditional Orosi windows. Also in this section climatic and luminance-based metrics is used to select geometric patterns and variables. Sixty historical patterns were digitized using AutoCAD/Rhino 7 and analyzed for daylight/thermal performance via Ladybug and Honeybee plugins, with colored glass combinations optimized through the Octopus plugin. Key objectives included optimizing thermal comfort (21–26°C), reducing glare (Daylight Glare Probability), and achieving Useful Daylight Illuminance (100–3000 lux). Simulation data from 840 scenarios were statistically processed in MATLAB/SPSS to identify optimal geometric patterns and glass color combinations for Isfahan's semi-arid climate. In Simulation section, the model Girih patterns, grid-based room and window, as well as the simulation process employing energy and optimization tools are introduced. The Results section provides numerical values, selecting optimal Girih tile and Orosi's colored glass patterns. Finally, the Conclusion section summarizes the study, suggesting optimal patterns and climatic/luminance ranges Fig. 1.

The present study aims to answer the following research questions:

- How can multi-objective optimization of Girih tile patterns in window designs contribute to thermal comfort, visual comfort, and glare reduction in buildings?
- What is the optimal geometric pattern of Girih tile (considering useful daylight illuminance, visual comfort, and thermal comfort) for the openings in buildings of Isfahan city?
- What is the optimal color arrangement in Girih tile patterns (considering useful daylight illuminance, visual comfort, and thermal comfort) for the openings in buildings of Isfahan city?

2. RESEARCH METHODOLOGY

This study employs an applied research approach grounded in quantitative methods. In alignment with the research questions and objectives, a semi-experimental design has been adopted, utilizing

Fig. 2. (a) The location of Iran on the world map, (b) the map of Iran, (c) the location of Isfahan city in Iran, (d) the map of Isfahan city [32].

numerical simulation techniques as the primary methodological framework [25].

2.1. The city of Isfahan

Isfahan is located in central Iran at approximately 32.65°N latitude and 51.67°E longitude, with an altitude of about 1,570 meters above sea level (Fig. 2). The city has a cold semi-arid climate (BSk in the Köppen climate classification), characterized by hot, dry summers and cold winters [26,27]. The average annual temperature is around 16°C, with summer highs exceeding 35°C and winter lows occasionally dropping below freezing [27]. Isfahan receives an average annual precipitation of approximately 120–150 mm, mostly occurring between late autumn and early spring. Solar radiation levels are generally high due to the city's low humidity and clear skies, with an average of over 2,800 hours of sunshine per year [28]. However, Isfahan experiences some cloudy days, particularly in winter, with an estimated 80–100 overcast days annually. These climatic conditions significantly influence energy consumption, building design, and natural ventilation strategies in the region [29,30,31]. Table 3 represents climatic and technical details Include climatic graphical charts of the Isfahan city with their legends beside them.

2.2. Motif morphology

To collect the prevalent Girih tile patterns in Iranian architecture, library-based investigations were conducted. A total of 60 Girih tile pattern images were extracted from the Orosi windows of twenty traditional houses in Isfahan, sourced from a variety of architectural and historical reference books.

Orosi is a traditional architectural element in Iran, typically composed of colored glass set within intricate wooden frames, and commonly found in central courtyard houses. These features serve multiple functions: filtering and controlling daylight, reducing glare and heat, enhancing visual comfort, providing privacy, and contributing aesthetic value. The colored glass functions as a passive daylight filter, improving indoor comfort while reducing heat gain [9].

The use of Girih tile patterns in Orosis is deeply connected to the scientific and technological advancements of the Middle East, Iran, and Central Asia, which facilitated their widespread application. Girih patterns are based on geometric units such as triangles, rectangles, and pentagons, forming the foundation of much of Islamic decorative art. These intricate motifs frequently appear on architectural elements like walls, doors, and windows. Morphologically, Girih tile patterns are broadly categorized as geometric or floral, with geometric forms being more common, likely due to the mathematical and constructional techniques involved in their creation [9]. These patterns are further divided into nine primary groups [33], providing a framework for systematic classification and analysis.

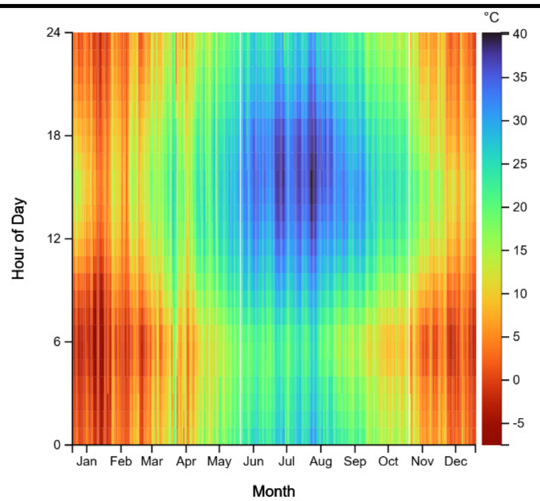
The selection of 60 samples was designed to offer a representative dataset reflecting the diversity of design, complexity, and historical significance found in traditional Isfahani architecture. The buildings studied span several historical periods, including the Safavid era (16th–18th century) and the Qajar period (19th–20th century). All selected patterns originate from architecturally and culturally significant buildings, such as Chehel Sotoun, Ali Qapu, Hasht Behesht, the Grand Mosques of Isfahan and Nain, and other prominent traditional structures. The goal was to classify the Girih tile patterns effectively to enable comparative analysis in subsequent simulation and optimization phases of the research.

2.3. Numerical simulations

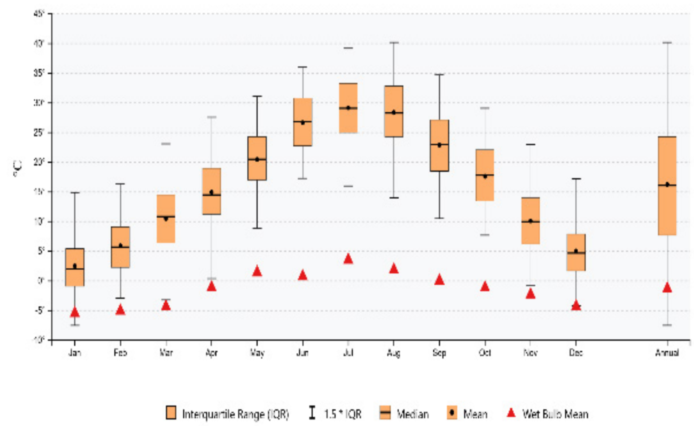
The process began with digitizing 60 historical Girih tile patterns obtained from archival sources using AutoCAD and Rhino 7 (Fig. 3). In this stage, morphological analysis and a series of environmental simulations were carried out using Rhino 7 with the Ladybug/Honeybee plugins (v1.6.0) by assessing daylight performance, glare, and thermal behavior. During this phase, the glass color was held constant to isolate the effects of geometry. In alignment with the defined research objectives, the simulation results were analyzed and the most suitable Girih tile pattern was identified and selected from the initial set of 60 patterns during this preliminary phase.

Table 3. Climatic graphical charts of the Isfahan city.

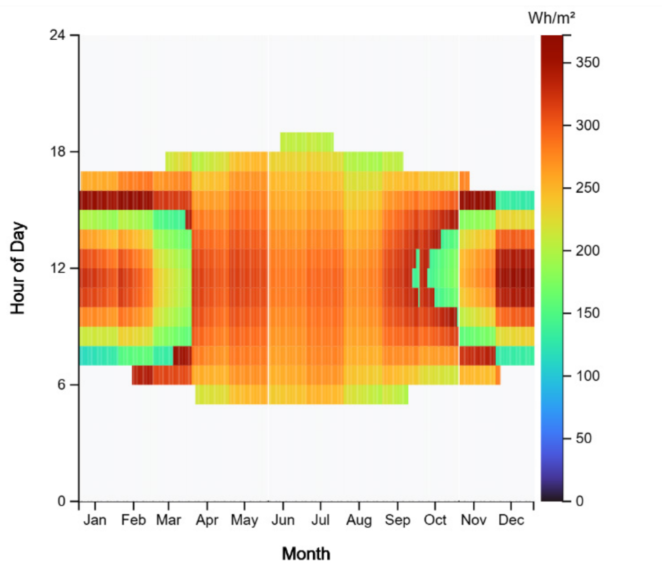
Annual Dry Bulb Temperature



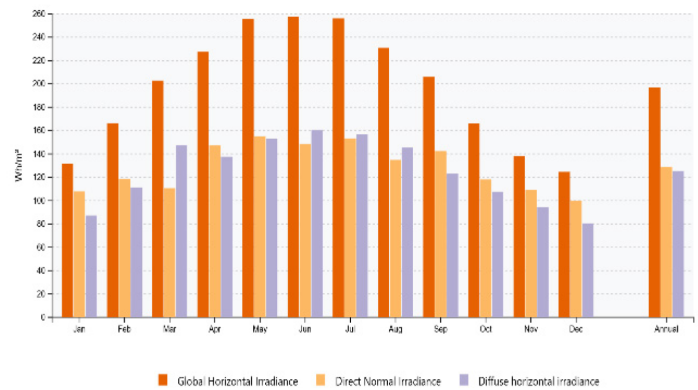
Monthly Temperature Distribution



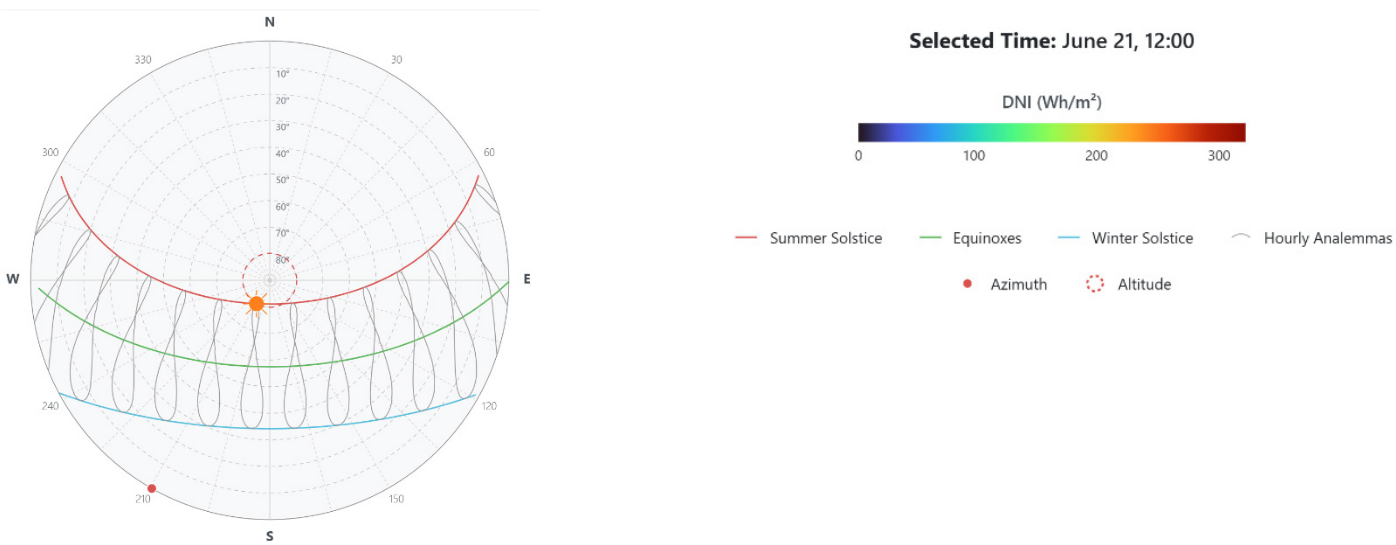
Annual Direct Normal Radiation (DNI)



Average Monthly Solar Radiation



Annual Sun Path with Direct Normal Irradiance Intensity



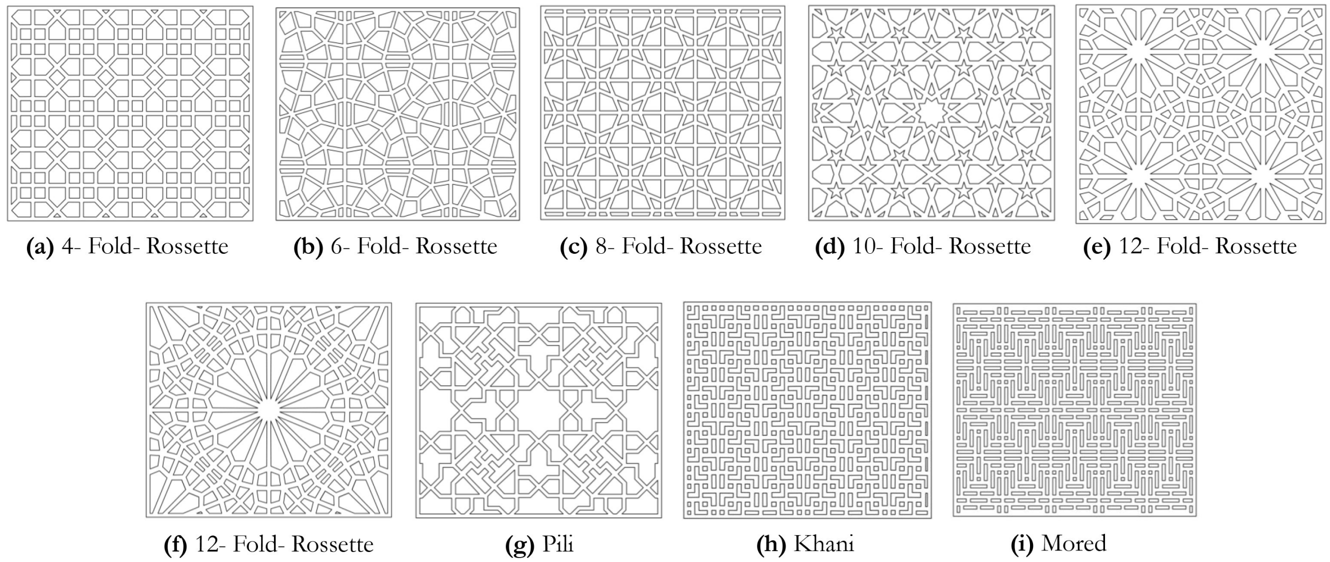


Fig. 3. Knots classification and a sample image of each group [33].

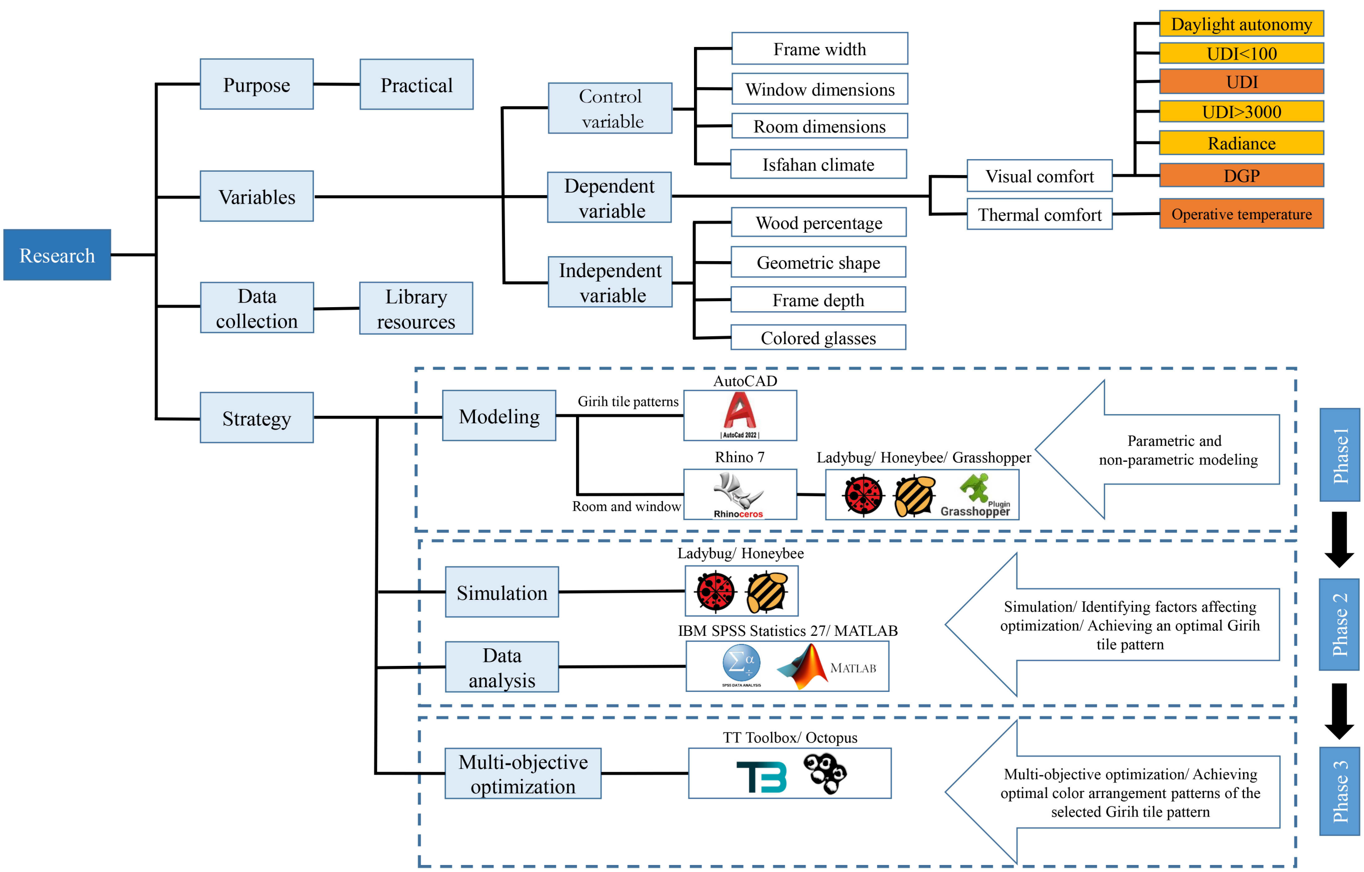


Fig. 4. Conceptual model of search.

In the following phase, after varying frame depth from 0 to 10 centimeters to allow a separate analysis of how the depth of the frame relates to the simulation results, the glass elements of the selected Girih tile pattern were assigned various color combinations for multi-objective optimization. The color assignments were structured so that each color appeared only once in each combination group, ensuring non-repetitive use across glass segments. A total of 120 distinct color combination samples were generated and evaluated.

Multi-objective optimization was then performed using the Octopus plugin, aiming to determine the most effective colored glass configuration for the selected Girih tile pattern in terms of maximizing both visual and thermal comfort. In total, 840 simulations were conducted by spanning both the evaluation of Girih tile patterns and their corresponding glass color arrangements. The runtime for each simulation varied between 30 and 90 minutes, depending on the complexity of the pattern and the number of nodes (knots).

These simulations produced data across multiple environmental performance indicators, including Daylight Autonomy, UDI <100, Useful Daylight Illuminance (UDI), UDI >3000 [34], Daylight Glare Probability (DGP), Radiance, Operative Temperature, and overall Thermal Comfort. Among these, UDI, visual comfort (via DGP), and thermal comfort specific to Isfahan's climate were identified as the three primary optimization objectives.

Following the simulation phase, the generated numerical data were analyzed using MATLAB 2019 and IBM SPSS Statistics 27. This analysis focused on identifying statistical correlations between pattern characteristics and performance metrics, with the aim of uncovering the physical attributes most critical to optimization. Ultimately, this process led to the selection of both the optimal Girih tile pattern from the original dataset and the best-performing colored glass configuration. A visual summary of the overall methodology and workflow is presented in Fig. 4.

2.4. Measurement and evaluation

This study focuses on three primary research objectives: thermal comfort (Adaptive), visual comfort (DGP analysis), and Useful Daylight Illuminance (UDI) in the context of Isfahan's specific climatic conditions. The criteria and standards for each variable are clearly defined and systematically applied throughout the research.

2.4.1. Thermal comfort performance

Thermal comfort refers to an individual's satisfaction with the thermal conditions of an environment, influenced by factors such as temperature, humidity, and personal attributes like acclimatization, clothing, health, and physiological characteristics. It is achieved when the body's thermoregulation processes operate with minimal effort [35,36]. Thermal comfort is defined as the temperature range of 21–26°C with relative humidity levels of 30–60%, where individuals feel at ease without altering the indoor environment [37]. Discomfort arises when humidity increases and temperature decreases, influencing perceived comfort levels [38]. This study adopts an adaptive thermal comfort approach, allowing occupants to regulate their environment by adjusting clothing or window positions. Since thermal comfort is subjective, it varies among individuals. According to simulations, the thermal comfort index of this research includes surface temperatures, indoor and outdoor air temperatures, radiant temperatures, relative humidity, and air speeds taken directly from EPW. All these energy properties of the model geometry are what determine the outcome of the simulation. Notably, no artificial heating or cooling systems were used; all heat transfer occurred naturally. In this research, a thermal comfort range of 21–26°C has been applied. In this study, the thermal comfort threshold and range for selecting the optimal Girih patterns were considered to be between 99% and 100%.

2.4.2. Visual comfort

Visual comfort or useful daylighting is influenced by human eye physiology; various factors such as light intensity and quality affect how visual stimuli are perceived and impact residents' comfort levels [39]. Insufficient lighting can cause dimness and fatigue, while excessive brightness, high contrast, or strong reflections may impair performance [40]. This study did not utilize artificial lighting, instead focusing on optimizing natural light and heat transfer through various lattice patterns.

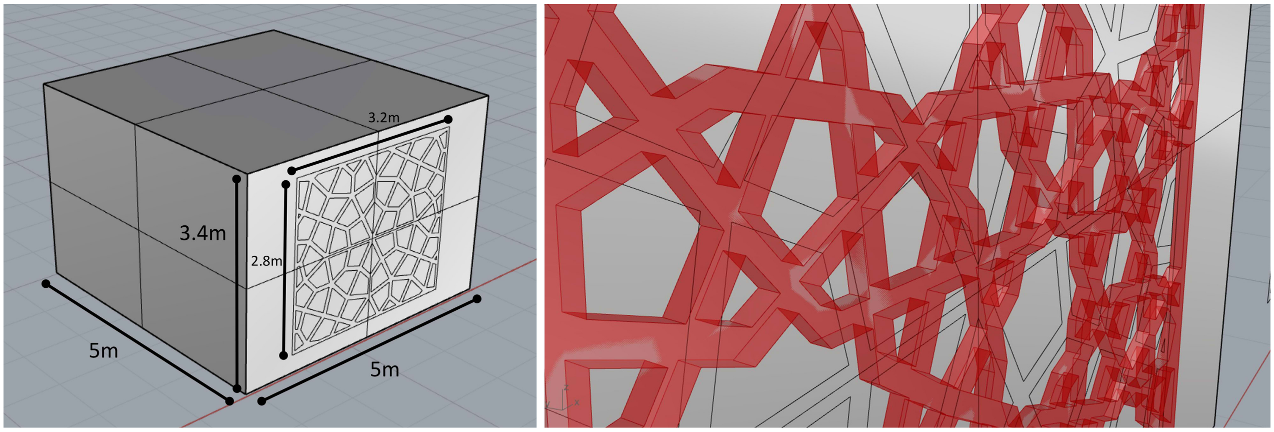
Daylight performance was evaluated through the measurements of three indicators: useful daylight illuminance (UDI), glare, and daylight glare probability (DGP). UDI measures the percentage of annual hours when daylight falls within an optimal range of 100–3000 lux. Levels below 100 Lux are too dim, while those above 3000 Lux are excessively bright [34]. This study defines the UDI index within this range. In this research, the applied UDI range is also 100-3000 Lux. The UDI threshold and range for selecting the optimal Girih tile patterns were considered to be between 87% and 100%.

Excessive brightness can cause glare, leading to eye strain and reduced visual comfort [41]. Glare, which can be direct (from light sources) or indirect (from reflections), restricts vision and causes discomfort [42]. This study uses the Daylight Glare Probability (DGP) index, analyzed annually via the HB Imageless Annual Glare feature in the Honeybee plugin. A higher DGP percentage indicates reduced glare, improving visual comfort. Since minimizing glare enhances overall comfort, this study equates glare reduction with improved visual well-being. The DGP threshold and range for selecting the optimal Girih tile patterns were considered to be between 97% to 100%.

The simulations focused on three main variables: Useful Daylight Illuminance (UDI=100-3000) [34], visual comfort by evaluating DGP, and adaptive thermal comfort, which are central to this research and are highlighted with orange color in the conceptual model of search chart (Fig. 4). Additionally, other energy metrics such as radiance, daylight autonomy, high daylight illuminance (UDI>3000) [9,18], low daylight illuminance (UDI<100), and operative temperature were analyzed to enhance understanding of the interrelations among these variables Fig. 4.

3. SIMULATION SETTINGS

According to conventional building designs, Girih tile patterns were mostly used in large and full-height windows rather than modern small openings. In this research, based on a common method for planning the rooms and courtyards in Iranian traditional architecture, the room plan dimensions are 5 × 5 meters with a height of 3.4 meters from the top of the floor to the bottom of the ceiling. The thickness of the walls is 0.2 meters, while the ceiling and floor are 0.3 meters. Moreover, the window measuring



(a) (b)

Fig. 5. (a) Window and room dimensions of simulation, (b) An example of a knotted frame with a width and depth of 5cm.

Table 4. Different layers of insulted external wall and their specifications.

Layer number	External wall layers	Thickness (m)	Conductivity (W/m.K)	Density (kg/m3)	Special heat (J/kg.K)
1	Brick	0.04	1.33	1700	840
2	Cement-sand mortar	0.075	0.3	500	836
3	Clay block	0.4	0.51	1700	840
4	Rock wool insulation	0.0508	0.38	40	1000
5	Cement-sand mortar	0.075	0.3	500	836
6	Plasterboard/soil	0.02	1.10	1300	200
7	plasterboard	0.05	0.4	900	200

Table 5. Specifications of wooden frames and double-glazed glass panels.

Window wooden frame	Solar reflectance	Visible reflectance	
	0.4	0.4	
Double-glazed glass	**U-factor (Wm^2.K)**	**Thickness (m)**	**Solar heat gain coefficient**
	0.29	0.028	0.45

2.3 × 2.8 meters is located in the center of the south façade with a ratio of 0.52 for window-to-wall (Fig. 5(a)). It is also important to note that the index of refraction (IOR) for glass is typically set at 1.52.

Existing studies and observations indicate that the standard frame thickness for Girih tile patterns typically ranges between 0.8 and 1.5 centimeters. Given the time-consuming process of the simulations, a default of 5 centimeters was assumed for the frames. In the initial phase of this research, which focuses on the relationship between the Girih tile pattern and optimality, the depth of the frame is fixed at 5 centimeters (Fig. 5(b)). However, in the final phase of the study, frame depth will be considered as an independent variable, varying from 0 to 10 centimeters. This adjustment will allow a separate analysis of how the depth of the frame relates to the simulation results. Since each Girih tile pattern is unique to its grid layout, it is crucial to simulate all patterns individually, as done in this study. This approach allows for a comparative analysis of the simulation results and helps determine how the Girih tile's geometric pattern influences the study's dependent variables.

It is crucial to highlight that the simulations were designed to ensure that, while the window size was scaled up, the geometric proportions of the Girih tile pattern joints remained constant. In this context, constant values are defined for the thickness and depth of the frames. Consequently, when evaluating different alternatives, the ratio of wood surface area to glass serves as a significant and reliable variable for comparison.

Each Girih tile pattern which is intended for use in contemporary buildings, has been scaled up beyond its traditional dimensions to enhance the reliability of comparative results. To improve strength and increase the glass-holding capacity, it is essential to proportionately increase the thickness of the frames. If these Girih tile patterns are implemented at a 1:1 scale in actual designs, the reported figures and percentages in this study will differ from those at full scale. The results will primarily offer a comparative measure of optimality across various samples. Since this research focuses on comparative analysis among case samples, altering the scale of these samples will not impact the comparative outcomes.

Given that the percentage of wooden frame density in the samples ranges from 30% to 70%, depending on the type and

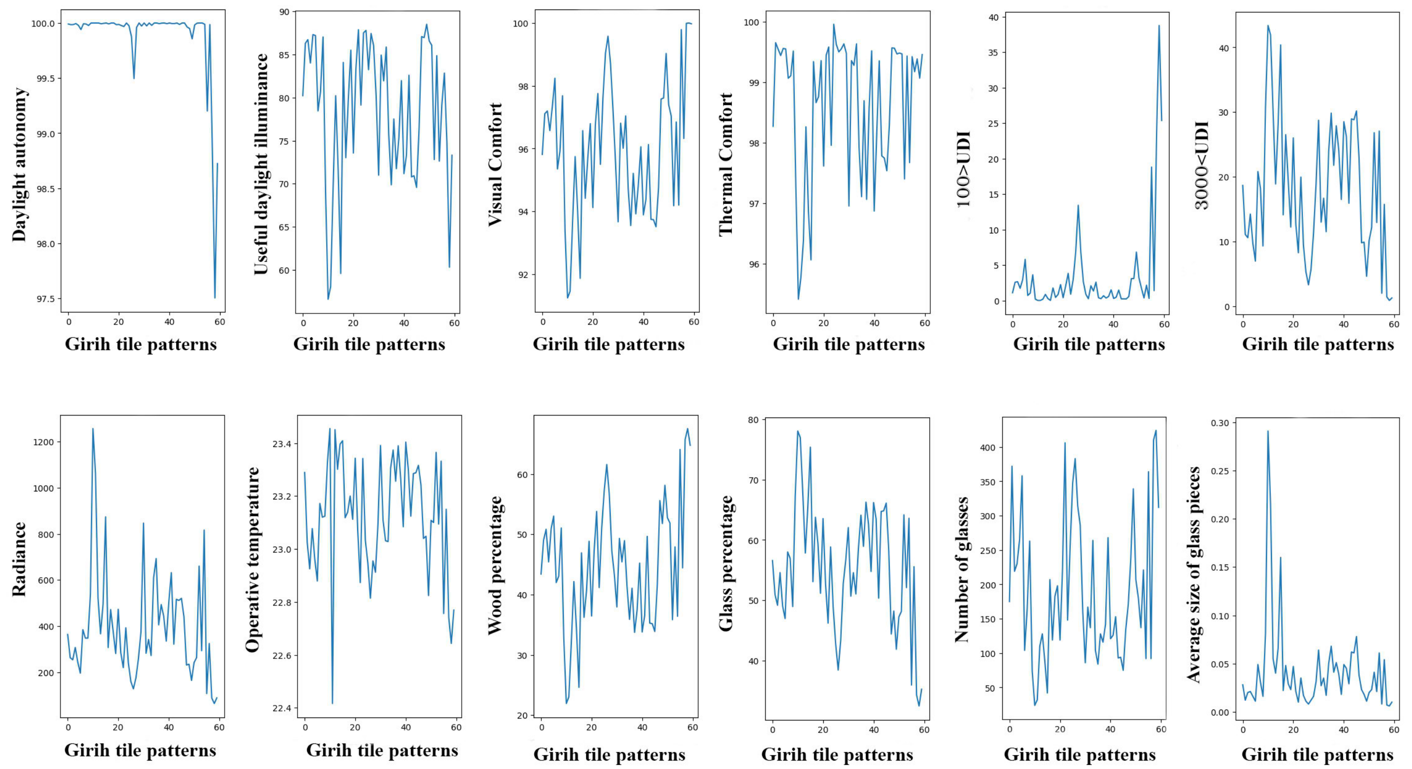


Fig. 6. Performance and configurations of sixty Girih tile patterns.

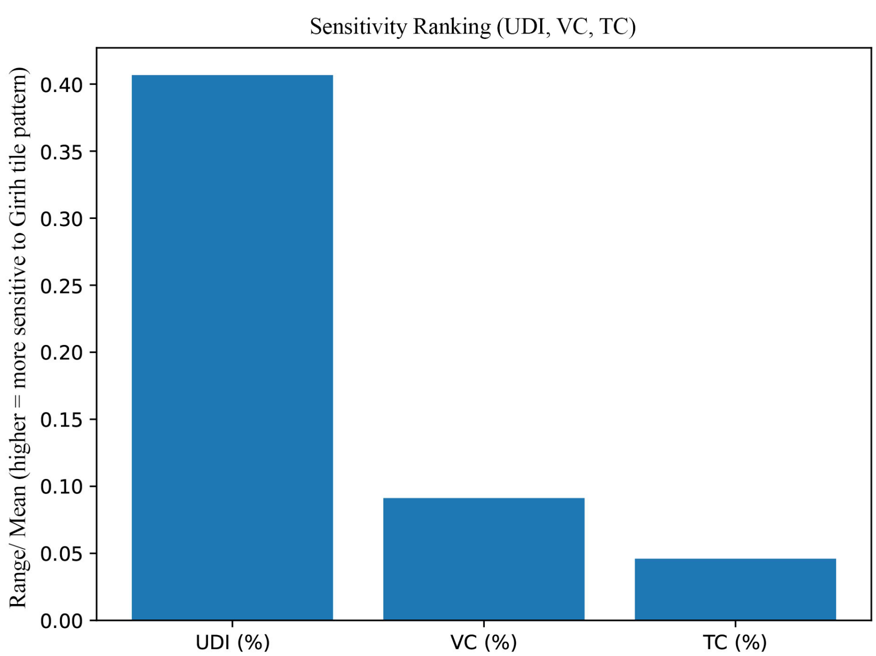


Fig. 7. Sensitivity analysis for Girih tile pattern.

construction method of each Girih tile pattern, it can be inferred that the large and continuous nature of the windows can compensate for the standard dimensions of openings, even with a high frame density. This may elucidate why Girih tile patterns have been employed in traditional architecture for expansive openings and transoms. Conversely, using Girih tile patterns in smaller openings often leads to inadequate light penetration, compromising visual and thermal comfort.

Table 6. Numerical results of 60 Girih tile sample simulation.

Useful daylight illuminance (%)				Visual Comfort (%)				Thermal Comfort (%)			
<75%	75% - 85%	85% - 87%	>87%	< 94%	94%- 97%	97%-99%	>99%	< 97%	97% - 99%	99%- 99.6%	>99.6%

GN	GT	DA (%)	UDI (%)	VC (%)	TC (%)	UDI< 100 (%)	UDI> 3000 (%)	R (W/m2-sr)	OT (C)	WD (%)	NG	ASG	WGR (%)
1	4-Fold-Rossette	99.991	80.216	95.814	98.271	1.106	18.677	364.284	23.289	43.41	175	0.028	43.41
2	4-Fold-Rossette	99.985	86.297	97.112	99.651	2.589	11.112	263.408	23.025	49.04	372	0.012	49.04
3	4-Fold-Rossette	99.986	86.723	97.198	99.543	2.671	10.605	254.579	22.925	50.84	219	0.020	50.84
4	4-Fold-Rossette	99.995	84.01	96.573	99.438	1.735	14.254	307.816	23.077	45.42	230	0.021	45.42
5	4-Fold-Rossette	99.979	87.309	97.357	99.556	2.957	9.732	243.705	22.961	50.93	265	0.016	50.93
6	4-Fold-Rossette	99.941	87.196	98.239	99.547	5.811	6.992	196.678	22.879	53.04	358	0.011	53.04
7	4-Fold-Rossette	99.993	78.449	95.350	99.064	0.724	20.826	385.014	23.172	41.99	104	0.049	41.99
8	6-Fold-Rossette	99.991	80.689	95.917	99.105	1.061	18.248	348.306	23.120	43.06	163	0.031	43.06
9	6-Fold-Rossette	99.978	87.033	97.682	99.513	3.642	9.323	348.306	23.124	51.06	263	0.016	51.06
10	6-Fold-Rossette	100	69.053	93.377	97.278	0.214	30.732	539.405	23.325	32.74	74	0.081	32.74
11	6-Fold-Rossette	100	56.597	91.241	95.416	0.025	43.376	1255.831	23.455	21.93	24	0.291	21.93
12	6-Fold-Rossette	100	58.051	91.454	95.776	0.031	41.917	1061.688	22.416	23.02	32	0.215	23.02
13	6-Fold-Rossette	100	69.689	93.683	96.382	0.207	30.103	522.093	23.451	32.28	110	0.055	32.28
14	6-Fold-Rossette	99.993	80.219	95.744	98.262	0.878	18.901	366.800	23.301	42.17	128	0.040	42.17
15	6-Fold-Rossette	99.997	71.491	93.982	96.848	0.282	28.226	495.984	23.396	34.40	88	0.066	34.40
16	6-Fold-Rossette	100	59.58	91.867	96.065	0.035	40.375	873.488	23.409	24.61	42	0.160	24.61
17	8-Fold-Rossette	99.992	84.0744	96.572	99.338	1.783	14.141	307.337	23.118	46.93	207	0.022	46.93
18	8-Fold-Rossette	100	73.020	94.415	98.661	0.456	26.523	471.932	23.139	36.23	119	0.048	36.24
19	8-Fold-Rossette	100	79.788	95.693	98.761	0.8645	19.346	376.627	23.200	40.67	183	0.029	40.67
20	8-Fold-Rossette	99.985	85.498	96.795	99.354	2.258	12.242	281.473	23.112	48.85	198	0.023	48.85
21	8-Fold-Rossette	99.987	73.560	94.121	97.614	0.414	26.025	473.213	23.343	36.45	119	0.047	36.45
22	8-Fold-Rossette	99.977	83.322	96.770	99.444	2.031	12.646	285.487	23.068	47.25	223	0.021	47.25
23	8-Fold-Rossette	99.968	87.875	97.753	99.579	3.840	8.283	220.667	22.873	53.80	406	0.010	53.80
24	8-Fold-Rossette	100	79.123	95.497	97.956	0.908	19.967	392.836	23.342	41.16	148	0.035	41.16
25	8-Fold-Rossette	99.976	87.509	97.608	99.955	2.998	9.493	241.026	23.033	51.06	255	0.017	51.06
26	8-Fold-Rossette	99.876	87.792	99.036	99.623	6.897	5.309	159.886	22.946	57.25	347	0.011	57.25
27	8-Fold-Rossette	99.496	83.228	99.579	99.499	13.439	3.331	128.715	22.814	61.59	383	0.008	61.59
28	8-Fold-Rossette	99.960	87.430	98.698	99.549	6.860	5.708	175.905	22.955	56.63	314	0.012	56.63
29	8-Fold-Rossette	100	86.034	97.200	99.631	2.675	11.290	260.253	22.912	47.24	286	0.016	47.24
30	8-Fold-Rossette	99.973	80.221	95.517	99.474	0.892	18.886	376.808	23.095	43.32	160	0.031	43.32
31	8-Fold-Rossette	100	70.992	93.667	96.954	0.265	28.742	846.395	23.391	37.95	86	0.064	37.95
32	8-Fold-Rossette	99.974	84.924	96.809	99.355	2.096	13.006	282.664	23.109	49.33	167	0.027	49.33

33	8-Fold-Rossette	100	81.938	96.010	99.277	1.350	16.710	342.640	23.031	45.43	137	0.035	45.43
34	8-Fold-Rossette	99.979	85.858	97.041	99.631	2.609	11.531	272.740	23.028	48.96	264	0.017	48.96
35	8-Fold-Rossette	100	75.658	94.704	97.926	0.404	23.937	610.264	23.305	41.44	104	0.050	41.44
36	8-Fold-Rossette	100	69.871	93.549	97.108	0.275	29.853	692.906	23.374	35.89	84	0.068	35.82
37	8-Fold-Rossette	99.994	77.518	95.211	98.693	0.691	21.790	405.607	23.256	41.06	128	0.041	41.06
38	8-Fold-Rossette	99.999	71.745	93.918	97.065	0.364	27.890	493.540	23.390	33.73	116	0.051	33.73
39	8-Fold-Rossette	100	75.329	94.846	98.576	0.588	24.082	442.519	23.264	37.42	142	0.039	37.42
40	8-Fold-Rossette	99.994	81.964	96.057	99.516	1.521	16.514	335.297	23.084	45.23	268	0.018	45.23
41	8-Fold-Rossette	100	71.170	93.888	96.871	0.300	28.528	502.922	23.404	33.80	121	0.049	33.80
42	8-Fold-Rossette	99.995	73.311	94.378	98.138	0.481	26.206	631.819	23.300	36.52	126	0.045	36.52
43	10-Fold-Rossette	99.995	82.589	96.129	99.351	1.484	15.926	322.063	23.124	49.66	153	0.029	49.66
44	10-Fold-Rossette	100	70.788	93.744	97.781	0.252	28.958	516.566	23.285	35.27	93	0.062	35.27
45	10-Fold-Rossette	99.987	70.927	93.735	97.747	0.251	28.820	511.508	23.288	35.17	94	0.061	35.17
46	10-Fold-Rossette	100	69.567	93.508	97.537	0.246	30.186	520.683	23.316	33.88	75	0.078	33.88
47	12-Fold-Rossette	100	76.440	94.756	98.296	0.577	22.982	440.231	23.242	41.69	134	0.038	41.69
48	12-Fold-Rossette	99.964	87.078	97.577	99.565	3.096	9.825	231.990	23.040	55.61	171	0.023	55.61
49	12-Fold-Rossette	99.950	86.955	97.611	99.560	3.117	9.926	235.112	23.048	51.79	237	0.018	51.79
50	12-Fold-Rossette	99.856	88.507	99.029	99.465	6.840	4.652	165.267	22.824	58.14	339	0.011	58.14
51	12-Fold-Rossette	99.983	86.582	97.399	99.480	3.220	10.196	242.327	23.108	52.77	207	0.020	52.77
52	16-Fold-Rossette	99.999	86.069	97.038	99.465	1.746	12.184	264.026	23.100	51.86	180	0.023	51.86
53	16-Fold-Rossette	100	72.808	94.179	97.401	0.371	26.819	660.106	23.365	35.83	137	0.041	35.83
54	16-Fold-Rossette	100	84.862	96.847	99.431	2.179	12.958	293.736	23.094	47.92	221	0.021	47.92
55	Pili	99.988	72.622	94.199	97.671	0.305	27.071	816.347	23.332	36.40	92	0.061	36.40
56	Pili	99.986	82.838	96.322	99.171	1.402	15.759	325.169	23.150	44.43	92	0.054	44.43
57	Khani	99.201	79.144	99.790	99.420	18.825	2.030	108.009	22.756	64.08	364	0.008	64.08
58	Khani	98.724	73.308	99.974	99.455	25.384	1.307	89.665	22.769	64.77	312	0.010	64.77
59	Mored	98.832	74.816	99.989	99.383	23.713	1.4705	88.988	22.741	65.72	410	0.007	65.72
60	Mored	97.504	60.307	99.999	99.065	38.772	0.920	65.074	22.643	67.55	424	0.006	67.55

In this study, no heating systems or artificial lighting were used in the case study. Additionally, except for the external wall containing the openings, the thermal zones of the other walls and ceiling were treated as adiabatic. This approach assumes that these walls and ceilings are adjacent to neighboring structures, resulting in minimal energy loss that does not affect the simulation results. The research timeline has been designed to present simulation results annually, rather than being confined to a specific hour or month. Also daylight situation was examined for the whole hours of all days in one year. Tables 4 and 5 detail the materials used for the external wall, wooden frame, double-glazed glass, and their specifications.

4. RESULTS

4.1. Effect of Girih Pattern on Visual and Thermal Comfort

The results of this research are presented in two phases. The first phase focuses on identifying the optimal Girih pattern from a set of sixty samples by analyzing numerical outcomes related to visual and thermal comfort indicators. This phase is divided into three steps. The first step compares the performance of sixty patterns and reports the percentage of annual hours in which Useful Daylight Illuminance (UDI), Visual Comfort (VC), and Thermal Comfort (TC) fall within the standard range based on established criteria (Table 6). The second step utilizes statistical analysis tools to quantify correlations between variables and assess the impact of independent variables on visual and thermal comfort. The third step evaluates the overall performance of the patterns by calculating the average and standard deviation of thermal and visual comfort indicators.

The first step presents the numerical results of simulations, comparing the performance of sixty Girih patterns in terms of visual and thermal comfort (Table 6). It also includes geometric characteristics such as wood density percentage, the number of glass pieces, and the average glass panel size, which serve as independent variables in this study. To enhance clarity and facilitate comparison, different colors are used to represent UDI, VC, and TC levels. The optimal Girih tile pattern is identified as the one where all three objective functions reach their optimal values, which will be discussed in detail. To illustrate the performance of 60 Girih types and facilitate comparison, the numerical results are graphically presented in separate charts (Fig. 6).

Figure 6 composed of 12 distinct charts, illustrates the behavior of each variable. These charts represent the trend of changes for each variable over a range of 60 evaluated Girih tile patterns. From these charts, it can be observed that different Girih tile patterns, characterized by unique geometric patterns, wood-to-glass ratios, the number of glass pieces, and the average glass dimensions, exhibit distinct behaviors in terms of visual and thermal comfort. Meanwhile, it is inferred from Fig. 6 that some variables, such as thermal comfort, operative temperature, and daylight autonomy, exhibit less variation than useful daylight illuminance and radiance. Also, sensitivity analysis of Girih tile pattern selection for three main variables can be observed at Fig. 7. In this study, a sensitivity analysis was conducted to evaluate the relative responsiveness of daylight and comfort metrics (UDI, Visual comfort, and Thermal comfort to variations in design parameters. A variance-based analysis was performed by calculating descriptive indicators such as the mean, standard deviation, coefficient of variation, and normalized sensitivity (range-to-mean ratio). These measures quantify the degree of dispersion in each metric across different design alternatives and identify which outputs are most affected by geometric or material changes. Based on the sensitivity analysis in this section, it can be concluded that all three main variables (Useful Daylight Illuminance, Visual Comfort, and Thermal Comfort) have been affected by changes in the Girih pattern at different levels. Therefore, in the subsequent phase, all three variables will play a decisive role in selecting the optimal Girih pattern.

The second step evaluates the correlations and interrelationships among the variables, particularly between energy and light factors. This analysis, conducted using SPSS software, considers key parameters such as the percentage density of wood and glass, along with the number and size of glass pieces. By doing so, provides deeper insights into how the density of wood and glass in Girih tile patterns as the independent variables affect the study's dependent variables (Fig. 8).

Figure 8 displays a Pearson correlation matrix, showing correlation coefficients between variables. Positive values indicate direct relationships, while negative values signify inverse correlations. Higher absolute values represent stronger relationships, with coefficients above 0.6 indicating significant correlations. The analysis of this matrix reveals that wood density (WD) and glass density (GD) have an inverse correlation coefficient of -1.00, indicating that an increase in one directly leads to a decrease in the other. Useful daylight illuminance and thermal comfort have a direct relationship with wood density with correlation coefficients of 0.63 and 0.84. Similarly, visual comfort and wood density also exhibit a very strong correlation (0.99), while there is a significant positive relationship (0.86) between thermal comfort and two other main variables of research (visual comfort and useful daylight illuminance).

On the other hand, negative relationships are also noteworthy. For example, the percentage of daylight exceeding 3000 lux (UDI>3000 lux) has a strong negative correlation (-0.98) with wood density, suggesting that increasing the use of wood reduces excessive daylight in a room. Radiation and thermal comfort have a high negative correlation (-0.91), meaning that higher radiation levels decrease thermal comfort. Similarly, visual comfort and radiation display a significant negative relationship (-0.76), showing that increased radiation levels reduce visual quality in a space. Also, daylight autonomy and Radiance have a negative correlation with wood density. Additionally, Wood density and operative temperature have a moderate negative correlation (-0.69), suggesting that increased wood usage can contribute to lower indoor temperatures.

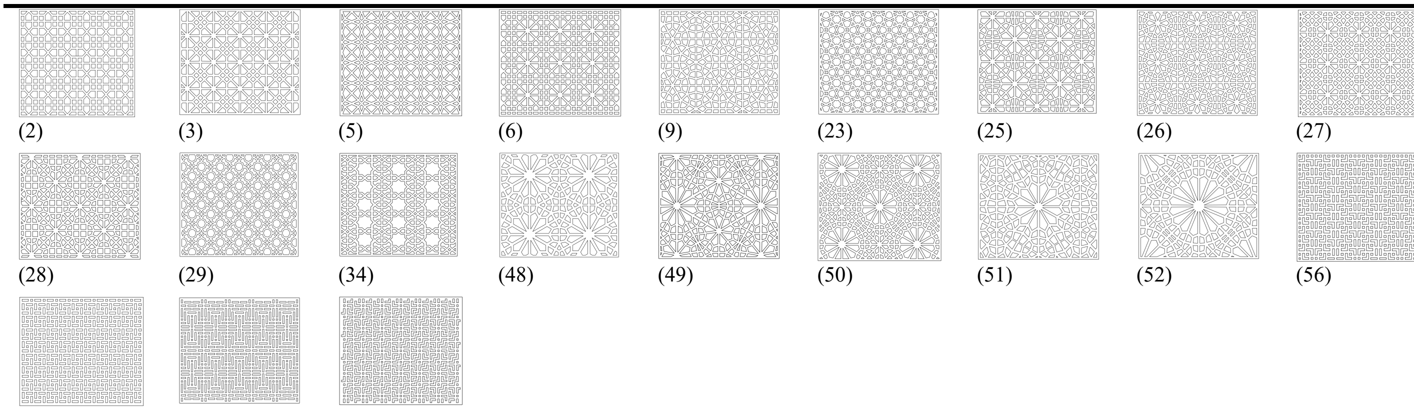
Alongside these strong relationships, some moderate correlations are also noteworthy. For instance, useful daylight illuminance and the number of glasses have a correlation of 0.55, indicating that increasing the number of glass panels can enhance effective daylight levels in a space. Moreover, daylight autonomy and operative temperature exhibit a positive correlation of 0.52, suggesting that greater daylight autonomy can contribute to higher indoor temperatures.

Overall, the analysis of this correlation matrix suggests that in architectural design, an increase in glass usage leads to higher radiation levels but reduces wood density. Additionally, increased radiation negatively impacts both visual and thermal comfort. On the other hand, visual and thermal comfort are strongly correlated, indicating that improving one generally enhances the other. These findings can be valuable in achieving a balance between material selection, daylight strategies, and comfort optimization in architectural design.

Overall, wood density (WD) plays a significant role in architectural design, influencing various aspects of daylight performance, thermal comfort, and material selection. As the use of glass increases, the reliance on wood tends to decrease, which impacts thermal and visual comfort. Higher wood density is generally associated with lower daylight penetration, suggesting its effectiveness in controlling excessive glare and solar exposure. Additionally, wood density appears to contribute to thermal

Table 7. More suitable Girih tile patterns for western and eastern use to adjust the glare on these fronts.

Girih patterns with visual comfort above 97%



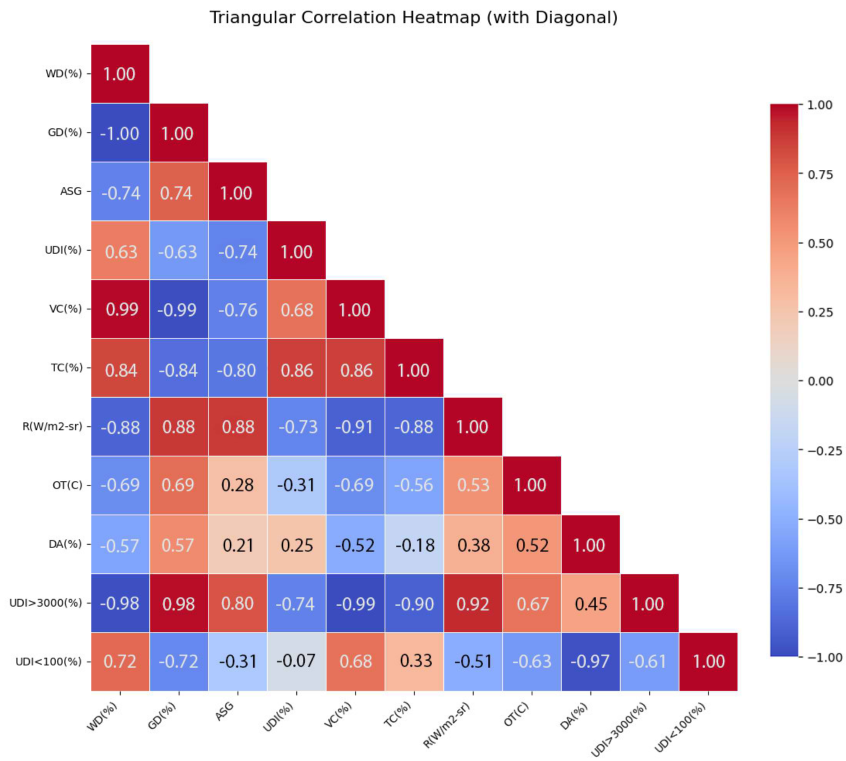


Fig. 8. Pearson's correlation heat map diagram.

regulation, as it is linked to reduced indoor temperatures, making it a valuable material for improving comfort in warmer climates. Based on the conducted analyses, it can be concluded that achieving an optimal state requires selecting Girih tile patterns that have a greater wooden frame with a lower percentage of glass, as well as a smaller average size of glasses.

Table 7 demonstrates that certain Girih tile patterns, which achieve visual comfort levels exceeding 97%, are particularly well-suited for eastern and western facades, where light conditions are often accompanied by increased glare. Additionally, all patterns exhibit a high percentage of useful daylight illuminance.

The third step evaluates the overall performance of the patterns by calculating the average and standard deviation of thermal and visual comfort indicators. Fig. 9, shows the average values for each of the 60 case samples of Girih tile patterns using IBM SPSS Statistics 27 software. Since the results of all three variables are reported as percentages, there was no need for data scale standardization at this stage. Additionally, all three target variables were considered equally weighted and of equal value, so the calculation of mean and standard deviation was performed directly without applying any weight or coefficient to any variable.

Fig. 9, shows that the higher the average of the three objective function variables (useful daylight illuminance, visual comfort,

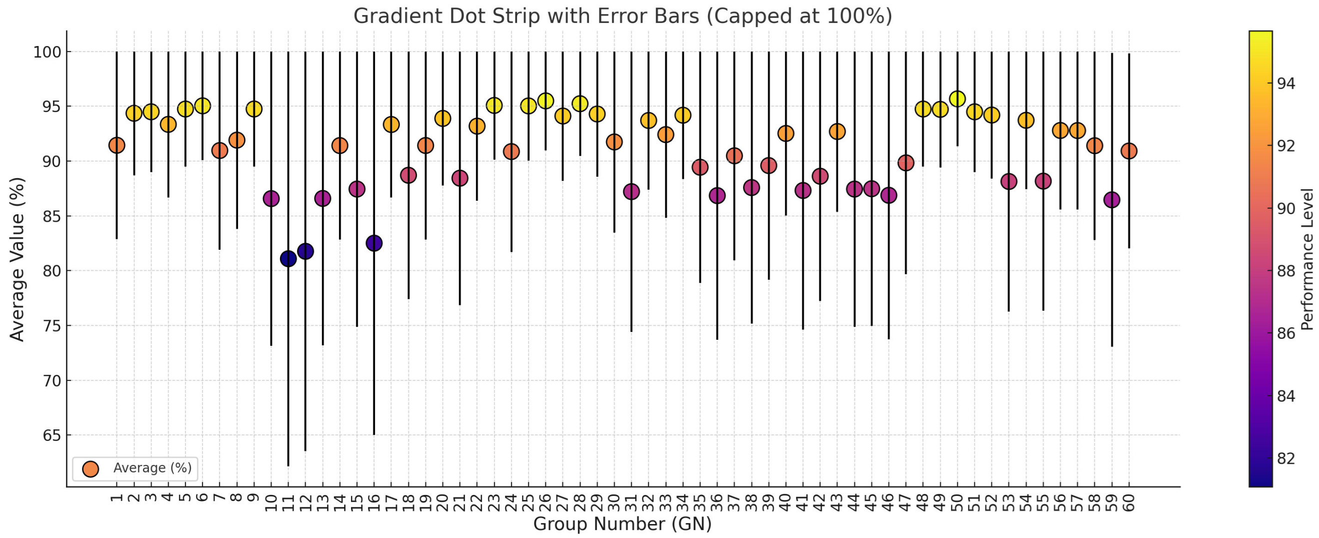


Fig. 9. Average values of three energy parameters (useful daylight illuminance, visual comfort, and thermal comfort).

and thermal comfort), the more optimal that case sample is. This is because the simulation in this research aims to find Girih tile patterns that provide greater visual comfort, useful daylight illuminance, and thermal comfort. Meanwhile, the lower the standard deviation of the selected Girih tile pattern, the more optimal the performance of the Girih tile pattern in terms of the variables under study. According to Fig. 9, Girih tile patterns 6, 23, 25, 26, 28, and 50, with an average above 95 percent, exhibit optimal performance in terms of light and energy. Additionally, these six cases of Girih tile patterns have the lowest standard deviation compared to the other patterns. Table 8 also presents the characteristics of the six selected Girih tile patterns based on their optimality among the 60 case samples examined.

Among the six selected Girih tile patterns, pattern number 50, which is a twelve-sided pattern located in the Safavid House of Isfahan, is the final choice based on optimization criteria. As Table 8 indicates, Girih tile pattern number 50 has the highest average value and the lowest standard deviation. Therefore, Girih tile pattern number 50, with 88.507% useful daylight illuminance, 99.029% visual comfort, and 99.465% thermal comfort, represents the optimal Girih tile pattern among the 60 case studies examined. Girih tile number 50 is statistically better than the others so this Girih tile pattern is the final selection of this research. Its superiority lies in the balanced performance across all evaluation criteria, combining high levels of useful daylight illuminance availability, visual comfort, and thermal comfort, while maintaining the lowest variability among the case studies are the main reasons of this Girih's selection .

This Girih tile pattern consists of 58.14% wooden frames and includes 339 glass pieces. Table 9 presents the heat maps and numerical results of the simulations for Girih tile pattern number 50, which has been selected as the optimal Girih tile pattern in this research. This table which contains 8 individual heat maps of 8 variables of this study (UDI<100, UDI, UDI>300, daylight autonomy, thermal comfort, operative temperature, visual comfort, and radiance) are recorded annually rather than being confined to a specific hour or month, so that more general and comprehensive results can be achieved.

4.2. Multi-objective optimization

Multi-objective optimization in this study was conducted using the Octopus plugin for Grasshopper on the selected Girih tile pattern (Fig. 10) to enhance Useful Daylight Illuminance (UDI) and Visual Comfort as the objective functions in this phase, with no constraints integrated into the model. The optimization process was carried out in two stages: first, by adjusting the frame depth, and subsequently, by optimizing the properties of the colored glass elements.

Octopus employs evolutionary strategies based on genetic algorithms, specifically the NSGA-II (Non-dominated Sorting Genetic Algorithm II), to explore a wide range of design alternatives and identify the Pareto-optimal front. The genetic algorithm was implemented with clearly defined chromosome structures representing parametric variations of the tile patterns. The algorithm was executed using the plugin's default settings for population size, number of generations, mutation rate, and crossover rate, and the weighted-sum method combined with Pareto front analysis was applied to ensure a balanced evaluation of objectives. The optimization process was validated by comparing selected solutions against baseline simulation results, confirming both the accuracy and reliability of the adopted method. This transparent and well-documented approach ensures that the influence of parametric design decisions on two performance criteria of daylight illuminance and visual comfort is comprehensively captured.

4.2.1. Frame depth optimization

Based on the results of this section and the sensitivity analysis in Fig. 11 conducted for variations in frame depth, it can be inferred that changes in frame depth lead to minimal variation in thermal

Table 8. The specifications of 6 selected Girih tile patterns in terms of optimality.

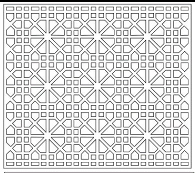
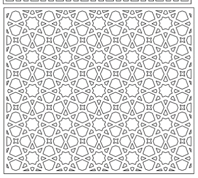
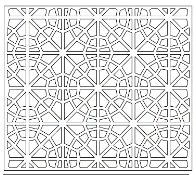
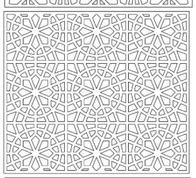
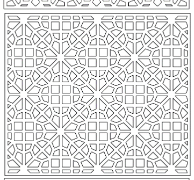
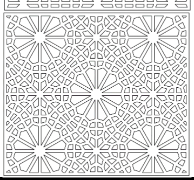
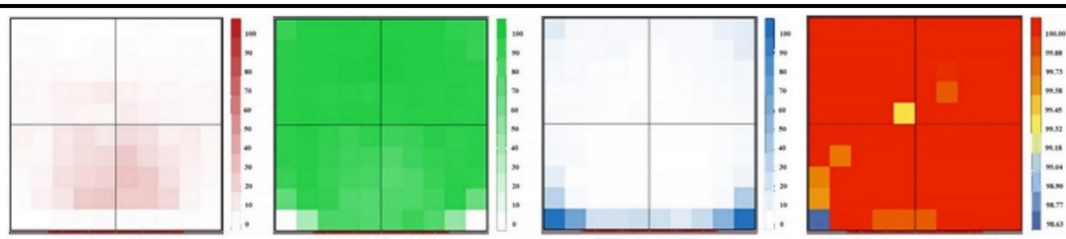
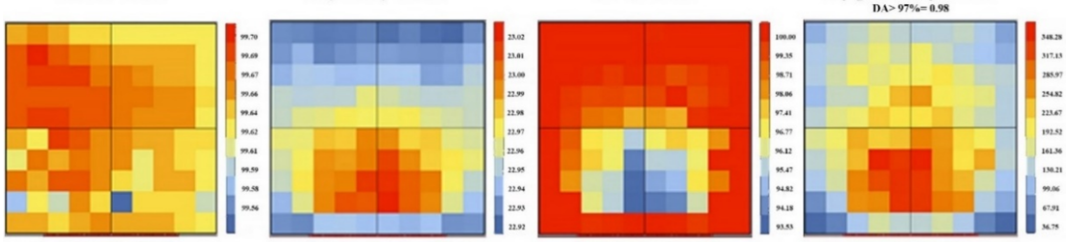
GN		**Pattern name**	Eight and four-sided	**Glass number**	358	**Useful daylight illuminance**	87/196
6		**Place**	Safavid House of Isfahan	**Average**	95/031	**Visual Comfort**	98/239
6		**Wood frame (%)**	53/04	**Standard deviation**	6/719	**Thermal Comfort**	99/547
23		**Pattern name**	Eight-sided	**Glass number**	406	**Useful daylight illuminance**	87/875
		Place	Chehelsotun	**Average**	95/069	**Visual Comfort**	97/753
		Wood frame (%)	53/80	**Standard deviation**	6/296	**Thermal Comfort**	99/579
25		**Pattern name**	Eight-sided	**Glass number**	255	**Useful daylight illuminance**	87/509
		Place	Safavid House of Isfahan	**Average**	95/024	**Visual Comfort**	97/608
		Wood frame (%)	51/06	**Standard deviation**	6/613	**Thermal Comfort**	99/955
26		**Pattern name**	Eight-sided	**Glass number**	347	**Useful daylight illuminance**	87/792
		Place	Safavid House of Isfahan	**Average**	95/483	**Visual Comfort**	99/036
		Wood frame (%)	57/25	**Standard deviation**	6/667	**Thermal Comfort**	99/623
28		**Pattern name**	Eight-sided	**Glass number**	314	**Useful daylight illuminance**	87/430
		Place	Safavid House of Isfahan	**Average**	95/225	**Visual Comfort**	98/698
		Wood frame (%)	56/63	**Standard deviation**	6/764	**Thermal Comfort**	99/549
50		**Pattern name**	Twelve-sided	**Glass number**	339	**Useful daylight illuminance**	88/507
		Place	Safavid House of Isfahan	**Average**	95/667	**Visual Comfort**	99/029
		Wood frame (%)	58/14	**Standard deviation**	6/204	**Thermal Comfort**	99/465

Table 9. Heat maps and numerical results of Girih tile number 50 (optimal pattern).

Heat Map Average	
Heat Map Average	

comfort. Specifically, thermal comfort levels remained highly consistent, indicating only negligible variation. Given these findings, further optimization of Girih tile patterns for thermal comfort is unlikely to be cost-effective or yield meaningful improvements. Therefore, as the research progresses into the third phase of multi-objective optimization, thermal comfort has been

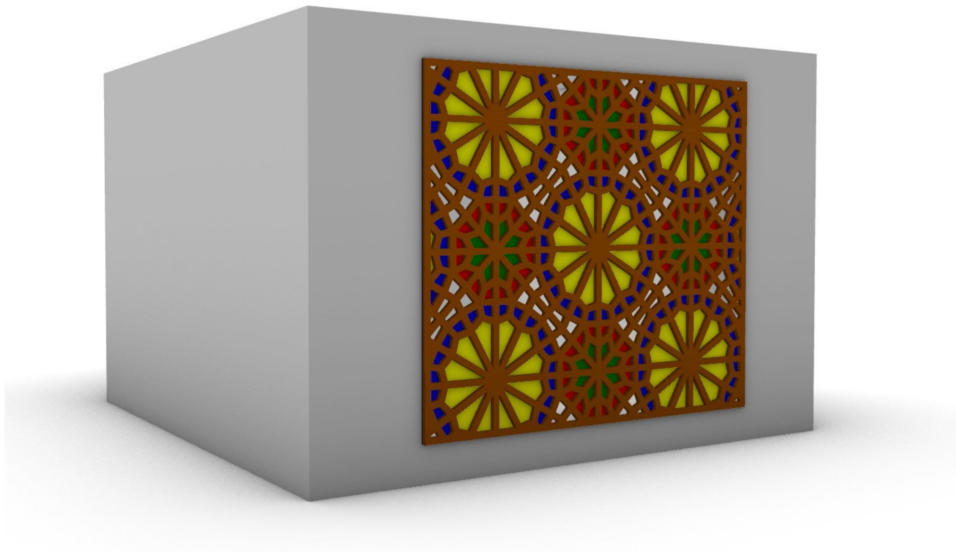


Fig. 10. The selected Girih tile pattern (GN50) for the multi-objective optimization process.

Table 10. Numerical results of multi-objective optimization of the Girih tile pattern with varying depths of the wooden frame.

Visual Comfort (%)	UDI (%)	Frame depth(m)	Visual Comfort (%)	UDI (%)	Frame depth(m)
98.3368	80.5416	0.00	99.9966	50.7771	0.06
99.3078	79.4797	0.01	100	43.8965	0.07
99.7219	76.2555	0.02	100	36.7277	0.08
99.9211	72.45	0.03	100	29.1603	0.09
99.9814	65.9227	0.04	100	23.9033	0.1
99.9947	58.0607	0.05			

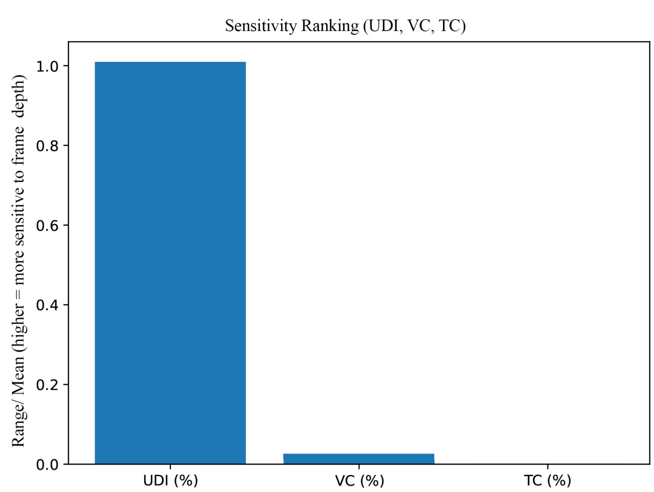


Fig. 11. Sensitivity analysis for frame depth.

excluded from the objective functions. The optimization will now focus solely on two key factors: useful daylight illuminance and visual comfort. These two factors are objective functions of the next phase of the research, multi-objective optimization.

The results indicate that visual comfort remains consistently high (99.99%–100%) across all frame depths, with a strong positive correlation (0.709) between frame depth and visual comfort. In contrast, useful daylight illuminance (UDI) decreases significantly as frame depth increases, showing a strong inverse correlation (-0.990). The highest UDI occurs at shallower depths (80.54% at 0.00m, 79.47% at 0.01m), dropping sharply beyond 0.02m. Given these findings, deeper frames may be preferable only when reducing daylight exposure is a priority (Table 10).

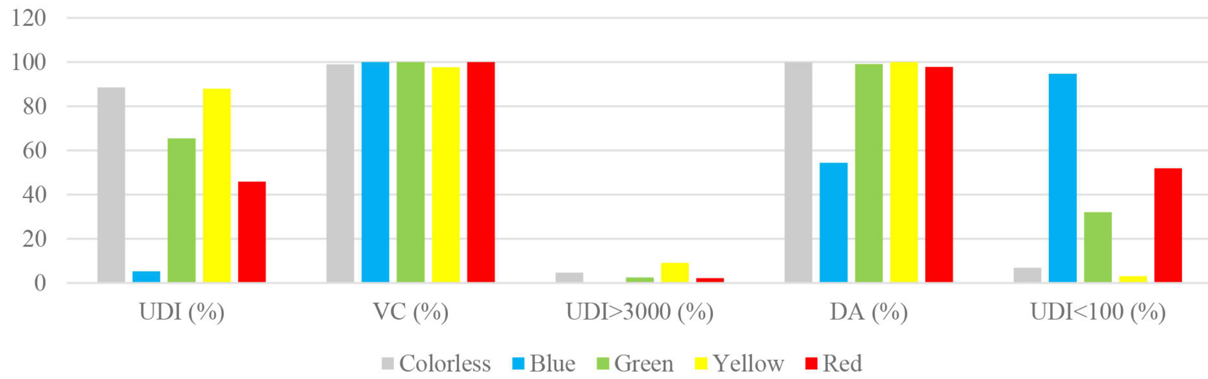


Fig. 12. The performance level of different colored glasses.

Table 11. The performance level of different colored glasses.

Glass color	UDI (%)	VC (%)	UDI>3000 (%)	DA(%)	UDI<100 (%)
Colorless	88.507	99.029	4.652	99.856	6.840
Blue	5.2974	100	0	54.3886	94.7026
Green	65.485	99.9932	2.4285	99.1439	32.0865
Yellow	87.9423	97.61	9.0475	99.9738	3.0104
Red	45.8403	99.9971	2.252	97.7604	51.9079

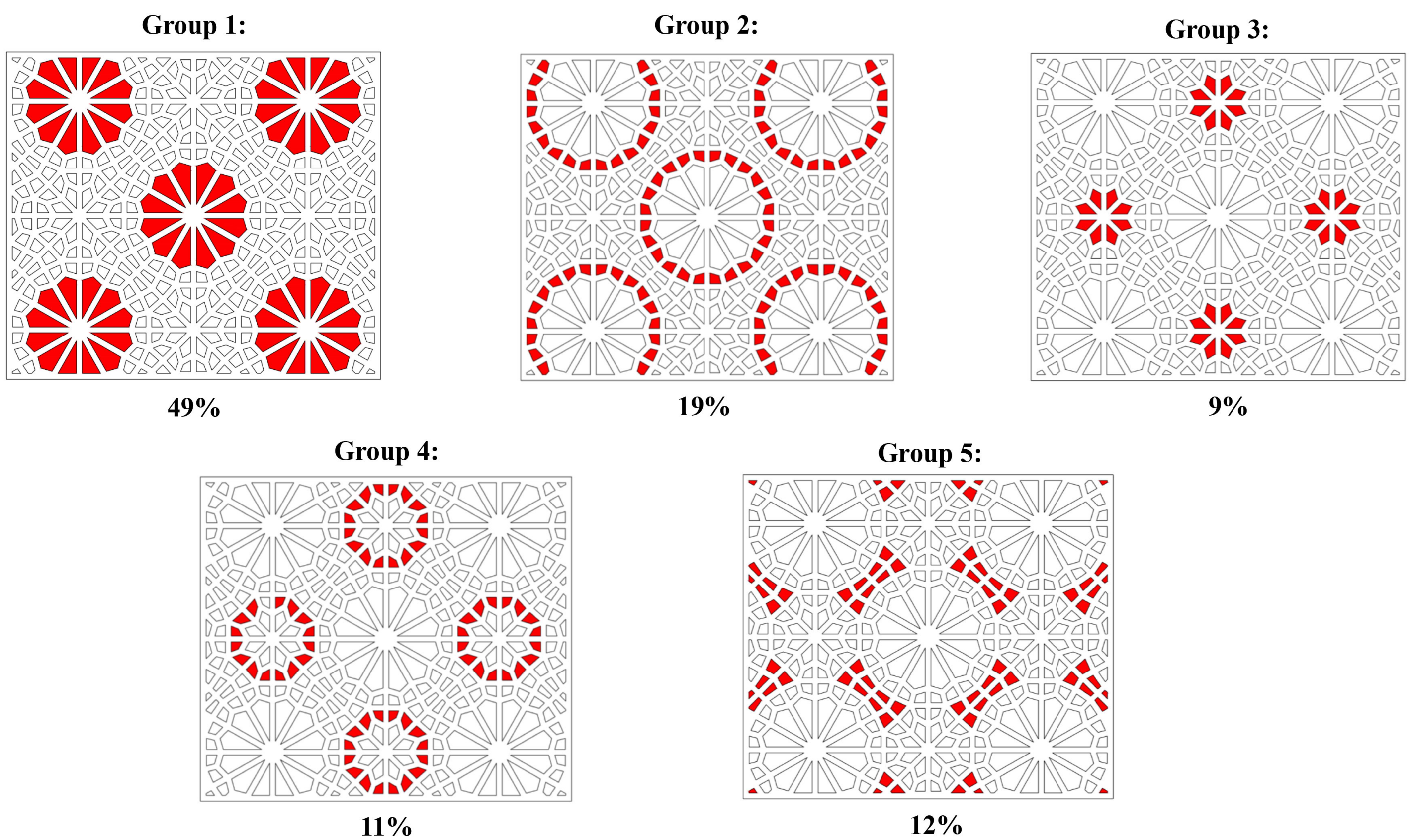


Fig. 13. Grouping glass pieces of the selected Girih tile pattern.

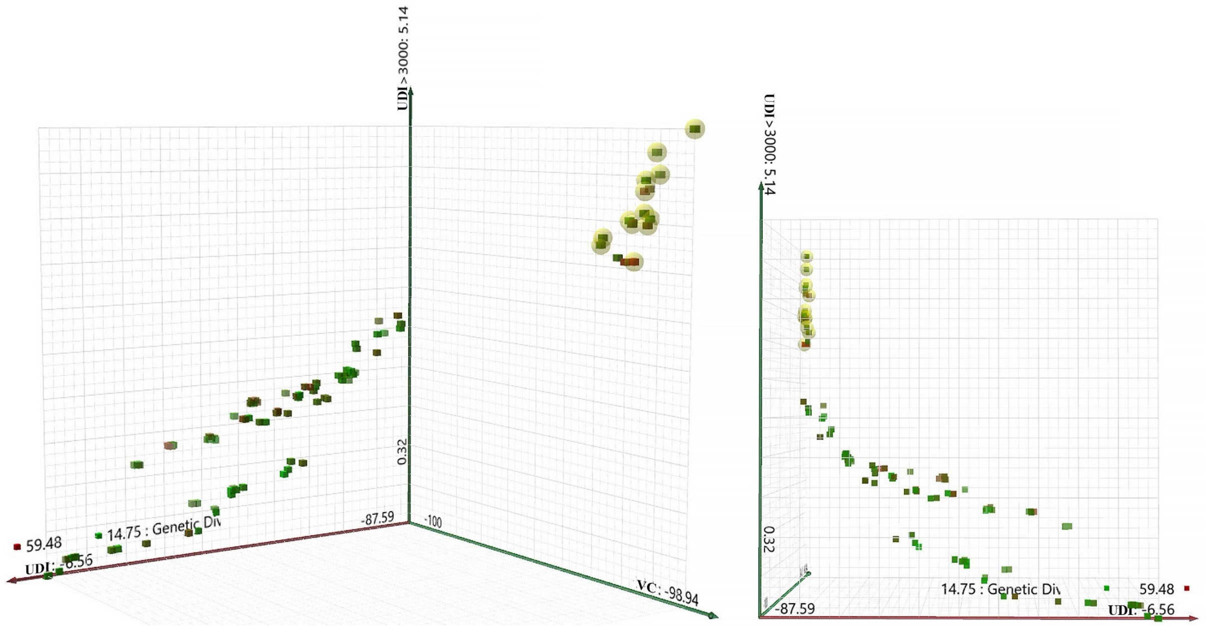


Fig. 14. Pareto chart of the optimization results for colored glasses.

4.2.2. Colored glasses optimization

To examine the relationship between colored glass and their visual performance level, each type of colored glass was initially analyzed individually. Subsequently, by grouping the glass pieces of selected Girih tile patterns and varying the color combinations, samples with high performance in terms of colored glass composition were chosen. According to the results obtained, after colorless glass, yellow glass has the highest amount of useful daylight illuminance and the lowest level of visual comfort. In contrast, blue glass has the lowest amount of useful daylight illuminance but the highest level of visual comfort. After yellow glass, green and red glasses exhibit higher levels of useful daylight illuminance and lower visual comfort, respectively. Despite providing a high amount of useful daylight illuminance, colorless glass ranks third in terms of visual comfort after blue, red, and green glasses. Table 11 and Fig. 12 present the results comparing the performance levels of different colored glasses.

To optimize the composition of colored glasses, the glass pieces in the selected Girih tile pattern must be systematically grouped, ensuring that colors transition sequentially within each group. Each color, green, blue, yellow, red, and colorless should appear in only one group per arrangement, with all colors included in every alternative combination. The glasses are organized into five structured groups to maintain visual harmony and order. Similar to the frame depth optimization, the Octopus plugin is used to generate random color distributions for each alternative before initiating the multi-objective optimization process.

Figure 13 illustrates the grouping of glasses and their respective contributions to the total composition of the Girih tile pattern. Given that Group 1 accounts for 49% of the total glass composition, the color assigned to this group will significantly influence the optimization results.

After grouping glass pieces of the selected Girih tile pattern (Table 12), multi-objective optimization was performed on 120 color combination alternatives. UDI>3000 has also been examined in all samples, as excessive amounts of this type of light can lead to increased glare and, consequently, reduced visual comfort. Figure 14 is related to the Pareto chart of Octopus output. The chosen optimal results are highlighted in this Figure. Also, Fig. 15 is the parallel chart of Optimization results for colored glasses, according to this chart, selected optimal alternatives are shown in green color, and alternatives with low performance are shown in red color.

According to the multi-objective optimization results for colored glass (Fig. 15) and sensitivity analysis of these results (Fig. 16), Thermal comfort variable has been omitted to carry on with the workflow. Same as frame depth sensitivity analysis (Fig. 11), thermal comfort variable is unlikely to be cost-effective or yield meaningful improvements at selecting optimal alternatives of colored glass combinations. Also according to these results, all alternatives exhibit a visual comfort level exceeding 98%. Furthermore, the percentage of UDI > 3000 is less than 6 for all 120 samples examined. This is because the selected Girih tile pattern in the previous stage already had a high visual comfort level, and the addition of colored glass has further enhanced this comfort in most alternatives. Therefore, it can be concluded at this stage that the visual comfort objective function is suitable for all alternatives, and the primary criterion for selecting optimal color patterns is the amount of useful daylight illuminance. In other words, UDI is the main variable for selecting optimal alternatives for colored glass combinations. These alternatives are prioritized based on their increase in UDI value. Figure 17 shows these alternatives in order of priority.

Table 12. Colored glasses grouping (R: Red, G: Green, B: Blue, Y: Yellow, -: Colorless).

	Group 1	Group 2	Group 3	Group 4	Group 5		Group 1	Group 2	Group 3	Group 4	Group 5
1	G	B	R	Y	-	50	R	G	B	-	Y
2	G	B	R	-	Y	51	R	G	Y	B	-
3	G	B	Y	R	-	52	R	G	Y	-	B
4	G	B	Y	-	R	53	R	G	-	B	Y
5	G	B	-	R	Y	54	R	G	-	Y	B
6	G	B	-	Y	R	55	R	B	G	Y	-
7	G	R	B	Y	-	56	R	B	G	-	Y
8	G	R	B	-	Y	57	R	B	Y	G	-
9	G	R	Y	B	-	58	R	B	Y	-	G
10	G	R	Y	-	B	59	R	B	-	G	Y
11	G	R	-	B	Y	60	R	B	-	Y	G
12	G	R	-	Y	B	61	R	Y	G	B	-
13	G	Y	B	R	-	62	R	Y	G	-	B
14	G	Y	B	-	R	63	R	Y	B	G	-
15	G	Y	R	B	-	64	R	Y	B	-	G
16	G	Y	R	-	B	65	R	Y	-	G	B
17	G	Y	-	B	R	66	R	Y	-	B	G
18	G	Y	-	R	B	67	R	-	G	B	Y
19	G	-	B	R	Y	68	R	-	G	Y	B
20	G	-	B	Y	R	69	R	-	B	G	Y
21	G	-	R	B	Y	70	R	-	B	Y	G
22	G	-	R	Y	B	71	R	-	Y	G	B
23	G	-	Y	B	R	72	R	-	Y	B	G
24	G	-	Y	R	B	73	Y	G	B	R	-
25	B	G	R	Y	-	74	Y	G	B	-	R
26	B	G	R	-	Y	75	Y	G	R	B	-
27	B	G	Y	R	-	76	Y	G	R	-	B
28	B	G	Y	-	R	77	Y	G	-	B	R
29	B	G	-	R	Y	78	Y	G	-	R	B
30	B	G	-	Y	R	79	Y	B	G	R	-
31	B	R	G	Y	-	80	Y	B	G	-	R
32	B	R	G	-	Y	81	Y	B	R	G	-
33	B	R	Y	G	-	82	Y	B	R	-	G
34	B	R	Y	-	G	83	Y	B	-	G	R
35	B	R	-	G	Y	84	Y	B	-	R	G
36	B	R	-	Y	G	85	Y	R	G	B	-
37	B	Y	G	R	-	86	Y	R	G	-	B
38	B	Y	G	-	R	87	Y	R	B	G	-
39	B	Y	R	G	-	88	Y	R	B	-	G
40	B	Y	R	-	G	89	Y	R	-	G	B
41	B	Y	-	G	R	90	Y	R	-	B	G
42	B	Y	-	R	G	91	Y	-	G	B	R
43	B	-	G	R	Y	92	Y	-	G	R	B
44	B	-	G	Y	R	93	Y	-	B	G	R
45	B	-	R	G	Y	94	Y	-	B	R	G
46	B	-	R	Y	G	95	Y	-	R	G	B
47	B	-	Y	G	R	96	Y	-	R	B	G
48	B	-	Y	R	G	97	-	G	B	R	Y
49	R	G	B	Y	-	98	-	G	B	Y	R

99	-	G	R	B	Y	110	-	R	G	Y	B
100	-	G	R	Y	B	111	-	R	B	G	Y
101	-	G	Y	B	R	112	-	R	B	Y	G
102	-	G	Y	R	B	113	-	R	Y	G	B
103	-	B	G	R	Y	114	-	R	Y	B	G
104	-	B	G	Y	R	115	-	Y	G	B	R
105	-	B	R	G	Y	116	-	Y	G	R	B
106	-	B	R	Y	G	117	-	Y	B	G	R
107	-	B	Y	G	R	118	-	Y	B	R	G
108	-	B	Y	R	G	119	-	Y	R	G	B
109	-	R	G	B	Y	120	-	Y	R	B	G

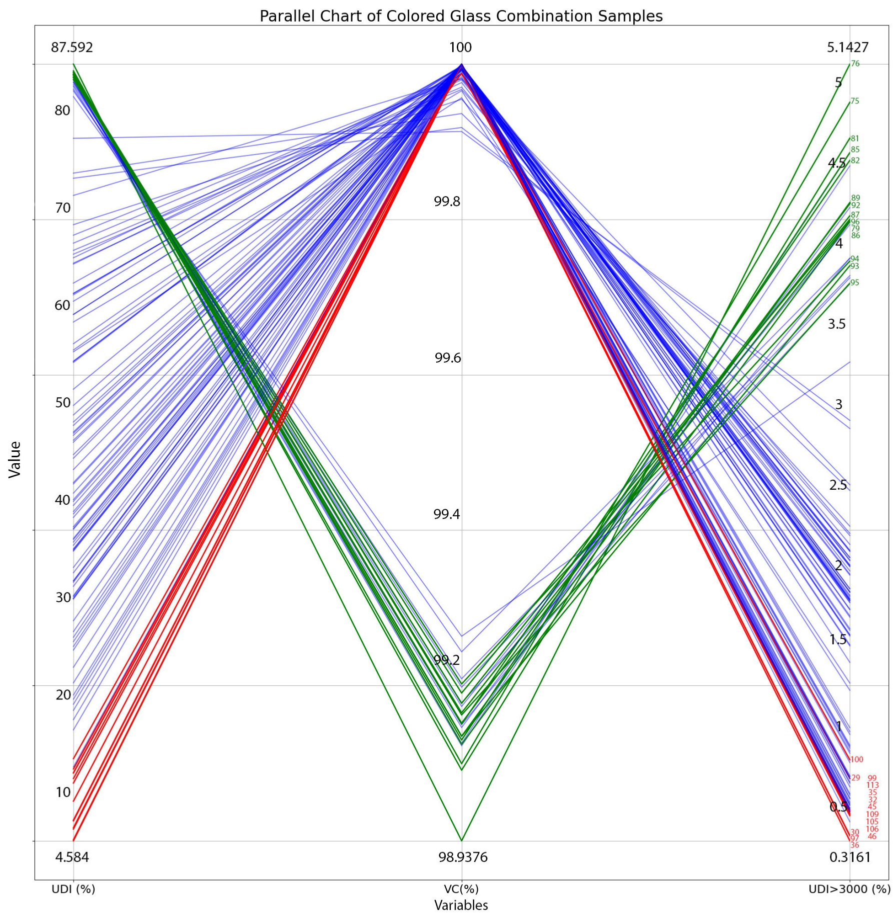


Fig. 15. Optimization results for colored glasses parallel chart.

4.3. Selection of optimal colored glass patterns

Based on the results in Fig. 15 and by examining the average results of each alternative, where the first group consists of similar colors, as shown in Table 13, it can be deduced that respectively maximizing the use of yellow, green, red, blue, and colorless glass increases the level of optimization.

Figure 17 presents the final selected samples of the optimal combination of colored glass applied to the selected Girih tile pattern from the previous phase with the highest amount of useful daylight in order. Also, Fig. 18 identifies 14 alternatives with low performance, which have very little useful daylight illuminance. The selection was based on performance criteria and predefined thresholds. Specifically, patterns with a Useful Daylight Illuminance (UDI) higher than 86% were categorized as optimal, while those with UDI values below 14% were considered unsuitable. Additionally, a larger number of optimal patterns were chosen to represent a diverse range of color combinations and arrangements, ensuring broader options for practical implementation.These results are completely based on simulation results without considering overlook in visual harmony, color coordination, and psychological effects of colors. Based on these results, it can be concluded that yellow glass usage in Group 1,

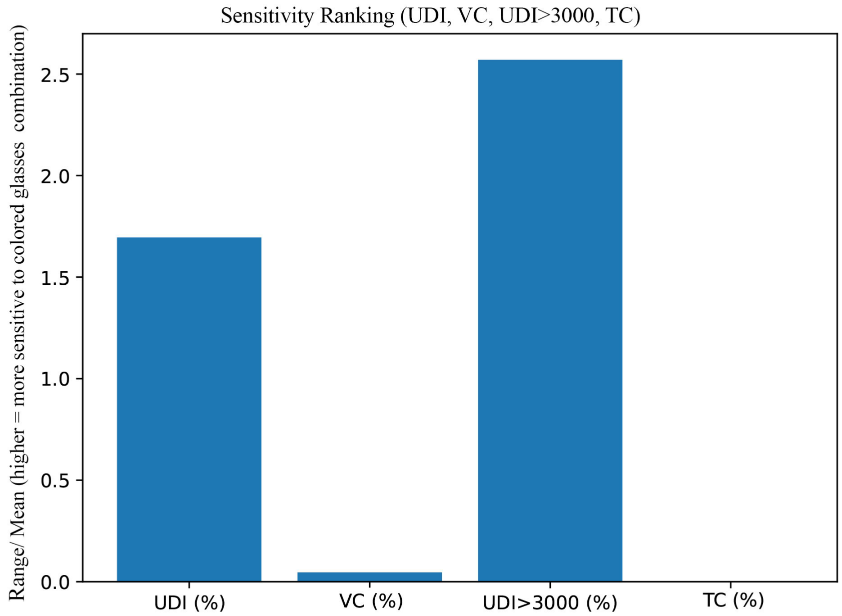


Fig. 16. Sensitivity analysis for colored glasses combination.

Table 13. The colors used in Group 1 and their average optimization level.

The color of Group 1 constitutes 49% of the glass density	**Green**	**Blue**	**Red**	**Yellow**	**Colorless**
Average percentage of optimization level (%)	58.0425	29.9858	49.1206	86.0325	21.5997

which constitutes 49% of the glass density, maximizes optimization. In contrast, colorless and blue glasses usage in Group 1 leads to low performance. As mentioned before, according to Table 11, colorless glass has a higher amount of useful daylight illuminance than yellow glass; however, after combining other colors with colorless glass to create new color patterns, this optimization significantly decreases. Therefore, it can be inferred that in addition to the color of the glass in Group 1, the colors from other groups and their combinations are critically important and have a significant impact on optimization results.

5. DISCUSSION

Based on the findings of this research, the use of Girih tile patterns and colored glass in modern designs not only reflects a return to traditional and authentic Iranian architecture and its aesthetic considerations but also contributes to energy-related issues. According to the trends observed in this research and the conducted simulations, Girih tile patterns and colored glass usage in the traditional architecture of Isfahan's cold and semi-arid climate provide an appropriate response for optimizing visual comfort, glare reduction, and thermal comfort. Furthermore, incorporating these openings into modern designs in Isfahan can enhance aesthetic appeal and serve as an intelligent solution to energy-related issues.

In response to the first and primary question of this research, it was determined that factors such as the geometric shape of the Girih tile patterns, the density of wood, the depth of the wooden frames of the Girih tile patterns, and the colored glasses are related to the optimization of these openings. Maximum optimization can be achieved by adhering to design principles related to each of these variables. According to the investigations, the percentage of wood used has a direct correlation with useful daylight illuminance (0.63), visual comfort (0.99), and thermal comfort (0.84) throughout the year, thereby creating optimal conditions. Therefore, it can be concluded that samples with a higher percentage of wooden frames and lower percentage of glass, are optimal examples. However, this amount of wood should not exceed a certain percentage; otherwise, it would hinder daylight penetration and reduce the aforementioned optimal conditions.

Subsequently, based on the results obtained from simulating 60 Girih tile patterns and examining the relationship between wood density and optimization, the second question was answered. Initially, by considering the criteria and range for selecting optimal Girih tile patterns six top patterns were identified. These six top patterns have UDI of (87-100%), visual comfort of (97-100%), and thermal comfort of (99-100%). Also, the Average value of these patterns is between 95 to 100% and their standard deviation is between 0 to 7. Based on these results, the patterns used in Safavid houses in Isfahan are optimal. Five types of these optimal patterns are eight-sided, while one is a twelve-sided pattern.

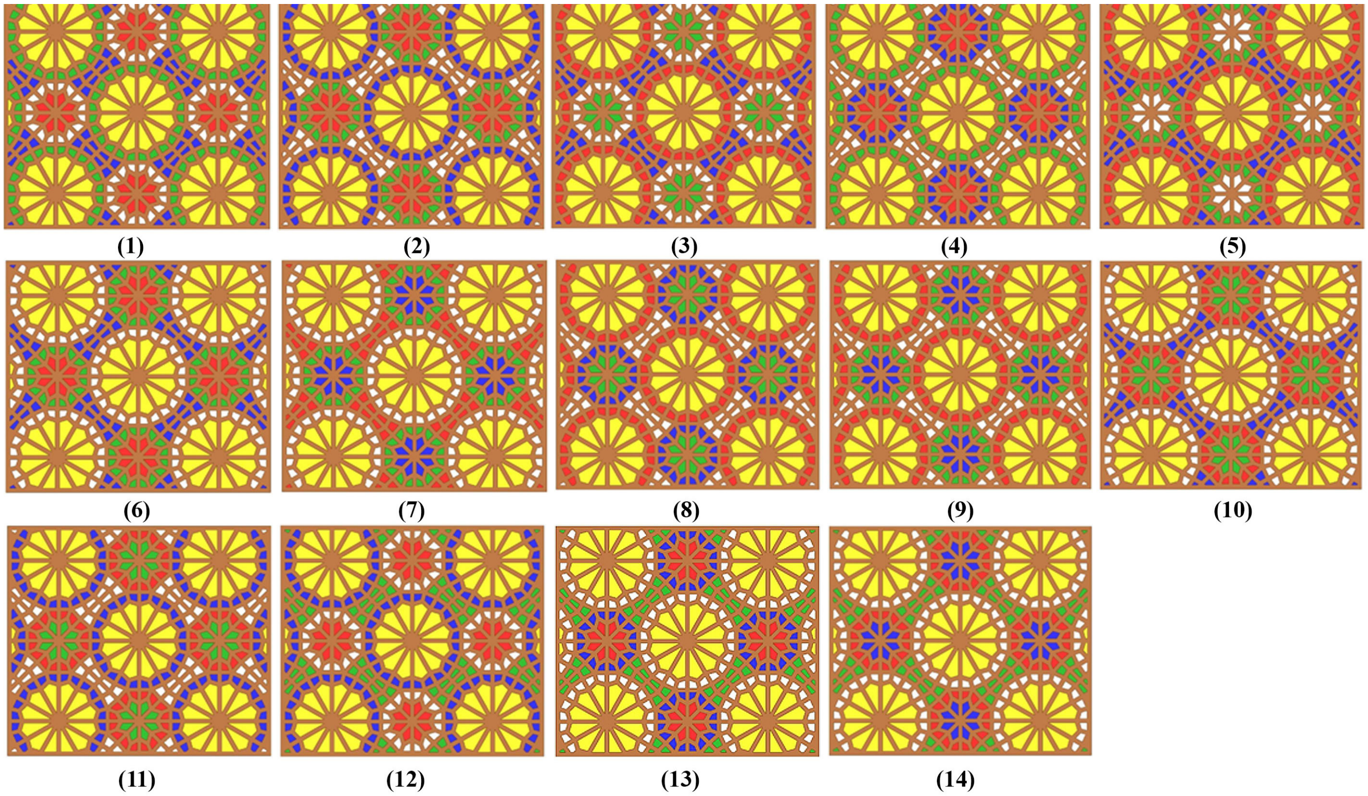


Fig. 17. Selected optimal alternatives of colored glass combinations.

Ultimately, according to the research objective, Girih tile pattern number 50, which is a twelve-sided pattern located in the Safavid house in Isfahan, was selected as the optimal Girih tile pattern in terms of visual comfort and thermal comfort. This selection was based on the energy variable values extracted from its simulation, along with high wood density between 53 to 59%. Girih tile pattern number 50, with 88.507% useful daylight illuminance, 99.029% visual comfort, 99.465% thermal comfort, and 58.14% wood density has the highest average value of 95/667% and the lowest standard deviation of 6/204.

After Girih tile pattern number 50, Girih tiles with wood densities of 51.06, 53.04, 53.80, 56.63, and 57.25 are optimal girih tile patterns. Girih tile patterns with wood density above 59%, are not patterns with high performance due to the inability to transmit sufficient light.

According to the multi-objective optimization results, it was found that as the depth of the wooden frame of the Girih tile pattern as another independent variable in this study decreases, the level of optimization in the results increases. Subsequently, to address the third research question, the relationship between colored glass and optimization was initially examined. Then, by altering the arrangement of colored glasses among 120 samples, the optimal alternatives for comparison with others were selected. According to the criteria and range for selecting optimal samples, alternatives with UDI<14% are selected as low-performance samples while alternatives with UDI>86% are selected as optimal samples.

It was proved through the simulations that using a higher percentage of yellow glass in the composition of colored glass leads to more optimal outcomes. In contrast, a higher percentage of colorless and blue glasses results in less optimal outcomes. The colored glass pattern with a combination of yellow, green, red, colorless glass, and blue in groups 1 to 5, respectively, with UDI of 87.89% is the optimal colored glass pattern and the colored glass pattern with a combination of colorless glass, green, blue, red, and yellow in groups 1 to 5, respectively, with UDI of 4.58% has the lowest performance among 120 colored glass patterns. In other words, it can be inferred that using color combinations that respectively maximize the use of yellow, green, red, blue, and colorless glass in openings enhances optimization levels. However, these findings differ when single-colored glasses are used. Utilizing single-colored windows made from colorless glass followed by yellow, green, red, and blue respectively, increases the performance levels of the opening in Isfahan's cold and semi-arid climate. Therefore, it can be concluded that the way colors are combined is also related to optimization results. These results are not based on aesthetic considerations for color combinations, as far as the study employs a quantitative research.

A comparison of the results of this study with previous research reveals both similarities and differences. For instance, in earlier studies, yellow was also identified as the optimal color based on

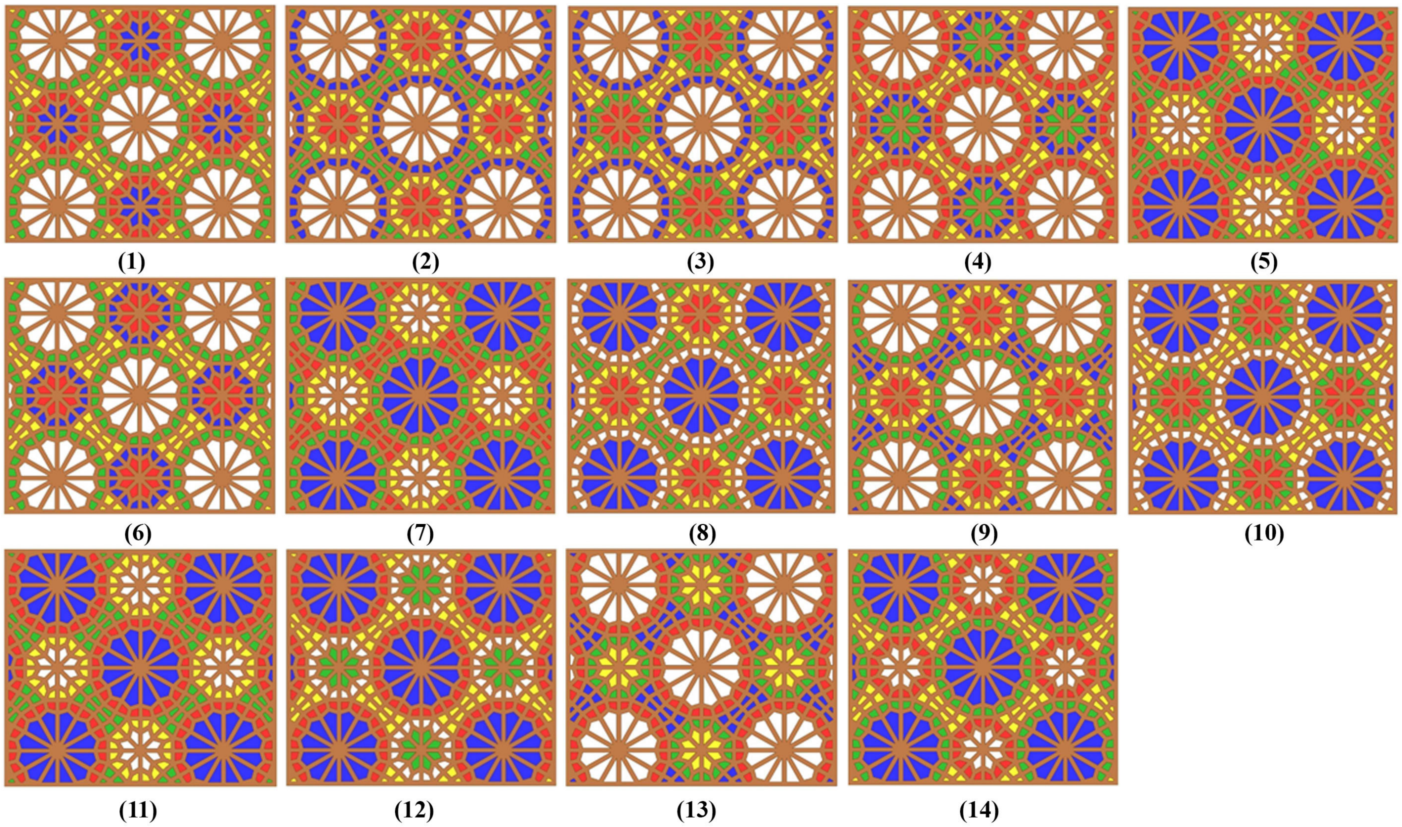


Fig. 18. Alternatives with low performance.

lighting indices [20]; however, the prioritization of blue and red in terms of light optimization differs. Specifically, red was found to provide more useful daylight illuminance than blue in this study. Additionally, some previous studies reported useful daylight illuminance percentages and the impact of colored glass by dividing rooms into three sections: dark, semi-dark, and bright [4,9].

In contrast, this research presents results for a single room without such divisions. This variation in results across different studies and the differing orders of optimization for colored glass can be attributed to differences in the daylight indices examined as well as the climate and city under study. Previous research has not selected an optimal geometric pattern for different climates that would allow for comparative analysis, which represents one of the innovations of this study. Overall, this study advances knowledge by integrating geometric patterns and colored glass optimization in a comparative framework, offering evidence-based design strategies that improve both visual and thermal performance beyond what has been achieved in previous studies.

The study also highlights practical limitations. The implementation of a GN50 frame with 339 glass pieces and 58% wooden coverage may face challenges in terms of cost and constructability. Additionally, as the results are derived from simulations, their direct application to real-scale buildings requires further validation, particularly considering user behavior, material properties, and construction methods. Future studies are recommended to test different orientations (e.g., openings on east and west façades), extend investigations to other cities and climates, and apply multi-objective optimization to additional building elements such as shading devices and façade skins.

6. CONCLUSION

This research examined the role of Girih tile patterns and colored glass in the traditional architecture of Isfahan’s cold and semi-arid climate, demonstrating their potential for optimizing visual comfort, reducing glare, and enhancing thermal comfort. By integrating parametric simulations of 60 Girih tile patterns with colored glass configurations, the study identified a strong correlation between wood density and performance, showing that higher wood ratios produce superior results. Among the alternatives, pattern number 50, a twelve-sided design from a Safavid house, achieved the highest performance in terms of UDI, Visual comfort and thermal comfort.

The results also revealed that colored glass composition significantly influences optimization outcomes. Patterns with higher proportions of yellow, followed by green and red, produced the most favorable results, while those dominated by colorless and blue glass performed poorly. These findings indicate that color combinations affect performance outcomes beyond their aesthetic value.

The study's results both align with and diverge from earlier research. Similar to prior studies, yellow glass was consistently identified as highly effective in optimizing daylight; however, the prioritization of red and blue differs from previous works. In this study, red glass contributed more positively to useful daylight illuminance than blue, which contrasts with earlier findings that emphasized blue. Furthermore, while previous studies often divided rooms into dark, semi-dark, and bright zones, this study examined optimization across a single space, which partly explains the observed differences. Variations can also be attributed to differences in climatic conditions, indices used for evaluation, and the scope of comparative analysis. Unlike prior research, this study introduced an explicit selection of optimal geometric pattern for Isfahan's climate as its main innovation.

The study also underscores the importance of integrating both geometric design and material selection into energy-conscious architectural strategies. Ignoring these factors in simulations and design processes could lead to inaccurate predictions and suboptimal design choices.Although the findings indicate optimal Girih patterns and colored glass arrangements, their effectiveness may need adjustment when implemented in real buildings. Therefore the results of this research may require adjustment in real-scale applications. For instance, there is technical and execution limitations of the GN50 frame design in full-scale construction. Speaking about limitations of this research, there is also lack of economic and practical Feasibility Assessment the cost implications of implementing such windows with large wooden frames and stained glass.

Future research should extend the analysis to different climates and building components, test seasonal variations, and include vegetation as a variable to understand combined effects on daylight and thermal comfort. Systematic parametric studies on building form variables such as frame depth, height, density, and orientation will help isolate their effects. Moreover, the development of simplified predictive tools using artificial intelligence and machine learning can provide architects and urban designers with fast and reliable methods to apply these insights at the early stages of the design process.

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CONTRIBUTIONS

M. A. Arshad contributed to Conceptualization, Methodology, Formal Analysis, Investigation and Writing. L. Medghalchi contributed to Writing- review and editing and Supervision. P. Saadatjoo contributed to Writing- review and editing and Supervision.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

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