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BALANCING THERMAL AND VISUAL COMFORT THROUGH MULTI-OBJECTIVE PARAMETRIC FORM OPTIMIZATION: A CASE FROM YAZD, IRAN

Mohammadmehdi Moulaii, Maryam Younesi*

Department of Architecture, Faculty of Art and Architecture, Bu-Ali Sina University, Hamadan, Iran

*Corresponding author's email: m.younesi@art.basu.ac.ir

Abstract

Introduction. Building form plays a critical role in determining energy efficiency and occupant comfort, particularly in hot-arid climates such as Yazd, Iran. **This study proposes** a passive design strategy that leverages parametric modeling and simulation to optimize residential building forms for both thermal and visual comfort. **Methods.** A multi-objective genetic algorithm was employed to identify optimal geometric configurations across four different floor area scenarios (250, 350, 450, and 650 m²). Four primary form typologies — cubic, L-shaped, U-shaped, and O-shaped — were parametrically generated and evaluated using thermal performance metrics and daylight indicators. **The results** demonstrate that a rectangular cuboid with a shape factor of approximately 1.8, oriented along the north-south axis, consistently provides superior thermal comfort compared to other forms. Energy analysis revealed that the optimized configurations can reduce total energy consumption by up to 38.6 % while maintaining acceptable indoor environmental quality. This methodology supports data-driven decision-making in the early conceptual design phase, facilitating the development of context-sensitive, energy-efficient housing solutions in arid regions.

Keywords: multi-objective optimization; parametric form; thermal comfort; visual comfort; genetic algorithm; sustainable design; energy efficiency.

Introduction

Buildings are fundamental to human life, serving as physical environments for a wide range of activities. However, the environmental footprint of the modern construction industry poses serious ecological concerns (Zou et al., 2021). As global efforts intensify to minimize the negative impact of buildings and enhance their benefits, energy efficiency has become a key objective for architects and urban planners. The energy crisis has been a focal point of scientific inquiry for decades, particularly because buildings account for approximately 36 % of final global energy consumption and 39 % of energy-related CO_2 emissions (Si et al., 2019). These figures underline the necessity of integrating energy-efficient strategies during the design process. Among all design stages, the conceptual design phase is the most critical, as it determines the majority of architectural decisions and holds the greatest potential for energy-saving outcomes (Fang and Cho, 2019).

Despite the growing implementation of active and passive energy strategies, these are often introduced after the initial design concept is developed (Feng et al., 2021). To achieve meaningful energy reductions, the form and geometry of buildings must be carefully addressed early on through passive strategies, which can reduce the need for later active systems and significantly decrease operational energy consumption. Optimizing form during the conceptual phase not only enhances energy performance but can also significantly reduce annual energy use, particularly during peak demand periods.

The growing construction activities in hot-arid regions like Yazd have created unprecedented environmental challenges and energy demands (Moulaii et al. 2011). In hot-arid climates, passive cooling strategies are particularly crucial for sustainable thermal comfort. The vernacular architecture of Iran's hot-dry regions offers valuable insights into effective passive design principles. Studies of traditional buildings in cities such as Yazd, Kashan, and Isfahan have identified sophisticated passive cooling systems that work in harmony with the local climate (Izadpanahi et al., 2021). These include strategic shading through tall courtyard walls, earth coupling via deep basements, natural ventilation systems utilizing wind catchers, evaporative cooling through courtyard pools, and the strategic use of thermally massive materials like adobe. These integrated approaches created comfortable microclimates while minimizing energy

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consumption (Foruzanmehr, 2015). Particularly in Dezful, underground spaces known as Shavadans demonstrate remarkable thermal performance, maintaining stable temperatures around 23–25 °C despite extreme outdoor conditions reaching 45–50 °C (Sadooghi et al., 2019).

Numerous studies have examined the influence of building geometry on energy consumption. For instance, Hemsath and Bandhosseini (2015) demonstrated that variations in building form can impact energy use as much as changes in material selection. With the advancement of computational tools, artificial intelligence, and optimization algorithms, designers are now able to generate and assess parametric design alternatives using performance-based criteria (Østergaard et al., 2016; Wortmann and Nannicini, 2017). This shift enables more informed decision-making in early design stages. The role of climate-responsive design becomes even more critical in hot-arid regions, where building performance is tightly linked to occupant comfort and energy demand. The city of Yazd, Iran, serves as an exemplary case due to its long-standing vernacular tradition in adapting to extreme climate conditions (Jamalpour and Arbaban, 2016). Historic courtyard houses in Yazd utilized compact, inward-focused forms to mitigate harsh solar exposure and high temperatures (Zarei and Mirdehghan, 2015). In contrast, many modern residential developments disregard these passive strategies, resulting in built environments that perform poorly in terms of thermal comfort and energy efficiency (Jamalpour and Arbaban, 2016).

The objective of the present study is to address this gap by investigating how parametric geometric configuration optimization, grounded in these proven passive design principles, can support the development of climate-adapted residential buildings in Yazd with enhanced energy performance. By combining environmental simulation with multi-objective optimization, the research seeks to propose high-performance building forms that balance thermal and visual comfort while respecting the unique climatic and cultural context of the region.

This research builds upon a previous study conducted in Persian, which explored the conceptual design of energy-efficient buildings in Yazd using passive strategies (Moulaii and Younesi, 2025). The current study expands that work by integrating a multi-objective optimization approach, considering both thermal comfort and daylight performance, to generate a set of optimal design solutions. By applying adaptive thermal comfort models and daylight simulation indices (UDI), the study aims to assist decision-making in the early stages of architectural design, providing a foundation for further passive strategies such as window sizing, shading, and thermal mass considerations. Furthermore, the study quantifies the energy-saving implications of these geometric optimizations, providing economic justification for implementing passive design strategies.

Materials and Methods

Research Framework and Objectives

A considerable body of research has focused on optimizing building form for enhanced energy performance and occupant comfort. In a 2020 study, an intelligent control algorithm was employed to design and simulate an optimized HVAC system using Fanger's comfort model and a genetic algorithm (Mohammed et al., 2020). A 2016 study introduced a novel performance-based optimization framework for passive design strategies during early architectural phases, targeting parameters such as daylighting, solar control, and natural ventilation (Konis et al., 2016). Similarly, 2021 research utilized a simulation-optimization approach to minimize energy consumption in residential buildings using RIUSKA simulation software (Feng et al., 2021).

However, these studies often focus on specific systems or later design stages. A significant research gap remains in the comprehensive optimization of the initial building form and orientation — the very foundation of passive design — particularly for hot-arid climates. This research addresses this gap by developing an integrated methodology for optimizing vernacular residential buildings in Yazd's hot-arid climate, aiming to generate optimal building forms that balance thermal and visual comfort while providing foundational solutions for subsequent passive strategies.

Literature Review and Theoretical Foundation

Passive Design and Climate-Responsive Architecture

Recent systematic reviews have demonstrated that integrating traditional wisdom with modern technology offers the greatest potential for achieving sustainable thermal comfort (Manshour and Lehmann, 2025). Studies of vernacular architecture in various Iranian climates, including mountainous regions (Bahramifar et al., 2021) and hot-humid areas (Mohammadia et al., 2018), confirm that passive strategies such as compact urban fabric, proper orientation, semi-open spaces, and high thermal mass materials can reduce cooling energy consumption by 26–46 % and decrease discomfort hours by 12–34 %.

Traditional Iranian architecture, based on five principles of "Introversion", "Autonomy", "Human-conformity", "Structure and Modulation", and "Purposefulness" (Shahamat, 2014), shows complete conformity with sustainable architecture principles. Passive design strategies tailored to specific climatic contexts have been extensively optimized, as demonstrated by a 2020 case study in Morocco that applied Pareto front optimization to enhance thermal insulation and building mass using local bioclimatic charts (Ameur et al., 2020). In China, a 2017 study optimized passive design features for hot summers and cold winters using NSGA-II and Artificial Neural Networks to explore 37 design variables (Gou et al., 2017).

Parametric and Multi-Objective Optimization

The integration of parametric design with multi-objective optimization has been widely explored. The H.D.S. Beagle prototype platform combined computational parametric modeling with performance-based analysis for iterative design exploration (Gerber and Lin, 2013). Parametric tools like Grasshopper and its Octopus plugin have been employed to balance daylight and thermal performance through strategic skylight placement (Shahbazi et al., 2019). Other studies have optimized building form, envelope, and shading systems using EnergyPlus and GenOpt with Particle Swarm Optimization (Lu et al., 2017).

Advanced optimization frameworks have demonstrated that parametric optimization processes can explore extensive design alternatives, automatically identify optimal solutions, and significantly improve building performance across different climate zones. Multi-objective optimization methods have proven superior to single-objective approaches in building performance optimization. Research showed that while multi-objective optimization might increase total energy consumption by 2.9–11.3 %, it can dramatically reduce thermal discomfort (PPD) by 49.1–56.8 % (Delgarm et al., 2016). This multi-objective approach enables the identification of design solutions that not only enhance occupant comfort but also optimize energy performance — a critical factor in design decision-making. Similarly, studies optimizing windows and shading systems have demonstrated that proper configuration can reduce total energy consumption by up to 26.7 % while improving thermal comfort (Sun et al., 2021). Building on this foundation, the current study extends energy performance optimization to the fundamental level of building form and geometry, examining how these primary design decisions can achieve even greater energy savings through integrated passive strategies.

Daylight and Thermal Comfort Optimization

Optimizing daylight and thermal comfort simultaneously has attracted significant attention. A 2019 simulation-based study in Tehran assessed optimal window-to-wall ratios, finding that 25–35 % on southern façades provided the best balance between daylight access and thermal load (Motazedian, 2019). Further studies explored automated window control systems and intelligent thermal comfort prediction algorithms for enhanced energy performance (Stazi et al., 2017, Tang and Wang, 2019).

The present study leverages these findings by establishing an optimized building form and orientation as a foundational step, which subsequently informs and constrains the design parameters for elements such as windows and shading, which are explored in later stages of the design process.

Methodology

Overall Research Framework

The optimization framework for a single-story residential building was developed through the following three main phases:

1) Parametric Modeling. A parametric model of the building was constructed, where key design variables — such as aspect ratio, courtyard placement, and orientation — were defined, and their ranges were determined based on the local climatic conditions and design constraints.

2) Energy and Daylight Simulation. Energy performance and daylight availability were simulated under the hot and dry climate of Yazd.

3) The operative temperature during the summer was calculated using the Adaptive Thermal Comfort Model, assuming no mechanical ventilation.

4) The Useful Daylight Illuminance (UDI) was computed to evaluate daylight performance throughout the year.

5) The objective in this phase was to minimize the average operative temperature during the summer and to maximize the annual average UDI.

6) Multi-objective Optimization. The design variables and performance metrics were integrated into a genetic algorithm-based multi-objective optimization process. The goal was to identify optimal building forms that enhance both thermal and visual comfort. The overall process of the optimization workflow is illustrated in Fig. 1.

Parametric Form Modeling

Parametric modeling was employed using Grasshopper (within Rhinoceros 3D) to generate a set of cube-based architectural forms (Fig. 2). This approach supports exploration of multiple configurations prior to final design selection (Lucarelli et al., 2020).

Cubic geometries were selected due to their prevalence in global architecture (Steadman, 2006) and vernacular residential structures in Yazd (Zarei and Mirdehghan, 2015). Each form was created by subtracting a movable smaller cube from a fixed-volume base, with variable dimensions and orientation relative to geographic north (Fig. 3).

Four typologies — Cubic, L-shaped, U-shaped, and O-shaped — were developed while maintaining constant horizontal cross-sectional area across four floor area categories (250, 350, 450, and 650 m²), based on local housing data. To eliminate impractical designs, constraints were applied regarding aspect ratio (0.25–4), minimum external wall distances (≥3 m), and a fixed height of 3.5 m. Due to differing parametric inputs, models were executed independently for each form type. Table 1

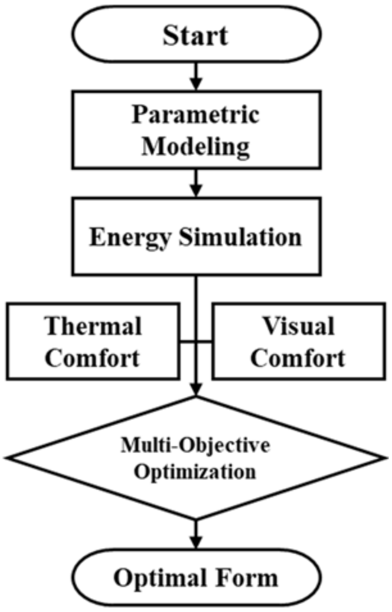


Fig. 1. The workflow for identifying the optimal configuration

and Table 2 illustrate representative forms and parameter sets, and the modeling workflow is shown in Fig. 4.

Building Energy Simulation

Building geometry plays a crucial role in optimizing energy consumption (Omrani and Marsono, 2015). This study employs energy simulation using Honeybee and Ladybug plugins (version 1.5.0) to evaluate the impact of architectural form variables on heating and cooling demand. The key variables used in this study are briefly described in Table 3.

The simulations utilized the 'HB Construction Set by Climate' component, which automatically assigns building envelope properties based on climate zone and building vintage according to ASHRAE 90.1 standards, ensuring reproducibility and compliance with industry norms. The specific settings used were as follows:

− Climate Zone: Climate Zone 2B (Hot - Dry);

− Building Vintage: ASHRAE 90.1 - 2019 and IECC 2021;

− Construction Type: Steel Framed.

Based on these inputs, the Honeybee engine automatically assigns a complete set of constructions for all envelope components, including insulated walls and double-glazed windows with low solar heat gain coefficients appropriate for hot climates. This configuration ensures envelope properties — such as wall U-values (~0.332 W/m²K), window U-values (~3.24 W/m²K), and solar heat gain coefficients (SHGC ≤ 0.25) — comply with ASHRAE 90.1–2019 requirements for Climate Zone 2B, representing typical energy-efficient construction for hot-dry climates. The simulation incorporates zoning, climate

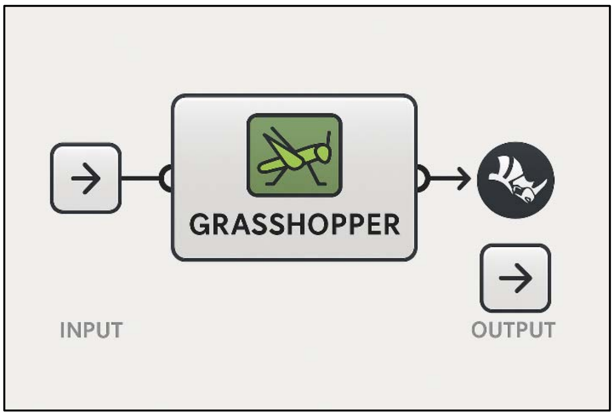


Fig. 2. Software used for computational parametric modeling approach

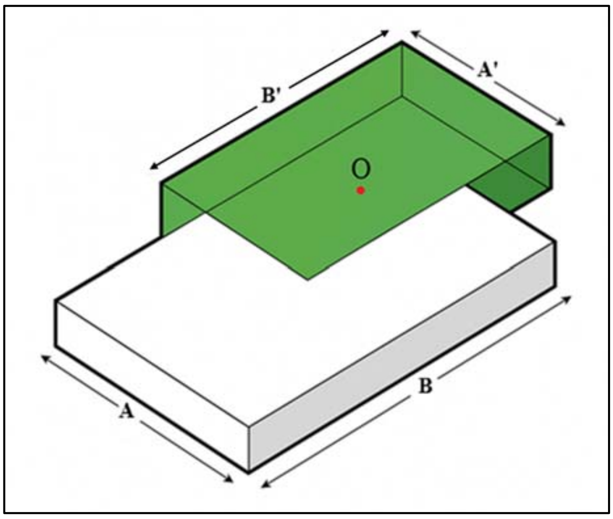


Fig. 3. Sample parametric form: A = width of the main cube, B = length of the main cube, A′ = width of the subtracted cube, B′ = length of the subtracted cube, O = center point of the subtracted volume in the plan

Table 1. **Examples of general form types achievable through computational parametric modeling approach**

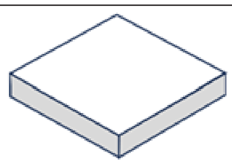
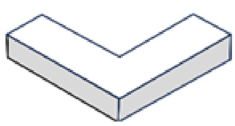
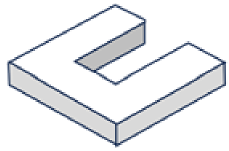
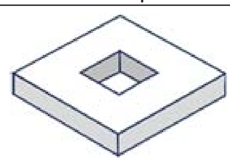
Cube	L-Shape	U-Shape	O-Shape
			

Table 2. **Required parameters for each form category**

Form Type	Orientation (°)	Main Cube Length (m)	Subtracted Cube Length (m)	Subtracted Cube Width (m)	Sub cube Center X (m)	Sub cube Center Y (m)
Cube	✓	✓	–	–	–	–
L-Shape	✓	✓	–	–	✓	✓
U-Shape	✓	✓	–	✓	✓	✓
O-Shape	✓	✓	✓	✓	✓	✓

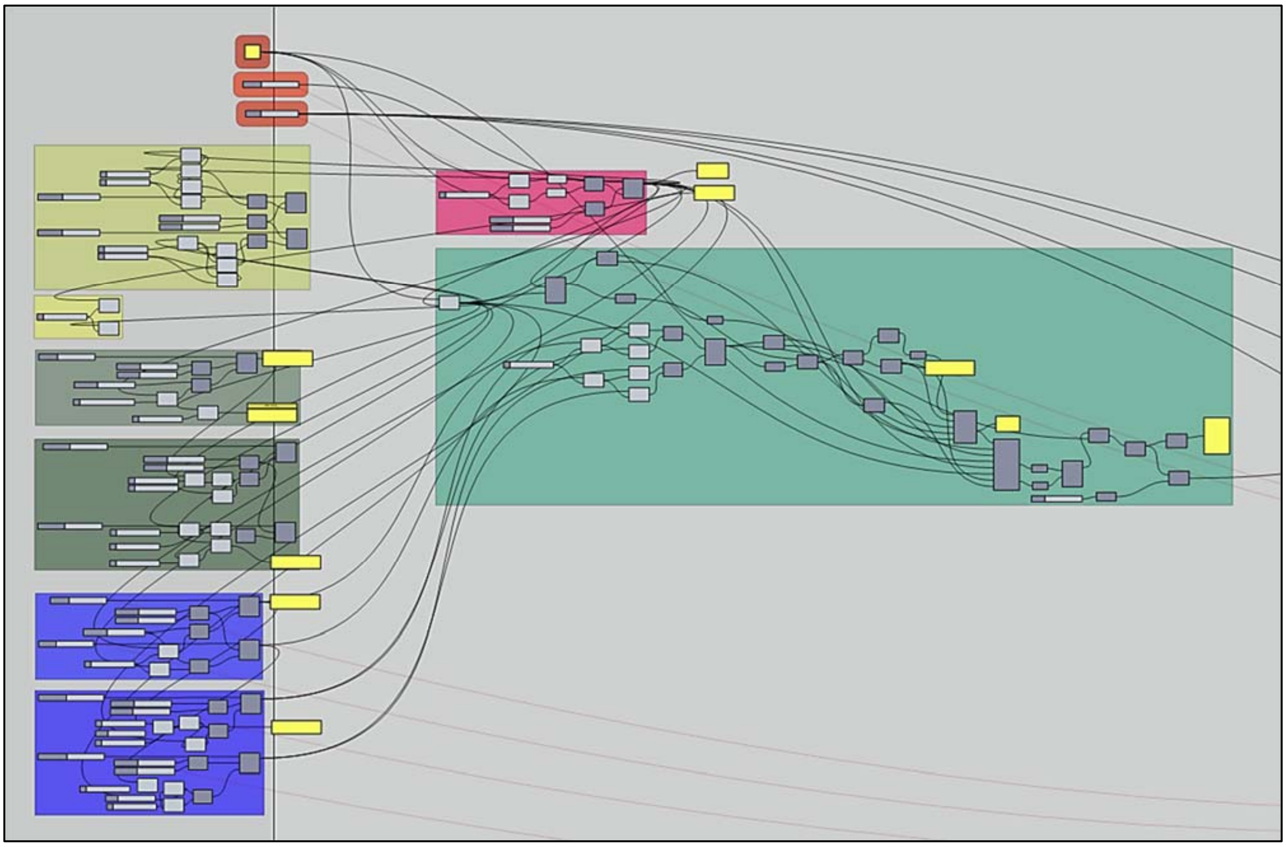


Fig. 4. General schematic of the computational parametric modeling approach process

Table 3. **Form and shape-related variables used in the study**

Variable	Definition	Example of Application
Compactness Index	Ratio of a building's volume to its exterior surface area	Bekkouche et al. (2013) examined the impact of compactness on thermal behavior in hot-arid climates. Their findings showed that increased compactness improves indoor thermal comfort.
Shape Factor	Ratio of building length to width	Aksoy and Inalli (2006) showed that optimizing shape and orientation can reduce heating energy demand by up to 36 %. Mingfang (2002) studied how variations in length, depth, and width influence solar gains in tubular buildings.
Building Orientation	Angle between the building's transverse axis and geographic north	Faizi et al. (2011) analyzed orientation effects using Ecotect software and found that a 0° alignment provides optimal solar exposure in Tehran

settings, and window configurations, with the building type set as "apartment" — representing a standalone residential unit. The analysis utilizes ASHRAE 90.1 2019 and IECC 2021 data for accurate assessment. The results from the building envelope energy modeling serve as key inputs for thermal and visual comfort simulations. This configuration ensures high-performance assemblies typical for hot climates, including insulated walls and double-glazed windows with low solar heat gain coefficients. An overview of the building envelope energy simulation process in Grasshopper software is presented in Fig. 5.

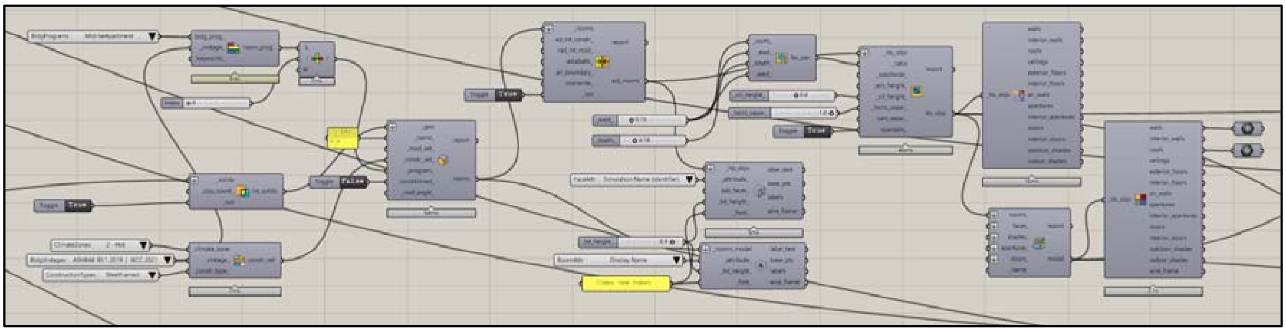


Fig. 5. Building energy simulation section

Considering that climatic data for Yazd is essential for the simulation section of this study, a brief description of the studied climate is provided here. Climate Context — Yazd, Iran: Given that energy simulations in this study are tailored to the local conditions of Yazd, a concise understanding of its climate is essential. Yazd is located in central Iran (latitude: ~32 °N, elevation: 1220 m above sea level), classified as BWh (hot desert climate) according to the Koppen system (Jahanbakhsh and Esmaeelpour, 2004). The region is characterized by low annual precipitation (average ~56 mm), high evaporation rates, and very low relative humidity, particularly in the summer months, where it falls below 15 %. The mean annual temperature is approximately 20.5 °C, with summer highs exceeding 40 °C and winter lows occasionally falling below freezing, resulting in an average of 33 frost days per year. Yazd also experiences over 3400 hours of sunshine annually, making solar radiation a significant factor in building energy performance. Seasonal rainfall occurs mostly in winter and early spring, while summer is extremely dry (Fallahpour, 2015). The dominant wind directions are from the west, northwest, and southeast, with an average annual wind speed of 2.4 m/s. In line with Jahan-Bakhsh and Esmaeilpour (Jahanbakhsh and Esmaeelpour, 2004), window-to-wall ratios (WWR) were set at 15 % in energy simulation models, reflecting vernacular design strategies for hot arid climates, where minimal window area helps reduce cooling loads. Yazd's extreme climate conditions emphasize the importance of passive design elements, making it a relevant testbed for this study's parametric simulations.

Thermal Comfort

According to the study by Orosa and Oliveira (2011), in naturally ventilated buildings, the Adaptive Model provides a more accurate prediction of thermal comfort compared to the PMV (Predicted Mean Vote) index, which is more suitable for buildings equipped with HVAC systems. Given that the present study considers only natural ventilation, the Adaptive Model was employed to evaluate indoor thermal comfort. Humphreys and Nicol (1988) investigated human thermal neutrality, defining it as the temperature at which individuals feel thermally neutral or "comfortable". Their findings, based on laboratory and field studies, led to the development of the Adaptive Model through regression analysis.

In this study, thermal comfort was calculated using the Adaptive Comfort component within the Honeybee and Ladybug plugins for Grasshopper, linked to the building energy simulation outputs. Sensors were distributed across a 1-meter grid, positioned 20 centimeters above the floor level, to collect operative temperature data for optimization purposes. Thermal comfort conditions in Yazd were evaluated based on the study by Jahanbakhsh and Esmailpour (2004). At night, thermal comfort is typically achieved only during June, July, and August, while other months are characterized by cool or cold nighttime conditions. During daytime, April and October offer comfortable conditions, whereas the summer months (June to August) present extreme heat. Regarding building orientation, Fallahpour (2015) found that the majority of residential complexes in Yazd are oriented either north-south or northwest-southeast. North-south oriented buildings are less exposed to strong seasonal winds but receive higher solar radiation during the hot season, while northwest-southeast orientations provide a balanced solar exposure but are more influenced by prevailing winds. Based on meteorological data from Shahid Sadoughi Airport, the hottest week of the year typically occurs between July 3 and July 9, and the coldest week between January 11 and January 17. Therefore, thermal comfort simulations in this study focused on daytime hours (8:00 a.m. to 6:00 p.m.) during the hottest week of the year to represent critical thermal stress periods. Fig. 6 illustrates the thermal comfort simulation framework implemented in Grasshopper.

Visual Comfort

Visual comfort is defined as a mental response to the quantity and quality of light in a given space. In this study, Useful Daylight Illuminance (UDI) was utilized as the primary metric for visual comfort evaluation. UDI calculates the annual occupied hours during which daylight levels fall within the

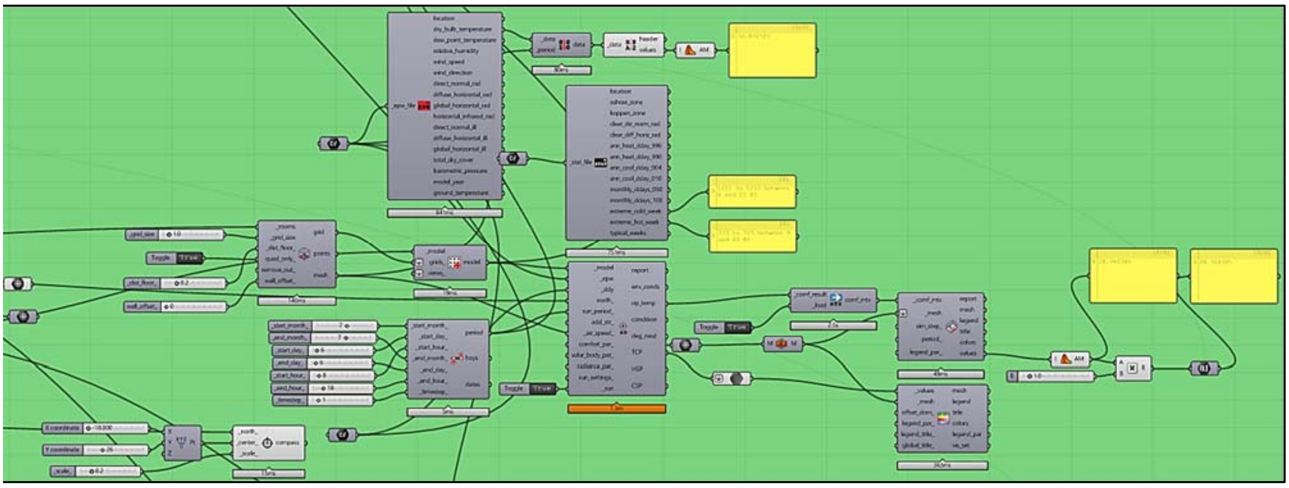


Fig. 6. Thermal comfort section

range of 300-3000 lux, ensuring optimal lighting and preventing visual discomfort (Rana et al., 2021). The calculations were conducted using the Annual Daylight component of the Honeybee Radiance plugin, integrated with building energy simulation outputs (Shafavi Moghaddam et al., 2019). The assessment timeframe included all days of the year between 8 a.m. and 6 p.m., with the goal of maximizing UDI to optimize daylight utilization and reduce energy consumption. Fig. 7 illustrates the thermal comfort simulation framework implemented in Grasshopper.

Table 4 presents the average operative temperature and UDI values, along with thermal and daylight visualizations on the floor plan, for 10 randomly generated L-shaped plan samples with varying parameters. These samples are based on the climate of Yazd and a total floor area of 650 m². The average values obtained from these random samples are used as a reference for comparison with the optimal configurations derived from the optimization process.

Optimization

Optimization for four primary forms was carried out individually using a genetic algorithm through the Octopus plugin in Grasshopper software. Octopus is a Grasshopper plugin used for optimization processes. It employs genetic algorithms for single or multi-objective optimization and enables users to select diverse parameters, enhancing the search space for solutions. In addition to allowing users to define population size and the maximum number of generations prior to optimization, it prevents process interruptions when encountering infeasible solutions by moving to the next solution after reaching a maximum runtime (Lucarelli et al., 2020). The tool generates a Pareto front of optimized points at the end of the process, from which users can select the most suitable solutions based on their requirements. In this study, the Octopus plugin was used to optimize the form of a single-story residential villa. The mean annual UDI (Useful Daylight Illuminance) and mean operative temperature were defined as objectives, while the design parameters described in the parametric section (Table 2) were assigned as genes. The goal was to achieve dual-objective optimization: minimizing operative temperature and maximizing UDI for the four selected forms across various building footprint sizes, considering the hot and arid climate of Yazd. The endpoints of the Pareto optimization graph represent the minimum operative temperature during the hottest week of the year and the maximum annual UDI (Fig. 8).

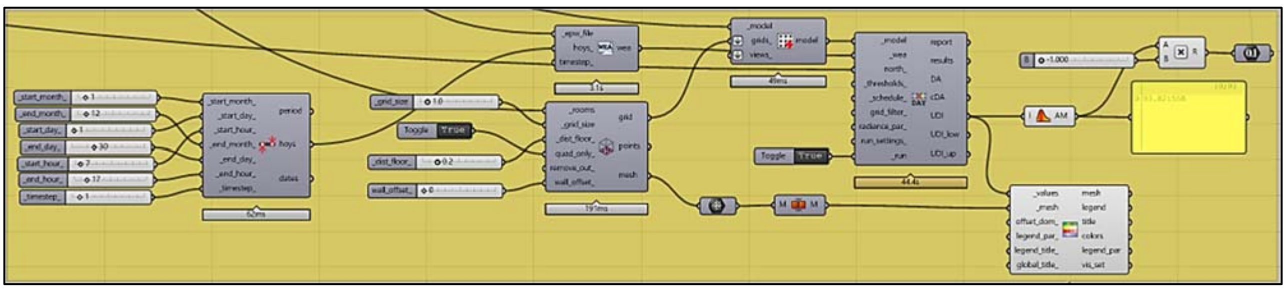
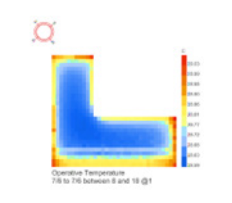
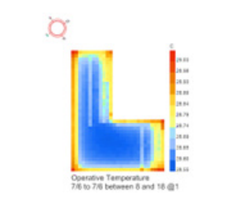
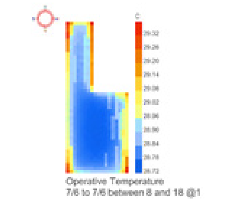
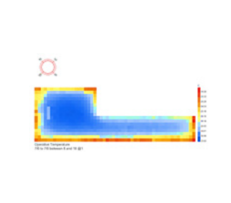
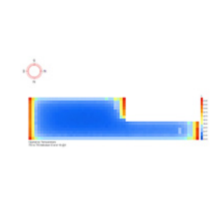
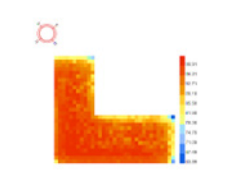
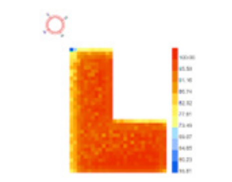
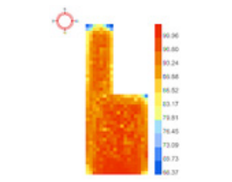
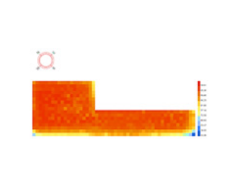
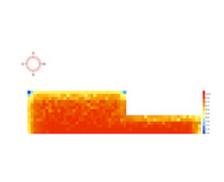
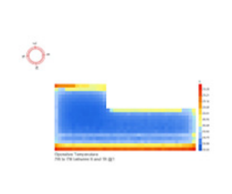
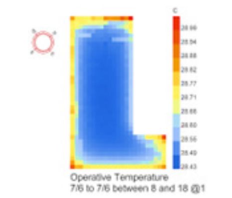
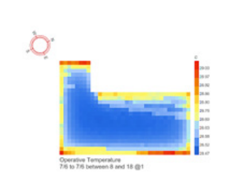
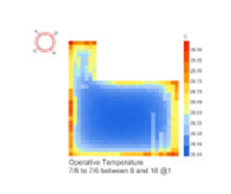
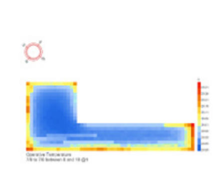
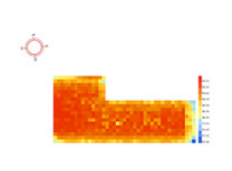
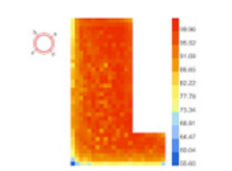
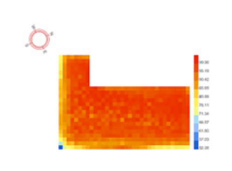
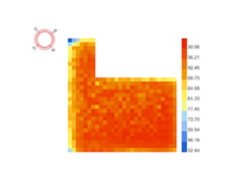
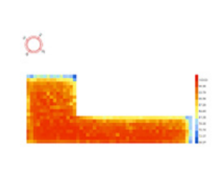


Fig. 7. Visual comfort section

Table 4. **Operative temperature and UDI averages for 10 random L-shaped plans in Yazd Climate**

					Operative Temperarture
					UDI
Case 5	Case 4	Case 3	Case 2	Case 1	Case Description
Average Op. Temp.: 28.8 Average UDI: 94.2	Average Op. Temp.: 28.8 Average UDI: 93.4	Average Op. Temp.: 28.9 Average UDI: 93.3	Average Op. Temp.: 29.1 Average UDI: 92.8	Average Op. Temp.: 28.6 Average UDI: 93.7	
					Operative Temperarture
					UDI
Case 10	Case 9	Case 8	Case 7	Case 6	Case Description
Average Op. Temp.: 28.8 Average UDI: 93.8	Average Op. Temp.: 28.5 Average UDI: 93.5	Average Op. Temp.: 28.6 Average UDI: 93.5	Average Op. Temp.: 28.6 Average UDI: 94	Average Op. Temp.: 29.1 Average UDI: 93.9	

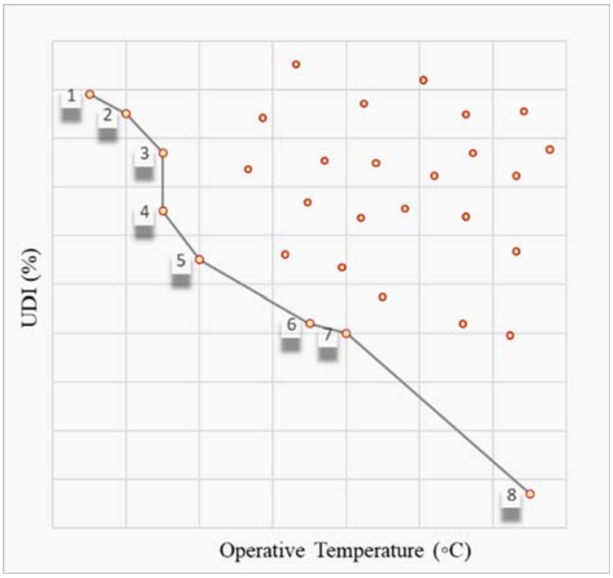


Fig. 8. An example of a Pareto front diagram and its extreme points generated by the Octopus plugin (Point 1: the start of the Pareto curve indicating the minimum operative temperature; Point 8: the end of the Pareto curve indicating the maximum UDI)

Optimization parameters:

– Initial population size: 85;

– Termination condition: 5 generations;

– 50 % elitism selection;

– 30 % mutation probability;

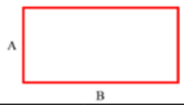
– 80 % mutation rate (to ensure extensive evaluation of solutions);

– 80 % crossover rate.

Results

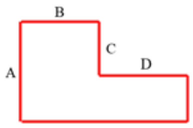
Multi-objective optimization was performed to minimize the average indoor operative temperature during the hottest week of the year and to maximize the annual average UDI for four different floor areas (250, 350, 450, and 650 m²) in Yazd's hot-arid climate. Considering four base form) cube, L, U, and O (the optimal points at both ends of the Pareto front (representing minimum operative temperature and maximum UDI) are reported in Tables 5, 6, 7, and 8. These tables present detailed geometric parameters, performance metrics, and derived indicators including compactness index and shape factor values. For energy performance analysis comparing all optimized configurations

Table 5. **Optimization results for cubic form**



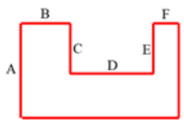
Cubic Form								
Area (m^2)	**Pareto Points**	**Average Op. Temp (◦C)**	**UDI (%)**	**Building Orientation (0° to 360°)**	**A(m)**	**B(m)**	**Compactness Index**	**Shape Factor**
250	Start	29.07	92.86	178	11.96	20.89	3.802	1.764
	End	29.42	93.13	132.8	19.13	13.06	3.880	0.682
350	Start	28.66	93.66	178	13.82	25.31	4.469	1.831
	End	28.94	93.87	220	17.97	19.47	4.672	1.083
450	Start	28.37	93.92	180.3	15.59	28.86	5.061	1.851
	End	28.38	94.08	176.8	15.85	28.37	5.084	1.789
650	Start	27.99	94.31	179.3	18.94	34.31	6.101	1.811
	End	27.99	94.31	179.3	18.94	34.31	6.101	1.811

Table 6. **Optimization results for L-shaped form**



L-Shaped Form									
Area (m^2)	**Pareto Points**	**Average Op. Temp (◦C)**	**UDI (%)**	**Building Orientation (0° to 360°)**	**A (m)**	**B (m)**	**C (m)**	**D (m)**	**Compactness Index**
250	Start	29.15	93.23	180.3	12.71	15.84	3.71	5.37	3.681
	End	29.56	93.62	205.8	11.28	12.58	3.24	13.42	3.351
350	Start	28.69	93.61	182	14.77	19.28	3.36	5.70	4.400
	End	28.81	94.43	194	15.78	8.85	3.00	16.46	4.259
450	Start	28.43	93.88	178.8	16.19	23.09	3.42	5.95	4.972
	End	28.56	94.58	194.3	17.86	10.82	3.12	17.40	4.489
650	Start	28.02	94.37	181.5	19.68	28.82	3.96	5.25	6.045
	End	28.29	94.78	206.9	17.04	28.71	3.19	11.59	5.665

Table 7. **Optimization results for U-shaped form**



U-Shaped Form											
Area (m^2)	**Pareto Points**	**Aver. Op. Temp (◦C)**	**UDI (%)**	**Building Orientation (0° to 360°)**	**A (m)**	**B (m)**	**C (m)**	**D (m)**	**E (m)**	**F (m)**	**Compactness Index**
250	Start	29.42	92.10	81.8	22.09	4.47	4.41	4.73	4.41	3.05	3.224
	End	29.55	92.94	186.3	14.65	3.10	4.48	3.03	4.48	11.84	3.368
350	Start	28.94	93.57	180	12.80	10.34	3.66	5.71	3.66	12.89	3.851
	End	29.13	94.08	195	16.06	6.63	4.20	14.76	4.20	4.24	3.810
450	Start	28.575	93.79	265.3	32.20	4.69	4.06	4.23	4.06	5.58	4.429
	End	28.816	93.92	205	16.49	12.72	4.08	3.93	4.08	11.58	4.607
650	Start	28.143	94.05	86.6	32.20	6.05	4.16	4.74	4.16	9.99	5.684
	End	28.451	94.63	172.5	15.52	11.21	3.58	34.78	3.58	3.90	4.710

against a suboptimal baseline, see Table 11 in the Discussion.

Discussion

Thermal and Visual Performance Analysis

As previously mentioned, the ambient temperature during the hottest week of the year in Yazd reaches approximately 35 °C. Table 9 presents a selection of suboptimal O-shaped configurations for a 650 m² floor area. While not representing the worst-performing cases, these examples illustrate the effectiveness of the optimization process. Compared to these cases, the optimized forms achieved

Table 8. **Optimization results for O-shaped form**

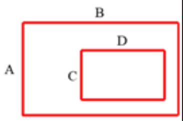
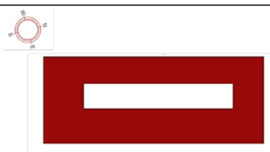
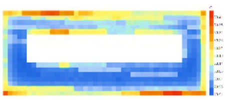
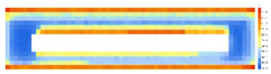
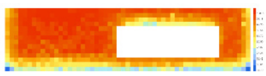
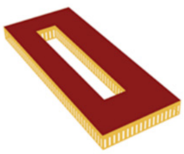
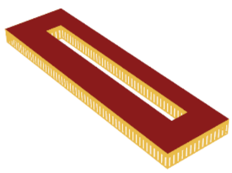
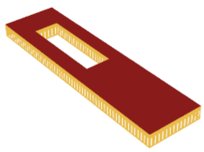
	**O-Shaped Form**										
Area (m²)	**Pareto Points**	**Aver. Op. Temp (°C)**	**UDI (%)**	**Building Orientation (0° to 360°)**	**A (m)**	**B (m)**	**C (m)**	**D (m)**	**X-axis Coordinate of the Subtracted Cube Center (m)**	**Y-axis Coordinate of the Subtracted Cube Center (m)**	**Compactness Index**
250	Start	29.53	91.18	98.2	22.63	11.46	3.13	3.05	5.37	15.67	3.101
	End	29.60	92.45	174.8	9.99	26.24	3.20	3.86	12.09	4.86	2.885
350	Start	29.02	93.01	186	13.74	26.25	3.21	3.38	18.50	8.87	3.755
	End	29.32	93.58	209	18.92	19.27	4.07	3.64	4.98	9.62	3.810
450	Start	28.66	93.51	273.6	29.15	15.74	3.00	3.00	10.66	15.07	4.419
	End	28.69	93.72	176.3	15.74	29.34	3.59	3.35	14.82	8.65	4.323
650	Start	28.30	93.89	169.2	17.31	38.24	3.27	3.75	18.63	9.17	5.191
	End	28.52	94.15	210	17.35	38.32	3.27	4.58	20.17	9.17	5.115

Table 9. **Selected examples of suboptimal building form configurations designed for the hot-arid climate of Yazd, used for comparative analysis against the optimized models**

			Top View of the Form
			Operative Temperarture
			UDI
			3D View of the Form
Operative Temperature: 31 Useful Daylight Illuminance: 91.5	Operative Temperature: 30.4 Useful Daylight Illuminance: 91	Operative Temperature: 29.14 Useful Daylight Illuminance: 91.2	Configuration Details

reductions of approximately 2–3 °C in operative temperature and a 3–4 % increase in annual UDI, confirming the tangible benefits of the proposed optimization strategy.

Before discussing the results, it is essential to note that the validity of the findings was verified through three approaches:

1) Reference: Bekkouche et al. (2013), which provides a validated analysis framework for the city of Yazd and supports the quality of this study's outcome;

2) A comparative check against 10 randomly generated L-shaped forms with a floor area of 650 m² (as shown in Table 4), none of which yielded a lower operative temperature or higher UDI than the Pareto-optimal points derived through the optimization process;

3) Consistency with the findings reported in Reference (Fallahpour, 2015), which are further elaborated in the section discussing orientation results.

Fig. 9 illustrates the lowest operative temperatures achieved through the optimization of various building forms across different floor areas.

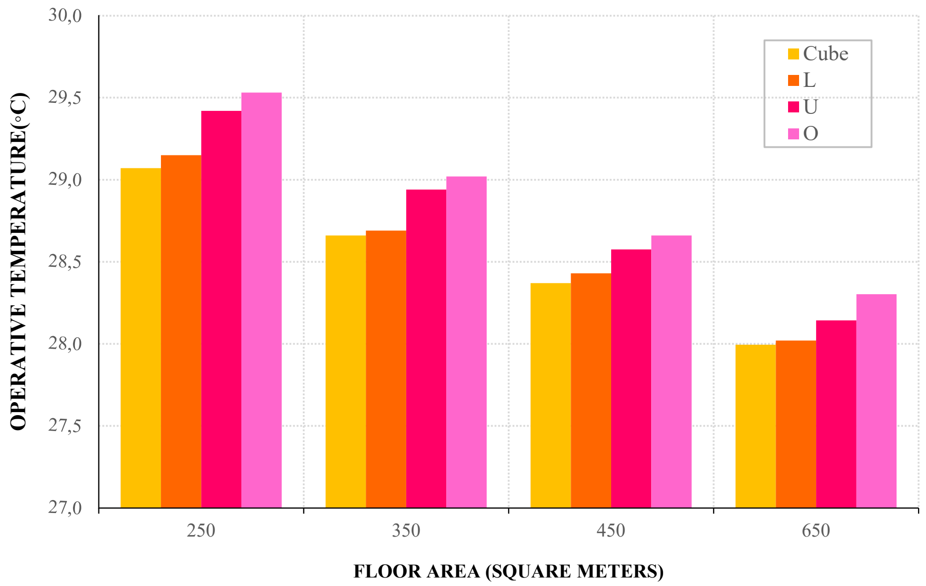


Fig. 9. Minimum operative temperatures from optimized forms across different floor areas in Yazd

This chart illustrates that, for each floor area category, the lowest operative temperature is achieved by the cube form, followed by the L, U, and O forms, respectively. It also demonstrates a consistent trend across all form types: as floor area increases, the minimum operative temperature achieved through optimization decreases. This indicates improved thermal comfort in single-story residential buildings with larger floor areas, with the cube form being the most effective in enhancing thermal comfort. Fig. 10 presents the compactness index of the forms with the highest thermal comfort for each floor area category, based on form type.

It can be observed that the highest compactness index for each floor area category corresponds to the cube form. Following that, the L, U, and O forms respectively exhibit the next highest compactness values across all floor area categories. Moreover, there is a general trend showing that as the building floor area increases, the compactness index also increases. By comparing the results in Fig. 9 with those in Fig. 10, a meaningful relationship between the compactness index and thermal comfort in Yazd can be identified. Specifically, higher compactness values are associated with improved thermal comfort performance. This correlation was previously demonstrated by Bekkouche et al. (2013), who found a direct relationship between form compactness and thermal comfort in hot-dry climates. The findings of the current study are consistent with those results. Additionally, Fig. 11 illustrates the average compactness index of all Pareto-optimal

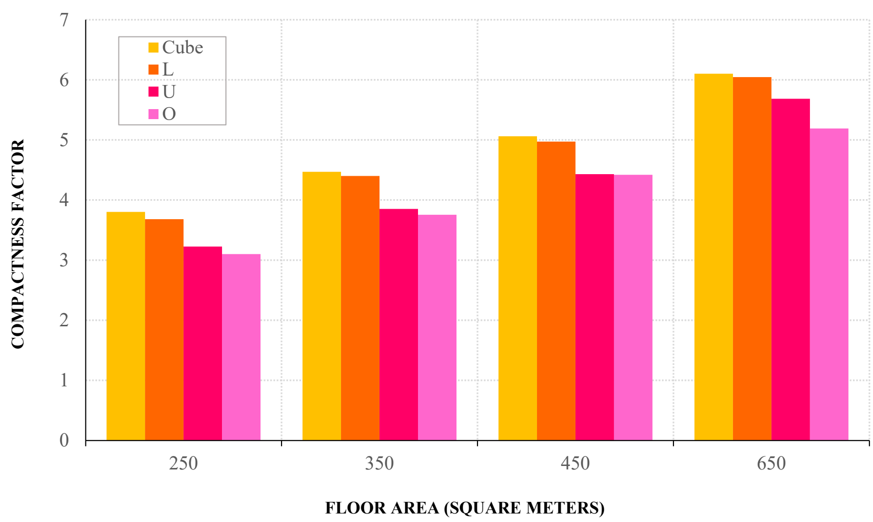


Fig. 10. Compactness index of optimized building forms achieving the highest thermal comfort for each floor area category in a hot-arid climate

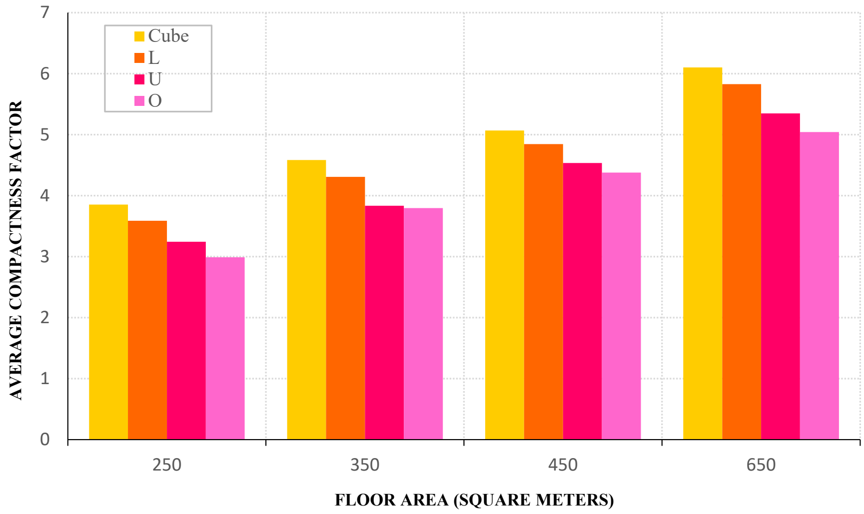


Fig. 11. The average compactness index of all Pareto-optimal solutions for each floor area-form type category

points obtained from the multi-objective optimization process, categorized by floor area and form type.

This chart also illustrates the average compactness index of all Pareto-optimal solutions for each floor area-form type combination. The highest average compactness values correspond to the cube form across all considered floor areas. This is followed, in descending order, by the L, U, and O forms. Fig. 12 presents the maximum UDI values obtained through the optimization process for each form type across the different floor area categories.

This chart shows that the highest UDI values – used in this study as an indicator of visual comfort – are consistently associated with the L-shaped form across all floor area categories. For the 250 m² category, the next highest UDI values after the L form are observed in the cube, U, and O forms, respectively. In the 350 m² category, following the L form, the order is U, cube, and O. For the 450 m² floor area, the sequence after the L form is cube, U, and O. Similarly, in the 650 m² category, the highest UDI values after the L form belong to the U, cube, and O forms in that order. It should be noted that no meaningful correlation was found between the maximum UDI values and the compactness index of the optimized forms. Fig. 13 illustrates the shape factor values of the optimized forms for each input floor area. Since the shape factor is derived from the building's length-to-width ratio, this metric is only valid for the cube form.

Fig. 13 includes two curves: the yellow line represents the variation of the shape factor for the thermally optimal form (i.e., with the minimum operative temperature) across each input floor area, while the red line shows the shape factor corresponding to the

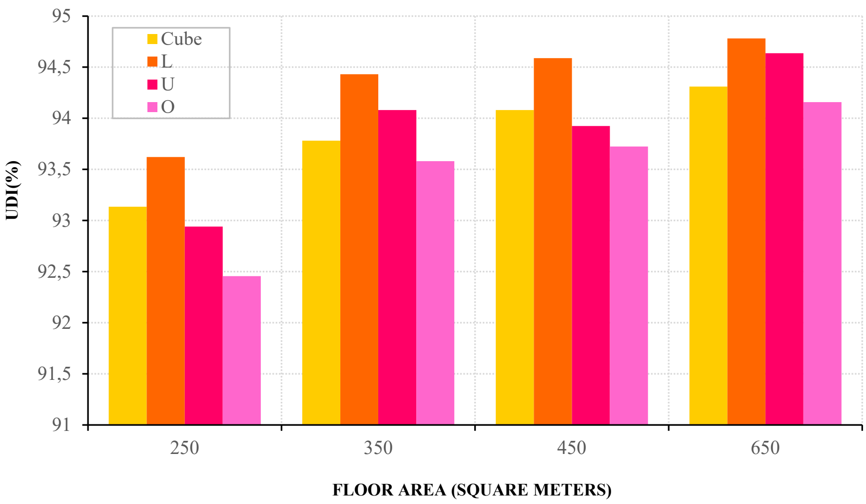


Fig. 12. Maximum UDI values resulting from the optimization of different building forms across various floor areas

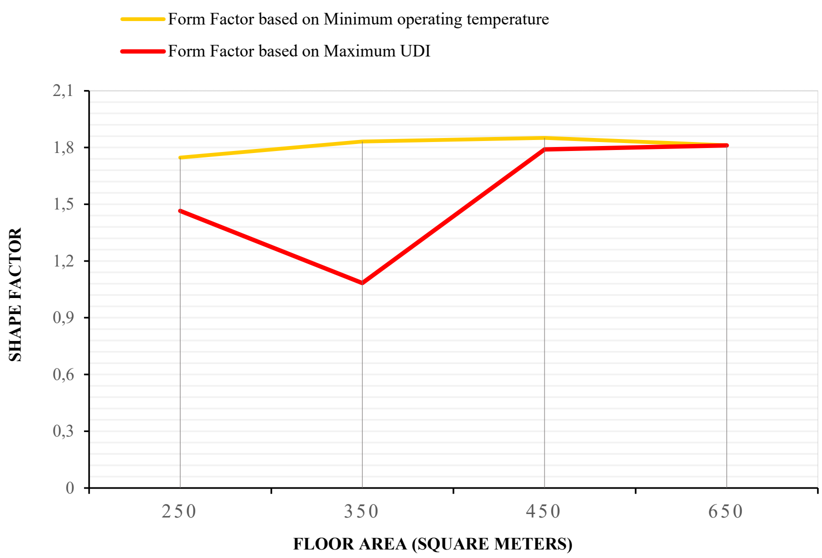


Fig. 13. Shape factor of optimized forms for each input floor area category

visually optimal form (i.e., with the maximum UDI) for each floor area category. The relatively stable trend observed in the shape factor of thermally optimal forms suggests that, for improved thermal comfort, the ideal cube form should maintain a shape factor of approximately 1.8, regardless of floor area. In contrast, no meaningful relationship is observed between the shape factor and floor area when maximizing UDI. Since previous results have shown that the cube form yields the highest thermal comfort across all tested floor areas within Yazd's hot-arid environmental conditions, it can be concluded that a cube form with a shape factor of approximately 1.8 is the thermally optimal configuration for single-story buildings up to 650 m² in this region. For a detailed analysis of building orientation in Yazd, refer to Fig. 14.

For the evaluation of building orientation, only the cube form was utilized to isolate the impact of orientation, as the orientation input for other forms — due to their asymmetry — interacts directly with form variation during optimization. In this chart, the optimal orientation of the cube form is shown based on the minimum operative temperature (yellow line) and the maximum UDI (red line). The results indicate that the orientation yielding minimum operative temperature remains nearly constant across varying longitudinal floor area inputs. Therefore, considering thermal comfort optimization during the hottest week of the year, it can be concluded that for floor areas up to 650 m², the optimal orientation is independent of floor area. The best-performing orientations for thermal comfort in Yazd are approximately 0°

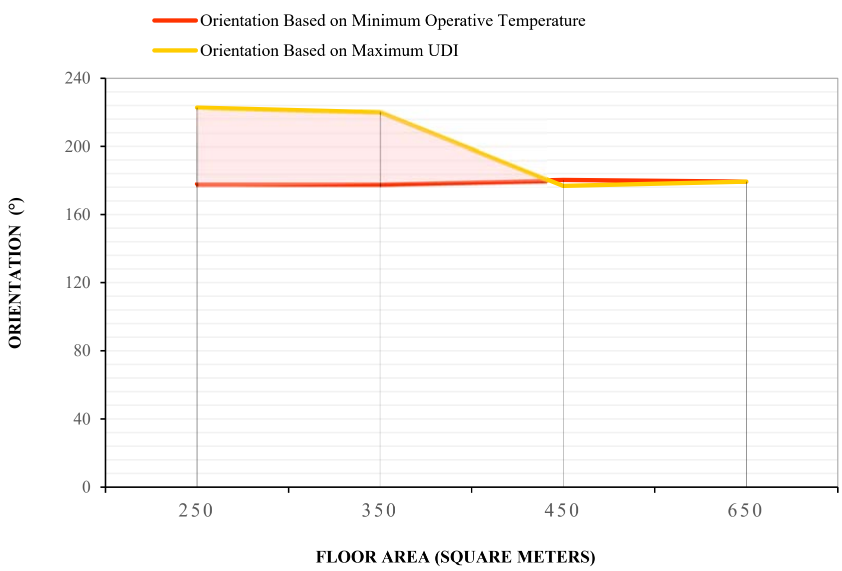


Fig. 14. Optimal building orientation chart for the City of Yazd

or 180°, owing to the symmetry of the cube. It is also noteworthy that the optimal orientations of the remaining Pareto points (excluding the endpoints shown in the chart) generally fall between the two plotted curves. This suggests that for floor areas of 250 and 350 m², optimal orientations range between 180° (north-south) and 220° (northwest-southeast), while for floor areas of 450 and 650 m², the preferred orientation is around 180° or 0° (north-south). In contrast, optimal orientation based on visual comfort (UDI) varies more noticeably with changing floor area. It is important to note that the findings of this study are consistent with those reported by Fallahpour (2015), who identified the optimal building orientation in Yazd's hot-arid climate as ranging between the north-south and northwest-southeast axes.

Energy Performance Analysis

Beyond comfort metrics, the energy implications of form optimization were quantified to assess economic viability. The total cooling and lighting energy consumption of all optimized configurations with a 650 m² floor area was calculated and compared against a suboptimal O-shaped reference case from Table 9 (Case #3). This reference case, characterized by a UDI of 91.5 % and an operative temperature of 31 °C, represents a conventional design without optimization. Table 10 presents the comparative energy analysis in kilowatt-hours (kWh).

The results demonstrate that the optimized cubic form achieves the highest energy performance with a 38.6 % reduction in total energy consumption compared to the suboptimal reference. Notably, even the least efficient optimized configuration (O-shaped End point) still yields a substantial 32.4 % energy saving. This clear hierarchy in energy performance — Cubic > L-shaped > U-shaped > O-shaped — directly correlates with the thermal comfort results, confirming that form optimization for thermal comfort simultaneously delivers significant energy efficiency gains.

The 6.2 % performance gap between cubic and O-shaped forms (38.6 % vs 32.4 %) underscores the significant impact of form selection on energy efficiency. This translates to approximately [2000–2500] kWh annual energy savings for a typical residential building in Yazd.

Convergence Phenomenon and Design Implications

The identical results for both Pareto endpoints in the cubic form indicate a unique convergence where a single configuration simultaneously minimizes operative temperature and maximizes daylight availability for the 650 m² floor area. This convergence phenomenon in the cubic form represents an exceptional finding in multi-objective optimization, where typically competing objectives are simultaneously satisfied by a single configuration. This convergence suggests that for this specific scale in Yazd's climate, the cubic form achieves an ideal balance between thermal and visual comfort objectives, presenting designers with an unambiguous optimal solution. In contrast, the other form typologies exhibit the expected trade-off between the two objectives, requiring designers to select between thermal-driven (Start point) or daylight-driven (End point) configurations based on project priorities.

Integration with Building Control Systems

Building upon these geometric and orientational optimizations, this study has primarily targeted the building form as a fundamental passive strategy. The collective results demonstrate that geometric parameters — especially the compact cube form with north-south orientation — establish a significant passive thermal baseline. However, in a dynamically changing climate, achieving consistent year-round comfort requires combining this passive foundation with low-energy control mechanisms. The identified optimal orientation and window-to-wall ratios in optimized forms create an ideal platform for implementing adaptive shading systems. As demonstrated in the vernacular architecture of the region, fixed shading elements have long been employed for solar control (Izadpanahi et al., 2021). Modern interpretations could incorporate

Table 10. **Energy consumption comparison between optimized configurations and the suboptimal reference case (650 m²)**

FORM TYPE	PARETO FRONTS	TEMP. REDUCTION (◦C)	UDI INCREASE (%)	COOLING ENERGY SAVING (KWH)	LIGHTING ENERGY SAVING (KWH)	TOTAL ENERGY SAVING (%)
CUBIC	Start	3.01	2.81	2071.4	418.5	**38.6**
	End	3.01	2.81	2071.4	418.5	**38.6**
L-SHAPED	Start	2.98	2.87	2050.1	431.3	**38.4**
	End	2.71	3.28	1864.3	518.8	**36.9**
U-SHAPED	Start	2.85	2.55	1965.5	362.9	**36.1**
	End	2.54	3.13	1753.6	486.8	**34.7**
O-SHAPED	Start	2.7	2.39	1857.4	328.8	**33.9**
	End	2.48	2.65	1706.1	384.3	**32.4**

automated or manually controlled external louvers that maximize solar heat rejection in summer while allowing beneficial passive heating in winter, thereby enhancing the thermal performance achieved through form optimization alone. Furthermore, the L-shaped forms' superior daylighting performance, evidenced by their higher UDI values, presents significant potential for integration with daylight-responsive lighting controls. This approach aligns with the optimization goals in early design stages, where form parameters are determined before specific system selections (Feng et al., 2021). In such an integrated setup, the building's inherent daylight distribution capacity would be complemented by dimmable artificial lighting, maintaining visual comfort while reducing electricity consumption — an important consideration beyond the current simulation scope but logically connected to the visual comfort findings. Therefore, the optimized configurations identified in this research should be regarded not as complete solutions but as a robust passive framework. Subsequent design development can build upon this foundation by incorporating adaptive control systems for solar gain management, ventilation, and artificial lighting.

This integrated approach – where passive form establishes the performance foundation and active controls provide fine-tuning for diurnal and seasonal variations – represents not merely an optimization strategy but a fundamental shift toward resilient, low-energy architectural practice in hot-arid regions.

Conclusion

This study highlights the critical importance of energy consumption considerations in the architectural and design processes of buildings. With the advancement of simulation and modeling technologies in the built environment, the practical application of these tools has gained traction as a means to optimize building performance — striving to reduce energy consumption while enhancing occupant comfort. The energy analysis revealed that form optimization can yield 32.4–38.6 % energy savings, with cubic forms demonstrating both superior thermal comfort and energy performance. The unique convergence observed in cubic forms provides designers with unambiguous optimal solutions for the 650 m² scale in Yazd's climate. In this context, and with an emphasis on optimized design approaches, the research focused on minimizing energy use through the optimization of building form within Yazd's hot-arid environmental conditions — an approach historically embedded in the city's architectural heritage. Unlike passive analyses alone, this study employed a performance-based design strategy to identify optimal forms under natural ventilation conditions. The resulting configurations can serve as foundational references for architects prioritizing energy efficiency in the early stages of design in climates similar to Yazd. By integrating geometric configuration optimization into the conceptual design phase, the proposed framework enables not only passive but also active strategies to be developed on a sound basis — ultimately contributing to the realization of ideal, high-performance buildings suited to Yazd's environmental context.

Thermal comfort during the hot season and visual comfort were selected as the two primary objectives for multi-objective optimization. The results were presented in the form of Pareto fronts for each area-form combination (across four base geometries: compact cube, L-shaped, U-shaped, and O-shaped). Owing to the multi-objective nature of the analysis, a spectrum of optimal solutions was generated for each scenario. However, this study primarily analyzed the extreme ends of the Pareto front — those representing the minimum operative temperature during the hottest week of the year, and the maximum annual Useful Daylight Illuminance (UDI). To validate the optimization outcomes, the optimal forms were compared with randomly generated samples of the same form type, floor area, and climate zone. Additionally, comparative findings from two peer-reviewed studies were used to further verify the credibility of the results, which confirmed the robustness of the optimization outputs. The multi-objective optimization for Yazd's climate indicated that, when prioritizing thermal comfort during the hot season, the most efficient solution is a compact cubic form with a shape factor of 1.8 and an orientation of 0 degrees. In contrast, when visual comfort is given higher priority, the optimal configuration is an L-shaped form, with dimensions provided in results. In general, building orientations ranging from 180° (north-south axis) to 220° (northwest-southeast) are preferable for vernacular architecture in Yazd. Furthermore, the results revealed that increasing the floor area of the buildings correlates positively with improved thermal and visual comfort during the hot season. It is worth noting that all design solutions presented in the results tables are valid optimized outcomes for dual objectives and can be readily applied by designers. Future studies are encouraged to explore winter season optimization to further refine design strategies for year-round performance in Yazd's climate.

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БАЛАНСИРОВАНИЕ ТЕПЛОВОГО И ВИЗУАЛЬНОГО КОМФОРТА ПОСРЕДСТВОМ МНОГОЦЕЛЕВОЙ ПАРАМЕТРИЧЕСКОЙ ОПТИМИЗАЦИИ ФОРМЫ: ПРИМЕР ИЗ ЯЗДА, ИРАН

Мохаммадмехди Мулаи, Марьям Юнеси*

Кафедра архитектуры, Факультет искусства и архитектуры, Университет Бу-Али Сина, Хамадан, Иран

*E-mail: m.younesi@art.basu.ac.ir

Аннотация
Введение. Форма здания играет решающую роль в определении энергоэффективности и комфорта жильцов, особенно в жарком засушливом климате, таком как Язд, Иран. **В этом исследовании предлагается** стратегия пассивного проектирования, которая использует параметрическое моделирование и симуляцию для оптимизации форм жилых зданий с точки зрения теплового и визуального комфорта. **Методы.** Для определения оптимальных геометрических конфигураций в четырех различных сценариях площади помещений (250, 350, 450 и 650 м²) был использован многоцелевой генетический алгоритм. Были параметрически сгенерированы и оценены четыре основных типа форм — кубическая, L-образная, U-образная и O-образная — с использованием показателей тепловых характеристик и индикаторов дневного света. **Результаты** показывают, что прямоугольный параллелепипед с коэффициентом формы приблизительно 1,8, ориентированный вдоль оси север-юг, обеспечивает неизменно более высокий уровень теплового комфорта по сравнению с другими формами. Энергетический анализ показал, что оптимизированные конфигурации могут снизить общее энергопотребление до 38,6 % при сохранении приемлемого качества внутренней среды. Эта методология поддерживает принятие решений на основе данных на ранней стадии концептуального проектирования, способствуя разработке контекстно-чувствительных, энергоэффективных решений для жилья в засушливых регионах.

Ключевые слова: многоцелевая оптимизация; параметрическая форма; тепловой комфорт; визуальный комфорт; генетический алгоритм; устойчивое проектирование; энергоэффективность.