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The effect of building plan form on thermal comfort in the traditional residential patterns of the hot and dry climate of Qom

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Abstract

Buildings should be constructed such that their energy efficiency is high in different climatic conditions while providing acceptable thermal comfort at the same time. Climatic and architectural incompatibilities will increase energy consumption to provide thermal comfort but have adverse effects, both economically and environmentally. Climatic design is the best and most effective way to maximize the use of renewable energy sources. Traditional Iranian houses have always exhibited this type of architecture and can provide suitable examples for design for contemporary architects. This study aimed to investigate the effect of building plan forms on the thermal comfort temperature in residential buildings with the help of traditional architectural patterns. The method of this research is descriptive-analytical and has been conducted through case studies and simulation tests. Data collection has been undertaken through literature review and field observations. The houses in this study were classified based on their building plan form. Ecotect and EnergyPlus software were used for modeling and Climate Consultant software was used for climate analysis. Findings reveal that the Building Coverage Ratio (BCR) and the introverted plan forms are two significant factors in climatic design to provide thermal comfort in the hot and dry climate of Iran. Among the investigated models, results show that the one-sided form with northeast-southwest orientation and northeast placement has the most hours (2609 h per year) in the range of thermal comfort and the best plan form among the studied forms.

Keywords: Building plan form, Thermal comfort, Residential building, Traditional architectural patterns, Hot and dry climate

Introduction

Increased urbanization growth and the wasteful use of fossil fuels and non-renewable energy have led to climate change and the production of greenhouse gases. The depletion of fossil fuel resources, low efficiency, and high cost of their environmental impacts, have made energy consumption optimization and the use of renewable energy in construction inevitable. By improving the standard of living, people expect a better level of comfort, which ultimately necessitates the use of air conditioning [1]. Buildings consume one-third of the world's total annual energy, a ratio that continues to increase as population and urbanization grow [2]. Most of the energy is consumed in buildings located in the urban areas of developing countries and due to the modernization of buildings in the construction sector, climatic conditions and local materials are neglected [3]. Buildings play a vital role in creating a safe and comfortable living environment. To create thermal comfort in buildings, heating, ventilation, and air conditioning (HVAC) systems use about 50% of the building energy [4]. Providing thermal comfort in buildings has always been one of the main concerns of architects worldwide, and among these, residential buildings have always been of special importance [5]. Buildings should be constructed such that they

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have high energy efficiency in different climatic conditions while providing acceptable thermal comfort. Nowadays, although the occupant`s need for thermal comfort is met by mechanical equipment, to some extent the desired can be achieved in any climate through proper design. Mechanical equipment should only be used when weather conditions are unacceptable [6]. Climate and architectural incompatibilities will increase energy consumption to provide thermal comfort, which has many adverse effects, both economically and environmentally. Climatic design is the best and most effective way to maximize the use of renewable energy sources. Therefore, climatic building design to achieve thermal comfort has always been considered. Climatic design mainly seeks to lead the architectural forms to the best conditions which would be effective in optimizing energy consumption while providing comfort for users. Buildings that are designed and built according to climatic design considerations reduce the need for mechanical heating and cooling to a minimum and instead use natural energy. Therefore, this design creates optimal spaces for human comfort in a way that reduces energy consumption. Climatic factors also affect the form of buildings such that the most appropriate form of residential buildings is determined by the climate. This effect is readily observed in the formation of vernacular and traditional buildings [7]. The utilization of traditional Iranian architectural principles can play an important role in the sustainable design of future buildings. The implementation of these principles can lead to buildings that are more adaptive and harmonious with their surrounding environment and are more energy-efficient. In traditional Iranian architecture, choosing a form appropriate to the climate to reduce energy consumption has been a priority for architects, for example, sloping the roofs of houses in rainy areas, choosing closed and low-opening forms in cold areas, and installing windbreaks in hot and dry or hot and humid areas. The form of the building can have a great impact on the harmonization of the building with the climatic conditions and the adjustment of the indoor air. Additionally, the climatic design creates buildings with a more comfortable atmosphere [8].

The remaining traditional houses in the city of Qom are part of the valuable architectural heritage of the hot and dry climate of Iran. Although these traditional houses are similar to the architecture of other cities in this climate, there are subtle artistic differences in details. Adaptation to the harsh climate of Qom is one of the general features of the traditional houses of this city. The Qom`s climate in the climatic classification of Iran is considered a semi-desert climate (part of desert and arid climate) due to its vicinity to the desert region in the center of the country. Its summers are hot and dry and its winters are more or less cold. The annual temperature difference is relatively high and the air is dry most of the time. As stated above, the amount of energy required to provide heating, cooling, and lighting can be reduced with the proper design of the building form. This study intends to investigate the effect of the building plan form on thermal comfort temperature in traditional houses in Qom to create more harmony between the houses and the climate. Therefore, these questions arise: what are the features of the appropriate plan form for this climate? And which form provides thermal comfort temperature in more hours without the need for cooling and heating equipment?

Background

Predicting indoor thermal comfort improves occupant satisfaction and reduces building energy consumption [4]. Thermal comfort also significantly affects the health of residents and work productivity and is determined by the body's thermal balance and thermal adaptations [9]. Since achieving adequate levels of comfort in living environments often requires the use of high-energy mechanical equipment, the concept of thermal comfort in buildings is related to energy consumption and the direct and indirect effects of energy consumption on the environment. Therefore, achieving adequate thermal comfort levels while minimizing energy consumption is a key goal in the building services industry [10].

The form of the building has a significant effect on its energy consumption. [11]. The building form manipulation and changes will deter the heat calculated for the cooling load. Therefore, it is significant to explore the optimum building form that improves energy efficiency [1]. The selection of the optimal form and geometry for the building is an important initial step in designing sustainable buildings [11]. The form of the building strongly affects the internal thermal comfort of any air-conditioned or naturally ventilated building. The most important parameters affecting thermal comfort are building shape, orientation, and window-to-wall ratio (WWR) of the building [12]. The building form manifests its indirect effect on the thermal performance of the building in several ways [13]. It plays a crucial role in the amount of cooling and heating required in the building [14]. In addition to building materials, the form of the building and other related factors strongly influence the internal thermal comfort and energy consumption for lighting and ventilation of buildings [15]. The form of a building is essential in absorbing solar energy. The orientation of the building, the angle of the walls, and the ceiling to the sun in different seasons, according to latitude and longitude are of paramount importance for the optimal use of solar energy. In winter, the building needs more solar energy and the angle of sunlight is more inclined. Thus, vertical surfaces are more efficient in receiving solar energy. Conversely, in summer due to the verticality of sunlight, the roof of the building receives more energy. By reducing the roof area and rising in the floors, vertical surfaces can be increased and the horizontal surfaces can be reduced to take full advantage of solar energy in summer and winter. The form of the building determines the creation of shaded areas in hot seasons [16]. Some of the most important parameters affecting the thermal comfort and lighting of the indoor environment include the form of the building, the orientation, and the ratio of the window to the building wall [17]. Therefore, the search for the most suitable building form based on optimal thermal performance has been the subject of many studies.

The research in Iran has investigated six geometric shapes square, rectangle, hexagon, octagon, hexagon, and triangle with the same area and height. The results of this study showed that the most suitable building form in the studied cities is a rectangular form with an east–west orientation [5]. In another study, Soheili-Fard et al. examined the interaction of form, orientation, and symmetry of the building with solar energy, by analyzing the Abbasian Historical House in Kashan, which confirmed that the thermal comfort in the Iranian house is due to climatic design [18]. Rafieian et al. in a study investigated the effect of the form and density of residential blocks on energy consumption. The research findings demonstrated that by changing the form, density, orientation, and height of residential buildings, the energy consumption of the building is reduced by about 45% [19]. Shafiee et al. analyzed the appropriate form of tall buildings to receive radiant energy and showed that the most suitable form is that receives the most amount of sunlight in winter and the least amount in summer. The maximum absorption of sunlight during the winter season by relying on passive systems is of utmost significance. Finally, to achieve a suitable solar form, suggestions such as increasing the level of the southern façade of the building form, shading the building itself in summer, avoiding convex and concave forms, and using pyramid or incomplete pyramid forms have been proposed [20]. Zarghami et al. explored the relationship between the shape of the plan of residential buildings and their energy consumption in hot and dry climates, which showed that among the shapes without shadows (square, rectangle, and trapezoid), a square plan is better than a rectangle. Among the shading shapes (L, U, H, and T), the L shape with a depth ratio of 2 to 3 is the best option in terms of energy efficiency. The results also illustrated that in comparison between shading and non-shading shapes, L-shape shows the highest energy efficiency [21].

Kazanasmaz et al. analyzed the thermal performance of the building based on its architectural form, which showed that about half (50%) of the differences in energy consumption in two buildings that have similar power supply systems are due to differences in their architectural form (Table 1). The results also showed that the ratio of surface to volume and orientation of the building directly affect the energy consumption of the building [22]. In a study to determine the amount of building consumption, Granadeiro et al. used a new tool to simulate energy consumption and analyzed the physical properties affecting the amount of energy consumption by modeling various building forms. The results of this study found that materials, windows area, and building form are the most important factors influencing its consumption [23]. Kantersa and Horvat investigated the relationship between the optimal use of solar energy and the geometric shape of buildings in southern Sweden. The results showed that the effect of building form on the solar energy absorption potential is significant and can make up to twice the difference [24].

Methodology

This is applied research and consists of 5 steps (Fig. 1). The method of this research is descriptive-analytical and has been done through case studies and simulation tests. Data collection has been done through literature review and field observations and studies. The sampling method is a non-randomly convenient judgmental sampling method and its statistical population is historic houses that were allowed to be visited in Qom. As the first step, 27 historical houses in Qom were selected for this study.

These houses belonged to the Qajar (1789–1925) and the first Pahlavi periods (1925–1941) and their locations are shown in Fig. 2. The number of houses in this study was limited due to some restrictions such as partial destruction of the house, abandoned houses, and lack of permission from private or government owners.

In the first step, the physical data from these houses were collected and categorized in Excel software. In the second and third steps, Ecotect and EnergyPlus software was used for modeling and simulation. EnergyPlus is one of the most prominent software for simulation and analysis of energy in buildings, which is fully validated using the analytical and comparative methods specified in the ASHRAE 140-17 standard [25]. This standard demonstrates the accuracy of simulation results. Validation results show that EnergyPlus outcomes are accurate and reliable. The fourth step has two parts: The first part is the results of the plan form analysis and the second part is the results obtained from EnergyPlus. These results were converted into evaluable charts by Excel software and categorized. It is noted that climate analysis in this study has been extracted by Climate Consultant software.

Table 1 Summary of research background

No	Researcher(s)	Location	Year	Independent variable	Conclusion
1	Akbari and Rashid Kalvir	Iran (Tabriz, Yazd, Bandar Abbas)	2018	Geometric form	The most suitable building form in the studied cities is a rectangular form with an east–west direction
2	Zarghami et al.	Iran (Semnan)	2016	Plan form (Rectangular and non-rectangular)	The L-shaped plan shows the highest energy efficiency
3	Soheili Fard et al.	Iran (Kashan)	2014	Direction, form, symmetry	Iranian architecture manages the amount of energy entering the building in proportion to the function of different spaces throughout the year
4	Kazanasmaz et al.	Turkey (Izmir)	2014	Building form	Form-related factors that directly affect energy consumption are the surface-to-volume ratio and the orientation of the building
5	Shafiee et al.	Iran (Tehran)	2014	Tall building form	The appropriate form of a tall building in terms of receiving solar radiation is the form that has the highest amount of radiation received in winter and the lowest in summer
6	Granadeiro et al.	Portugal	2013	Physical characteristics of the building	Materials, windows area, and building form are the most important factors affecting its consumption
7	Kantersa and Horvat	Sweden	2012	Geometric form of the building	The form of the building can double the potential for solar energy absorption
8	Rafiyan et al.	Iran (Hashtgerd)	2011	Form, density, orientation, height of the building	By changing the form, density, orientation, and height of residential buildings, the energy consumption of the building can be reduced by about 45%

Description of Qom`s arid climate

The city of Qom is located in the west of the central desert of Iran. Geographical features such as the salt desert and Howz-e Soltan Salt Lake, long hours of direct sunlight and high evaporation, lack of significant altitudes in the region, and east and west winds have caused climate instability. Therefore, Qom`s climate is hot and dry in summer and cold and dry in winter. Figure 3 shows the monthly and annual air temperature information of Qom city. The maximum and minimum recorded temperatures are + 44 and − 6 °C. Figure 4 shows the hourly air temperature in Qom in five temperature ranges according to the climate information extracted from the Climate Consultant software and the thermal comfort range calculated according to the ASHRAE standard 55 [26] is 21–27 °C.

Introduction of the case studies

According to the purpose of the study, 27 of Qom`s traditional houses were selected. 20 of these houses belong to the Qajar period and 7 belong to the first Pahlavi period. Their plan's physical data were collected and completed through the available documents and field observations of the authors, and are presented in Table 2.

Analyzing the plan forms of case studies

After data collecting and determining the dimensions, the plans of the houses were drawn and the site area and the closed space were calculated. Then, BCR[1] was calculated for each house, and this information can have significant results (Table 2). According to the form of the plans, the houses were classified into 4 types: O form, U form, L form and I form. To prepare the data for the modeling step, the average site areas, closed space areas, and height were calculated as shown in Table 3.

Modeling and simulation

Building energy simulation software is used to calculate and analyze building energy consumption over a period of time and to estimate the peak thermal loads of heating and cooling systems. Simulation software has developed rapidly in recent years. Thus, simulation can help reduce the energy consumption of the building (before construction) by modeling different strategies. There is no other way to achieve energy-saving techniques in the design phase These architectural techniques can determine the optimal form of the building, orientation, proportions of openings, window shades, natural ventilation, and

[1] Building Coverage Ratio.

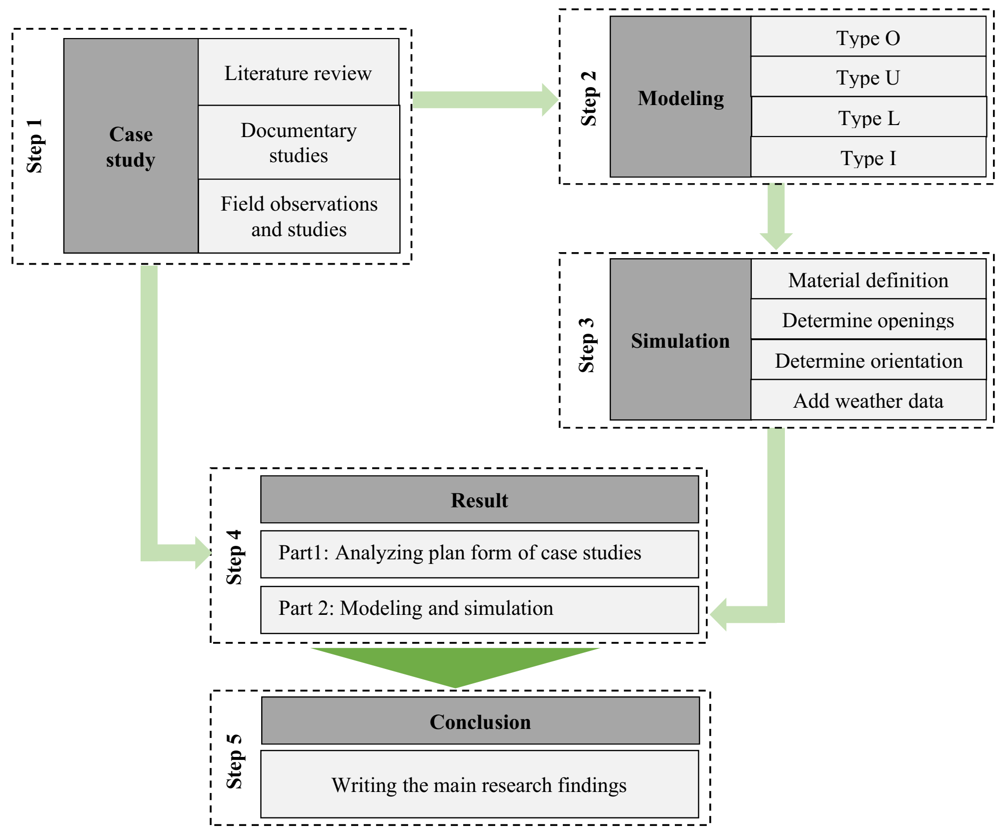


Fig. 1 Research process

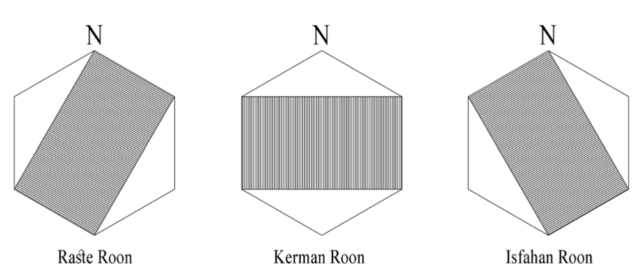
so on. There is various energy simulation software with different capabilities and features, among which EnergyPlus is one of the most popular and effective energy simulation programs that simulates and analyzes many mechanical, environmental, structural, and architectural characteristics.

Modeling in this study was applied in Ecotect software based on the average dimensions from case studies, which are shown in Table 3. Then, the average areas were drawn and modeled in four main types: four-sided (O form), three-sided (U form), two-sided (L form), two-part, and one-sided (I form), and a total of twelve plan forms were derived. These forms are illustrated in Table 4 and Fig. 5. Also, these models were considered separately and without neighborhood proximity.

(Models marked with * have been added for comprehensive analysis.)

As the completion of the modeling, their data were transferred to Energy Plus software for analysis. The ratio of openings on each side was determined based on the case buildings (Fig. 6). The material of the window frames is wooden and their thickness is 10 cm. Their glass is single glazed and its thickness is 6 mm. Details of wall materials and roofing were defined according to the case studies given in Figs. 7 and 8. The floor material is defined as 20 cm brick, which does not transfer heat because it is adjacent to the soil. The orientation of the models was considered in the northeast-southwest (Raste Roon[2] [27]) direction, which is the predominant orientation of buildings in hot and dry climates.

[2] There are three main orientations in Iran's vernacular architecture called "Roon":
(1) Raste (NE–SW) used for example in cities of Yazd, Tehran and Tabriz.
(2) Isfahan (NW–SE) used for example in cities of Isfahan and Shiraz.
(3) Kerman (E–W) used for example in cities of Kerman and Hamedan.



These orientations are used based on climatic specifications such as prevailing wind direction and sun path. Traditional masons guarantee a level of comfort for the dwellers in different cities by following the correct orientation.

Fig. 2 Location of case studies in Qom

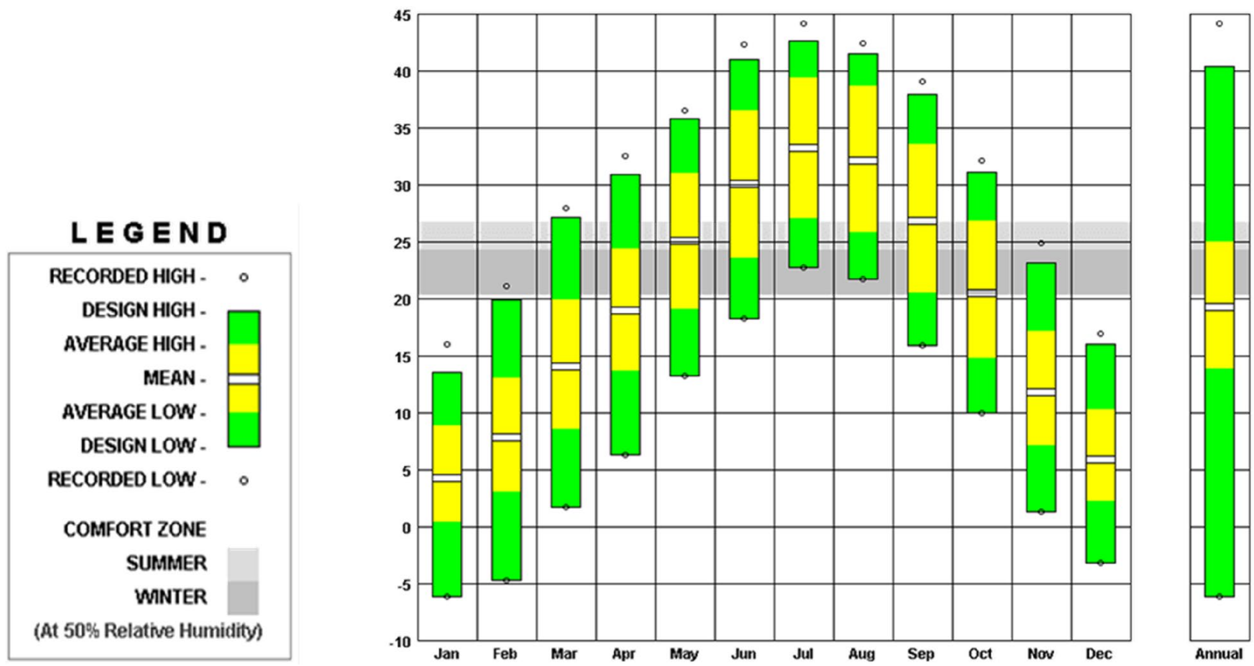


Fig. 3 Monthly and annual temperature information of Qom city,extracted by Climate Consultant software

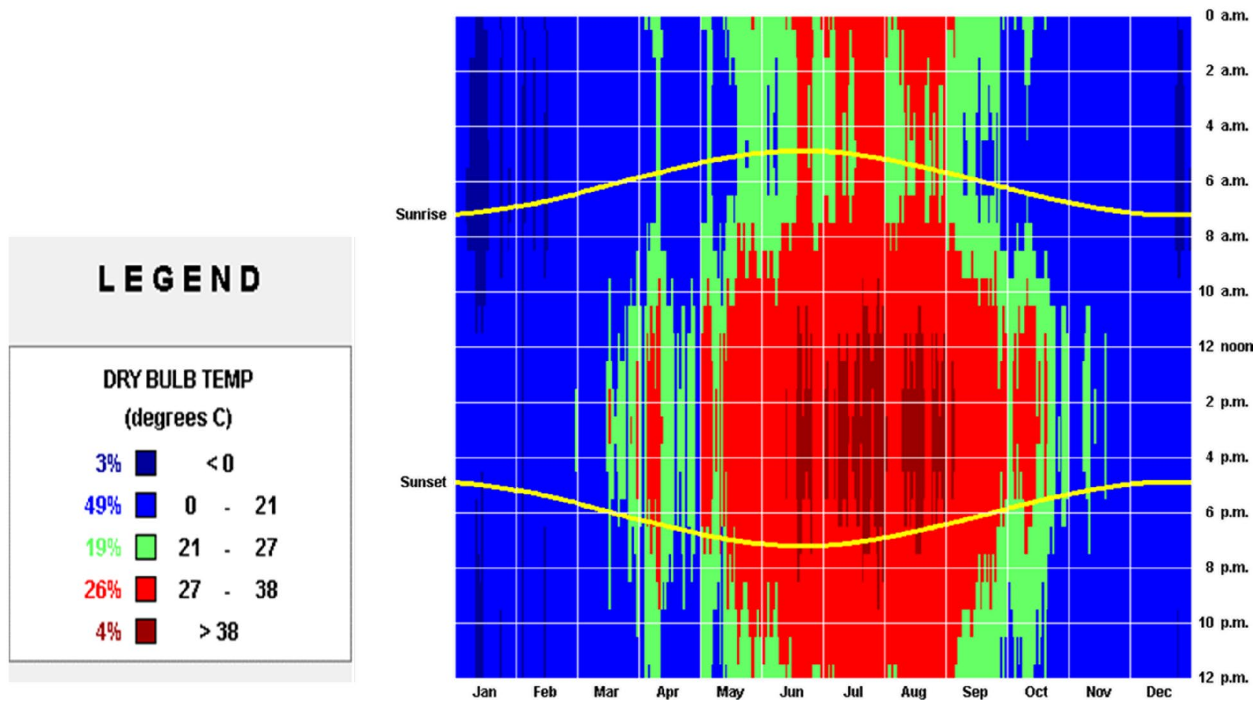


Fig. 4 The hourly air temperature in Qom, extracted by Climate Consultant software

Table 2 Historical and physical information of traditional case studies

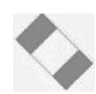
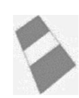
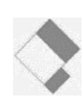
No	Name	Historical period	Stories	Height (on the ground)	Site Area	Closed Space Area (Ground level)	BCR %	Plan 
1	Sarkeshikzadeh House	First Pahlavi	2	5.48 m	254.4 m^2	135.8 m^2	53.4%	
2	Emam House	First Pahlavi	2	5.41 m	373 m^2	212 m^2	56.8%	
3	Jannati House	First Pahlavi	2	4.4 m	406.2 m^2	132.1 m^2	32.5%	
4	Movahedi House	First Pahlavi	2	Mar-81 m	395 m^2	188 m^2	47.6%	
5	Sadeghian House	First Pahlavi	2	3.32 m	188.3 m^2	95.4 m^2	50.7%	
6	Poustchi House	First Pahlavi	2	5.75 m	300 m^2	186 m^2	62%	
7	Tahmasbi House	First Pahlavi	2	6 m	365.4 m^2	210.2 m^2	57.5%	
8	Bagher Rohani House	Qajar	2	6.4 m	1355.5 m^2	510 m^2	37.6%	
9	Sadegh Rohani House	Qajar	2	5.55 m	431 m^2	223 m^2	51.7%	
10	Zaad House	Qajar	2	4 m	678 m^2	353 m^2	52.1%	
11	Dopirezan House	Qajar	2	4.1 m	231 m^2	143.4 m^2	62.1%	
12	Tavakoli House	Qajar	2	6.1 m	570 m^2	470 m^2	82.5%	
13	Khanombala House	Qajar	2	4.12 m	252 m^2	129.5 m^2	51.4%	

Table 2 (continued)

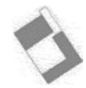
No	Name	Historical period	Stories	Height (on the ground)	Site Area	Closed Space Area (Ground level)	BCR %	Plan 
14	Darbeheshti House	Qajar	2	5.12 m	334.5 m^2	160.6 m^2	48%	
15	Hajikhan Zand House	Qajar	2	5.15 m	677 m^2	344.2 m^2	50.8%	
16	Hajalikhan Zand House	Qajar	2	5.5 m	938 m^2	490.7 m^2	52.3%	
17	Niazmand House	Qajar	2	6.12 m	603.4 m^2	175.6 m^2	29.1%	
18	Yazdanpanah House	Qajar	2	6.6 m	1043.3 m^2	407.8 m^2	39.1%	
19	Broujerdi House	Qajar	2	5.22 m	1200 m^2	425 m^2	35.4%	
20	Harampanahi House	Qajar	2	5.26 m	402.5 m^2	162.6 m^2	40.4%	
21	Golpaygani House	Qajar	2	4.2 m	308 m^2	160.8 m^2	52.2%	
22	Shakeri House	Qajar	2	5.27 m	661.7 m^2	265.2 m^2	40.1%	
23	Molavi House	Qajar	2	4.3 m	595 m^2	311 m^2	52.3%	
24	Feiz House	Qajar	2	5.5 m	243.7 m^2	117 m^2	48.1%	
25	Almasi House	Qajar	2	5.27 m	509 m^2	307 m^2	60.3%	
26	Salamat House	Qajar	2	5.87 m	834.5 m^2	299.6 m^2	35.9%	

Table 2 (continued)

No	Name	Historical period	Stories	Height (on the ground)	Site Area	Closed Space Area (Ground level)	BCR %	Plan 
27	Lajevardizadeh House	Qajar	2	5.8 m	695 m^2	247.2 m^2	35.6%	

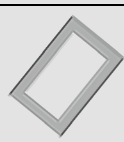
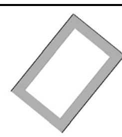
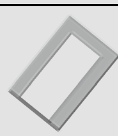
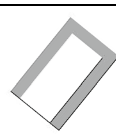
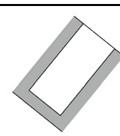
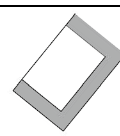
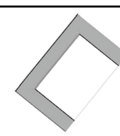
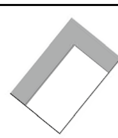
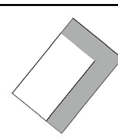
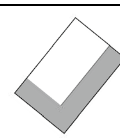
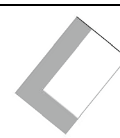
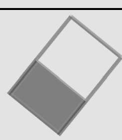
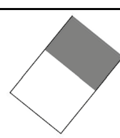
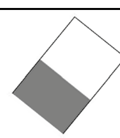
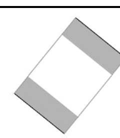
Table 3 Height, Site area, Closed space area, and BCR of case studies

Extremums	Height (on the ground)	Site area	Closed space area (Ground level)	Building coverage ratio (BCR)
Max	6.6 m	1355.5 m^2	510 m^2	82.5%
Min	3.3 m	188.3 m^2	88.7 m^2	29.1%
AVG	5 m	551 m^2	245 m^2	48.4%

Validation

To validate the simulations, the actual air temperature in one of the selected houses was measured by Datalogger to be compared with the information extracted from Energy Plus software. Among the research case studies, Mohammad Zand's house was selected so that it was possible to enter and measure the temperature. The data logger was placed in the north room of the house for 20 h a day in winter (Figs. 9, 10). According to the software

Table 4 Classification of traditional case studies for modelling

No.	Type		Model Name			
1		 Four-sided Plan (O)	 O_1			
2		 Three-sided Plan (U)	 U_1*	 U_2*	 U_3	 U_4
3		 Two-sided Plan (L)	 L_1	 L_2	 L_3*	 L_4
4		 One-sided or Two-parted Plan (I)	 I_1*	 I_2	 I_3	

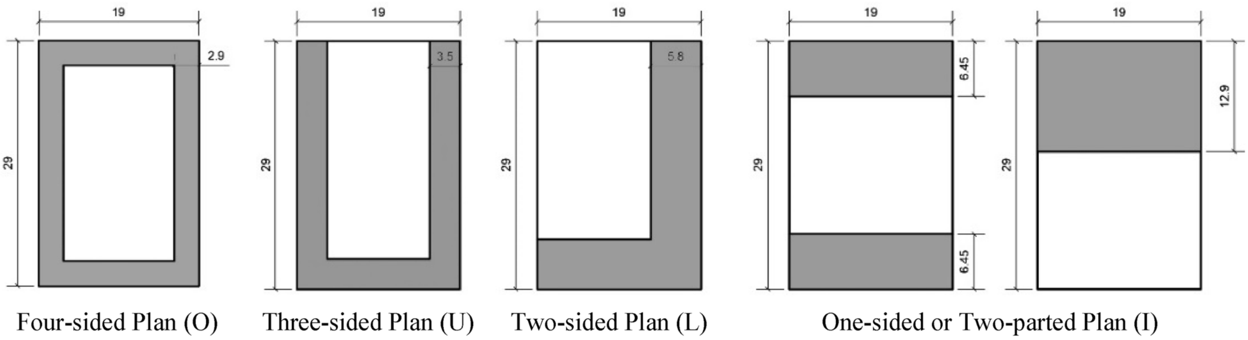


Fig. 5 Dimensions of plans in research models

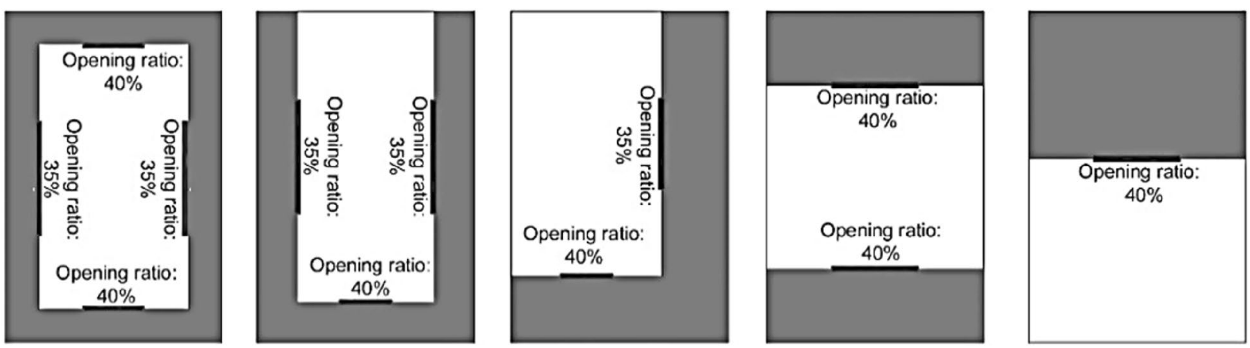


Fig. 6 Opening ratio of each wall in research models

models, this room did not have a cooling and heating system and all windows are closed.

Figure 11 shows a comparison of the actual measured temperature, the temperature output of the software, and their differences. As can be seen, these two graphs are close to each other and the output information of Energy Plus software can be used for the analysis of this research.

Results and Discussion

According to the research method, the results and discussion were divided into two parts:

Part 1: analyzing plan form of case studies.
Part 2: modeling and simulation.
This is followed by the limitations of the study and suggestions for future research.

Part1: Analyzing plan form of case studies

According to Table 2, the site area, the closed space area, and BCR were calculated for each plan. Figure 12 shows that in most cases (20 houses), BCR is between 40 and 60. As shown in Table 3, the average BCR is 48.4%, which is also in this range. BCR is one of the important factors in the design stage of buildings. In previous studies, its effect on the thermal comfort of the building has not been investigated, but due to its effect on the dimensions of the solar energy absorbing surfaces and shading of the building, it can affect the energy received by the building. Therefore, it also affects the thermal comfort temperature in the building.

Another result of this analysis is how the buildings were established on the site. In all these houses, the building is located on the edge of the site and the center is the yard.

This placement creates a protected space that is introverted and makes the temperature conditions suitable for the residents by creating a microclimate. This is one of the important and valuable principles of the architecture of hot and dry climate in Iran, that the closed space protects the open space, and instead, the open space reduces the harsh weather conditions by using water and plants. These results contain important information for construction in hot and dry climates that can be used by urban planners and contemporary architects.

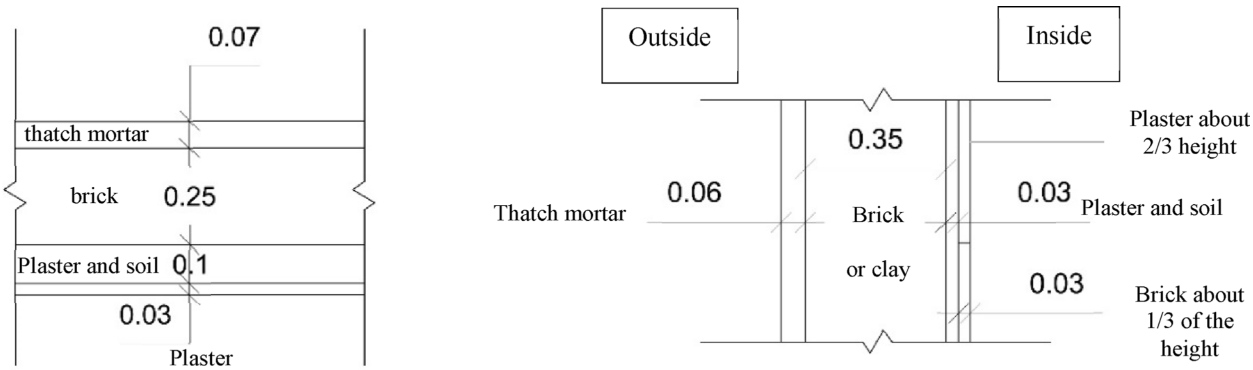


Fig. 7 Details of wall materials and roofing in research models

Fig. 8 Details of wall materials and roofing in case studies

Fig. 9 Validation in Mohammad Zand's house

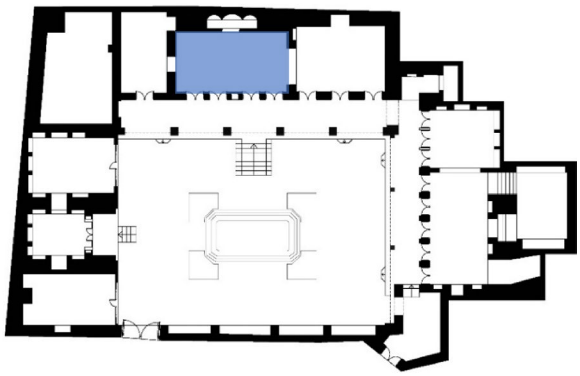


Fig. 10 Zand's house plan and north room location

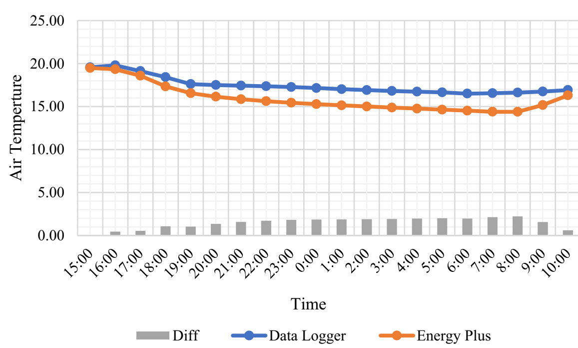


Fig. 11 Comparison of the actual measured temperature, the temperature output of the software, and their differences

Part 2: modeling and simulation

According to the main purpose of this article, which is to investigate the effect of plan form on thermal comfort temperature, the variables of orientation, materials, area, and height were assumed to be fixed in the Energy Plus software (exact measurements are specified in the research method section) and the average indoor air temperature of each model was calculated at any hour of the year by adding the annual weather data for Qom city to the research models in Energy Plus software. The numerical data output for each form was captured and sorted in Excel. According to the climate information extracted from the Climate Consultant software and ASHRAE standard 55, these data were classified into five temperature ranges: freezing, cold/cool, comfort, warm, and hot (Fig. 4). Subsequently, the number of annual hours for each temperature range was calculated for each form (A year is considered 8760 h). The temperature information of these ranges, maximum, minimum, and average annual internal temperature calculated in each form of the plan are given in Tables 5, 6, 7 and 8. In each table, the green column shows the comfort temperature range and the total annual hours that each form is in this range. In fact, during these hours, the temperature of the building is within the range of thermal comfort without the need for a cooling or heating system, and the building is in harmony with the climatic conditions.

The findings of the software analysis are compared in the following charts. Figure 13 shows the maximum, minimum, and average temperatures calculated in these twelve models. The highest maximum temperature and the lowest minimum temperature for the O_1 model are + 44.6 and + 1.1 °C, respectively. The lowest maximum temperature is recorded for model I_2, which is + 33.5 °C, and the highest minimum temperature is recorded for model I_1, which is equal to + 12.6 °C. Also, the highest temperature difference in model O_1 is 43.5 °C and the lowest temperature difference is in model I_1 which is 22.4 °C. The average temperature calculated in the research models is also shown in Fig. 13. The highest average annual temperature is recorded for the U_2 model,

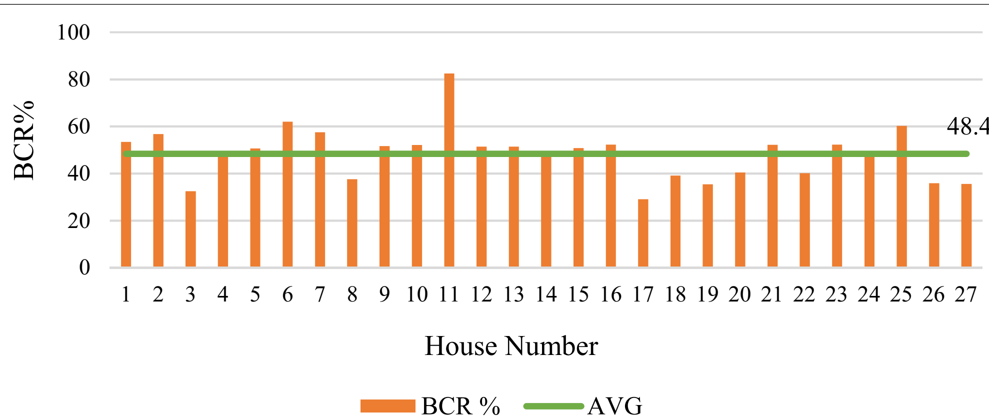
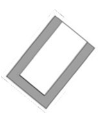


Fig. 12 Comparing the BCR of the case studies with each other and their average

Table 5 Temperature information and hours for each temperature range in the four-sided (O form)

N	Model type	Temperature °C	Freezing	Cold/Cool	Comfort	Warm	Hot	Max	Min	AVG
			< 0	0–21	21–27	27–38	38 <			
O_1		Hour(s) Per Year	0 H/Y	3834 H/Y	1458 H/Y	2946 H/Y	522 H/Y	+ 44.6 ºC	+ 1.1 ºC	+ 22.8 ºC
			0%	43.8%	16.6%	33.6%	6%			

Table 6 Temperature information and hours for each temperature range in the three-sided (U form)

N	Model type	Temperature °C	Freezing	Cold/Cool	Comfort	Warm	Hot	Max	Min	AVG
			< 0	0–21	21–27	27–38	38 <			
U_1		Hour(s) Per Year	0 H/Y	3120 H/Y	1457 H/Y	3663 H/Y	520 H/Y	+41.1 ºC	+8.5 ºC	+ 25.7 ºC
			0%	35.6%	16.6%	41.8%	5.9%			
U_2		Hour(s) Per Year	0 H/Y	2908 H/Y	1520 H/Y	3708 H/Y	624 H/Y	+ 41.5 ºC	+ 9 ºC	+ 26.2 ºC
			0%	33.2%	17.4%	42.3%	7.1%			
U_3		Hour(s) Per Year	0 H/Y	2894 H/Y	1815 H/Y	4021 H/Y	30 H/Y	+ 38.5 ºC	+ 9.9 ºC	+ 25.5 ºC
			0%	33%	20.7%	45.9%	0.3%			
U_4		Hour(s) Per Year	0 H/Y	3310 H/Y	1818 H/Y	3632 H/Y	0 H/Y	+ 37.2 ºC	+ 8.5 ºC	+ 24.1 ºC
			0%	37.8%	20.8%	41.5%	0%			

equal to + 26.2, and the lowest average temperature is recorded for the I_3 model, equal to + 22.6. The range of thermal comfort (21–27 °C) is highlighted in green in the chart. It is noteworthy that the average annual temperature of all forms falls in this range.

As shown in Tables 5, 6, 7 and 8, the annual temperature is divided into five temperature ranges according to Climate Consultant software. The temperature range of 21–27 is the range of thermal comfort and determines the total number of hours during the year when heating and cooling systems are not required for occupants. Figure 14 shows the hours and months when the internal temperature of each model is within the comfort range without the need for a cooling and heating system. Among the research models, model U_1 with 1457 h per year has the lowest, and model I_1 with 2609 h per year has the highest hours in this comfort temperature range.

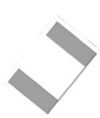
On the other hand, according to the information extracted from Climate consultant software, in Qom, the air temperature is in the comfort range (21–27 °C) for 19% of the total hours of a year (Fig. 4), which is shown in Fig. 14 with a horizontal line and is equal to 1665 h. The three models O_1, U_1, and U_2 are below this line and the other models are above this line. The distance of each column from this horizontal line indicates the amount of harmony between form and climatic conditions.

As reviewed in the background, the investigation of the building form and its relationship with thermal comfort and energy consumption has been the subject of several studies. In these studies, geometric forms such as square, rectangle, hexagon, and similar forms, have been investigated and analyzed, which have confirmed the effect of form on thermal comfort [5, 17–24]. These studies have proven that the thermal comfort temperature of

Table 7 Temperature information and hours for each temperature range in the two-sided (L form)

	Model type	Temperature °C	Freezing	Cold/Cool	Comfort	Warm	Hot	Max	Min	AVG
			< 0	0–21	21–27	27–38	38 <			
L_1		Hour(s) Per Year	0 H/Y	3300 H/Y	2023 H/Y	3437 H/Y	0 H/Y	+37.1 ºC	+10 ºC	+ 24 ºC
			0%	37.7%	23.1%	39.2%	0%			
L_2		Hour(s) Per Year	0 H/Y	3268 H/Y	1848 H/Y	3644 H/Y	0 H/Y	+ 37.5 ºC	+ 10.1 ºC	+ 24.4 ºC
			0%	37.3%	21.1%	41.6%	0%			
L_3		Hour(s) Per Year	0 H/Y	2899 H/Y	1938 H/Y	3923 H/Y	0 H/Y	+ 37.7 ºC	+ 11 ºC	+ 25.3 ºC
			0%	33.1%	22.1%	44.8%	0%			
L_4		Hour(s) Per Year	0 H/Y	3022 H/Y	2019 H/Y	3719 H/Y	0 H/Y	+ 37.5 ºC	+ 10.8 ºC	+ 24.8 ºC
			0%	34.5%	23%	42.5%	0%			

Table 8 Temperature information and hours for each temperature range in the one-sided and two-part (I form)

	Temperature °C	Model type	Freezing	Cold/Cool	Comfort	Warm	Hot	Max	Min	AVG
			< 0	0–21	21–27	27–38	38 <			
I_1		Hour(s) Per Year	0 H/Y	2581 H/Y	2609 H/Y	3570 H/Y	0 H/Y	+35 ºC	12.6 ºC	+ 24.8 ºC
			0%	29.5%	29.8%	40.8%	0%			
I_2		Hour(s) Per Year	0 H/Y	3498 H/Y	2287 H/Y	2975 H/Y	0 H/Y	+ 33.5 ºC	+ 10.6 ºC	+ 23 ºC
			0%	39.9%	26.1%	34%	0%			
I_3		Hour(s) Per Year	0 H/Y	3805 H/Y	1799 H/Y	3083 H/Y	73 H/Y	+40.2 ºC	+3.3 ºC	+ 22.6 ºC
			0%	43.4%	20.5%	35.2%	0.8%			

the building is dependent on the amount of solar energy received by the building and this is affected by features of the form such as surface-area-to-volume ratio of the building, the surface, the ratio of surface to volume, orientation, and materials. The results of this study also confirm the relationship between the received solar energy of surfaces and thermal comfort temperature. The I_1 model, which has less surface-area-to-volume ratio, has the lowest maximum temperature in summer and the highest minimum temperature in winter among the investigated models. In contrast, the O_1 model that has the highest surface-area-to-volume ratio has the highest maximum temperature in summer and the lowest minimum temperature in winter (Fig. 13).

The innovation of this article is the use of traditional architectural patterns. The forms that were analyzed in this article were obtained from the investigation of the plan of 27 traditional houses. The plans of these houses

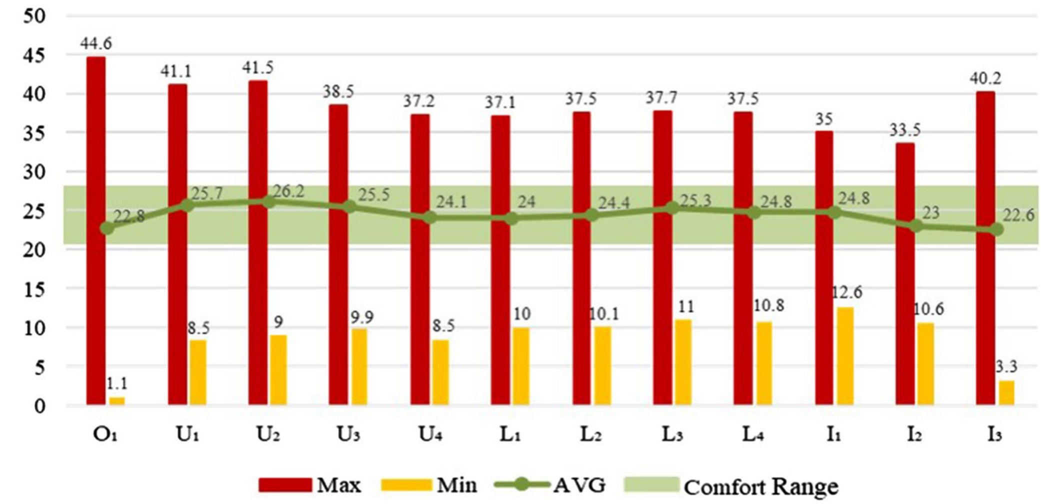


Fig. 13 Calculated annual internal temperatures of models

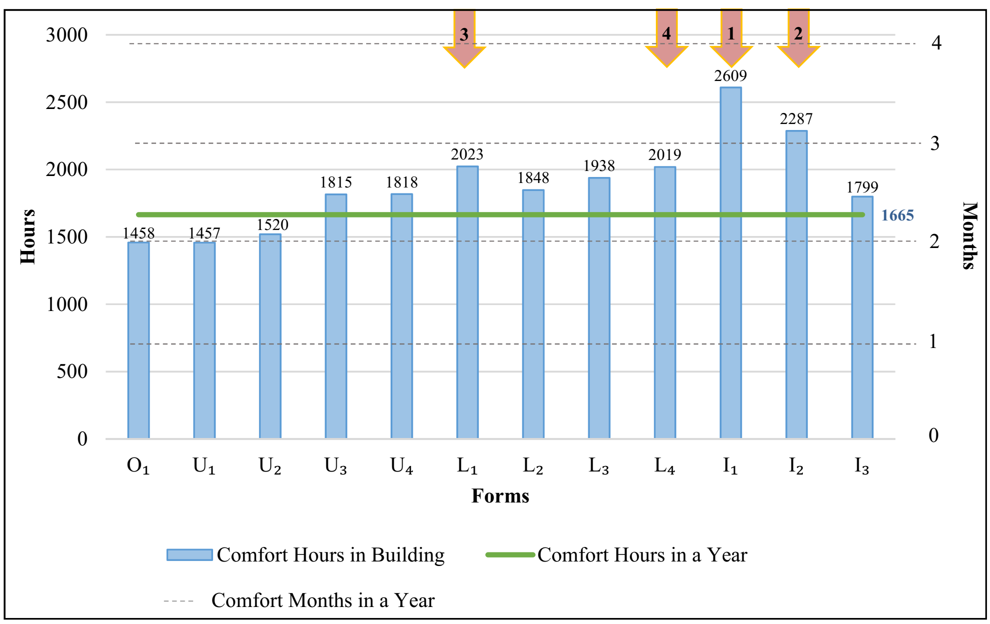


Fig. 14 Total hours of thermal comfort per year

were carefully studied classified into four main models. The dimensions of these forms, placement direction, window-to-wall ratio, and materials were completely based on valuable real models. In general, results of this study prove the harmony of architecture and climate in traditional Iranian architecture. Therefore, it is obvious that the architects of the past considered the climatic conditions in their architecture to create buildings in harmony with the climate, can be a guide and attractive for those interested in the heritage of traditional architecture and can be useful and practical for contemporary city planners and architects considering the energy crisis that is happening in the world.

Study limitations

The case studies selected for this study are houses belonging to the Qajar and Pahlavi periods. Most of these houses are vacant and part or all of them have been destroyed. So collecting data and drawing up their plan was a difficult task and took a long time. On the other hand, other cases whose data was not available due to destruction were not investigated.

Suggestions for further studies

In this paper the effect of various forms of plan on thermal comfort was investigated, however, there are many other important factors including floor area ratio, orientation, building height, the opening rate of each wall, use of semi-open spaces such as porch, use of water and plants. These other factors can be studied in future research to determine valuable principles of traditional Iranian architecture.

Conclusion

Traditional Iranian architecture provides valuable principles for achieving sustainable development. These principles are everlasting and can be used in different periods. Therefore, this research was conducted to investigate the effect of plan form on thermal comfort temperature in buildings and the main findings of this research are:

(1) Calculating and investigating BCR in case studies is one of the findings of this study. The average of this ratio in the investigated houses is 48.4%. This is an important point that can be used as the principles of climatic architecture in hot and dry regions by contemporary architects and urban planners.
(2) In all the case studies, the closed space is located on the edge of the site and the center of the site is yard. This finding is another principle of climatic architecture in hot and dry regions. This introversion creates a protected environment that makes the climatic conditions smoother for the occupants.
(3) The analysis of modeling and simulation results shows:

- The I_1 plan form (one-sided with northeast placement) is the best form which is 2609 h per year (out of 8760 h), and the internal temperature is within the thermal comfort range. This time is about 3.6 months and it is a considerable time.
- The plan forms I_2, L_1, and L_4 models are the second most efficient plan forms with comfortable internal temperature hours over 2000 h annually.
- Although forms O_1, U_1, and U_2 fall slightly below the 1665 h line, these forms are still considered economical.

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Author contributions
This article has been derived from NZ Ph.D. thesis entitled "Synergy of occupants' behavior and optimal energy consumption in contemporary housing in Qom". MSTTD was the supervisor of this Ph.D. thesis. SB as an expert in the history of Qom architecture has collaborated in the field collection and classification of information about case studies. All authors read and approved the final manuscript.

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Availability of data and materials
All the data generated or analyzed during this study are included in this published paper.

Declarations

Competing interests
The authors declare they have no competing interests.

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