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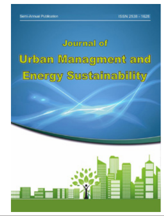

ORIGINAL RESEARCH PAPER

Optimizing Courtyard Design for Thermal Performance: A Study on Shadow and Sunlight Dynamics in Traditional Houses

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ABSTRACT

The rising interest in outdoor activities in modern society is influenced by evolving urban lifestyles and complex city infrastructures. Courtyards are central in this shift, impacting microclimates and managing shadows and sunlight for thermal comfort. This study explores how traditional houses, particularly courtyards, adapt to challenging weather, focusing on the relationship between their design elements and their impact on shadow and sunlight. The goal is to optimize courtyard design for better shadow and sunlight during both summer and winter. Data from 16 traditional courtyard houses in the hot, dry climate of Yazd were analyzed using ENVI-met software for the Shadow-Sunlit index. The findings highlight the significant effects of width-to-height and length-to-width ratios, and courtyard orientation on this index, accounting for 70.9%, 25.7%, and 3.4% respectively. The Arab-ha House emerged as an exemplar for optimizing shadow and sunlight dynamics. This research emphasizes the importance of courtyards in urban design and contributes to advancing sustainable architectural practices.

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INTRODUCTION

Over the last thirty years, the world population has doubled alongside improved living standards (Cao et al., 2016). Therefore, it has caused an increase in energy consumption in the building sector (Teshnehdel, Soflaei, & Shokouhian, 2020). The impact of climate change is particularly severe in extreme climates, such as hot or cold zones (Karimi et al., 2022). Given the swift deterioration of this scenario, urgent action is imperative (Amasyali & El-Gohary, 2018). Numerous studies have explored renewable and sustainable energy solutions across various sectors of the building industry. Passive building design emerges as a highly effective strategy in this context (Sun et al., 2018). This approach achieves passive efficiency by adjusting a building's exposure to environmental factors such as shadow, sunlit, wind, and through strategic considerations in building orientation, layout, shape, aspect ratio, as well as the choice of materials and systems (Liu et al., 2020). In these methods, it is important for all the main elements of the building to control solar heat, keeping the building cool in the summer and warm in the winter (Taleb, 2014). Traditional Iranian buildings have a history dating back several thousand years BC and have successfully responded to harsh climatic conditions by providing better microclimatic conditions compared to other houses (Rodríguez-Algeciras et al., 2018; Taleghani et al., 2015). Creating shade in the courtyard, as one of the main passive cooling solutions, is a common practice in traditional Iranian buildings and can also be applied in modern buildings (Shaeri et al., 2018). These traditional houses have demonstrated an excellent adaptation to the climate of their region throughout history, along with a harmonious integration with their surroundings (Soflaei et al., 2016).

Courtyards have gained widespread acceptance as a successful passive design strategy (Soflaei et al., 2017). However, improper design of courtyards can reduce the thermal efficiency of courtyard houses (Teshnehdel, Mirnezami, et al., 2020). A courtyard, centrally or corner positioned within a building and enclosed by walls, optimizes sunlight exposure for winter heating and reduces it for summer cooling (Abass et al., 2016). It also facilitates summer breeze circulation while blocking cold winter winds (Hao et al., 2019). In arid climates, courtyards help regulate humidity using vegetation and water features (Yang et al., 2020) and improve thermal comfort by maximizing natural lighting and offering varied thermal conditions (Zamani et al., 2018).

Many buildings featuring courtyards are situated in hot and dry climates. Currently, about one-sixth of the world's population lives in areas with a hot and arid climate. With the ongoing trajectory of climate change, it is anticipated that such climatic conditions will become increasingly prevalent (Coffel et al., 2019). Therefore, it is important to study the parameters that affect the reception of radiation energy, such as the orientation, geometry, dimensions, and proportions of the courtyard, particularly in hot and dry climate buildings (Kubota et al., 2017).

The geometric indices of a courtyard are among the most influential design variables for the microclimate within the courtyard. For instance, a narrow courtyard provides more shade during the summer, while a wide courtyard benefits from increased sunlight during the winter (Soflaei et al., 2017). The dimensions and location of the courtyard are generally determined by the latitude of the area, although the size of the building area also has some influence.

Numerous studies have confirmed the effectiveness of courtyard residences in maintaining thermal comfort for occupants during the summer in hot and arid climates (Teshnehdel et al., 2019). Courtyards have been shown to autonomously provide thermal comfort, significantly reducing or even eliminating the need for mechanical cooling systems, which leads to a considerable decrease in energy consumption (Fazlikhani et al., 2017; Foruzanmehr, 2012; Soflaei et al., 2017). However, there is ongoing debate and diverse perspectives regarding the optimal geometric attributes and aspect ratios of courtyards (Muhaisen & Gadi, 2006a, 2006b). Research predominantly focuses on courtyards' adaptability to summer climates, but there is an increasing recognition that courtyards are more effective in warmer climates than cooler ones.

For instance, Aldawoud (2008) simulation of energy consumption patterns in a single-story courtyard dwelling in both cold and hot climates indicated a 36% reduction in energy use during summer compared to winter with a 30% glazing surface area. Martinelli and Matzarakis (2017) observed similar improvements in thermal performance in courtyards across six different climate zones in Italy over a period of 30 years, with more pronounced effects in summer than in winter. Yet, the necessity of heating in hot-dry climates during temperate winters, a process typically more energy-intensive than cooling, suggests that overlooking the adaptability of courtyards in winter can lead to inefficiencies (Yaşa & Ok, 2014).

Furthering this discourse, Sabzevar et al. (2014) investig ated the impact of various yard proportions on solar radiation and thermal efficiency. Their subsequent study on a student dormitory in Yazd exemplified the most efficient approach to minimize heating and cooling energy consumption through strategic modifications in dimensions and orientation (Sabzevar et al., 2017).

Akbari and Niazi Motlagh Joonaghani (2022) analyzed thirty historical courtyard houses in Isfahan, identifying key geometric and natural features for modeling these parameters, enhancing understanding of Iranian courtyard architecture. Similarly, de la Flor et al. (2021) conducted a study in Seville's hot and arid climate, thoroughly examining the influence of courtyards on building cooling demands. Their extensive summer monitoring campaign revealed significant thermal differences of up to 12 °C between outdoor and courtyard temperatures, correlating with elevated outdoor temperatures. Their research showed thermal differences of up to 12 °C between outdoor and courtyard temperatures, resulting in an average cooling demand reduction of 7%. These findings emphasize the importance of the courtyard's geometric configuration, specifically the ratio of its envelope area to the floor area of the enclosed space (Nasrollahi et al., 2017).

Based on previous research, the shape and geometry of courtyards, including the ratio of their dimensions and orientation, can influence the amount of radiation received during summer and winter. This, in turn, affects the thermal comfort conditions and the energy consumption of courtyard houses. Therefore, selecting these parameters is crucial in the design of courtyards. This study aims to evaluate the efficiency of shadows and sunlight as passive design elements in traditional courtyard houses in Iran, with a specific focus on Yazd. The central research question investigates the dimensions, proportions, and ideal angles of traditional courtyards in Yazd to effectively control shade and sunlight. For this purpose, 16 traditional courtyard houses in Yazd were carefully selected to assess their compatibility with the local climate and analyze their geometric indices. Using the ENVI-met software (Bruse & Fleer, 1998; Simon et al., 2018) for numerical modeling, the Shadow index was calculated for the first day of June, and the Sunlit index for the first day of December. The data collected was then organized according to geometric patterns to identify the most effective courtyard configurations. The goal of this categorization is to develop a geometric framework that will serve as an essential reference for both mass builders and researchers in designing courtyards suitable for hot and dry climates.

Materials and Methods

This article evaluates and collects information on 16 traditional courtyard houses in Yazd, constructed during the Qajar period (1232 to 1282 AH). Information was gathered through library studies and from historical documents of the Yazd Cultural Heritage Organization, focusing on house forms, courtyard orientations, and dimension ratios (Haji-Qassemi, 2003).

To assess the effects of shadow and sunlight on the courtyard's horizontal and vertical surfaces, shadow and light indices were calculated for the floor and walls facing north, south, east, and west. These calculations, for the first days of June and December at 9, 12, and 15 hours, were performed using ENVI-met software simulation.

A linear multiple regression analysis in Excel software was utilized to predict shadow and sunlit indices. This analysis led to an equation for investigating correlations through numerical simulation, aiming for an optimal design pattern for a climatic courtyard (Figure 1).

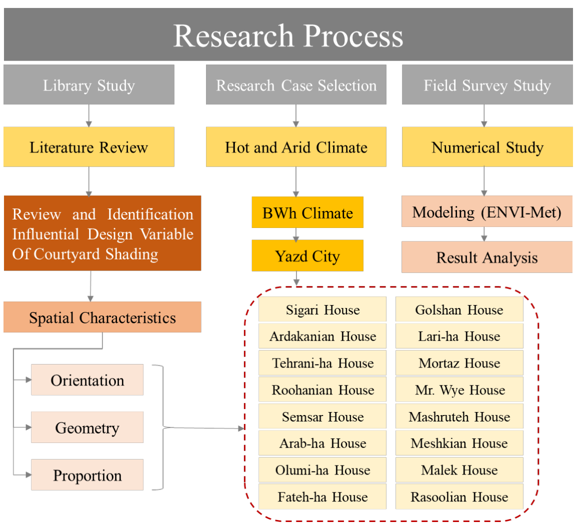


Figure 1: Research methodology workflow.

ENVI-met, a modern software program, uses fluid dynamics and thermodynamics principles to simulate micro-environmental climates' impact from various structural and urban variables (Mushtaha et al., 2021).

2.1. Analysis of climatic conditions of Yazd

Yazd, located in central Iran at 31.8 degrees latitude and 54.3 degrees longitude, experiences hot, dry summers and cold winters. The average annual temperature is 19.1°C, peaking in June at approximately 31.8°C and dropping to around 4.9°C in December. Temperature fluctuations range from -6 degrees at night to +43 degrees during the day (Izadpanahi et al., 2021).

2.2. Numerical modelling

An analysis was conducted on the effect of geometry, dimensions, proportions, and orientation on the courtyards' climatic performance. The physical characteristics of the case studies are in Table 1.

For clarity, the walls surrounding the courtyard are numbered 1 to 4, denoting north, east, south, and west directions. In houses with multiple courtyards, only the larger one was analyzed. Vegetation shade calculation within the courtyard was excluded from this study.

Reviewing Table 1 revealed that most traditional courtyard houses in Yazd city have a northeast-southwest orientation. In most cases, the courtyards' southern fronts (wall 3) are taller than the other sides, designed to maximize summer shade.

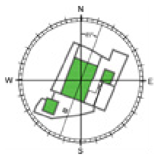
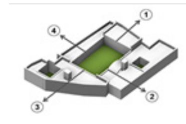
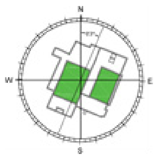
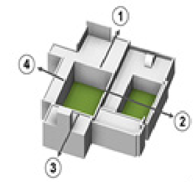
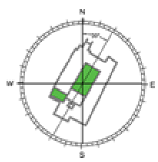
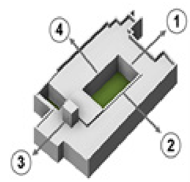
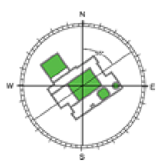
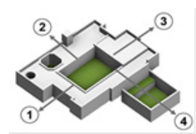
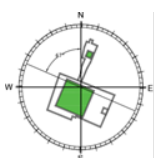
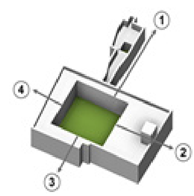
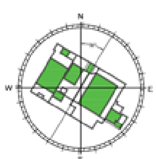
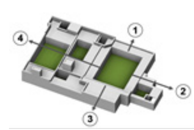
3. Results

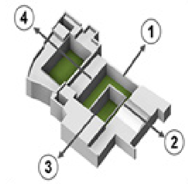
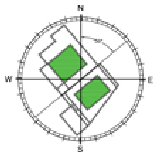
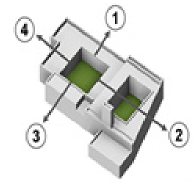
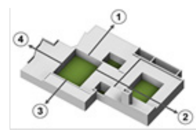
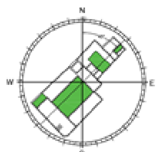
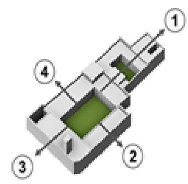
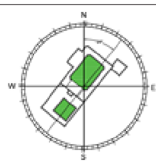
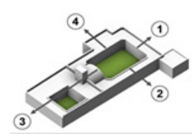
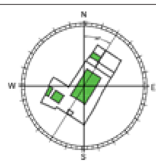
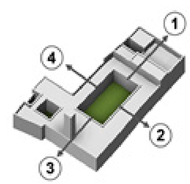
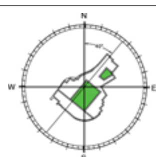
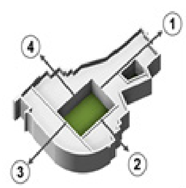
Table 2 presents results from numerical simulations using ENVI-met software, focusing on the percentage of shadow on the floor and walls of Yazd houses at 9, 12, and 15 hours on the first day of June. It includes calculations of horizontal (ground) and vertical (north, south, east, and west facades) surface areas facing the courtyard, along with corresponding shadow areas during the summer solstice. The Shadow Index (Ish) for each level was calculated by dividing the shadow area by the total wall area.

Table 2 shows that the entire surface of the walls is exposed to shadow at different times: north and east walls (wall 1 and 2) at 9 hours, east and south walls (wall 2 and 3) at 12 hours, and south and west walls (wall 3 and 4) at 15 hours. This indicates that the wall height significantly affects the shadow area on the courtyard floor.

Table 3 displays results from numerical simulations with ENVI-met software, focusing on the percentage of sunlight on the floor and walls of Yazd houses at 9, 12, and 15 hours on the first day of December. Similar to Table 2, it includes calculations of horizontal (ground) and vertical (north, south, east, and west) surface areas facing the courtyard, along with corresponding sunlit areas. The Sunlit Index (Isl) for each surface was calculated by dividing the sunlit area by the total wall area.

Table 1: Analysis of the studied traditional courtyard houses.

No.	Courtyard House	Orientation and Rotation angle from the north	Length (m)	Width (m)	Height(m)	Model
1	AkhavanSigari	 21◦	23.05	14.65	Wall 1: 6.9 Wall 2: 5.5 Wall 3: 6.6 Wall 4: 5.5	
2	Ardakanian	 23◦	21.7	15	7.9Wall 1: 7.9Wall 2: Wall 3: 9.5 Wall 4: 7.9	
3	Tehrani-ha	 30◦	16.9	9.4	Wall 1: 6.45 Wall 2: 6.45 Wall 3: 7.05 Wall 4: 6.45	
4	Roohanian	 55◦	16.25	12.15	Wall 1: 5.5 Wall 2: 5.5 Wall 3: 6.3 Wall 4: 5.5	
5	Semsar	 67◦	17.37	16.8	Wall 1: 6.6 Wall 2: 6.6 Wall 3: 6.6 Wall 4: 6.6	
6	Arab-ha	 31◦	24.15	17.1	Wall 1: 5.8 Wall 2: 5.8 Wall 3: 7.5 Wall 4: 5.8	

No.	Courtyard House	Orientation and Rotation angle from the north	Length (m)	Width (m)	Height(m)	Model
7	Olumi-ha	 43◦	19.7	14.8	Wall 1: 11.2 Wall 2: 11.2 Wall 3: 14 Wall 4: 11.2	
8	Fateh-ha	 50◦	17.45	14.7	Wall 1: 6.2 Wall 2: 6.2 Wall 3: 9 Wall 4: 6.2	
9	Golshan	 43◦	19.25	15	5Wall 1: 5.3 Wall 2: 5.35 Wall 3: 7.15 Wall 4: 5.35	
10	Lari-ha	 45◦	28	16.8	Wall 1: 6.05 Wall 2: 6.05 Wall 3: 8.6 Wall 4: 6.05	
11	Mortaz	 39◦	23.6	16	Wall 1: 7 Wall 2: 7 Wall 3: 8.3 Wall 4: 7	
12	Mr. Wye	 32◦	23.3	12.6	Wall 1: 6.7 Wall 2: 6.7 Wall 3: 6.7 Wall 4: 6.7	
13	Mashruteh	 40◦	14.7	10.42	Wall 1: 5.25 Wall 2: 5.25 Wall 3: 6.4 Wall 4: 5.25	

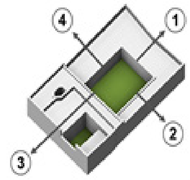
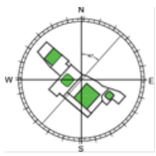
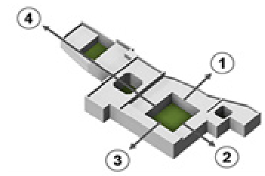
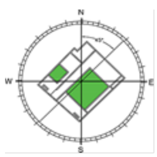
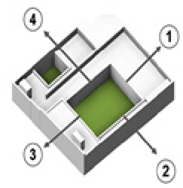
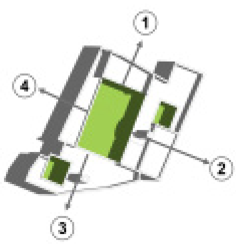
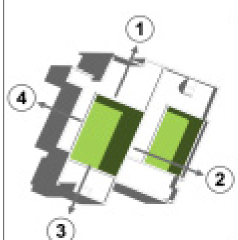
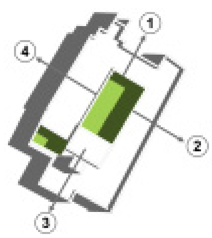
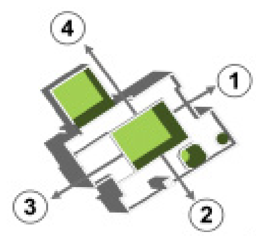
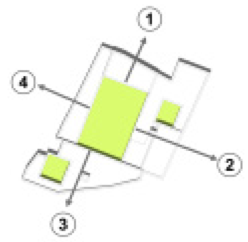
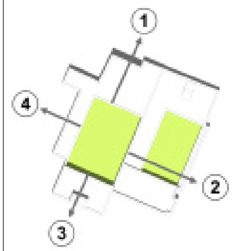
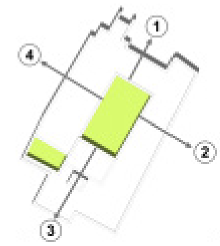
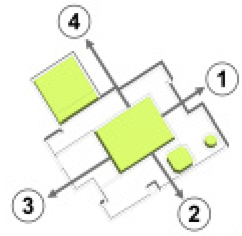
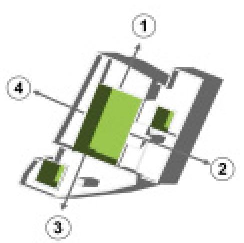
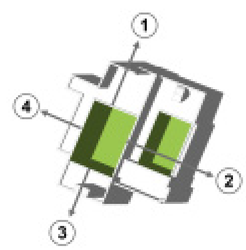
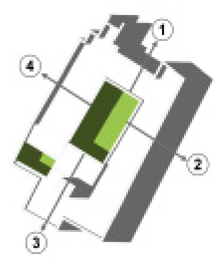
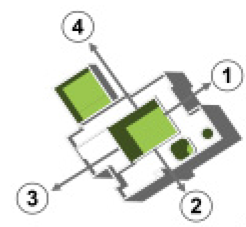
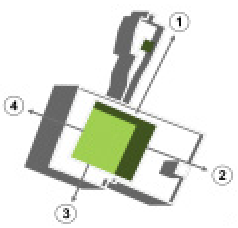
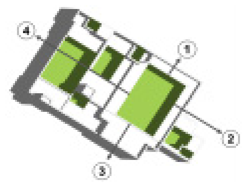
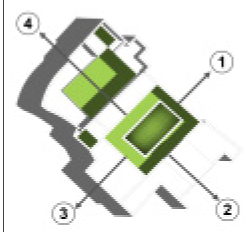
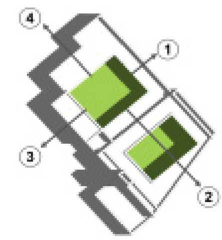
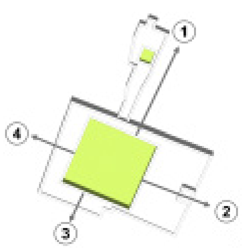
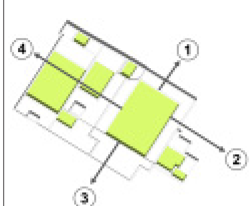
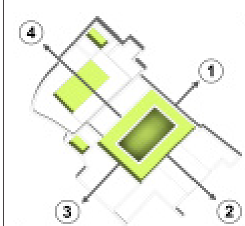
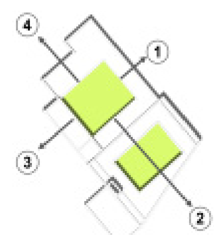
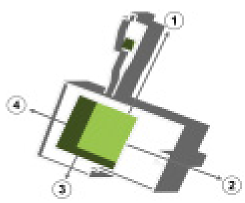
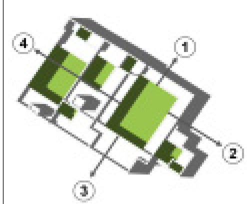
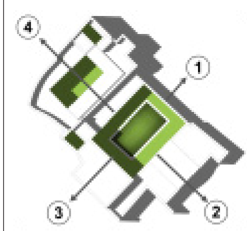
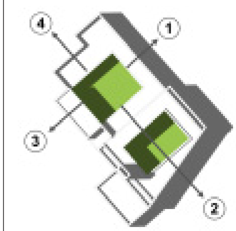
No.	Courtyard House	Orientation and Rotation angle from the north	Length (m)	Width (m)	Height(m)	Model
14	Meshkian	 32◦	18.95	14.85	Wall 1: 5.45 Wall 2: 5.45 Wall 3: 7.5 Wall 4: 5.45	
15	Malek-Al-Tojjar	 41◦	14.77	13	Wall 1: 5.85 Wall 2: 5.85 Wall 3: 7.05 Wall 4: 5.85	
16	Rasoolian	 45◦	20.28	15.81	Wall 1: 6.2 Wall 2: 6.2 Wall 3: 8.3 Wall 4: 6.2	

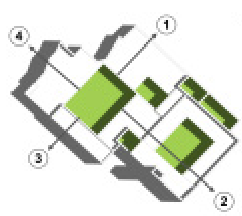
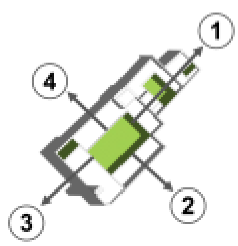
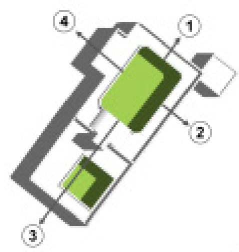
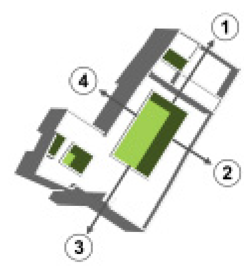
Table 2: Shadow index in traditional courtyard houses of Yazd in the summer solstice.

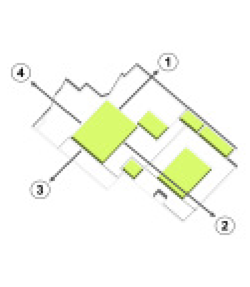
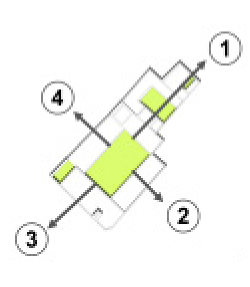
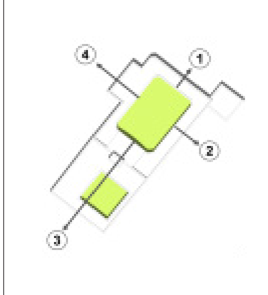
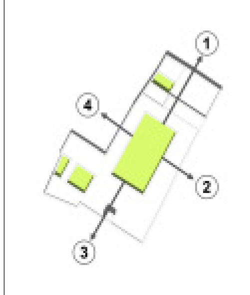
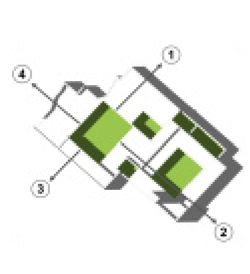
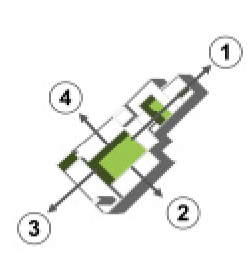
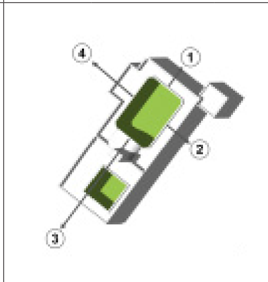
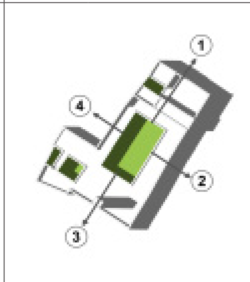
Date	AkhavanSigari			Ardakanian			Tehrani-ha			Roohanian		
22 June 9 A.M.												
	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shad-ow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)
Floor	337.7	122.7	36.3	325.5	151.3	46.5	158.9	90	56.6	197.4	77.6	39.3
Wall 1	101.1	101.1	100	118.5	118.5	100	60.6	60.6	100	66.8	66.8	100
Wall 2	133.4	133.4	100	171.4	171.4	100	109	109	100	89.4	89.4	100
Wall 3	96.7	11.8	12.2	142.5	23.6	16.6	66.3	14.9	22.5	76.5	7.2	9.5
Wall 4	127.9	6.3	4.9	171.4	9.45	5.5	109	8.1	7.4	89.4	9.9	11.1

Date	AkhavanSigari			Ardakanian			Tehrani-ha			Roohanian		
22 June 12 P.M.												
	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shad-ow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)
Floor	337.7	18	5.3	325.5	26.5	8.1	158.9	14.7	9.2	197.4	17.2	8.7
Wall 1	101.1	0.5	0.5	118.5	1.1	0.9	60.6	1.1	1.8	66.8	1.6	2.4
Wall 2	133.4	133.4	100	171.4	171.4	100	109	109	100	89.4	89.4	100
Wall 3	96.7	96.7	100	142.5	142.5	100	66.3	66.3	100	76.5	76.5	100
Wall 4	127.9	3.1	2.4	171.4	6.4	3.7	109	3.4	3.1	89.4	2	2.2
22 June 15 P.M.												
	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shad-ow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)
Floor	337.7	114.1	33.8	325.5	168.4	51.7	158.9	98	61.7	197.4	88.8	45
Wall 1	101.1	12.8	12.7	118.5	25.6	21.6	60.6	16.1	26.6	66.8	7.8	11.7
Wall 2	133.4	6.7	5	171.4	15	4.5	109	10.9	10	89.4	14.2	15.9
Wall 3	96.7	96.7	100	142.5	142.5	100	66.3	66.3	100	76.5	76.5	100
Wall 4	127.9	127.9	100	171.4	171.4	100	109	109	100	89.4	89.4	100

Date	Semsar			Arab-ha			Olumi-ha			Fateh-ha		
22 June 9 A.M.												
	Total Area (m2)	Shad-ow Area (m2)	Ish (%)	Total Area (m2)	Shad-ow Area (m2)	Ish (%)	Total Area (m2)	Shad-ow Area (m2)	Ish (%)	Total Area (m2)	Shad-ow Area (m2)	Ish (%)
Floor	292.6	109.2	37.3	413	129.6	31.4	290	90.3	31.1	256.5	101.4	39.4
Wall 1	110.6	110.6	100	99.2	99.2	100	121.9	121.9	100	91.1	91.1	100
Wall 2	114.5	114.5	100	140.1	140.1	100	191.1	191.1	100	108.2	108.2	100
Wall 3	111.5	16.3	14.6	128.2	11.9	9.3	162.7	20.5	12.6	132.3	10.3	7.8
Wall 4	114.8	6.9	6	140.1	6.8	4.8	184.3	16	8.7	108.2	11.8	10.9
22 June 12 P.M.												
	Total Area (m2)	Shad-ow Area (m2)	Ish (%)	Total Area (m2)	Shad-ow Area (m2)	Ish (%)	Total Area (m2)	Shad-ow Area (m2)	Ish (%)	Total Area (m2)	Shad-ow Area (m2)	Ish (%)
Floor	292.6	20.7	7.1	413	25.3	6.1	290	22.4	7.7	256.5	24.7	9.6
Wall 1	110.6	0.9	0.81	99.2	0.9	0.9	121.9	2.8	2.3	91.1	1.9	2.1
Wall 2	114.5	114.5	100	140.1	140.1	100	191.1	191.1	100	108.2	108.2	100
Wall 3	111.5	111.5	100	128.2	128.2	100	162.7	162.7	100	132.3	132.3	100
Wall 4	114.8	3.2	2.8	140.1	3.9	2.8	184.3	6.6	3.6	108.2	4.1	3.8

Date	Semsar			Arab-ha			Olumi-ha			Fateh-ha		
22 June 15 P.M.												
	Total Area (m2)	Shad-ow Area (m2)	Ish (%)	Total Area (m2)	Shad-ow Area (m2)	Ish (%)	Total Area (m2)	Shad-ow Area (m2)	Ish (%)	Total Area (m2)	Shad-ow Area (m2)	Ish (%)
Floor	292.6	118.7	40.6	413	150.3	36.4	290	117	40.3	256.5	129.9	50.6
Wall 1	110.6	17.7	16	99.2	13	13.1	121.9	22.1	18.1	91.1	11.1	12.2
Wall 2	114.5	7.7	6.7	140.1	12.1	8.6	191.1	32.4	16.9	108.2	24.8	22.9
Wall 3	111.5	111.5	100	128.2	128.2	100	162.7	162.7	100	132.3	132.3	100
Wall 4	114.8	114.8	100	140.1	140.1	100	184.3	184.3	100	108.2	108.2	100

Date	Golshan			Lari-ha			Mortaz			Mr. Wye		
22 June 9 A.M.												
	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)
Floor	288.7	96.7	33.5	470.4	145.3	30.9	374.2	144.8	38.7	294	131.7	44.8
Wall 1	80.2	80.2	100	101.6	101.6	100	107	106.4	99.4	83.6	83.6	100
Wall 2	103	103	100	169.4	169.4	100	160	160	100	155.8	155.8	100
Wall 3	137.6	8.7	6.3	144.5	10.8	7.5	132.8	15.95	12	85.5	15.9	18.6
Wall 4	103	7.8	7.6	169.4	10.3	6.1	159.5	9.5	5.95	156.2	9.4	6

Date	Golshan			Lari-ha			Mortaz			Mr. Wye		
22 June 12 P.M.												
	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)
Floor	288.7	21.5	7.4	470.4	31.5	6.7	374.2	28.9	7.7	294	20.3	6.9
Wall 1	80.2	1.2	1.5	101.6	1.6	1.6	107	0	0	83.6	1.3	1.5
Wall 2	103	103	100	169.4	169.4	100	160	157.1	98.2	155.8	155.8	100
Wall 3	137.6	137.6	100	144.5	144.5	100	132.8	132.8	100	85.5	85.5	100
Wall 4	103	3	2.9	169.4	3.9	2.3	159.5	8.3	5.2	156.2	3.1	2
22 June 15 P.M.												
	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)
Floor	288.7	116.8	40.4	470.4	176.4	37.5	374.2	167.4	44.7	294	142.4	48.4
Wall 1	80.2	9.4	11.7	101.6	11.6	11.4	107	16.6	15.5	83.6	17	20.3
Wall 2	103	14.4	14	169.4	20.8	12.3	160	16.8	10.5	155.8	10.5	6.7
Wall 3	137.6	137.6	100	144.5	144.5	100	132.8	132.7	99.9	85.5	85.5	100
Wall 4	103	103	100	169.4	169.4	100	159.5	159.5	100	156.2	156.2	100

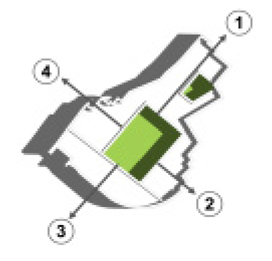
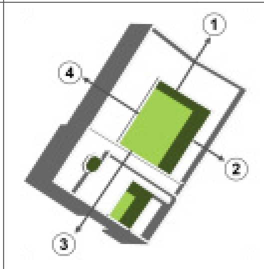
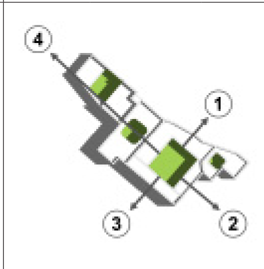
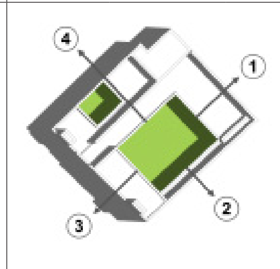
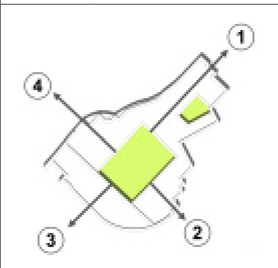
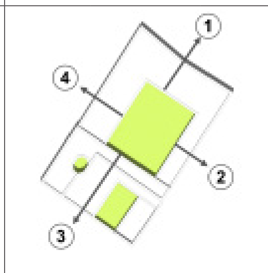
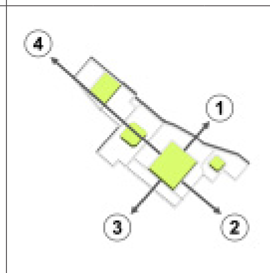
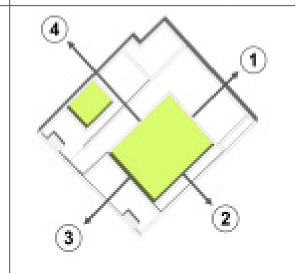
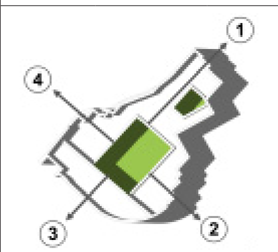
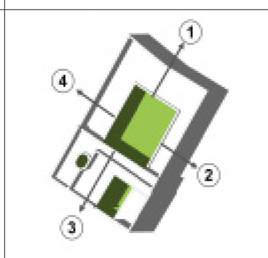
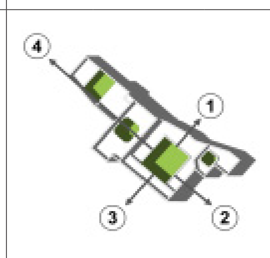
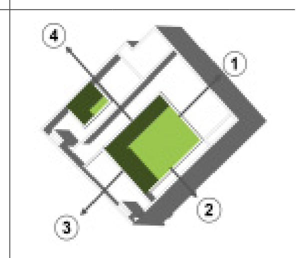
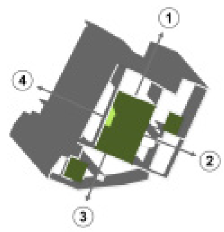
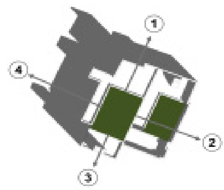
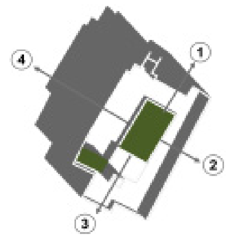
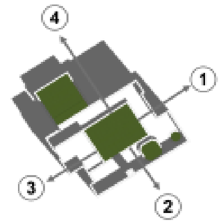
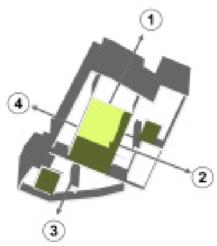
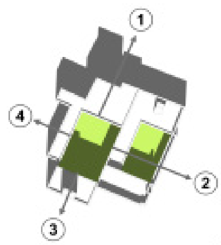
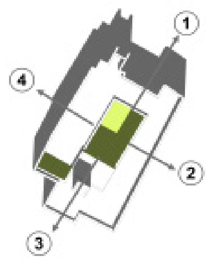
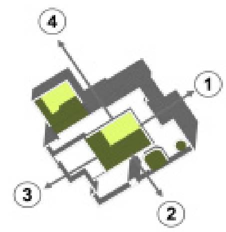
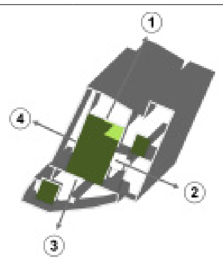
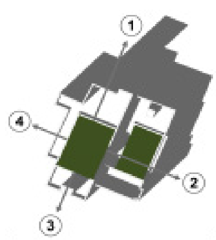
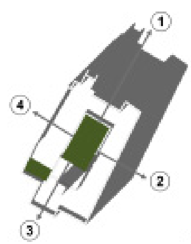
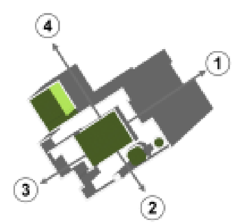
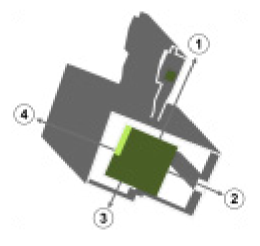
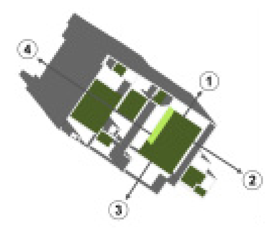
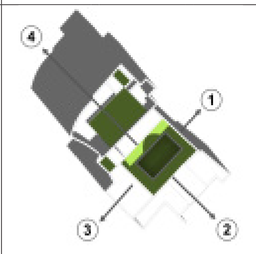
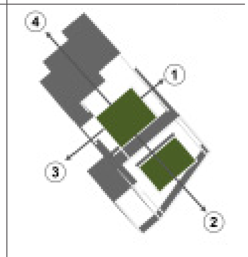
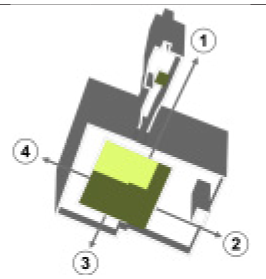
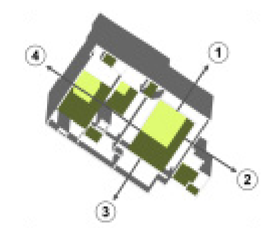
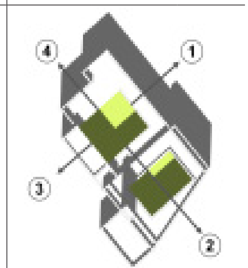
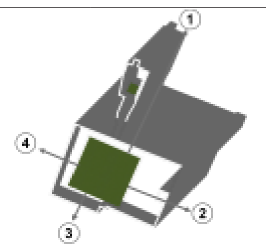
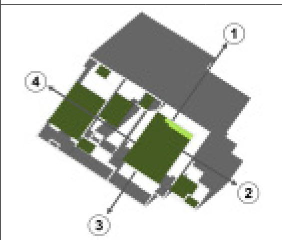
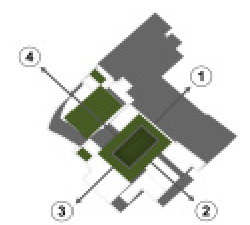
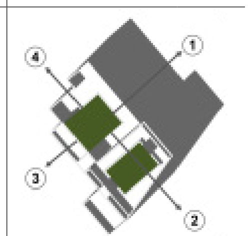
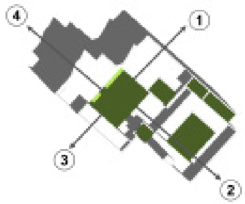
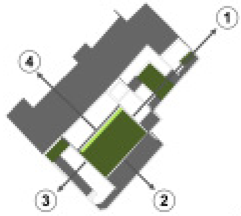
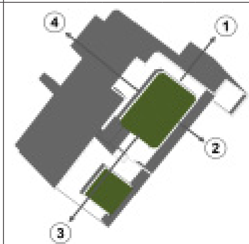
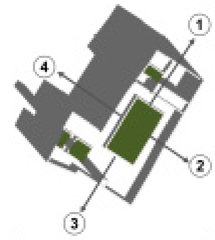
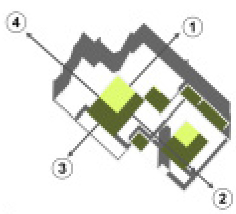
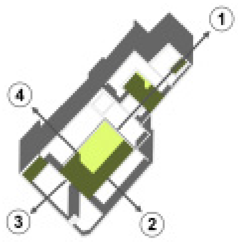
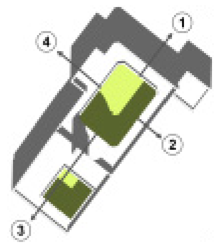
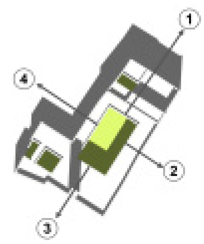
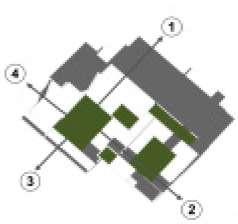
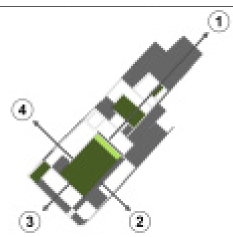
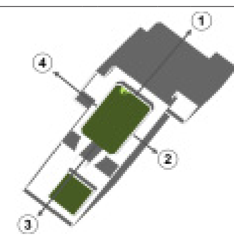
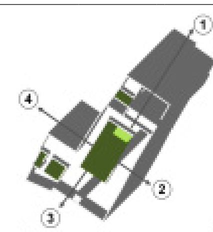
Date	Mashruteh			Meshkian			Malek-Al-Tojjar			Rasoolian		
22 June												
	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)
Floor	153.7	68	44.2	281.4	97.4	34.6	192.1	84.7	44.1	320.9	116.5	36.3
Wall 1	54.8	54.8	100	80.9	80.9	100	76.05	76.05	100	98	98	100
Wall 2	76.9	76.9	100	103.3	103.3	100	87.1	87.1	100	125.7	125.7	100
Wall 3	66.7	8.8	13.2	111.4	10.4	9.3	91.65	10.7	11.7	131.2	11.3	8.6
Wall 4	77.8	7	9	103.3	6.2	6	85.8	8.9	10.4	125.6	10.8	8.6
22 June 12 P.M.												
	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)
Floor	54.8	1.1	2	80.9	0.9	1.1	76.05	1.4	1.8	98	1.7	1.7
Wall 1	76.9	76.9	100	103.3	103.3	100	87.1	87.1	100	125.7	125.7	100
Wall 2	66.7	66.7	100	111.4	111.4	100	91.65	91.65	100	131.2	131.2	100
Wall 3	77.8	2.6	3.3	103.3	3.6	3.5	85.8	3	3.5	125.6	3.9	3.1
Wall 4	153.7	14.2	9.2	281.4	21	7.5	192.1	18	9.4	320.9	26.4	8.2
22 June 15 P.M.												
	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)	Total Area (m2)	Shadow Area (m2)	Ish (%)
Floor	153.7	77.6	50.5	281.4	115.9	41.2	192.1	95.8	49.8	320.9	141	43.9
Wall 1	54.8	9.5	17.3	80.9	11.3	14	76.05	11.5	15.1	98	12.2	12.4
Wall 2	76.9	11	14.3	103.3	12.15	11.8	87.1	14.3	16.4	125.7	21.5	17.1
Wall 3	66.7	66.7	100	111.4	111.4	100	91.65	91.65	100	131.2	131.2	100
Wall 4	77.8	77.8	100	103.3	103.3	100	85.8	85.8	100	125.6	125.6	100

Table 3: Sunlit index in traditional courtyard houses in Yazd on the first day of December

Date	AkhavanSigari			Ardakanian			Tehrani-ha			Roohanian		
22 Dec. 9 A.M.												
	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)
Floor	337.7	12.9	3.8	325.5	0	0	158.9	0	0	197.4	0	0
Wall 1	101.1	60.7	60	118.5	48.55	41	60.6	18.2	30	66.8	0	0
Wall 2	133.4	0	0	171.4	0	0	109	0	0	89.4	0	0
Wall 3	96.7	0	0	142.5	0	0	66.3	0	0	76.5	39	50.8
Wall 4	127.9	93.2	72.9	171.4	107.1	62.5	109	57.45	52.7	89.4	68.7	76.8
22 Dec. 12 P.M.												
	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)
Floor	337.7	165.1	48.9	325.5	92.7	28.5	158.9	40	25.2	197.4	62.9	31.9
Wall 1	101.1	94.05	93	118.5	102.8	86.7	60.6	46.8	77.2	66.8	49.8	74.55
Wall 2	133.4	0	0	171.4	0	0	109	0	0	89.4	0	0
Wall 3	96.7	0	0	142.5	0	0	66.3	0	0	76.5	0	0
Wall 4	127.9	98.7	77.2	171.4	101.8	59.4	109	77.2	70.8	89.4	77.1	86.2
22 Dec. 15 P.M.												
	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)
Floor	337.7	26.9	8	325.5	0	0	158.9	0	0	197.4	0	0
Wall 1	101.1	82	81.1	118.5	76.2	64.3	60.6	38.35	63.3	66.8	51.9	77.7
Wall 2	133.4	60.1	45	171.4	22.6	13.2	109	18.6	17.1	89.4	0	0
Wall 3	96.7	0	0	142.5	0	0	66.3	0	0	76.5	0	0
Wall 4	127.9	0	0	171.4	0	0	109	0	0	89.4	32.6	36.5

Date	Semsar			Arab-ha			Olumi-ha			Fateh-ha		
22 Dec. 9 A.M												
	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)
Floor	292.6	18.6	6.35	413	50.9	12.3	290	42.3	14.6	256.5	0	0
Wall 1	110.6	55.6	50.3	99.2	58	58.5	121.9	46.3	38	91.1	0	0
Wall 2	114.5	0	0	140.1	0	0	191.1	0	0	108.2	0	0
Wall 3	111.5	0	0	128.2	0	0	162.7	0	0	132.3	42.2	31.9
Wall 4	114.8	80.05	69.7	140.1	119.4	85.2	184.3	94.55	51.3	108.2	98.8	91.3
22 Dec. 12 P.M.												
	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)
Floor	292.6	107.2	36.6	413	191.3	46.3	290	118	40.7	256.5	69.7	27.2
Wall 1	110.6	103.2	93.3	99.2	87.6	88.3	121.9	86	70.5	91.1	70.7	77.6
Wall 2	114.5	0	0	140.1	0	0	191.1	0	0	108.2	0	0
Wall 3	111.5	0	0	128.2	0	0	162.7	0	0	132.3	0	0
Wall 4	114.8	82.2	71.6	140.1	106	75.7	184.3	108.1	58.6	108.2	72.2	66.7
22 Dec. 15 P.M.												
	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)
Floor	292.6	0	0	413	29	7	290	0	0	256.5	0	0
Wall 1	110.6	78.4	70.9	99.2	86.6	87.3	121.9	55.8	45.8	91.1	44.45	48.8
Wall 2	114.5	41.6	36.3	140.1	62.7	44.7	191.1	25.1	13.1	108.2	0	0
Wall 3	111.5	0	0	128.2	0	0	162.7	0	0	132.3	0	0
Wall 4	114.8	0	0	140.1	0	0	184.3	0	0	108.2	13.8	12.75

Date	Golshan			Lari-ha			Mortaz			Mr. Wye		
22 Dec. 9 A.M.												
	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sun-lit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)
Floor	288.7	19.3	6.7	470.4	35.5	7.5	374.2	0	0	294	0	0
Wall 1	80.25	43.7	54.4	101.6	54.9	54	107	46.8	43.7	83.6	31.8	38
Wall 2	103	0	0	169.4	0	0	160	0	0	155.8	0	0
Wall 3	137.6	0	0	144.5	0	0	132.8	0	0	85.5	0	0
Wall 4	103	89.8	87.2	169.4	164.6	97.2	159.5	104	65.2	156.2	110	70.4
22 Dec. 12 P.M.												
	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sun-lit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)
Floor	288.7	113.4	39.3	470.4	200.5	42.6	374.2	134.2	35.9	294	117.6	40
Wall 1	80.25	66.8	83.2	101.6	83.8	82.5	107	88.4	82.6	83.6	68.1	81.45
Wall 2	103	0	0	169.4	0	0	160	0.25	0.15	155.8	0	0
Wall 3	137.6	0	0	144.5	0	0	132.8	0	0	85.5	0	0
Wall 4	103	76.5	74.3	169.4	131.5	77.6	159.5	115.9	72.7	156.2	123.2	78.9
22 Dec. 15 P.M.												
	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)
Floor	288.7	0	0	470.4	41.9	8.9	374.2	4.5	1.2	294	28.5	9.7
Wall 1	80.25	68.1	84.8	101.6	101.6	100	107	63.65	59.5	83.6	68.1	81.45
Wall 2	103	32.1	31.2	169.4	0	0	160	81.2	50.7	155.8	12.55	8.05
Wall 3	137.6	0	0	144.5	0	0	132.8	0	0	85.5	0	0
Wall 4	103	0	0	169.4	0	0	159.5	0.9	0.6	156.2	0	0

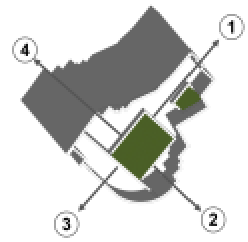
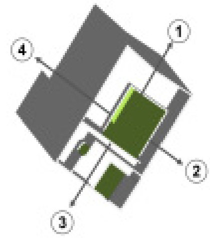
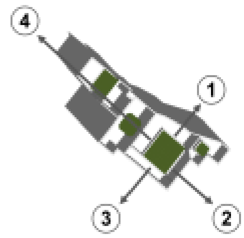
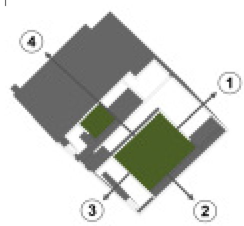
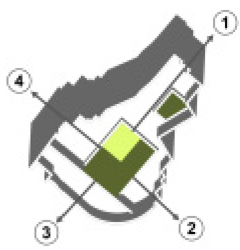
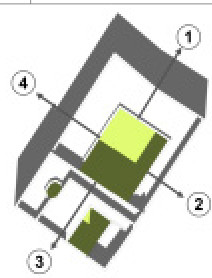
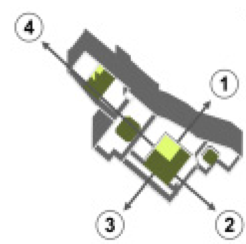
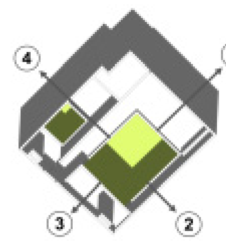
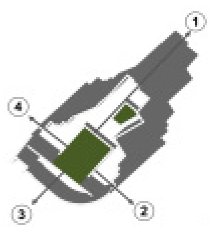
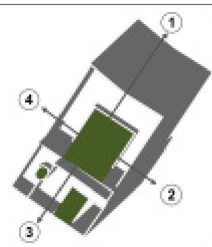
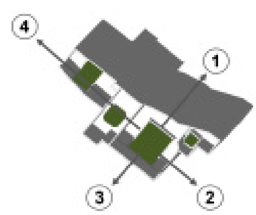
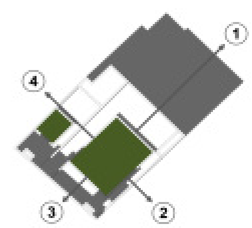
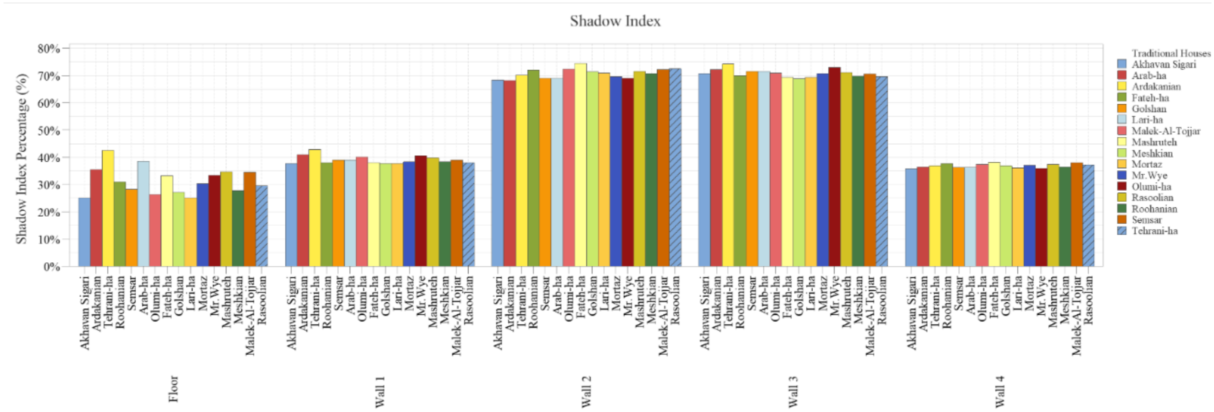
Date	Mashruteh			Meshkian			Malek-Al-Tojjar			Rasoolian		
22 Dec. 9 A.M.												
	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)
Floor	153.7	0	0	281.4	19.3	6.85	192.1	0	0	320.9	0	0
Wall 1	54.8	21.5	39.2	80.9	44.4	54.9	76.05	33	43.4	98	32.8	33.5
Wall 2	76.9	0	0	103.3	0	0	87.1	0	0	125.7	0	0
Wall 3	66.7	0	0	111.4	0	0	91.65	0	0	131.2	0	0
Wall 4	77.8	58	74.5	103.3	84.2	81.5	85.8	69.25	80.7	125.6	99.2	79
22 Dec. 12 P.M.												
	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)
Floor	153.7	42.6	27.7	281.4	104.1	37	192.1	52.9	27.5	320.9	111.4	34.7
Wall 1	54.8	42.8	78.1	80.9	70.4	87	76.05	58.7	77.2	98	79.35	81
Wall 2	76.9	0	0	103.3	0	0	87.1	0	0	125.7	0	0
Wall 3	66.7	0	0	111.4	0	0	91.65	0	0	131.2	0	0
Wall 4	77.8	57.95	74.5	103.3	70.4	68.1	85.8	60.7	70.7	125.6	91.2	72.6
22 Dec. 15 P.M.												
	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)	Total Area (m2)	Sunlit Area (m2)	Isl (%)
Floor	153.7	0	0	281.4	0	0	192.1	0	0	320.9	0	0
Wall 1	54.8	37.6	68.6	80.9	59.3	73.3	76.05	46.9	61.7	98	67.5	68.9
Wall 2	76.9	21.2	27.6	103.3	28.9	28	87.1	19.05	21.9	125.7	9.05	7.2
Wall 3	66.7	0	0	111.4	0	0	91.65	0	0	131.2	0	0
Wall 4	77.8	0	0	103.3	0	0	85.8	0	0	125.6	0	0

Table 4 provides the average Shadow Index of each wall, calculated at specified hours during the summer solstice, and the average Sunlit Index of each wall, calculated at specified hours during the winter solstice. The Shadow Index of total surfaces (IshT), derived from the average Shadow Index of each wall, is used for comparison among houses.

The results indicate that the Tehrani-ha House exhibits the highest shade on the floor and walls of the courtyard during warmer months. Conversely, the Sunlit Index of total surfaces (IslT), derived from the average Sunlit Index of each wall, compares houses based on sunlight on the floor and walls of the courtyard during colder months. The Arab-ha House shows the highest level of sunlight exposure on the courtyard's floor and walls.

Table 4: Shadow index and sunlit index in traditional courtyard houses in Yazd at the beginning of the summer and winter solstices.

	Ish						Isl					
	Floor	Wall1	Wall2	Wall3	Wall4	Total	Floor	Wall1	Wall2	Wall3	Wall4	Total
Sigari	25.1%	37.7%	68.3%	70.7%	35.8%	47.5%	20.2%	78.0%	15.0%	0.0%	50.0%	32.7%
Tehrani-ha	42.5%	42.8%	70.0%	74.1%	36.8%	53.3%	8.4%	56.8%	5.7%	0.0%	41.2%	22.4%
Arab-ha	38.6%	38.9%	68.9%	71.5%	36.3%	50.8%	21.9%	78.0%	14.9%	0.0%	53.6%	33.7%
Olumi-ha	26.4%	40.1%	72.3%	70.9%	37.4%	49.4%	18.4%	51.4%	4.4%	0.0%	36.7%	22.2%



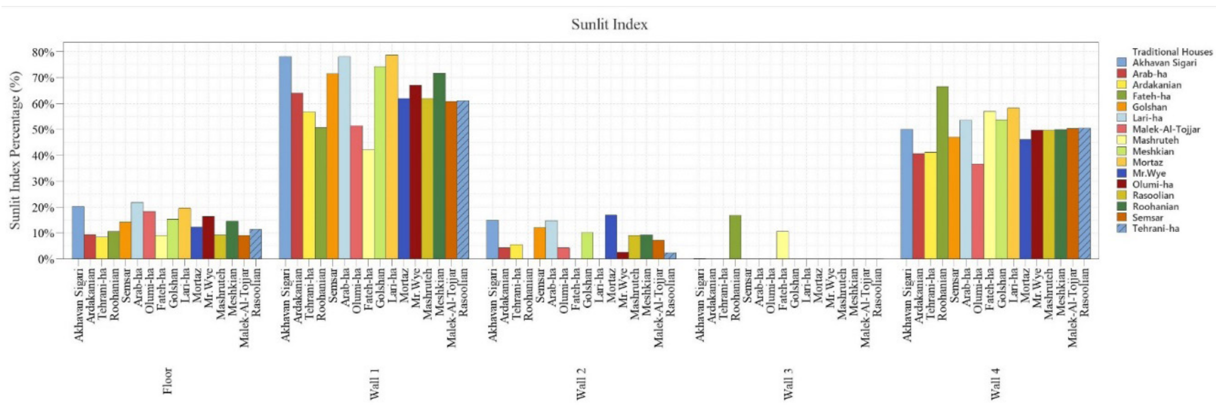


Figure 2: Top) Shadow index on the floor of the courtyard and the surrounding walls on the first day of June, bottom) Sunlit index on the floor of the courtyard and the surrounding walls on the first day of December.

4.Discussion:

The findings in Figure 2 emphasize the crucial role of diurnal variation in shadow and sunlit index distribution within Yazd's courtyard houses. The shading concentration on the east and south walls during June is a strategic response to intense summer sun, aligning with architectural principles aimed at minimizing heat gain. Conversely, solar radiation on the north and west walls suggests effective sunlight utilization, beneficial for passive heating strategies.

In Yazd's hot and arid climate, summer's primary concern is shading residential spaces, while winter focuses on effective sunlight utilization. The Shadow-Sunlit Index calculates the average of the Shadow Index and Sunlit Index at the onset of summer and winter solstices, quantifying the ratio of shaded to sunlit areas relative to total wall area.

Traditional Yazd courtyard houses ideally maintain a higher Shadow-Sunlit Index for balance. However, as Table 5 indicates, these houses provide ample shade in warm months but lack sufficient sunlight in colder months, falling short of expectations for Yazd's climate.

Figure 3 compares Tehrani-ha House and Arab-ha House, highlighting their differing characteristics. Tehrani-ha House, with the highest Shadow Index, prioritizes effective shading for Yazd's summers. In contrast, Arab-ha House, with the highest Sunlit Index, excels in capturing sunlight, vital for winter warmth. Arab-ha House's balance between shading and sunlight exposure suggests a potential architectural model.

A linear multiple regression analysis was conducted to predict the Shadow-Sunlit Index, resulting in an equation. The design parameters in equation (1) include orientation (°), length-

Table 5: Shadow index, Sunlit index and Shadow-Sunlit index in traditional courtyard houses in Yazd.

Name	Sigari	Ardakanian	Tehrani-ha	Roohanian	Semsar	Arab-ha	Olumi-ha	Fateh-ha
IshT	47.54%	50.61%	53.26%	49.72%	48.79%	50.84%	49.42%	50.62%
IslT	32.66%	23.71%	22.42%	28.96%	29.00%	33.69%	22.18%	23.75%
Ish-sl	40.10%	37.16%	37.84%	39.34%	38.90%	42.27%	35.80%	37.19%
Name	**Golshan**	**Lari-ha**	**Mortaz**	**Mr. Wye**	**Mashruteh**	**Meshkian**	**Malek**	**Rasoolian**
IshT	48.36%	47.75%	49.18%	50.35%	50.87%	48.60%	50.82%	49.33%
IslT	30.75%	31.35%	27.49%	27.20%	26.02%	29.11%	25.54%	25.13%
Ish-sl	39.55%	39.55%	38.34%	38.77%	38.44%	38.86%	38.18%	37.23%

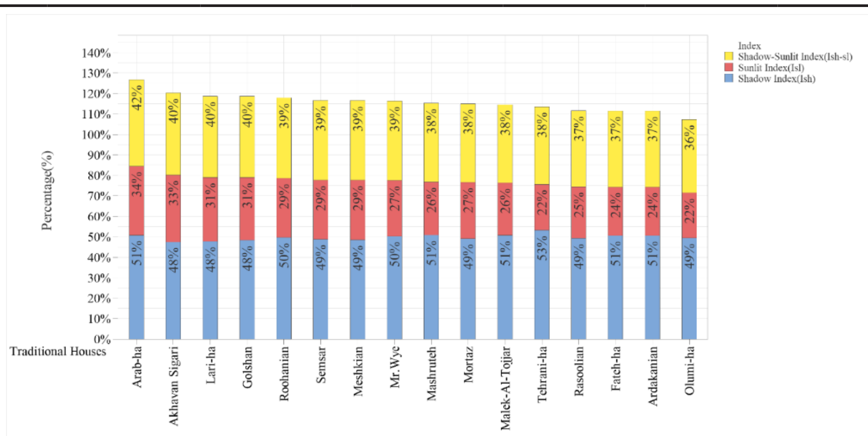


Figure 3: Shadow index (IshT), Sunlit index (IslT) and Shadow-Sunlit index (Ish-sl) on the courtyard floor and the surrounding walls.

to-width ratio, and width-to-height ratio.

(Length / Width) × 2.04 + (Width / Height) × 3.97 + Orientation°× 0.02 + 27.86 = Shadow-Sunlit index (1)

Equation (1) is useful for predicting the Shadow-Sunlit Index in the design of climatic courtyard buildings in modern architecture in Yazd. The equation establishes a relationship between the Shadow-Sunlit Index and the courtyard's orientation and geometric properties. Table 6 details the geometric characteristics of traditional Yazd courtyards, including orientation, rotation angle from geographical north, courtyard area, length-to-width ratio, width-to-height ratio of the southern front, and the Shadow-Sunlit Index derived from numerical studies and Equation 1.

Specifically, Arab-ha House and Olumi-ha House are notable, showing the largest and smallest indices of shadow and sunlight at 42.27% and 35.80%, respectively. This variability evidences the adaptability of courtyard design to climatic conditions. These houses' differing performances highlight the impact of architectural elements on thermal behavior, underscoring the importance of tailored design strategies.

The data range of the design parameters in Equation 1 based on Table 6 is as follows:

55 > Orientation > -67

2.55 > Width / Height > 1.06

1.85 > Length / Width > 1.03

Equation (1)'s design parameters, as outlined in Table 6, offer valuable insights into factors influencing the Shadow-Sunlit Index. The orientation parameter, with a range from 55 to -67 degrees, suggests a spectrum of building alignments for optimizing sunlight utilization or shading according to climate needs.

The width-to-height ratio, ranging from 2.55 to 1.06, highlights how building proportions affect sunlight interaction with vertical surfaces. The length-to-width ratio, varying from 1.85 to 1.03, emphasizes the importance of spatial layout in courtyard design, providing architects with a range of design adaptation possibilities.

Table 6: Geometric characteristics of traditional Yazd courtyards and Shadow-Sunlit index.

No.	Case Study	Orientation and Rotation Angle from the north	Courtyard Area (m2)			Ish-sl Based on Numerical studies	Ish-sl Based on equation (1)
1	Sigari	21 °	337.7	1.57	2.22	40.10	40.30
2	Ardakanian	23 °	325.5	1.45	1.58	37.16	37.54
3	Tehrani-ha	30 °	158.9	1.80	1.33	37.84	37.42
4	Roohanian	55 °	197.4	1.34	1.93	39.34	39.34
5	Semsar	-67 °	292.6	1.03	2.55	38.90	38.73
6	Arab-ha	31 °	413	1.41	2.28	42.27	40.41
7	Olumi-ha	43 °	290	1.33	1.06	35.80	35.63
8	Fateh-ha	50 °	256.5	1.19	1.63	37.19	37.77
9	Golshan	43 °	288.7	1.28	2.10	39.55	39.67
10	Lari-ha	45 °	470.4	1.67	1.95	39.55	39.92
11	Mortaz	39 °	374.2	1.48	1.93	38.34	39.30
12	Mr. Wye	32 °	294	1.85	1.88	38.77	39.74
13	Mashruteh	40 °	153.7	1.41	1.63	38.44	38.00
14	Meshkian	32 °	281.4	1.28	1.98	38.86	38.96
15	Malek-Al-Tojjar	41 °	192.1	1.14	1.84	38.18	38.32
16	Rasoolian	45 °	320.9	1.28	1.90	37.23	38.94

Figure 4 shows the correlation between numerical study results and the equation for the Shadow-Sunlit Index. The strong agreement, evidenced by a correlation coefficient of 0.85, confirms the predictive model's reliability, enabling architects and planners to forecast thermal behavior based on specific design choices.

The equation's practical application in real-world scenarios, optimizing courtyard designs for different climatic conditions, has significant implications for architectural practice. It allows architects to customize orientation, proportions, and spatial layout to achieve optimal thermal outcomes, incorporating climatic considerations at the early design stages.

The current model, while promising, requires ongoing research for parameter refinement and the incorporation of factors like local climate conditions and specific building materials. This will enhance accuracy and applicability in various architectural contexts. Continuous improvement and validation are essential to maintain its relevance in diverse architectural scenarios.

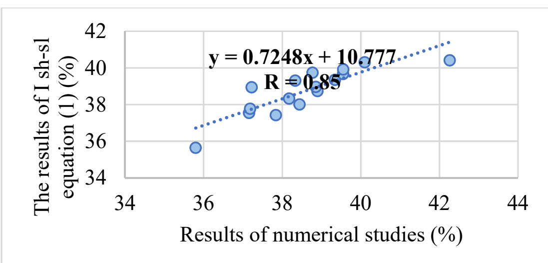


Figure 4: Correlation between the results of the numerical studies and the proposed equation (1) for the Shadow-Sunlit index.

In summary, this discussion underscores the significance of specific design parameter ranges, Figure 4's correlation, and the practical implications of the validated predictive model for architects and planners.

The loss of information about old houses due to urbanization highlights the challenges of rapid urban development. The deliberate selection of the Qajar period mitigates these challenges, allowing focused investigation into architectural practices of that era. This study reveals patterns in Qajar-period courtyard houses, contributing to historical knowledge preservation and understanding of environmental integration in architectural designs.

The multifunctional role of courtyards, the influence of their intended use on geometry, and the call for broader exploration in diverse climates are crucial for a comprehensive understanding of courtyard design. This study's dedication to meticulous research practices promises refined patterns and a deeper understanding of architecture, climate, and function interplay.

5. Conclusions

In different regions, diverse climates have led to subtle variations in the dimensions and layouts of courtyards. Architectural aspects like size, proportions, orientation, materials, and shape play a crucial role in how shade and sunlight interact within these courtyards. This interaction is important because it impacts how much cooling or heating is needed - with shadows helping to cool in summer but requiring more heating in winter, and sunlight increasing the need for cooling in summer while helping with heating in winter. The goal of an ideal courtyard design is to achieve a balanced pattern of sunlight, ensuring enough shade in summer and sufficient light in winter. This study assesses how shadows and sunlight are affected by the geometrical dimensions of traditional Iranian courtyard houses, and how these can be used for passive cooling and heating.

The Shadow index increases with taller buildings and smaller length-to-width ratios of the courtyards, while the Sunlit index shows the opposite pattern. To find the best geometric design, a new Shadow-Sunlit index is introduced, calculated by averaging the Sunlit and Shadow indices. This index helps in understanding how the geometry of courtyards in Yazd is optimized for summer conditions. However, in winter, this leads to a disadvantage due to a lack of sufficient solar radiation, a significant issue considering that Yazd experiences temperatures below 20 degrees Celsius for more than half of the year.

To develop an optimal design pattern, a precise equation is derived from numerical simulations, taking into account the direction, size, and shape of traditional courtyard houses in Yazd. This equation, with a strong correlation coefficient of 0.85, can be applied to modern courtyard designs in hot, dry climates. The width-to-height ratio is particularly important, as is the angle of rotation. The Arab-ha House is identified as a model example based on the Shadow-Sunlit index. The study shows that the width-to-height ratio, length-to-width ratio, and orientation of the courtyard contribute 70.9%, 25.7%, and 3.4% respectively to the Shadow-Sunlit index. Future research should broaden the analysis of the Shadow-Sunlit index to different climates and examine its impact on energy use and thermal comfort. These studies could enhance our understanding of the intricate relationship between courtyard design, climate responsiveness, and sustainable architecture.

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