International Journal of Sustainable Built Environment (2016) 5, 99–113

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International Journal of Sustainable Built Environment

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Investigation of Iranian traditional courtyard as passive cooling strategy (a field study on BS climate)

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Received 23 April 2015; accepted 16 December 2015

Abstract

The use of passive systems for climate control in providing indoor thermal comfort minimizes global trends in increasing the energy demand for active systems of climate control which has unacceptable negative impacts on the natural environment. This concept is ignored for designing of contemporary buildings which care less about the environmental impacts. The main objective of this study is to investigate the concept of the traditional central courtyard as a passive cooling strategy for improving indoor thermal comfort in the BS climate of Iran. An empirical field study was conducted to analyze three important courtyard design variants including orientation, dimensions and proportions, as well as opaque (walls) and transparent surfaces (windows), in fourteen valuable traditional houses in five ancient cities located in the BS climate of Iran. Results of this quantitative study, show that Iranian traditional central courtyards were designed based on a careful attention to orientation and geometrical properties regarding the physical and natural parameters to act as an effective passive cooling system. In conclusion, all data sets were integrated to propose a physical–environmental design model for central courtyards as a useful passive strategy which can be generalized for the wider use of environmentally sustainable design principles in future practice concerning courtyards for buildings in BS climate.

Keywords: Passive cooling strategy; Iranian traditional central courtyard; BS climate; Physical–environmental design model

1. Introduction

Passive cooling is a building design approach that focuses on heat gain control and heat dissipation in a building in order to improve the indoor thermal comfort with low or nil energy consumption (Santamouris and Asimakoupolos, 1996). This approach works either by preventing heat from entering the interior (heat gain prevention) or by removing heat from the building (natural cooling). Natural cooling utilizes on-site energy, available from the natural environment, combined with the architectural design of building components, rather than mechanical systems to dissipate heat (Niles and Haggard, 1980). One of the most successful samples of climatic responsive architecture is traditional courtyard houses which were designed with the careful attention to the climatic requirements and socio-cultural contexts. They were responding

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Peer review under responsibility of The Gulf Organisation for Research and Development.

http://dx.doi.org/10.1016/j.ijsbe.2015.12.001
2212-6090/

Symbols

A_{total}	total house area
A_{cy}	area of courtyard
A_{cs}	total area of closed spaces
A_N	area of the north part
A_S	area of the south part
A_E	area of the east part
A_W	area of the west part
L_{cy}	courtyard length
W_{cy}	courtyard width
H_{cy}	average height of courtyard
A_{cy}	area of courtyard
SH_{cy}	shape of courtyard
N_{wt}	number of areas assigned to water in the courtyard
SH_{wt}	shape of the area assigned to water in the courtyard
A_{wt}	total area assigned to water in the courtyard
N_{sl}	number of areas assigned to soil earth in the courtyard
SH_{sl}	shape of area assigned to soil earth in the courtyard
A_{sl}	total area assigned to soil earth in the courtyard
A_{Nel}	area of courtyard north elevation
A_{sel}	area of courtyard south elevation
A_{Eel}	area of courtyard east elevation
A_{Wel}	area of courtyard west elevation
A_{Tel}	total area of the elevations
A_{ONel}	area of openings in courtyard north elevation
A_{Osel}	area of openings in courtyard south elevation
A_{OEel}	area of openings in courtyard east elevation
A_{OWel}	area of openings in courtyard west elevation

to the most environmental challenges over a long period of time, and used various passive cooling techniques such as Showdan, Khishkhan, Shabestan, Hozkhaneh, central courtyard, wind catcher, air-vent of dome roof, etc. for improving indoor thermal comfort in the hot climate of Iran (Soflaee and Shokouhian, 2005).

This research focuses on the concept of Iranian traditional central courtyards as natural cooling strategy, and its potential application for improving indoor thermal comfort in BS climatic as a case study. Traditional central courtyards in Iran as one of the oldest civilizations in the world go back to 3000 BC (Edwards et al., 2005), and as a design pattern has been used for different functions such as cooking, praying, working, playing, gathering and even sleeping during the hot summer nights. They have roots in Persian-Islamic culture and social perceptions; inspire the sense of introspection with respect to privacy in Islamic ideology. In addition to ideological, social, and cultural characteristics, Iranian traditional central courtyard provided other benefits in hot arid regions. It creates a self-sufficient microclimate area between the outdoor and indoor environments, when it is decorated with trees, flowers and shrubs, not only does it offers a beautiful setting and calm environment, but also supplies shades and increases the relative degree of humidity of the courtyard area as a microclimate modifier.

The saving in the cooling energy needs of the building due to the passive cooling performance of the courtyard was determined by some scholars (Rajapaksha et al., 2003; Toe and Kubota, 2015; Fardeheb, 2007; Rajapaksha, 2004). The passive cooling of the courtyard consists of the following features: (a) The shading effects of the walls of the courtyard on the ground and the south-facing wall and windows of the building, (b) The shading effects of the trees on the ground and on the south facing the windows of the building, (c) The effects of the pool, the lawn, shrubs and flowers in lowering the courtyard ground temperature, (d) The wind-shading effects of the courtyard walls and trees on the infiltration rate of air through the building. All these features reduced the heat gains of the traditional courtyard houses of the building (Safarzadeh and Bahadori, 2003). Protection from or prevention of heat gains encompasses all the design techniques that minimize the impact of solar heat gains through the building's envelope and of internal heat gains that are generated inside the building due to occupancy and equipment (Santamouris and Asimakoupolos, 1996). Microclimate and site design are one of these techniques, by taking into account the local climate and the site context; specific cooling strategies can be selected to apply which are the most appropriate for preventing overheating through the envelope of the building. The microclimate can play a huge role in determining the most favorable building location by analyzing the combined availability of sun and wind (DeKay and Brown, 2014). Previous research has identified that the level of thermal comfort in a courtyard is determined by the microclimatic factors on it, particularly solar radiation and wind. The effect of these parameters may be evaluated with respect to the courtyard's geometry, dimensions, proportions and its orientation as the most influential design variants to provide appropriate thermal comfort in the courtyards (Meir et al., 1995; Meir, 2000; Almhafdy et al., 2013; Givoni, 1976). This research attempts physical–environmental analyses of the traditional central courtyard as the passive cooling technique in BS climatic of Iran to propose an appropriate design model for contemporary sustainable buildings.

2. Literature review

Despite abundant research and literature on the passive performance of buildings in general, the use of "courtyards" in buildings for passive climate control in particular has received only limited appraisal in architectural scholarship. The existing literatures emphasize on the potential of courtyards as microclimatic modifiers in hot dry and tropical climates (Donham, 1960; Bagneid, 2006; Cho and Mohammadzadeh, 2013; Al-Masri and Abu-Hijleh, 2012; Muhaisen and Gadi, 2006; Saeed, 2007), however only very few research works have been investigated either empirically or theoretically on the potential of this concept for BS climate of Iran.

Rajapaksha et al. (2003) investigated the potential of a courtyard for passive cooling in a single story high mass building in a warm humid climate. Their results revealed that, a significant correlation between wall surface temperatures and indoor air temperatures is evident. From a computational analysis, several airflow patterns were identified. The earlier pattern was promoted when the courtyard is ventilated through openings found in the building envelope.

Toe and Kubota (2015) investigated vernacular passive cooling techniques and their potential application for improving the indoor thermal comfort of naturally ventilated, modern brick terraced houses in Malaysia. Field measurement was conducted in two traditional timber Malay houses and two traditional masonry Chinese shop houses to examine their indoor thermal environments.

Fardeheb (2007) evaluated the thermal performance of a courtyard house in a hot and arid climate of Los Angeles, and determined whether the courtyard is cooler than the rooms surrounding it during the day and also if that the courtyard is cooler than the street outside during the day.

Hassan (2012) investigated the potential of a ventilated courtyard for passive cooling in a small building in a hot desert climate in New Aswan City, Egypt. Results show that the courtyard orientation and the courtyard geometry are among the most significant factors which affect the thermal performance of the courtyard building model.

There are a number of studies focusing on courtyard houses in different countries but less research was conducted in Iran. In addition, most of the literature describes the courtyard houses with prior attention to the socio-cultural characteristics in a historical context and have left the passive cooling performance of courtyards in hot arid climates, particularly in BS climatic as the current research case.

This study goes further to analyse the concept of the Iranian traditional central courtyard as a passive cooling strategy in BS climate to propose an appropriate design model for contemporary sustainable buildings. In this regard, two types of research methodologies were used in this study; first is a library study that focuses on sustainable architecture, BS climatic identification, and passive cooling effect of the courtyard. The second is a survey study which concentrates on physical–environmental analysis of fourteen valuable traditional courtyard houses in five ancient Iranian cities. Fig. 1 shows the research scope including climatic scales, cities and houses that were selected in the present research.

Regarding the selection of the fourteen valuable traditional courtyard houses as case studies, it should be noted that, the research conducted by Iran Cultural Heritage, Handcrafts and Tourism Organization (Haji-Qassemi and Karbassi, 2005), illustrates that these cases are among the best traditional courtyard houses which all were designed by the famous Iranian architects with careful consideration of environmental aspects to provide appropriate thermal comfort. It can be concluded that the principle design of mentioned cases can be employed as a passive cooling strategy to affect the thermal performance of the courtyard building model for BS climate zones.

3. Identification of BS climate, BSks and BShs mesoclimates in Iran

There are various geographical regions and sub-regions with specific climate characteristics in Iran. In this regard, various climatic classifications are available, however Dr. Ganji's classification is the most acceptable one. He

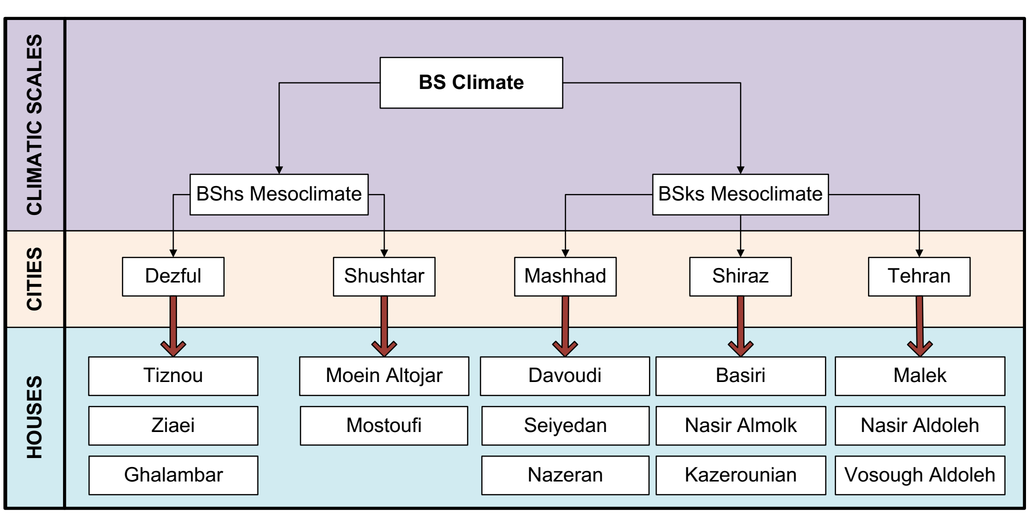

Figure 1. Research scope.

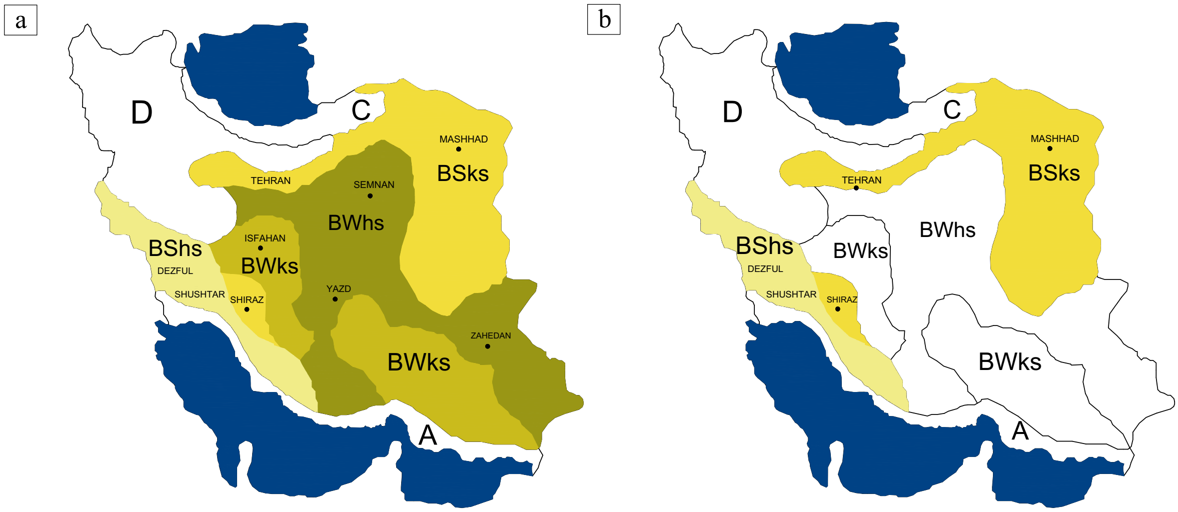

Figure 2. Hot-arid climate divisions in Iran based on the Köppen classification method (a) Mesocclimate divisions of the hot-arid region in Iran, (b) BS climate including BSks and BShs Mesoclimates.

divided Iran, based on Köppen's climate classification, into four climatic regions including A: hot-humid climate, B: hot-arid climate, C: mild-humid climate, and D: cold climate (Kasmai, 2005).

This study concentrates on B: hot-arid climate region which almost covers two thirds of this country, where receives almost no rain for at least six months of the year. Hot-arid climate sub divisions were identified based on the Köppen climate classification as the most widely used climate classification system. In this regard, statistical analysis of the local meteorological data from several stations was employed and Iranian cities in this climate were climatically classified. According to this classification, hot-arid climate subdivided into two climates including desert biome-dry tropical climate (BW) and steppe-dry mid-latitude climate (BS). In addition, BW and BS also are divided into four mesoclimates including BWhs, BWks, BShs and BSks (Fig. 2a).

This research specifically focuses on BShs and BSks mesoclimates. The Steppe climate comes under Köppen's BS classification (Fig. 2b), the B stands for dry climates, and the S for Steppe climate. It is characterized by grasslands, and this is a semiarid climate. It can be found between the desert climate (BW) and more humid climates of the A, C, and D groups.

4. Field investigation: environmental physical analysis of Iranian traditional central courtyards in BS climate

Five ancient cities in the BS climate of Iran were selected including Mashhad, Shiraz and Tehran from BSks mesoclimate, as well as Dezful and Shushtar were located in BShs mesoclimate zone. Three valuable courtyard houses from each city were chosen in order to examine as a case study. Traditional courtyards can be analyzed based on various approaches, such as historical, cultural, spatial, structural, ornamental and constructional details, etc. Most of scholars are unanimous in that dimensions and proportions of Iranian traditional central courtyards are appropriate and the main reason for acting as passive cooling systems (Rajapaksha et al., 2003; Toe and Kubota, 2015; Fardeheb, 2007; Rajapaksha, 2004). This research tries to extract a design model regarding size, dimensions, and proportions based on results of physical–environmental analysis of fourteen valuable cases in five ancient cities including Mashhad, Shiraz and Tehran from BSks mesoclimate, as well as Dezful and Shushtar which were located in BShs mesoclimatic zone. Analysis was based on three design variants including:

1) Courtyard's orientation, extension and rotation angle
2) Courtyard's dimensions and proportions regarding
   (a) Positive spaces (enclosed areas),
   (b) Negative spaces (open areas),
   (c) Natural bodies (water and soil earth)
3) Courtyard's opaque (walls) and transparent surfaces (windows) in respect to access points to the prevailing wind flow.

4.1. Criterion 1: Courtyard's orientation, extension and rotation angle

This section of research tries to examine the orientation, extension direction, and rotation angle, in fourteen research cases in order to identify the most appropriate climatic orientation to gain maximum radiation to passive heating and daylight during the cold seasons, and also maximum suitable airflow to passive cooling, and natural ventilation for indoor spaces during the hot seasons.

Orientation and aspect ratio of a courtyard are two design factors that are critical to the microclimatic performance of courtyards (Meir et al., 1995). The amount of solar energy absorbed within an urban space, such as the courtyard, during a given time period, is determined by the penetration of short-wave radiation into the space and by the albedo of the overall system. While the latter is largely a function of material reflectivity, both are affected by the courtyard's orientation and geometry (Meir, 2000).

Most of Iranian traditional courtyard houses in hot-arid climate are formed along north–south, northeast-southwest or northwest-southeast directions which are the best orientations in order to maximize usage of summer and winter living spaces, as well as service spaces at the east façade (receiving west daylight) acting as a buffer zone for the heat (Pirnia, 2005).

Despite the geographical location of different cities in hot-arid climate, spaces mostly are located in the northern part of the courtyard which faces to the south, in order to absorb the maximum radiation for passive heating and daylight during the cold seasons. In the opposite, spaces that are located in southern part of the courtyard face to the north, to gain minimum radiation and maximum suitable airflow for passive cooling, and natural ventilation during the hot seasons. This seasonal movement occurring between summer and winter spaces is one of the human responses to climate condition (Memarian and Sadoughi, 2011).

Among the fourteen research cases, Fig. 3 as an example shows the analysis of criterion 1 for Nasir Almolk house in Shiraz. As can be seen, house and courtyard both were oriented along the Northeast-Southwest direction and courtyard was rotated 45° from the north direction.

Table 1 illustrates the results of Criterion 1 for fourteen research cases that were selected in this paper. As can be seen, houses located in Mashhad and Shiraz have similar orientation and those were extended in Northeast–Southwest direction, however different rotation angles can be

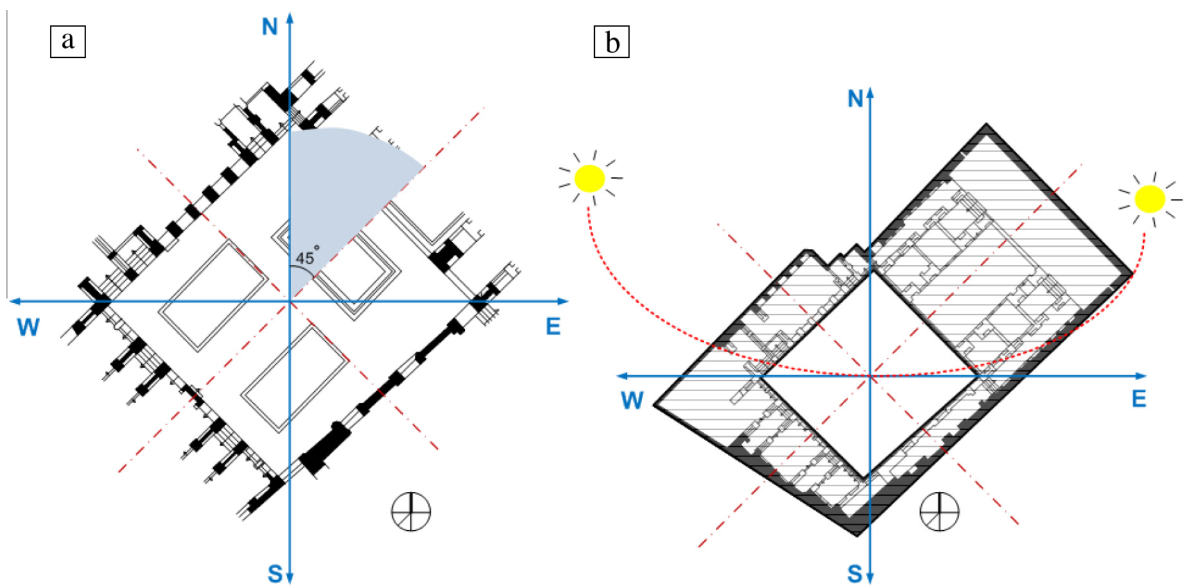

Figure 3. Analysis of Criterion 1 for Nasir Almolk house in Shiraz, (a) Orientation and rotation angle of the courtyard, (b) Orientation and rotation angle of the house.

Table 1
Results of Criterion 1, Courtyard orientation and rotation angle of courtyard houses.

		Cities	Houses	Orientation	Rotation
BS Climate	BSks Mesoclimate	Mashhad	Davoudi	Northeast-Southwest	10°
			Seiyedan	Northeast-Southwest	35°
			Nazeran	Northeast-Southwest	23°
		Shiraz	Basiri	Northeast-Southwest	42°
			Nasir Almolk	Northeast-Southwest	45°
			Kazerounian	Northeast-Southwest	10°
		Tehran	Malek	Northeast-Southwest	15°
			Nasir Aldoleh	North–South	0°
			Vosough Aldoleh	North–South	0°
	BShs Mesoclimate	Dezful	Tiznou	East–West	0°
			Ziaei	East–West	0°
			Ghalambar	East–West	0°
		Shushtar	Moein Altojar	East–West	0°
			Mostoufi	East–West	0°

observed in these cases. Regarding houses in Tehran, except Malek's house which followed the same orientation as other cases in BSks mesoclimate, the other two houses were oriented in the North–South direction without any rotation angle. On the other hand, houses in Dezful and Shushtar from BShs mesoclimate, all have the same orientation, extension and rotation angle, with East–West direction and no rotation.

4.2. Criterion 2: Courtyard's dimensions and proportions

Proportion is one of the determinant criteria in architecture for the perception of harmony, and harmony is the discipline and regularity which exists between components of phenomena (Kurt Grutter, 1987). Iranian traditional architects also used special unit traditional measurements in designing of traditional buildings. This unit called "Peimoun" in Persian, basis of that system was human body proportions like "Arash" (40 cm) which was the distance from elbow to the end of the fingers, "Gaz" (60 cm), which was 24 fingers, and "Govar" (1.60 cm) that was the distance from right hand fingers to left ones when they are completely stretched. Each part of the traditional building was measured based on this module which could be divided into smaller sub-modules for detailed design to reduce the diversity of sizes, easy building and matching of the components. With regard to building form, Iranian traditional architects used the modular geometrical design method, they used a golden rectangular design with specific proportions of width and length which it is drawn inside a regular hexagon (Pirnia, 2005).

Criterion 2 deals with the investigation of dimensions and proportions of Iranian traditional courtyards regarding : a) Positive spaces (enclosed areas), b) Negative spaces (open areas), and c) Natural bodies (water and soil earth).

4.2.1. Positive spaces (enclosed areas)

Within the Islamic culture of Iran, the notion of the void has an important philosophical meaning, the negative space of the courtyard, surrounded by rooms as positive spaces, has roots in the metaphysical principle of unity in Islam (Nasr, 1987). Climatic function of the traditional central courtyard as a microclimate modifier for improving comfort conditions of the surrounding environment is another considerable factor. It creates a comfortable living environment with seasonal usage of all spaces around; north and sunny side of courtyard is used in winter, and vice versa, south and shading side is used in summer.

In this regard, Fig. 4 as an example, shows four divisions of enclosed spaces including living spaces in north, south, west, and east parts of Nasir Almolk courtyard house in Shiraz, alongside of its negative (open) space which called the central courtyard.

Table 2 shows the analysis results of different areas assigned to the enclosed spaces for the fourteen courtyards in BS mesoclimate zone. As can be seen, most areas are assigned to the northern part of enclosed spaces in BSks mesoclimate with 43%, 30%, and 45% of total enclosed area for Mashhad, Shiraz, and Tehran cities' cases respectively. Results reveal that the total area assigned to the north and south in all cases are greater than the total area of the eastern and western parts. There are some exceptions that some portions have an area of zero such as Davoudi, Seiyedan, and Nazeran houses in Mashhad, as well as the Vosough Aldoleh house in Tehran. The reason behind this assignment is certainly due to the local land restrictions.

4.2.2. Negative spaces (open areas)

Since courtyard's geometry, dimensions and proportions; particularly height to width ratio of a courtyard are among the most influential parameters to improve the

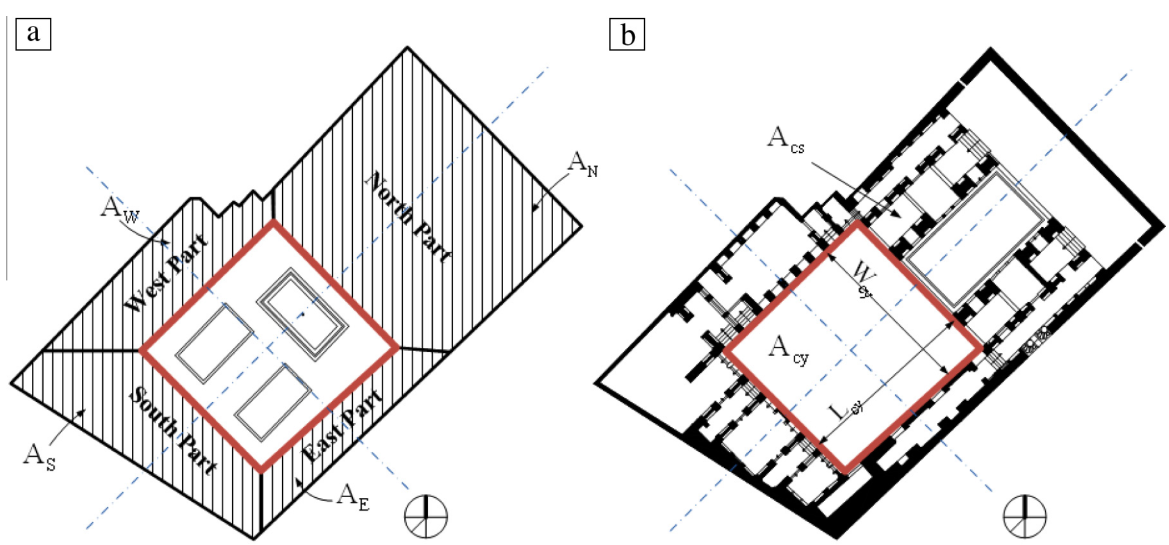

Figure 4. Analysis of positive spaces for Nasir Almolk house in Shiraz, (a) Areas assigned to positive (enclosed) spaces in the north, south, west, and east courtyard, (b) Positive (enclosed) spaces and negative (open) spaces.

Table 2
Dimensions and proportions of positive spaces of courtyards.

Unite: (m)

		Cities	Houses	A_{total}	A_{cy}	A_{cs}	A_N	A_S	A_E	A_W	$\frac{A_N}{A_{cs}}$ (%)	$\frac{A_S}{A_{cs}}$ (%)	$\frac{A_E}{A_{cs}}$ (%)	$\frac{A_W}{A_{cs}}$ (%)
BS Climate	BSks Mesoclimate	Mashhad	Davoudi	1114	555	559	271	0	104	184	48	0	19	33
			Seiyedan	395	140	255	116	55	0	84	45	22	0	33
			Nazeran	468	225	243	83	45	115	0	34	19	47	0
			Average								**43**	**13**	**22**	**22**
		Shiraz	Basiri	1046	247	799	96	340	105	258	12	43	13	32
			Nasir Almolk	602	169	433	186	113	52	82	43	26	12	19
			Kazerounian	584	210	374	131	53	96	94	35	14	26	25
			Average								**30**	**28**	**17**	**25**
		Tehran	Malek	1006	75	931	331	86	315	199	36	9	34	21
			Nasir Aldoleh	1823	228	1595	416	630	451	98	26	39	28	6
			Vosough Aldoleh	551	295	256	188	0	0	68	73	0	0	27
			Average								**45**	**16**	**21**	**18**
	BShs Mesoclimate	Dezful	Tiznou	475	96	379	28	267	31	53	7	70	8	14
			Ziaei	284	60	224	64	21	82	57	29	9	37	25
			Ghalambar	684	95	589	34	235	242	78	6	40	41	13
			Average								**14**	**40**	**29**	**18**
		Shushtar	Moein Altojar	1622	157	1465	178	478	139	670	12	33	9	46
			Mostoufi	2013	750	1263	238	332	516	177	19	26	41	14
			Average								**15**	**29**	**25**	**30**

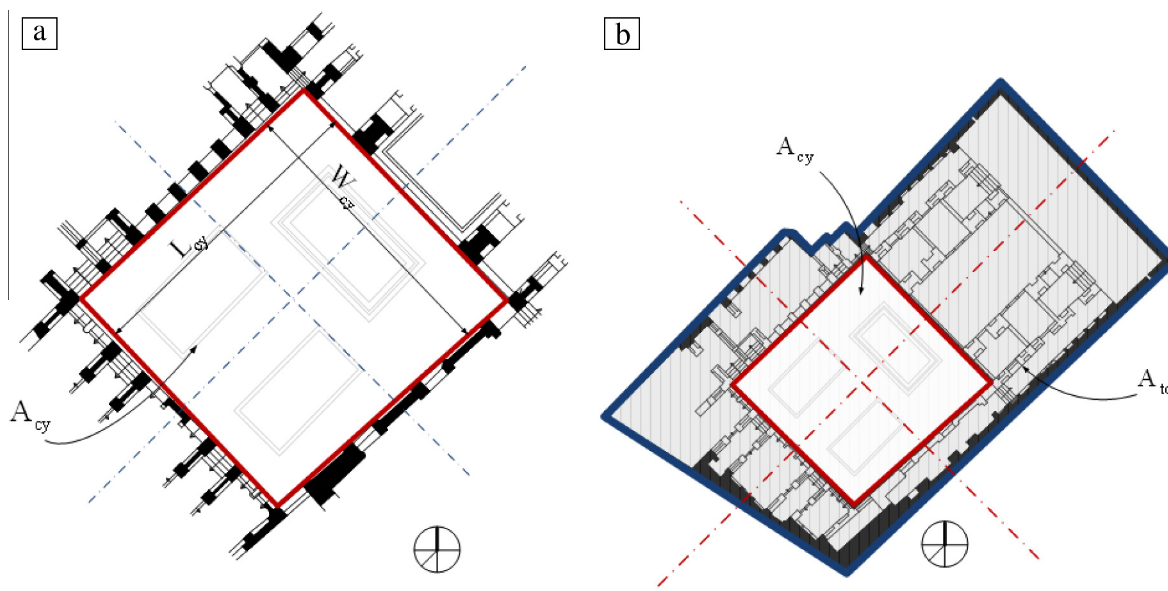

Figure 5. Analysis of negative space for Nasir Almolk house in Shiraz, (a) Dimensions and area of open space (courtyard), (b) Area assigned to the house and courtyard.

thermal performance of surrounding spaces (Meir et al., 1995; Meir, 2000; Almhafdy et al., 2013; Givoni, 1976), this part of the study deals with investigation of form and dimensions of traditional central courtyards regarding length, width, height, as well as their proportions, including height to length, height to width, and length to width ratios. The aim is to identify the best form, appropriate dimensions and proportions of central courtyards to act as microclimate to energy efficiency in contemporary buildings. In this regard, Fig. 5 as an example shows the dimensions and area of the open space of Nasir Almolk house in Shiraz as well as its total area and the area assigned to the courtyard.

Table 3 shows the geometrical properties of the fourteen research cases in BS climatic zone. Results reveal that the maximum proportion of the courtyard area to the total area can be observed in Mashhad city with the amount of 44%, on the other hand the minimum proportion is in Dezful with the amount of 18%. The length to width ratio of the courtyards ranged between 1.09 and 1.68, however this ratio is greater in Dezful and Shushtar houses when compared with Mashhad, Shiraz and Tehran cities which were located in BSks mesoclimate. Due to this lower ratio, the square courtyard shapes in this climate zone such as Nazeran, Nasir Almolk, and Nasir Aldoleh houses can be seen.

Table 3
Dimensions and proportions of negative spaces of the courtyards.

		Cities	Houses	L_{cy}	W_{cy}	H_{cy}	A_{cy}	$\frac{H_{cy}}{L_{cy}}$	$\frac{H_{cy}}{W_{cy}}$	$\frac{L_{cy}}{W_{cy}}$	$\frac{A_{cy}}{A_{total}}$ (%)	Unite: (m) SH_{cy}
BS Climate	BSks Mesoclimate	Mashhad	Davoudi	25.8	21.5	8.9	555	0.34	0.41	1.20	50	Rectangular
			Seiyedan	12.2	11.5	5.1	140	0.42	0.44	1.06	35	Rectangular
			Nazeran	15	15	8	225	0.53	0.53	1.00	48	Square
			Average					**0.43**	**0.46**	**1.09**	**44**	
		Shiraz	Basiri	19	13	4.8	247	0.25	0.37	1.46	24	Rectangular
			Nasir Almolk	13	13	5.6	169	0.43	0.43	1.00	28	Square
			Kazerounian	15	14	8.4	210	0.56	0.60	1.07	36	Rectangular
			Average					**0.41**	**0.47**	**1.18**	**29**	
		Tehran	Malek	10.2	7.4	5.4	75	0.53	0.73	1.38	7	Rectangular
			Nasir Aldoleh	15.1	15.1	6	228	0.40	0.40	1.00	13	Square
			Vosough Aldoleh	18.1	16.3	4.2	295	0.23	0.26	1.11	54	Rectangular
			Average					**0.39**	**0.46**	**1.16**	**25**	
	BShs Mesoclimate	Dezful	Tiznou	15	6.4	5.8	96	0.39	0.91	2.34	20	Rectangular
			Ziaei	8.4	7.1	6.7	60	0.80	0.94	1.18	21	Rectangular
			Ghalambar	12	7.9	7	95	0.58	0.89	1.52	14	Rectangular
			Average					**0.59**	**0.91**	**1.68**	**18**	
		Shushtar	Moein Altojar	15.7	10	5.8	157	0.37	0.58	1.57	10	Rectangular
			Mostoufi	30.5	24.6	7.4	750	0.24	0.30	1.24	37	Rectangular
			Average					**0.31**	**0.44**	**1.40**	**23**	

4.2.3. Natural bodies (water and soil earth)

The modulation and heat dissipation techniques rely on natural heat sinks to store and remove the internal heat gains (Lechner, 2009) The Iranian traditional central courtyard as an ecosystem is made of natural bodies which can be divided into two major categories including water and soil earth.

The various types of water have been used in traditional central courtyards, and pool is one of them which was designed in various shapes, mostly rectangular. It was usually located at the center of the traditional courtyard, and often constructed along one of the main axes of the house (Tofan, 2006). Pool often had a low depth, in order to increase the water surface to absorb the solar radiation, increase evaporation and provide more humidity to decrease the dryness of air as well as create convective breezes to supply the passive cooling and natural ventilation for each house. In addition, soil earth as a thermal mass can be coupled with night ventilation if the stored heat that will be delivered to the space during the evening/night (Santamouris and Asimakoupolos, 1996).

Green surfaces including low water-usage trees and native plants which are selected for adoption to the hot-arid climate also play a considerable role in the balance of shade and sun in different seasons. Plants can contribute to the natural cooling of interior spaces by shading in summer to decrease the gain of radiation through the courtyard's floor and façades in the summer, and in contrast, by increasing the absorption of radiation through the courtyard's floor and bodies to provide passive solar heating in the indoor spaces in winter.

In this regard, this part of the study attempts to investigate dimensions and proportions of water and soil earth as natural bodies of traditional central courtyards in fourteen research cases. The aim is to identify the appropriate ratio of area assigned to water, soil earth, and plant to the total area of the courtyard based on the as-built dimensions in selected cases. Appropriate proportion of area assigned to water may significantly increase the humidity in the courtyard, on the other hand an appropriate ratio of soil earth and plant to the total area of courtyard can provide suitable shading or sunlight in different seasons.

As an example, Fig. 6 shows the area assigned to the water and plants of the Nasir Almolk house in Shiraz. It can be seen that 40 and 74 square meters were assigned to water and plants respectively in this research case.

Table 4 provides the result of analysis of natural bodies for all fourteen research cases. The maximum and minimum ratios of the water area can be seen in Tehran and Shushtar respectively. Due to the higher humidity level in Dezful and Shushtar cities which were located in BSh mesoclimate and are very close to the hot-humid region, it can be observed that less attention is paid to natural bodies when compared with the other three cities in BSk mesoclimate. The maximum and minimum ratios of the area assigned to the plants are in Shiraz and Dezful respectively. Despite dryness of cities located in BSk mesoclimate, it can be observed that in some cases no area was assigned to the plant and water which maybe due to local land restrictions. The area of natural bodies in all research cases shows that form of the area of water and soil earth is mostly of rectangular shape, except Basiri houses in Shiraz that have a shallow oval shape pool.

4.3. Criterion 3: Courtyard's opaque (walls) and transparent surfaces (windows)

In hot-arid regions, the function of façades in traditional central courtyards is to protect the indoor spaces from gaining the heat and outdoor high temperature. In this regard, dimensions, proportions, and especially height of

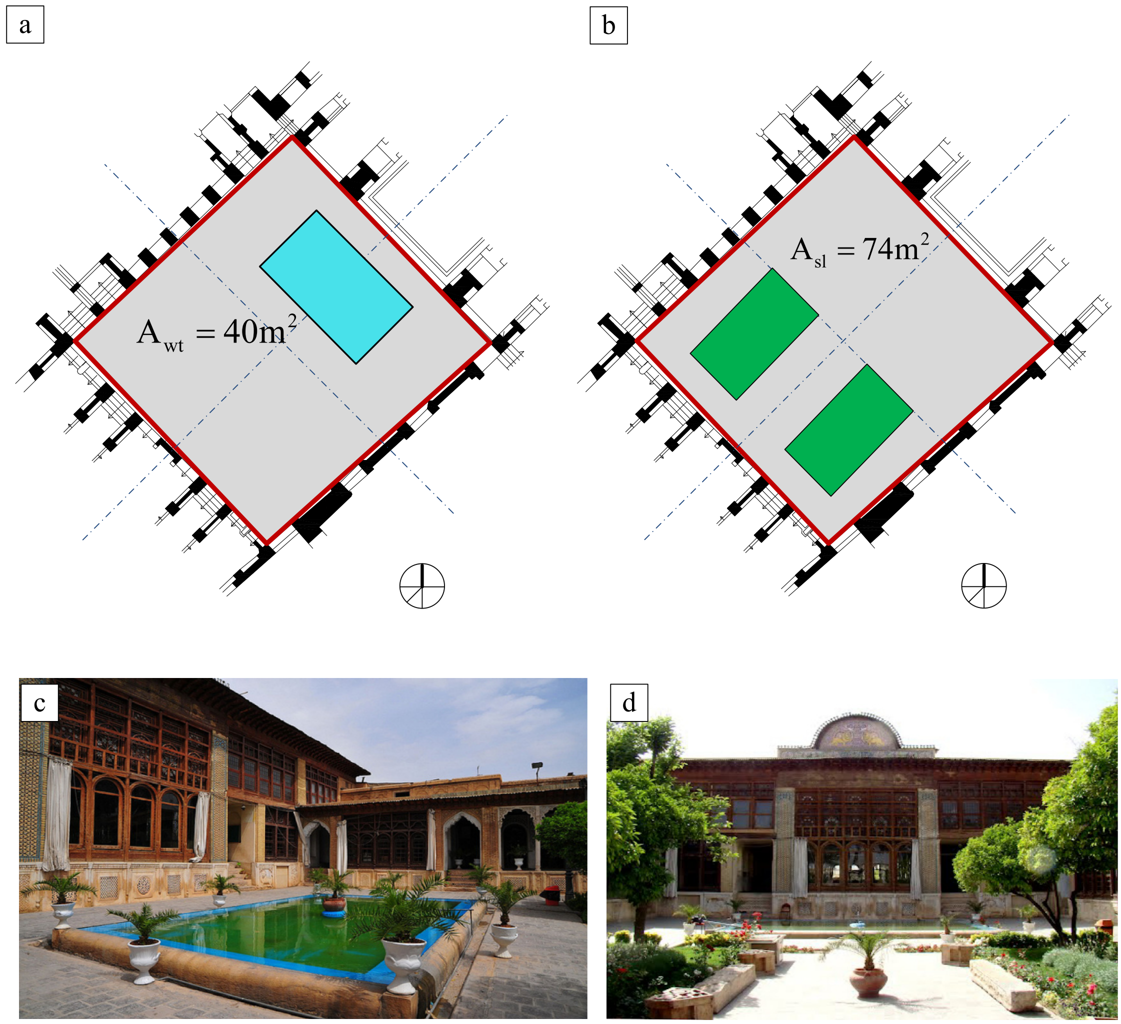

Figure 6. Analysis of natural bodies for Nasir Almolk house in Shiraz, (a) Area assigned to water in courtyard (b) Area assigned to soil earth and plants in courtyard, (c) Rectangular shallow pool, (d) Two rectangular areas assigned to soil earth and plants in the courtyard.

Table 4
Analysis result of natural bodies including the area assigned to water and soil earth.

Unite: (m)

		Cities	Houses	N_{wt}	SH_{wt}	A_{wt}	$\frac{A_{wt}}{A_{cy}}$ (%)	N_{sl}	SH_{sl}	A_{sl}	$\frac{A_{sl}}{A_{cy}}$ (%)
BS Climate	BSks Mesoclimate	Mashhad	Davoudi	1	Rectangular	57	10	4	Rectangular	116	21
			Seiyedan	0	-	0	0	0	-	0	0
			Nazeran	0	-	0	0	0	-	0	0
			Average				**3**				**7**
		Shiraz	Basiri	1	Oval	53	21	4	Rectangular	38	15
			Nasir Almolk	1	Rectangular	40	24	2	Rectangular	74	44
			Kazerounian	0	-	0	0	0	-	0	0
			Average				**15**				**20**
		Tehran	Malek	1	Rectangular	25	33	0	-	0	0
			Nasir Aldoleh	1	Rectangular	42	18	2	Rectangular	33	14
			Vosough Aldoleh	1	Rectangular	6	2	3	Rectangular	94	32
			Average				**18**				**15**
	BShs Mesoclimate	Dezful	Tiznou	1	Rectangular	5	5	0	–	0	0
			Ziaei	-	-	0	0	0	–	0	0
			Ghalambar	1	Rectangular	5	5	0	–	0	0
			Average				**3**				**0**
		Shushtar	Moein Altojar	0	-	0	0	0	–	0	0
			Mostoufi	1	Rectangular	5	1	4	Rectangular	49	7
			Average				**0**				**3**

north, south, west, and east elevations of courtyard usually are different in design. In Iranian traditional central courtyards with rectangular forms and north–south extension, the higher facades are situated in the northern and southern sides. This situation prevents the direct gain of solar radiation by the higher façades, whereas the shorter facades in western and eastern sides, gain the sunlight and heat directly in summer, and not in the winter.

This part of the study tries to investigate dimensions and proportions of the northern, southern, eastern and western area of elevations of traditional central courtyards in all fourteen research cases. The aim is to identify the appropriate dimensions and proportions of facades, particularly for façade height and ratio of the area of each façade to the total area of façades in central courtyard. This pattern can provide the most appropriate shading or sunlight in different seasons based on the similar pattern of most of the traditional courtyards in this climate zone. Fig. 7 shows a different elevation of Nasir Almolk's courtyard house in the north, south, east, and west portions. It can be seen that northern elevation has the maximum area of elevation compared with other parts.

Table 5 illustrates results of the areas and their proportions of different elevations of fourteen research cases in the BS climate zone. As can be seen houses in Mashhad, Shiraz, and Tehran which are located in the BSk mesoclimate assign the maximum area in the northern elevation, in contrary with houses in Dezful and Shushtar that the maximum area can be observed in the south elevation. However in all cases, area of the north elevation ranged between 23% and 34% of courtyard's total elevation area. It should be noted that the minimum ratio of the elevation's area in most of the cases can be found in east and west elevations.

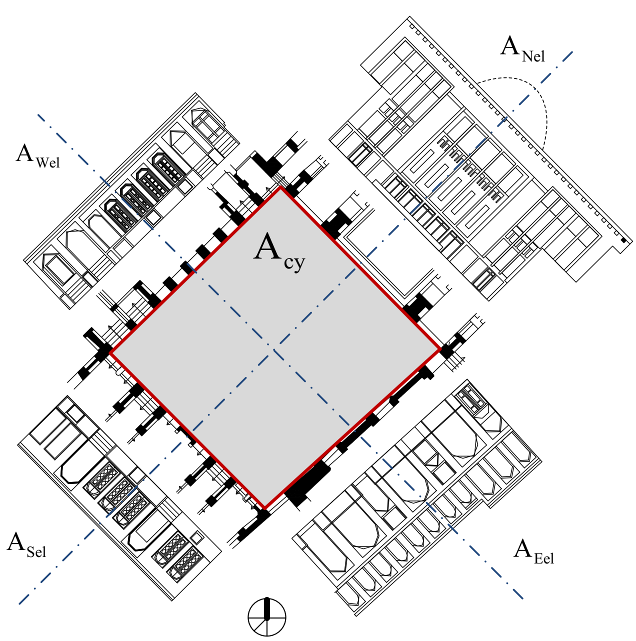

Figure 7. Courtyard's elevations in north, south, east and west of Nasir Almolk house in Shiraz.

Dimensions and proportions of openings in traditional central courtyards are different in various facades to provide passive heating or natural cooling for residents in different seasons. In the south facade of traditional central courtyards, the windows were not movable and mostly there were no top windows because there were sash-windows with vertical openings. Therefore, indoor spaces benefit from natural ventilation by these sash-windows in this façade. In the north facade, there were sash-windows with vertical openings similar to the south façade, the humidity and cool air of the central courtyard could be overcome by opening the sash-windows in the evenings and nights, because there is no wind catcher in this part of the house (Khorsand, 2012). In the north façade, there are rooms with three and five doors namely the Se-dary and Panj-dary respectively; the function is similar to providing indoor thermal comfort due to a reduction in indoor temperature fluctuations in winter times. Moreover, the symmetrical north elevation can be observed in all the cases which is due to achieving similar sunlight conditions in all the winter rooms. In the east and west facades, there are big movable windows with wooden lattice frames which are appropriate for autumn and spring seasons due to high intensity of solar gain in these facades.

This part of the study attempts to analyze the area assigned to openings in northern, southern, eastern and western elevations of traditional central courtyards for the fourteen research cases as well as the ratio of the total opening area to their corresponding façade's area. The aim is to identify the design pattern that it employed in designing of Iranian traditional courtyard houses located in BS climate zone regarding area of openings and its proportion to corresponding façades which may provide passive heating or cooling for residents in different seasons through an appropriate shading or sunlight in different seasons.

In this regard, as an example, Fig. 8 shows the opening of elevations in different facades for Nasir Almolk house in Shiraz.

Table 6 illustrates the area and proportions of the openings in courtyards' elevations based on the as-built dimensions. It can be seen that more attention was paid to the northern and southern opening ratios compared with the east and west parts in all houses. The maximum opening ratio in the north part can be observed in Basiri's houses in Shiraz with the amount of 94% that means almost all parts of the north elevation were covered by doors and windows, on the other hand the minimum ratio can be seen in Ghalambar's house with no opening which is because there is not any façade in the north part of this case. Compared with houses which were located in BSk mesoclimate, other house has less openings in their facades.

5. Physical–environmental analysis results for BSh and BSk mesoclimates

In this section, based on results of the analysis of fourteen courtyard houses, as case studies, tries to identify the design

Table 5
Areas and proportions of elevations in different parts of courtyards.

		Cities	Houses	A_{Nel}	A_{Sel}	A_{Eel}	A_{Wel}	$\frac{A_{Nel}}{A_{Tel}}$ (%)	$\frac{A_{Sel}}{A_{Tel}}$ (%)	$\frac{A_{Eel}}{A_{Tel}}$ (%)	Unite: (m) $\frac{A_{Wel}}{A_{Tel}}$ (%)
BS Climate	BSks Mesoclimate	Mashhad	Davoudi	242	184	156	264	29	22	18	31
			Seiyedan	81.2	36	39	113	30	13	14	42
			Nazeran	117	117	125	119	24	24	26	25
			Average					**28**	**20**	**20**	**33**
		Shiraz	Basiri	65	71	85	78	22	24	28	26
			Nasir Almolk	133	53	86	56	41	16	26	17
			Kazerounian	148	55	90	89	39	14	24	23
			Average					**34**	**18**	**26**	**22**
		Tehran	Malek	45	45	54	54	23	23	27	27
			Nasir Aldoleh	101	97	69	99	28	27	19	27
			Vosough Aldoleh	93	60	59	74	33	21	21	26
			Average					**28**	**23**	**22**	**27**
	BShs Mesoclimate	Dezful	Tiznou	66	115	60	63	22	38	20	21
			Ziaei	62	52	46	46	30	25	22	22
			Ghalambar	63	145	69	70	18	42	20	20
			Average					**23**	**35**	**21**	**21**
		Shushtar	Moein Altojar	75	100	62	51	26	35	22	18
			Mostoufi	252	252	206	98	31	31	25	12
			Average					**29**	**33**	**24**	**15**

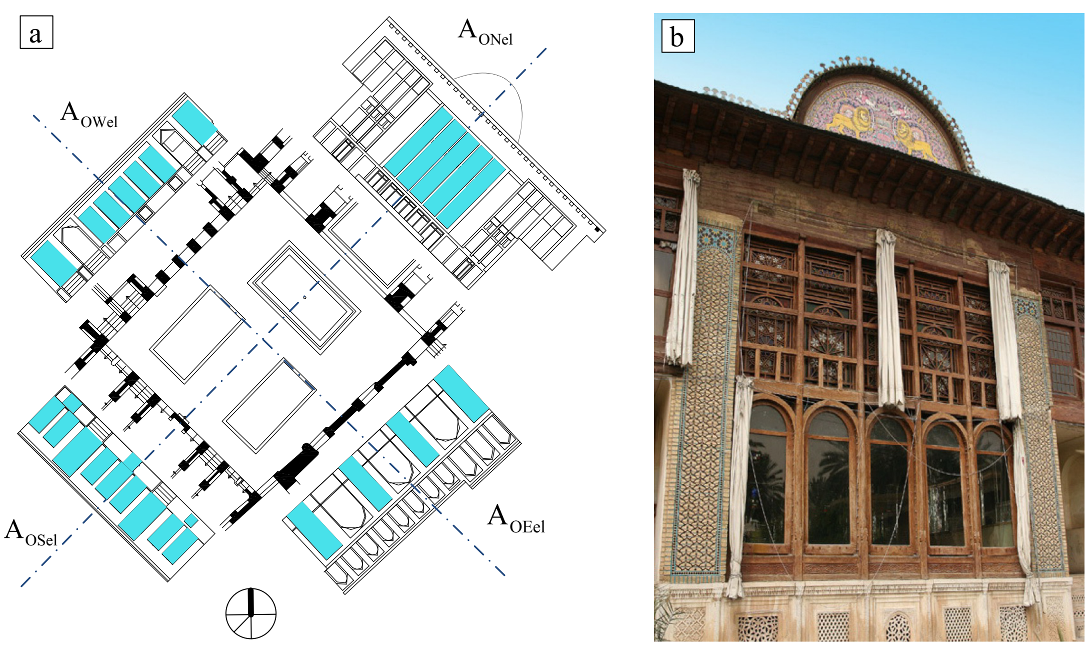

Figure 8. Analysis of courtyard's openings for Nasir Almolk house in Shiraz, (a) Opening of elevations in different facades, (b) Windows of north elevation.

pattern of courtyard houses at the level of cities. These cities including Mashhad, Shiraz, Tehran, Dezful, and Shushtar are located in BS Climate, and the selected courtyard houses are among the best traditional courtyard houses in Iran.

To present an appropriate model for designing of courtyard houses in these cities, summary results of analysis of criteria presented in last sections are provided in Table 7.

As can be seen in this table, Mashahad and Shiraz have similar orientation with a different range of rotation angle. Houses in Tehran were oriented in the north–south direction without a rotation angle, and Dezful and Shushtar have the same orientation in the east–west direction without any rotation.

Regarding the second criterion, in terms of the ratio of the enclosed area, the maximum area assigned to the north and south parts of the house can be observed in Tehran and Dezful respectively with the amount of 45% and 40%. The average results show that more attention was paid in the northern and southern part of enclosed spaces compared with the east and west.

Proportion of the courtyard as an open space, illustrates that the maximum and minimum length to width ratios can

Table 6
Results of area and proportion of the openings in courtyard elevations.

		Cities	Houses	A_{ONel}	A_{OSel}	A_{OEel}	A_{OWel}	$\frac{A_{ONel}}{A_{Nel}}$ (%)	$\frac{A_{OSel}}{A_{Sel}}$ (%)	$\frac{A_{OEel}}{A_{Eel}}$ (%)	Unite: (m) $\frac{A_{OWel}}{A_{Wel}}$ (%)
BS Climate	BSks Mesoclimate	Mashhad	Davoudi	35	0	33	50	14	0	21	19
			Seiyedan	35	16.5	0	43	43	46	0	38
			Nazeran	45	45	41	0	38	38	33	0
			Average					**32**	**28**	**18**	**19**
		Shiraz	Basiri	61	16	5.5	10	94	23	6	13
			Nasir Almolk	32	21	30	30	24	40	35	54
			Kazerounian	54	10	29	29	36	18	32	33
			Average					**51**	**27**	**25**	**33**
		Tehran	Malek	12	10	11	1.3	27	22	20	2
			Nasir Aldoleh	33	30	28	0	33	31	41	0
			Vosough Aldoleh	42	0	0	15	45	0	0	20
			Average					**35**	**18**	**20**	**8**
	BShs Mesoclimate	Dezful	Tiznou	0	19	7	12	0	17	12	19
			Ziaei	11	8	6	4	18	15	13	9
			Ghalambar	0	32	13	16	0	22	19	23
			Average					**6**	**18**	**15**	**17**
		Shushtar	Moein Altojar	21	10	10	9.5	28	10	16	19
			Mostoufi	23	40	15	0	9	16	7	0
			Average					**19**	**13**	**12**	**9**

Table 7
Summary results of analysis of three criteria for five city cases Mashhad, Shiraz, Tehran, Dezful and Shushtar.

Criteria	Parameter	Mashhad	Shiraz	Tehran	Dezful	Shushtar
No. 1	Orientation	NE-SW	NE-SW	N-S	E-W	E-W
	Rotation	10–35	10–45	0	0	0
No. 2	A_N/A_{cs}	43%	30%	45%	14%	15%
	A_S/A_{cs}	13%	28%	16%	40%	29%
	A_E/A_{cs}	22%	17%	21%	29%	25%
	A_W/A_{cs}	22%	25%	18%	18%	30%
	H_{cy}/L_{cy}	0.43	0.41	0.39	0.59	0.31
	H_{cy}/W_{cy}	0.46	0.47	0.46	0.91	0.44
	L_{cy}/W_{cy}	1.09	1.18	1.16	1.68	1.4
	A_{cy}/A_{total}	44%	29%	25%	18%	23%
	A_{wt}/A_{cy}	3%	15%	18%	3%	0%
	A_{sl}/A_{cy}	7%	20%	15%	0%	3%
No. 3	A_{Nel}/A_{Tel}	28%	34%	28%	23%	29%
	A_{Sel}/A_{Tel}	20%	18%	23%	35%	33%
	A_{Eel}/A_{Tel}	20%	26%	22%	21%	24%
	A_{Wel}/A_{Tel}	33%	22%	27%	21%	15%
	A_{ONel}/A_{Nel}	32%	51%	35%	6%	19%
	A_{OSel}/A_{Sel}	28%	27%	18%	18%	13%
	A_{OEel}/A_{Eel}	18%	25%	20%	15%	12%
	A_{OWel}/A_{Wel}	19%	33%	8%	17%	9%

be observed in Dezful and Mashhad respectively. Area assigned to the courtyard is also one of the important factors in designing, it can be seen that the maximum and minimum ratios of the courtyard to total area of the house can be found in Mashhad and Dezful respectively (Fig. 9). In terms of natural bodies, it can be observed that more attention was paid to water and plants in the courtyards in Shiraz and Tehran, compared with the other three cities. In contrast, less attention can be seen in Dezful and Shushtar which is due to the high level of humidity in these two cities.

Regarding the third criterion, except Mashhad city, in other city cases it can be seen that the maximum area was assigned to the north or south facades when compared with the east and west. The ratio of north, south, east and west facades' areas to the total area of elevations of the houses in Mashhad, Shiraz, Tehran, Dezful, and Shushtar ranged between 20–33%, 18–34%, 22–28%, 21–35%, and 15–31%, respectively. Results of this criterion also reveal that the maximum opening area was assigned to north or south elevations in all city cases.

6. Purposed design model for central courtyard in BS climate zone

As final results, a design model is presented in this section for courtyard houses in BS climate zone based on

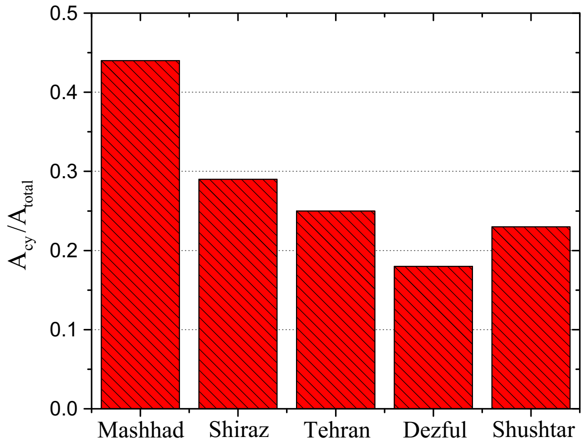

Figure 9. Proposed ratios of courtyard area to the total area of house for all five city cases.

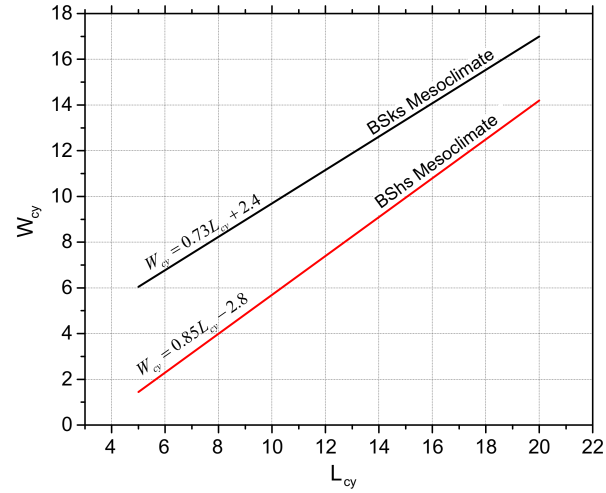

Figure 11. Linear design equation in BSks and BShs mesoclimate zones.

the size, dimensions and proportions of Iranian traditional courtyard houses through the three physical–environmental criteria.

The average results show that most of the area should be assigned to the southern part of the enclosed space of courtyard houses with a ratio of 30%. However the total area of north and south is always greater than east and west parts (Fig. 10a).

Appropriate orientation can be considered as northeast–southwest with 10–45° rotation or east–west directions with no rotation angle. However the local geography and environmental conditions as well as location latitude cannot be neglected for this consideration.

From the results of analysis of fourteen cases presented in this research, it was attempted to propose a model based on the proportions of length, width, and height. Linear fitting was employed and best line that matched with the scatters was found out. Design equations for expressing the relationship between length and width of the courtyard are presented in different scales, city scale, mesoclimate scale, and at the scale of BS climate (Table 8). Fig. 11 shows two proposed design equations for BShs and BSks mesoclimate zones, it can be observed that these two equations are relatively close and can be extracted as a generalized equation for BS climatic zone based on these results. (See Fig. 12)

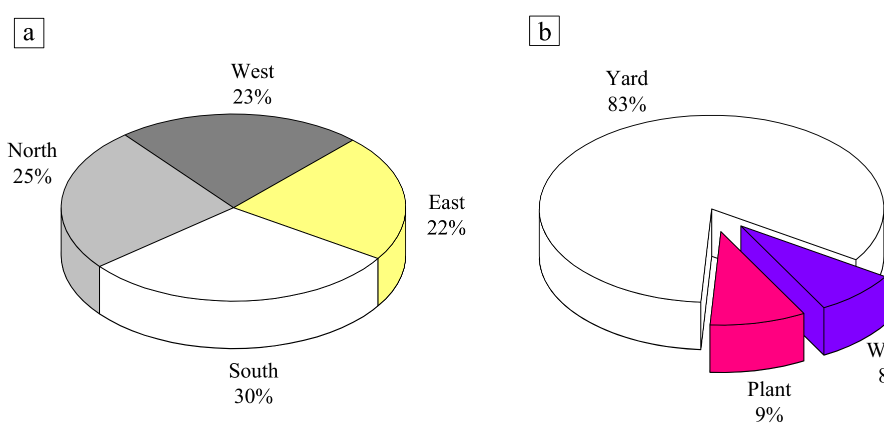

Figure 10. Proposed area for assigning to enclosed spaces and natural bodies, (a) North, south, east, and west sides of enclosed space, (b) Area of water and plants as natural bodies.

Table 8
Design equations and relationship between length and width of the courtyards in different scales.

Zone	Equation	Mesoclimate	Equation	City	Equation
BS	$W_{cy} = 0.8L_{cy} + 0.17$	BSks	$W_{cy} = 0.73L_{cy} + 2.4$	Mashhad	$W_{cy} = 0.7L_{cy} + 3.67$
				Shiraz	$W_{cy} = -0.04L_{cy} + 13.9$
				Tehran	$W_{cy} = 1.17L_{cy} - 4$
		BShs	$W_{cy} = 0.85L_{cy} - 2.8$	Dezful	$W_{cy} = -0.1L_{cy} + 8.26$
				Shushtar	$W_{cy} = 0.99L_{cy} - 5.49$

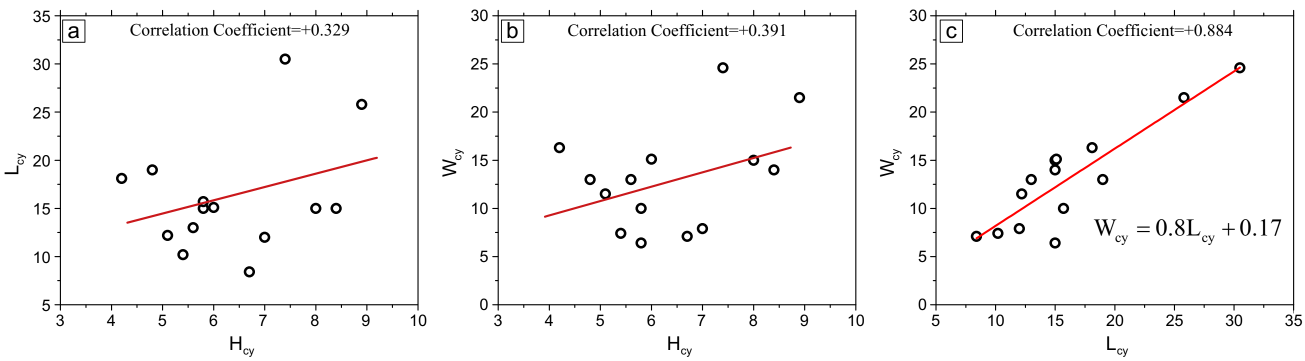

Figure 12. Proportions of length, width and height of central courtyards, (a) length versus height, (b) width versus height, (c) width versus length.

Results of the fitting process for different proportions is provided in Fig. 11, as can be seen three linear equations were proposed for designing courtyards based on its geometrical proportions. The best relationship between the length and width of the courtyard was obtained based on the following equation (Eq. (1)) which can be used for designing of contemporary courtyards in the BS climatic zone.

$$W_{cy} = 0.8L_{cy} + 0.17 \quad (1)$$

Based on the average results of the last section, it is recommended that about 17% of courtyard can be assigned to natural elements, 8% for water and 9% for plant. This ratio can be obtained for appropriate thermal comfort in the courtyard and surrounding areas as the observation and previous studies demonstrate (Fig. 10b).

It is proposed that the total area of the facades in north, south, east, and west parts of courtyard can be considered almost identical, but height of surrounding bodies must be designed differently. In fact, height of the facades in the north and south should be higher than east and west elevations.

Openings in elevations can be designed based on the ratio of total opening's area to its corresponding elevation with the amount of 21–29% for the north and south elevations, and 17–18% for the east and west elevations. It should be noted that there is also a relationship between the opening area ratio and size of the courtyard that can change the amount of these proportions.

7. Conclusion

Based on Köppen's climatic classification method, BS climate, BSks and BShs mesoclimates were identified in the hot-arid region of Iran. Three physical–environmental analysis criteria for traditional central courtyards as passive cooling strategies were defined, and employed to examine fourteen remarkable Iranian traditional courtyard houses in Mashhad, Shiraz, Tehran, Dezful, and Shushtar ancient cities located in BSks and BShs mesoclimate zones. Size, dimensions and proportions of physical and natural elements of traditional central courtyards were identified and the logical relationship between them was found. Recommendations were outlined for designing of courtyards as effective natural cooling systems regarding orientation as well as geometrical properties of their physical and natural elements. Design equations were proposed as a function of proportions and dimensions of courtyards, considering length, width and height. These design models and recommendations can be employed for designing of contemporary sustainable buildings in BS climate and results can be generalized to other climatic regions by carrying out similar investigation as future works.

Acknowledgement

The authors would like to express their thanks to Iran Cultural Heritage, Handcrafts and Tourism Organization and Islamic Azad University, Science and Research Branch in Iran for their support of this research.

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