RESEARCH

ENVIRONMENTAL IMPACT OF COURTYARDS— A REVIEW AND COMPARISON OF RESIDENTIAL COURTYARD BUILDINGS IN DIFFERENT CLIMATES

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ABSTRACT

Purpose—*This paper tries to clarify the environmental impacts of a traditional building form which was developed more than 5000 years ago, under the force of harsh hot climates: courtyard building. A courtyard is an outdoor space which is entirely surrounded by buildings or walls. The main purpose is to show if this building form can reduce the energy demand of low- rise residential buildings in order to reduce* CO_2 *emission which generally considered is the main root of climate change.*

Methodology—*From a literature review on courtyard buildings several climatic aspects of this building form can be extracted. In this step, the paper focuses on the climatic impact(s) in the context of hot-arid, snow, temperate and tropical climates.*

Findings—*Results for different configuration of courtyard building, natural elements used in it, and the situation of openings in different facades are the most important findings of this review paper.*

Research limitations—*The research is limited to considering residential courtyard buildings in four climates; hot- arid, snow, temperate, and tropical (based on Koppen-Geiger climate classification).*

Practical implications—*The results of the paper are general climatic characteristics of courtyard buildings. These characteristics can be used for designing new courtyard dwellings.*

Innovation—*Although the background information of the paper is based on literature, the innovation is the comprehensive consideration and comparison of environmental characteristics in different climates which has never been done before.*

KEYWORDS

courtyards, environmental impact, different climates, design characteristics.

1. INTRODUCTION

> "*Yet, the courtyard is more than just an architectural device for obtaining privacy and protection. It is, like the dome, part of a microcosm that parallels the order of the universe itself.*"
>
> Hassan Fathy (1986)

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In the light of energy reduction, courtyard buildings have been recognised as a way to create comfortable environments with limited energy use. A courtyard building typically contains an open space that is surrounded by buildings, rooms or walls. Although there is a wide range of variations in dimensions and shapes of courtyards, this spatial structure generally provides a secluded and private space, and often acts as a source of light, fresh air and heat. In different cultures, it can be used for rest, play with children, worship (meditation), women's activities and exercise.

This paper introduces courtyard buildings by presenting their definition, their differences from other similar building types (like atrium and patio), their historical evolution and their different impacts. Among the impacts, climatic issues will be discussed comprehensively. A comparison between different courtyards in different climates helps us to achieve a formal understanding of climate effects of this building type. The differences also show design characteristics which can be utilised in future designs. Moreover, three main climatic functions of courtyard buildings (cooling, lighting and ventilating) are discussed on the basis of three analytical studies.

1.1 Objectives

The main objective of this paper is to understand the climatic aspects of courtyard buildings. This will help us in clarifying if this building shape is efficient in case of energy; further research can consecutively work on actual ways of using and optimising this spatial form.

In this regard, it is necessary to consider different impacts of courtyard buildings in advance. Moreover, basic ideas and information related to the origins and genesis of courtyard buildings are supposed as background objectives.

1.2 Research Questions

The main research question that will be answered in this paper is if a courtyard can reduce the energy demand of low-rise houses. This question is raised in the context of a direct relationship between the energy consumption of residential buildings and climate change phenomena. Since the environmental impact of buildings is not the only effect of the built environment on natural systems, the paper needs to address and answer other possible aspects and impacts of courtyard buildings as well. Last but not least, understanding the roots and development of courtyard buildings is a fundamental question of this paper.

1.3 Methodology of the Literature Review

The research method of this paper is based first on classifying different papers and studies according to the type of transitional space they describe (Table 1); and second on further classifying studies into courtyard buildings by their impacts (Table 1). Organising recent studies helps other researchers in finding proper references in different approaches of looking to the courtyard buildings. The innovation part of the methodology is to compare different climatic characteristics of courtyard buildings (which are derived from literature) in different climates. The result of this comparison is presented in a table at the end of this paper. This table can be used by architects as design recommendations.

2. PROBLEM ANALYSIS

2.1 Climate Change and Buildings

There is a growing concern about energy use and its implications for the environment. Recent reports by the Intergovernmental Panel on Climate Change (IPCC) have raised public awareness of energy use and the environmental implications, and generated a lot of interest in having a better understanding of the energy use characteristics in buildings, especially their correlations with the prevailing weather conditions (IPCC, 2007; Levin et al, 2007).

It was estimated that in the year 2002 buildings worldwide accounted for about 33% of the global greenhouse gas emissions (Levermore, 2008). The European Commission (2000) reported that the 164 million buildings in the EU-15 (193 million in EU-25) accounted for about 40% of the final energy demand and about a third of all greenhouse gas emissions from the EU, of which about two-thirds are attributed to residential and one-third to commercial buildings.

2.2 The Effect of Residential Buildings and Courtyards

On a national level, energy consumption of the residential sector accounts for 16–50% of the consumption of all sectors, and averages approximately 30% worldwide as shown in Fig. 1 (Swan & Ugursal, 2009). This significant consumption level warrants a detailed understanding of the residential sector's consumption characteristics to prepare for and help guide the sector's energy consumption in an increasingly energy-conscious world: awareness from standpoints of supply, efficient use, and effects of consumption. In response to climate change, high energy prices, and energy supply/demand, there is interest in understanding the detailed consumption characteristics of the residential sector in an effort to promote conservation, efficiency, technology implementation, and energy source switching to, for instance, renewable energy harvested on-site.

As discussed earlier, buildings normally consume one third of national energy budgets, and residential buildings have a key role in this amount of consumption. Therefore, the energy consumption of residential buildings must be reduced. In this respect, this paper tries to introduce courtyard building as a passive and potentially effective way to minimise energy consumption in special regions and climates.

3. LITERATURE OVERVIEW

Several studies (Table 1) have shown social, cultural, formal, and environmental advantages of courtyard buildings. Future lack of fossil energy and the limited capacity of sustainable energy sources encourage us to investigate passive and efficient building forms; one such building form is the courtyard.

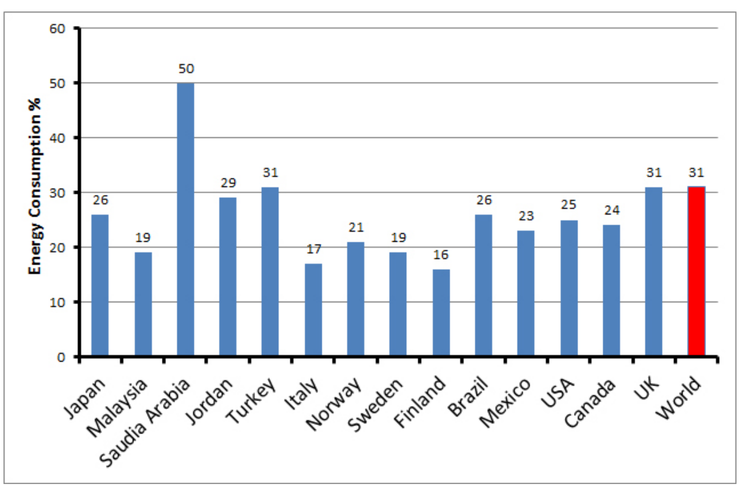


FIGURE 1. Residential energy consumption shown as a percentage of national energy consumption and in relative international form (image after Saidur et al., 2007).

TABLE 1. Classification of studies done in case of transitional spaces and courtyard buildings.

Transitional Spaces	Impacts	Related reference(s)
Underground shopping mall, station, passageway		(Chun et al., 2004), (Hou & Wang, 1999), (Zhang & Liu, 1989)
Entrance, Corridor		(Nakano et al., 1999)
Atrium		(Rundle et al., 2011), (Oosthuizen and Lightstone, 2009), (Qin, 2008), (Aizlewwod et al., 1997), (Cole, 1990), (Hopkirk, 1999), (Calcagni and Paroncini, 2004), (Mabb, 2008)
Passage, Arcade		(Potvin, 2000)
Pedestrian passage		(Schaelin, 1999)
Arcade, Covered street		(Tsujihara et al., 1999)
Veranda, Entrance		(Yamagishi et al., 1998)
Sunroom		(Yamazaki et al., 1996)
Balcony, Porch		(Zintani et al., 1999)
Courtyard	Social, Cultural and typological	**Afghanistan:** (Schadl, 2009)
		China: (Knapp, 1989)
		India: (Sinha, 1994), (Nangia, 2000), (Sobti, 2009)
		Singapore: (Chua, 1998)
		Iran: (Ghodar, 1978), (Memarian and Brown, 1996), (Memarian, 2006), (Forouzanmehr & Vellinga, 2011).
		Syria: (Al Abidin, 2006), (Wadah, 2006)
		Morocco: (Eleb, 2009)
		Turkey: (Eldem, 1984), (Lad, 2009), (Bekleyen and Dalkiliç, 2011)
		Algeria: (Abdelmalek, 2006)
		Egypt: (Scanlon, 1966), (Bey and Gabriel, 1921), (Creswell, 1959), (Behrens-Abouseif, 1993), (Chowdhury, 2009)
		North Africa: (Noor, 1991), (Sibley, 2006)
		Saudi Arabia: (Bahammam, 2006)
		Italy: (Giuliani, 1992), (Petruccioli, 2006)
		Spain: (Perez-de-Lama and Cabeza, 1998), (Cadima, 1998), (Reynolds, 2009)
		UK: (Edwards, 2006)
		S. Korea: (Hwangbo, 2009)
		Sri Lanka: (Pieris, 2009)
		Comparative analyses: (Rapoport, 1969), (Alexander 1976), (Kamau, 1979), (Banaji and Haynes, 1992), (Reynolds, 2002), (Oliver, 2006), (Rabbat, 2009).
	Climatic	**Hot & arid Climate:**(Fathy, 1986), (Bahadori, 1978), (Roaf, 1990), (Etzion, 1990), (Raydan, 2006), (Meir, 2000), (Heidari 2000), (Meir et al., 2004), (Yezioro et al., 2006), (Bagneid, 2006), (Rapoport, 2007), (Rabbat, 2009).
		Snow Climate: (Schoenauer and Seeman, 1962), (Manty, 1988).
		Tropical Climate: (Das, 2006)
		Temperate Climate: (Pfeifer and Brauneck, 2008)
		Comparative Studies: (Givoni, 1991), (Brown and DeKay, 2001), (Aldawoud, 2008), (Muhaisen, 2010).

As we can see in table 1, there are different types of transitional spaces including courtyard buildings. Among the different types close to courtyard buildings, the atrium is studied more as to its impact to natural lighting (Aizlewood et al., 1997), (Cole, 1990), (Hopkirk, 1999) and natural ventilation (Rundle et al., 2011), (Oosthuizen and Lightstone, 2009), (Qin, 2008). In this regard, natural heating is studied less frequently for atrium buildings (Blesgraaf, 1996).

Generally, in case of courtyard buildings, comprehensive investigations have been executed in the field of social and cultural impacts of this building form. However, specifically in case of environmental effects, most researchers have not yet addressed courtyard buildings' energy performance in sufficient depth in order to be able to reduce the energy demand for heating, cooling, ventilating, and lighting.

Most studies done in the field of energy in courtyard buildings are related to either the role of the glazing type in the thermal performance of courtyard buildings (Aldawoud, 2008), or day lighting in atria (Calcagni and Paroncini, 2004; Mabb, 2008), or courtyard acoustics (Ettouney and Fricke, 1973). Meir (2000) discusses that during the last forty years, there has been an increasing number of publications advocating the use of courtyard spaces as microclimate modifiers, especially in hot arid climates (Saini, 1980), (Mostafa & Costa, 1983), (Moore, 1983), (Talib, 1984), though not always based on actual calculations and field studies. This was claimed by Roaf (1990) and many of the authors of those papers based their assumptions on Dunham's thesis (1990) without questioning its theoretical basis in particular, and without checking whether in general the specific research results can be applied to different climatic regions. As a result, an in-depth analysis of the energy performance of (residential) buildings with courtyards is still lacking.

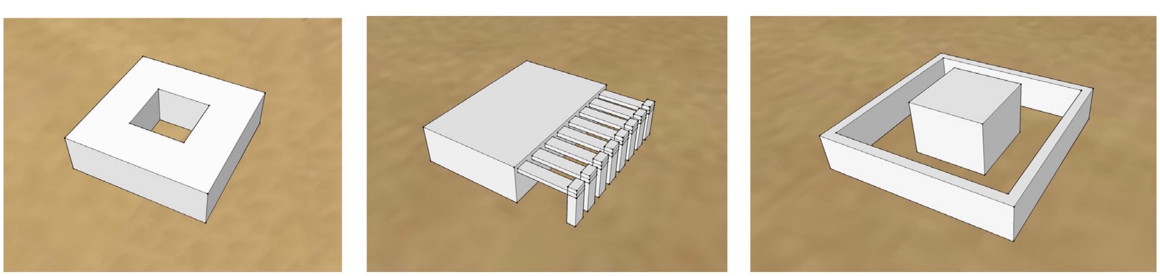
4. COURTYARD BUILDINGS

4.1 Definition of Courtyard Buildings

Courtyards belong to a specific type of space, called 'transitional space.' This term covers a wide range of spaces from a passageway and a corridor to a balcony or porch. Transitional zones are the 'in-between' architectural spaces where the indoor and outdoor climate is moderated without mechanical control systems. In these spaces the occupant may to a certain extent experience the dynamic effects of changes in the outdoor climate. The different types of transitional spaces can be divided to three main types (Fig. 2).

Type 1 covers courtyards, atriums and patios. The second type involves attached semi open spaces which are slightly covered such as a balcony, a porch, a corridor, a covered street or an arcade. In the third type, the building is entirely enclosed by open space like the situation in pergolas, bus stations, or pavilions (Chun et al., 2004).

FIGURE 2. (left): Type 1, open space inside the building, (middle): Type 2, open space is attached to the building, (right): Type 3, open space encloses the building.



Based on Oxford's Dictionary, courtyards are defined as "*An unroofed area that is completely or partially enclosed by walls or buildings, typically one forming part of a castle or large house.*" Moreover, the Cambridge Dictionary defines a courtyard as "*An area of flat ground outside which is partly or completely surrounded by the walls of a building.*"

Clearly, both definitions insist on an open space that has no coverage and is surrounded by walls or buildings.

Similar building types to the courtyard are the patio and the atrium:

a) A patio is a very small type of courtyard seen in Spanish or Spanish-American houses. It sometimes is slightly roofed like a pergola. Patios can also be found in temperature climates in Western Europe as well.
b) An atrium is a courtyard which is covered by a glass roof.

These building types have different thermal behaviour and are not included in this research.

4.2 Historical Evolution of Courtyards

Paul Oliver (2003, p. 136) wrote in his book "Dwellings: The House Across the World" that "Courtyard houses have an ancient history: examples have been excavated at Kahun, in Egypt, which are believed to be 5000 years old, while the Chaldean City of Ur, dating from before 2000 BC, was also comprised houses of this form." As we can see in figure 4, courtyards are distributed around many regions of the world, from different climates to different civilisations.

FIGURE 3. (left): a patio, (middle): a courtyard, (right): an atrium.

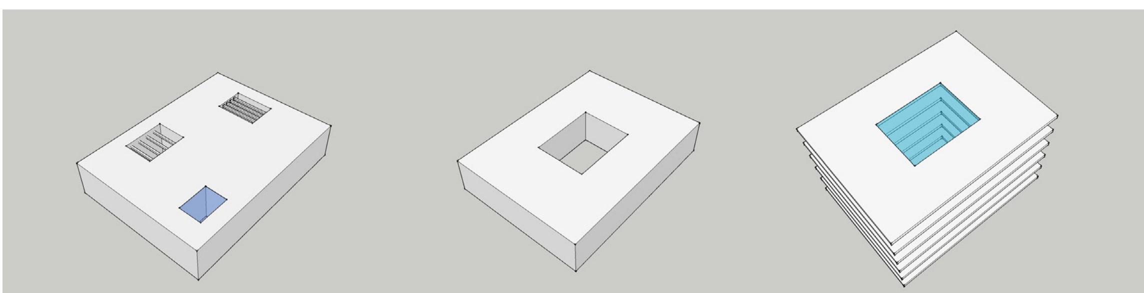
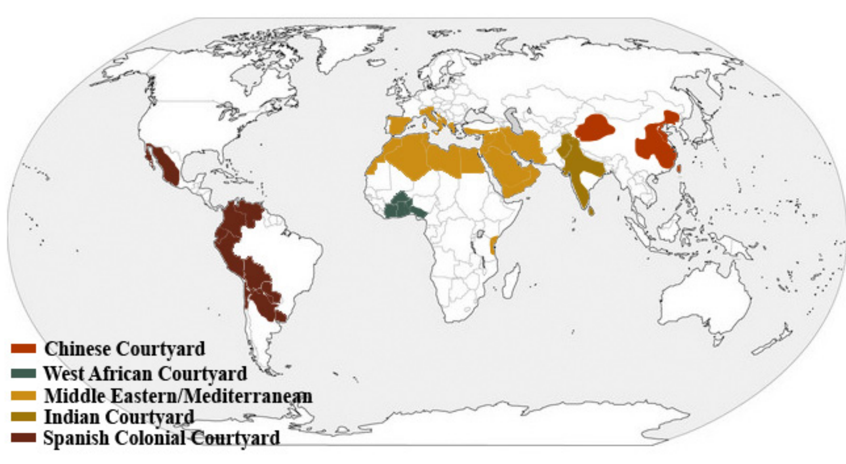


FIGURE 4. Distribution of Courtyards in the World (image after Vellinga et al, 2007).



Reviewing different literature shows four eras in the historic evolution of courtyards; a) ancient civilisations from North Africa to China, b) Classical civilisations in Greece and Rome, c) the Middle Ages and Renaissance civilisations involving the Islamic world as well, and d) the Modern Era.

4.2.1 Ancient Civilisations

Schoenauer and Seeman (1962) suggest in their book "The Court-Garden House" that the most primitive and homogeneous society to build courtyard houses was probably the one that built the Troglodyte villages in the Matmatas of Southern Tunisia. "*Each dwelling-unit is built around a crater open to the sky, having sloping walls and a flat bottom, which is the court*" (Schoenauer & Seeman, 1962, p13). This primitive building form was preceded by the 'douars' in North Africa, the encampments of nomadic tribes in West Africa, the "Kraals of Bechuanaland" in South Africa and the first rectangular dwellings in Morocco. Schoenauer and Seeman consider that the 'noualas,' the rectangular compound dwellings of Morocco, mark the transition between the primitive douars and the later conventional courtyard houses.

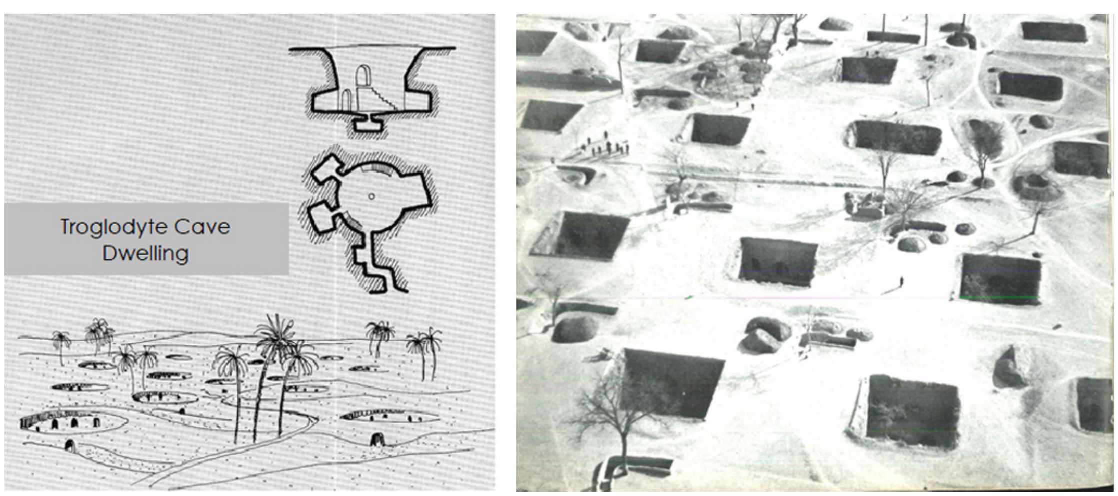
Around 2000–1500 B.C., similar houses were built in the Indus valley using the same philosophy. The houses were designed as a series of rooms opening on to a central courtyard (Nangia, 2000).

In another part of the world, the early Chinese houses were highly influenced by the principles of Yin and Yang. As we can see in figure 5 there is a striking similarity between the simplest form of Chinese underground settlements in Honan and the Troglodyte dwellings in Tunisia.

4.2.2 Classical Civilisations

The Classical Age of architecture, marked by sophisticated Greek and Roman design and planning, bears evidence to the universal appeal of courtyard houses. The Greeks discovered the thermal advantage of courtyard buildings and then, they designed their homes in a manner to allow low winter sun in the courtyard, while blocking the high summer sun by the overhanging eaves on the portico (Hinrichs, 1989, p. 4).

FIGURE 5. (left): Troglodyte Cave Dwellings in Tunisia (from Schoenauer and Seeman 1962), (right): Chinese Underground courtyards in Honan (from Rudofsky, 1964).



The Romans were later inspired by the light and airiness of Greek peristyle[1] houses and the atrium houses of the Etruscans. In this period of time, we can see the Roman atrium houses with two interior courts, the peristyle and the atrium. This atrium however was not a real courtyard according to the definition; it was almost entirely roofed with the exception of a small opening in the middle.

4.2.3 The Middle Ages and Renaissance Civilisation

During the Middle Ages the only traces of courtyard houses were found in Italian cortile[2] houses and monastic cloisters. Sullivan (2002, p. 102) observes that the "*Benedictine monastery life typically revolved around a central, enclosed, four sided space with a roofed walk about which the monks came to study and to meditate*."

After this period, courtyard houses can be seen in other regions bordering on the Mediterranean (in the Muslim countries of North Africa and the Middle East) (Schoenauer & Seeman, 1962). The four season Persian houses, the more refined interior gardens, the simple Arab houses, the unpretentious exterior with interior splendour of the Syrian (Damascus) houses all are results of the basic Islamic dwelling philosophy of "*privacy and seclusion with a minimal display of the occupant's social status to the outside world*" (Schoenauer & Seeman, 1962, p 29). During this period, underground spaces were added to the Middle Eastern courtyard buildings. These spaces were cellars or storages for food and water. Moreover they were used for sleeping in the hot days of the year. Hinrichs (1989) describes the Islamic adaptation of courtyard houses as an 'oasis concept.' The proportions of these buildings maintained a beautiful responsiveness to the hot-arid climate in most of the Muslim countries—"*where there exists an intentional contrast between the stark, bright, heat of the outside and the intimate confinement, shade, and coolness of the Dar*[3]*'s interior*" (Hinrichs, 1989, p3).

Courtyard houses were also popular in northern areas around the Mediterranean Sea, especially in southern Spain. The courtyard buildings here appeared in two main forms, gardens and patios. Nowadays, patio buildings can also be seen in Latin American countries like Mexico.

4.2.4 Courtyards in the Modern Era

In the last two centuries, the courtyard building form reached the West Coast of North America by the influence of the Spanish Colonial Revival movement in Southern California in the late 19th century. In this regard, Polyzoides et al. (1982) in their book "Courtyard Housing in Los Angeles: A Typological Analysis" argue that the huge influx of immigrants between 1880–1930 created an intense pressure for housing. "*Even the availability of land and easy mobility, however, could not deter denser clusters in the form of courtyard housing forms appearing within the city"* (Polyzoides et al., 1982, p. 12). Then, the courtyard type moved across the United States to the East Coast only after the period of Depression, when Marcel Breuer first conceived the idea of separating living and sleeping areas by implementing a courtyard.

In Europe, mass courtyard houses became a popular form though, Macintosh (1973) warns that these dwellings had nothing to do with the earlier precedents in architecture. He observes that the *"... symmetrical quadrangular plan has been reworked*" (p.8) since the early twentieth century. Generally, the single storey mass courtyard housing in Europe was mainly a social response to the housing demand for the low income working class. In Europe, Macintosh observes that the first modern detached court house overlooking a garden on the south was built by Hugo Haring in 1928. This style was later adopted into an L-shaped plan by two Bauhaus architects, Hannes Meyer and Ludwig Hilberseimer. This L-shaped modification of the quadrangular court-house became popular in both Germany and England by the 1950s and 1960s. Finally, courtyard architecture still survives today in almost all countries of the world, either in its original rectangular form or in modified shapes (Das, 2006).

5. IMPACTS OF COURTYARDS

5.1 Social-cultural Impacts

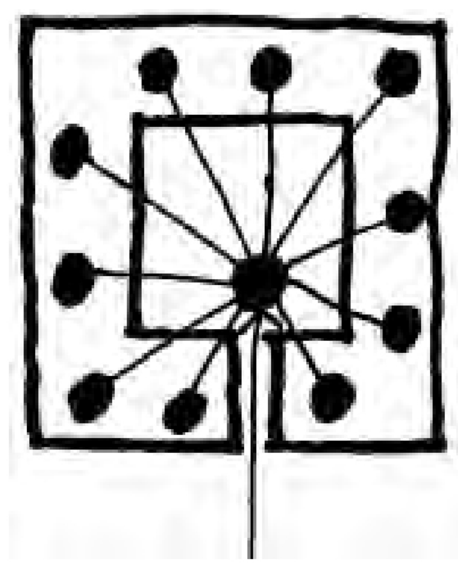
One of the biggest advantages of courtyards is the privacy caused by surrounding elements (buildings, rooms or walls) (Rapoport, 1969), (Kamau, 1979), (Fathy, 1973). This characteristic provides a safe place for rest, play with children, worship (meditation), activities and exercise. In this regard, different courtyard shapes are suitable for kindergartens, schools, ritual spaces (great mosques, basilicas), hospitals (places which are supposed to provide a quiet area for treating patients) and even prisons. In courtyard houses, the court acts as an outdoor room. This room can be used as an extension of the kitchen during mornings or as an extension of the living room during evenings for instance to entertain guests (Das, 2006). Moreover, visual privacy in a courtyard is an important item in Islamic and Middle Eastern countries. Furthermore, the buildings or rooms around a courtyard attenuate noises from surrounding buildings or from the street. Finally, since most of openings of this building shape is from the centre part, safety and security is increased.

5.2 Formal Impacts

Among all of the spaces of a courtyard building, the courtyard has the best view and access to the other spaces. On an urban scale, we can see that a central courtyard can be developed to an arena (or a stadium), a city centre, an urban block or a university campus (Abu Lughod, 1969), (Rapoport, 1986).

Rapoport (2007) discusses the formal impact of courtyard houses as an important attribute after their privacy: "*the courtyard itself provides a critically important setting or subsystem of settings, within which specific activities occur as part of a larger system of activities, within a larger system of settings (which is the dwelling)*" (Rapoport, 2007, p. 59).

FIGURE 6. Courtyard house in terms of access (Rapoport, 2007).



5.3 Environmental Impacts

One of the main reasons that courtyards have survived for more than 5000 years, is their potential to provide a thermally comfortable area for living. Courtyards can be a source of fresh air, light and heat or coolness. They have been generally referred to as a microclimate modifier in the house due to their ability to reduce peak temperatures, to channel breezes and to adjust the degree of humidity. Courtyards have been used in hot, temperate, tropical and snow climates with different characteristics.

The simple idea of including an open space (like a courtyard) in a building comes to mind when we need natural lighting, heating, cooling and ventilating in a solid building. Wadah (2006) numbers three main factors in the climatic function of a courtyard building; sun, wind and humidity.

a) Sun: Raydan (2006) discusses that courtyard buildings somewhere are sun collector and somewhere sun protector. In this regard, it is important to consider sunlight in addition to the thermal effect of the sun. Therefore, the correct orientation of the buildings and its court and the proper position of the void (court) in a solid mass (building) should be taken into account.
b) Wind: wind has two effects on a courtyard building. First it circulates between exterior space and inside the court; second it ventilates the interior building by the court air. In this regard, in hot areas during the night, warm air rises and exits the court. Then, the cooler air will enter to replace the exiting air. Hence, during the hot day, cool air is circulated to the rooms and the court can be a source of fresh and cool air (Al- Hemiddi & Al-Saud, 2001). In snow regions there is limited circulation between the court and the building. Moreover, in tropical regions, where the temperatures of outside and inside the building are close to each other, the court is used for refreshing the interior air.
c) Humidity: different natural elements can be utilised in the courtyard to increase the humidity. Humidity is needed in arid areas to achieve comfort by increasing the relative humidity of the air. Plants and water elements are the major elements used in hot and arid areas. The evaporation and corresponding increase of humidity are a result of sun and wind (Beazley, 1990). Obviously, in other climates in which humidity is not required, fewer natural elements are used.

6. COMPARATIVE CHARACTERISTICS OF COURTYARD BUILDINGS IN FOUR CLIMATES

In this section, the paper reviews the characteristics of courtyard buildings in four different climates: a hot climate, a snow climate, a temperate climate and a tropical climate. It is assumed that a courtyard house receives sun and wind from the courtyard only and the outdoor facades of the buildings are not considered as sources of heat, light or wind. Characteristics of courtyards in these climates are different in terms of the following criteria:

a) Configuration of the courtyard:
Since a courtyard can be a source of natural heating, cooling, ventilating and lighting, it is important to know the optimum shape and dimensions of the courtyard. The lengths of different facades of the building result from the dimensions of the courtyard. In addition, the size of the courtyard can affect the amount of breeze that can be employed for natural ventilation. Moreover, the position of the courtyard divides the building into four blocks. These blocks can be similar or different in size. Changing the symmetry of the building may provide different characteristics and indoor environments, which will be discussed for different climates in the next section.

b) Natural elements:
Using natural elements is an important device to make a courtyard a more comfortable area. Natural elements such as water pools, fountains, trees, shrubs and lawns affect the microclimate of a courtyard building (Givoni, 1991). These elements can on the one hand absorb, distribute or reflect solar radiation, and on the other hand cool air

by evaporation or evapo-transpiration (Bahadori, 1978). As a consequence, they can be used as temperature and condition modifiers while also influencing the heating and cooling loads of the building (Das, 2006). Too much vegetation, however, can also increase the energy consumption of artificial lighting if they reduce daylight entrance into the building.

c) Openings in different facades:
A courtyard can be a source of natural lighting for the building. In this regard, the amount of sunlight on different facades of a courtyard building is related to climate and latitude. Therefore, it is important to consider the climate in which the building is located when designing the size of openings (because natural lighting also affects the indoor (visual) climate of a building and solar radiation influences heating and cooling loads).

6.1 The Courtyard in a Hot Arid Climate

The courtyard is one important solution used in hot and arid climates to create a pleasant and comfortable outdoor space (Safarzadeh & Bahadori, 2004). Field measurements in the traditional courtyard houses of the Tunisian Sahara showed that the indoor building temperature was about 27°C when the ambient temperature was 49°C (though other factors like using high thermal mass and small windows helped to achieve this lower temperature) (Cole, 1981).

The primitive kinds of courtyards in hot and arid climates were like caves or underground buildings like Tunisian and Chinese underground courtyards shown in figure 5 (Schoenauer and Seeman, 1962). Through time, humans understood how to control solar radiation and protect the house from hot weather and provide a certain level of coolness. Using optimised dimensions and natural elements like trees and a water pool helped to increase shading and evaporative cooling. Here we can see the different characteristics of courtyards in hot climates:

FIGURE 7. A Courtyard house in hot arid climate of Iran, city of Kashan (Courtesy of Sara Fadaei Nejad).

a) Configuration of the courtyard:
In comparison to snow and tropical climates, courtyards in hot areas are the biggest ones. Apparently, the bigger courtyard allows more natural lighting into deeper parts of the building. However, more solar radiation increases the temperature. Therefore, vegetation and water pools will play a key role here. In other words, it is possible to plant deciduous trees which provide shading in summer and allow sun penetration in winter. In addition, the big courtyard was usually used for daily activities in the afternoon and also for sleeping during the night when the ambient temperature was acceptable.

TABLE 2. A study in two cities of Syria shows the high ratio of void to solid (courtyard/ the whole building) in a hot arid climate (Table after Wadah, 2006).

House	Total area m^2	Built area m^2	Courtyard area m^2	Courtyard/ building
Romia (Damascus)	450	316	133	0,29
Alshamameet (Damascus)	361	264	97	0,26
Mardam Beik (Damascus)	579	404	173	0,29
Fakhri Al Baroudi (Damascus)	945	575	370	0,39
Al Saboun khan (Aleppo)	2480	1670	810	0,32
Al Farrarien (Aleppo)	2484	1706	777	0,31

Courtyard dwellings in hot climates are known as 4 seasons' houses. In the northern hemisphere, the northern part of the house faces the sun and receives the highest amount of sun during the winter. In contrast, the courtyard facade of the southern part faces north and hardly has less solar exposure. Therefore, the southern part is suitable for hot summers. Consequently, in hot climates, the area of the southern part is bigger than the northern one, because on most days residents preferred to live in the cooler part of the house. Likewise, the western part has a bigger area compared to the eastern one because the eastern part receives the sun from the hottest time of the day (afternoon) till sunset (Petruccioli, 2006).

b) Natural elements:
In hot climates, the use of trees and water pools is common not only for courtyard buildings, but also for different open and transitional spaces. Using deciduous plants is a very effective strategy to reduce the temperature because of its shading and evaporative cooling. Because of this evaporation and evapo-transpiration, the humidity in the courtyard is increased as well (Raydan et al., 2006). Having adequate water, Southern Europe employs fountains to create an evaporative cooling effect (Edwards et al., 2006).

c) Openings in different facades:
In hot climates, the sizes and the numbers of openings in different facades of courtyard buildings differ. The northern façade which faces south in hot climates is very important because it receives solar radiation before and after noon (the hottest time of the day). This façade normally involves a porch that reduces the solar irradiation (Hyde, 2008). In this regard, the size and number of windows in this façade is smaller than in the opposite façade; the southern façade has more windows and with a larger size. Likewise, the eastern façade facing West, has smaller and less openings compared to the western façade; the eastern façade receives sun in the afternoon when the temperature of the eastern block has gotten warm during the day. Therefore the amount of sun needs to be reduced. The western façade, in contrast, has reduced in temperature during the night and needs more sun in the morning. Therefore it has larger and more openings (rather than the eastern façade).

FIGURE 8. Differences of size of openings between southern façade and northern façade in a courtyard house in hot arid climate of Iran (courtesy of authors).

Case Study on the Cooling Effect of Courtyards

Several case studies have demonstrated why the temperature inside courtyards in hot and arid climate is significantly cooler than the outdoor environment (e.g. Fathy, 1986; Bahadori, 1978; Roaf, 1990; Etzion, 1990; Meir, 2000; Bagneid, 2006). Among these studies, Ahmad et al. (1985) monitored a six-century-old courtyard house in a traditional neighbourhood of Ghadames, Libya during summer and winter and compared it to a modern detached house within a new urban development. In summer, the outdoor temperature ranged between 20°C and 40°C. During this period, the temperature inside the traditional courtyard house remained almost constant at 28°C, while inside the modern detached house it ranged between 34°C and 39°C. During winter, the ambient temperature ranged between 4°C and 23°C, while the temperature inside the traditional courtyard house remained nearly constant at 12°C. During winter, the indoor temperature of the modern house ranged between 12°C and 14°C. The researchers made a comparison between the two houses regarding the roof/floor area, exposed/floor area, window/floor area, perimeter to floor area, and the overall heat transmission coefficient, all of which showed much lower values for the traditional house.

Of most importance to this study is the fact that the mass/floor area ratio of the courtyard house was double that of the modern house (1620 kg/m^2 versus 3173).This study also showed the thermal comfort superiority of an indigenous courtyard house over a modern pavilion-type house (Ahmad et al., 1985).

TABLE 3. Comparative thermal data for the old and new houses at Ghadames (Ahmed et al., 1985).

Thermal Parameter	Old house	New house
Roof/Floor area	0.5	1
Exposed/Floor area	0.52	4
Window/Floor	0.006	0.1
Perimeter/Floor (m^{-1})	0	0.7
U (W/m^2°C)	1	2
Mass/Floor (kg/m^2)	3173	1620

6.2 The Courtyard in a Snow Climate

Courtyards in snow climates are more introverted. The dimensions of the courtyard are smaller because of limiting heat losses caused by the open courtyard; moreover, the building needs less ventilation in this climate. In contrast, the building needs natural heating during winter and also natural lighting all over the year. Finally, a courtyard in this climate acts as a temperature moderator and provides a comfortable area for living (Manty, 1988).

a) Configuration of the courtyard:
   In a snow climate, the northern block of a courtyard house is the largest part of the building. This block receives the highest amount of sun and light during winter. In contrast, the southern block receives the least amount of sun. Therefore, this block is the smallest block in courtyard buildings as it has sun only a few days of the year. The eastern and western blocks are larger than the southern block as they receive more sun compared to the southern block. The areas of the eastern and western blocks are normally equal in size in this region (Martin and March, 1972).

b) Natural elements:
   Natural elements are supposed to reduce the solar radiation and increase the humidity in hot climates. Therefore in snow climates, we have just few deciduous trees in courtyards. These trees allow the building to have shading in summer, and sun in winter.

c) Openings in different facades:
   In snow climates we need more sun and therefore, we don't see porches or any other heavy solar shading device; rather, we have eaves to prevent precipitation from hit-

FIGURE 9. Less natural elements in European urban courtyards in cold regions; Stockholm, Sweden. The courtyards are designed to obstruct the cold winds (picture from Google Earth).

ting the facades. These eaves also block the summer sun but allow the winter sun to penetrate into the house. Moreover, the size of the openings (windows) in all facades is smaller than in case of the courtyards in hot areas for large openings cause large heat losses (Shokouhian et al., 2007).

6.3 The Courtyard in a Temperate Climate

Courtyards in temperate climates are varied in terms of size; they are very small (like patios) and very large (like an urban courtyard). In patios, the dimensions of the courtyard are smaller because there is less need for natural heating or cooling; moreover, the building needs less ventilation in this climate. On the other hand, courtyards on an urban scale have different functions beyond environmental.

a) Configuration of the courtyard:
In a temperate climate, different blocks of a courtyard house are similar in case of size and dimensions since they are not deeply dependent on sun to compensate heating or avoid overheating.

b) Natural elements:
In temperate climates, natural elements only function as greenery. They are rarely used for their cooling effect. Therefore, they are not as important as in hot and arid climates.

c) Openings in different facades:
In temperate climates openings are larger than in hot and snow climates since the temperature is moderated. Therefore, the need for natural lighting and solar heat enlarges the windows (like the conservatories attached to a building to capture more light and solar radiation). Moreover, natural ventilation is not only a cooling strategy for hot climates. Natural ventilation can eliminate or drastically reduce the use of air conditioning in temperate climates.

Case Study on the Daylighting Effect of Courtyards

In a study regarding daylight factor in courtyard buildings, Ntefeh (et al, 2003) assessed the performance of different courtyard shapes. Their work presents the influence of the courtyard shape and its orientation on natural lighting duration and illumination levels of the ground and facades. The study was based on simulations with the SOLENE model developed by

FIGURE 10. Two small courtyards (patios) in Amsterdam (courtesy of Kees Hummel—left and ARHK—right).

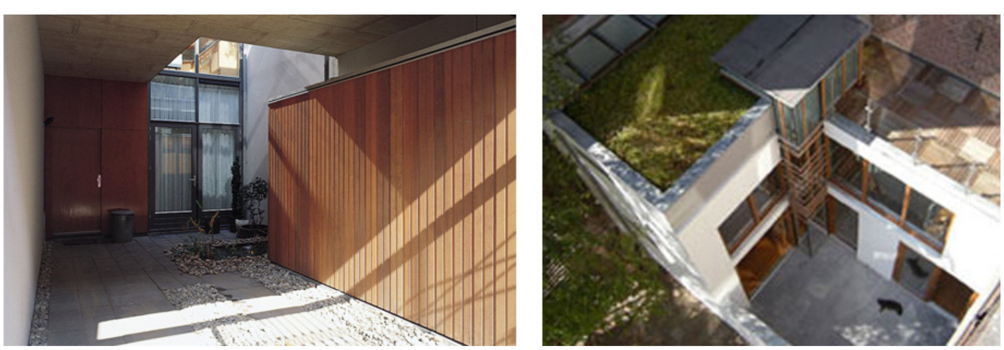
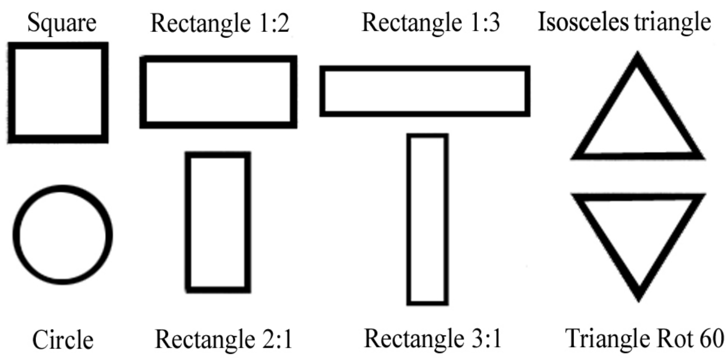


FIGURE 11. Solar simulations; in grey the surfaces receive less than two hours on winter (Ntefeh et al, 2003).



CERMA laboratory (at Ecole d'Architecture de Nantes). This model uses geometric modelling for the calculation of sunshine duration, and the radiosity method for the calculation of the amount of daylight (Groleau and Miguet, 2002). The choice of shapes studied was based on a group of existing courtyard buildings found in Mediterranean countries. The regular forms of square, rectangle, triangle and circle are mainly used, according to several orientations.

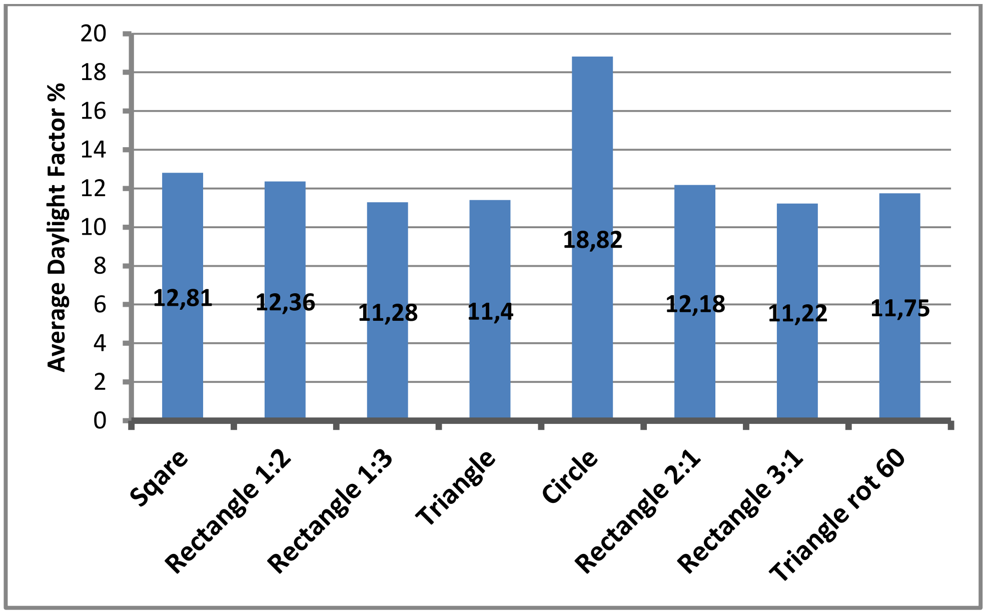
By comparing the different forms, the results show that the rectangle ratio (2:1) has the highest values in case of solar protection on summer and heat gain on winter. As the square form and the rectangle ratio (3:1), it appears more adequate compared to the others. Moreover, the square shows a good illumination of both facades, and the courtyard itself. The rotation angle 90°ccw gives an improvement in terms of solar protection in summer and heat gain in winter, as well as the rotation angle of 60° applied to the triangle. The results obtained in this case are more powerful compared to the triangular one.

On the contrary, the results of the circle are contradictory. This form presents a highest level of illumination and heat gain in winter, and the lowest level of solar protection in summer. Nevertheless, in this shaft form of patio, the upper levels are almost always exposed to the sun, and the four lower floors can't receive sufficient light and heat gain in winter. It seems that the obstruction of the sky, due to the higher number of levels, has not provided the best

TABLE 4. Daylight factor (%) on interior facades and in courtyard (Ntefeh et al, 2003).

Height on Façade (m)	Square	Rectangle (1:2)	Rectangle (1:3)	Isosceles Triangle	Circle	Rectangle (2:1)	Rectangle (3:1)	Triangle (rot 60)
Ground (0)	9,5	9,87	9,2	9,41	16,5	9,32	9,2	9,45
1,5	2,81	2,57	2,06	2,39	6,58	2,53	2,09	2,45
4,5	3,81	3,47	2,83	3,21	8,33	3,42	3,84	3,22
7,5	5,33	4,81	3,91	4,47	10,8	4,67	3,9	4,47
10,5	7,55	6,85	5,61	6,34	14,16	6,83	5,65	6,35
13,5	11,04	10,11	8,45	9,2	18,51	9,96	8,45	9,21
16,5	16,18	15,14	13,26	13,68	24,11	14,99	13,23	13,69
19,5	23,75	23,08	21,61	20,77	31,02	22,8	21,29	20,78
22,5	35,36	35,35	34,64	33,16	39,45	34,79	34,52	33,18

FIGURE 12. Average daylight factor % on facades from ground floor to upper level (Ntefeh et al, 2003).



solution for the thermal comfort and human use in habitat, especially in terms of heat gain in winter. The degree of openness to the sky is more important for illumination and solar heat gain in winter. By considering the requirements for daylight access in winter, it seems that the apartments should be placed in the sunny part of building on the upper levels or on the western, eastern, or southern facades. This implies a solar protection in summer especially on the last proposition (Ntefeh et al, 2003).

6.4 The Courtyard in a Tropical Climate

Among the four natural climatic functions of courtyards (heating, cooling, ventilating and lighting), heating does not have to be considered in case of courtyards in a tropical climate. In tropical climate, design consideration for ventilation frequently gains precedence over the concerns of shading, unlike in hot-arid climates. The characteristics of these courtyards mainly capture wind and breeze to ventilate the building (Salmon, 1990). Therefore these courtyard buildings are extroverted. Instead of solely considering the sun as in the other climates, in tropical climates, the wind direction for ventilation is mainly considered. Moreover, solar penetration needs to be limited (Fry and Drew, 1964).

a) Configuration of the courtyard:
In tropical regions, courtyards are designed to receive less solar radiation because there is no need for heating. Courtyard buildings are taller than in the other climates (Givoni, 1994), (Ghobadian, 1998) and narrow courtyards increase more cross ventilation (Das et al., 2005). The buildings also have tall parapets to block the sun incident on the roof. "*The difference between the central yard in this climate and that in hot and dry climate is that there is no entirely closed connection between internal spaces of building and those of External*" (Shohouhian and Soflaee, 2005).

b) Natural elements:
In a tropical climate there is a high level of humidity. Therefore natural elements are affected by both humidity and temperature. Water pools are not seen here because evaporation is limited. Besides, if there were some amount of evaporation, the relative humidity would only further increase. In addition, the trees used in these climates have leaves all year round (Akbari et al., 1990).

c) Openings in different facades:
Providing suitable openings is the most important design strategy used in these climates. The facades of courtyard buildings in these climates have the highest level of porosity to capture local winds and breezes for ventilation. These courtyards also have porches in different facades because these semi-open spaces provide a comfortable area being shaded while at the same time receiving natural ventilation.

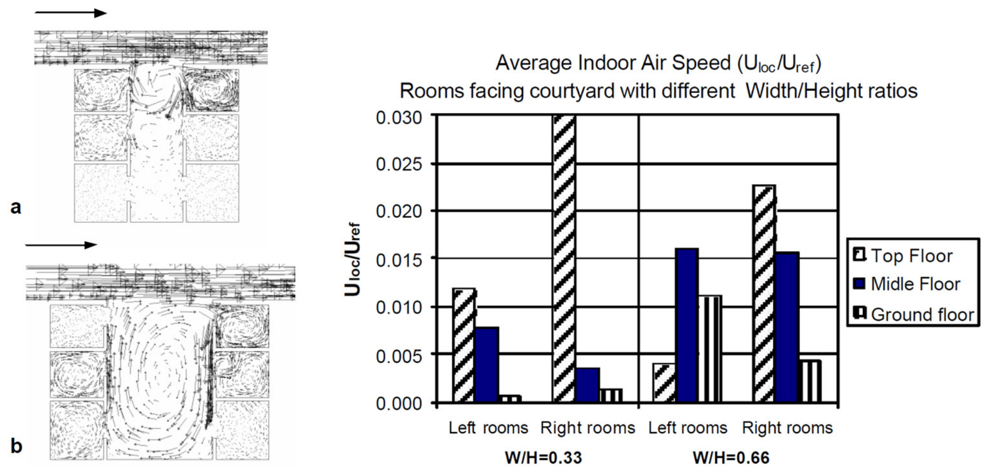
Case Study on the Ventilation Effect of Courtyards

It is well documented in literature that courtyards in tropical regions are mainly used as a source of ventilation. Tablada et al. (2005) made a comparison between two different geometries of courtyards in terms of wind flow characteristics and indoor air speed using validated Computational Fluid Dynamics (CFD) simulations and wind tunnel experiments. The simulations were isothermal, and thereby only the wind acted as a driving force. The dimensions of the two courtyards are 9 m height by 3 m width with a ratio W/H = 0.33 and 9 m by 6 m with a ratio W/H = 0.66. Rooms facing the courtyard with open windows were analysed in terms of average indoor air speed which was obtained from three lines up to the height of 2 metres inside each room. This average value considers the possible locations of the occupants inside the room.

Figure 14 shows the air flow in the two courtyards with different aspect ratios. In the narrow courtyard, the presence of open windows generates more than one vortex coinciding with the number of floors. In contrast, in the wider courtyard (second one), the influence of the open windows on the air flow in the cavity is less pronounced. As a consequence, the main vortex inside the courtyard is not affected. Moreover, it is observed in figure 14 that the air speed values inside the rooms are quite different between the different floors and the different

FIGURE 13. Porous facades and large openings in tropical region of Persian Gulf. The openings facilitate natural ventilation (courtesy of Sara Fadaei Nejad).

FIGURE 14. Average indoor air speed given as U_{loc}/U_{ref}. U_{loc} = local air speed, U_{ref} = reference air speed at 10m height. The values are given for both cavities ratios, on the left: W/H = 0.33, on the right: W/H = 0.66 (Tablada et al., 2005).



rooms at both sides of the courtyard and between both cases with different courtyard ratios. The top floor rooms of the narrow courtyard (W/H = 0.33) have higher air speeds than the top floors of the wider courtyard (W/H = 0.66) since they catch most of the air flow entering the courtyard cavity, provoking that the rooms on the lower floors have much lower air speeds. However, in the case of the wider courtyard, the rooms on lower floors have more similar and higher air speeds than in the rooms facing the narrow courtyard (Tablada et al., 2005).

7. CONCLUSIONS AND DISCUSSION

7.1 Conclusions

As we have seen, courtyard buildings are distributed throughout several places on earth. This universal building shape dates back to 5000 years ago and there are some reasons for this continuity. Among historic, socio-cultural and formal impacts of courtyard buildings, their climatic aspects were discussed in this paper. Table 5 summarises the different characteristics of courtyard houses in four distinct climates: hot arid, snow, temperate and tropical.

The different characteristics are based on climatic needs. The most important results are:

- Courtyards in tropical regions are more connected with the outdoor environment and they have a porous texture. In contrast, courtyards of hot and snow areas are more closed and protected from the harsh environments.
- In case of using natural elements, different types of vegetation and natural elements are used in hot arid climates to balance the environment. However, in other climates, the humidity or cooling effect of natural elements is not needed.
- The amount of openings in different facades have a direct relationship with required ventilation in the indoor environment. In tropical climate we have the largest openings along porches to capture winds and breezes. Moreover, in temperate climate the size of windows are large in order to achieve more sunlight.

TABLE 5. Comparison of courtyard building characteristics in four climates.

Characteristics	Hot arid	Snow	Temperate	Tropical
General Building Shape	• Introverted, • The highest ratio of void to solid • Southern block is the biggest	• Introverted, • The lowest ratio of void to solid • Northern block is the biggest	• Small, deep and narrow patio (to ease stack effect)	• Extroverted, • The ratio of void to solid between hot and snow climate, • Building height is high • Different blocks are equal
Natural elements	• Deciduous trees, water pool, shrub and lawn	• No element	• Few elements	• Rarely deciduous trees
Openings in facades	• Small vertical windows • Including porch	• Small & limited openings	• Large openings including conservatory	• Large openings • Including porch • Porous facades

The results show that courtyard buildings as a flexible shape can have different characteristics to work as a passive strategy in order to maximise the use of natural elements like the sun and wind. The function of the courtyard as a source of natural heating, cooling, ventilation and lighting were discussed in each climate.

7.2 Discussion for Further Studies

The paper considered courtyard buildings in hot arid, tropical, temperate and snow climates. In this regard, courtyards in Mediterranean climates (such as those in Spain, Italy and Greece) can be studied as further climates. Moreover, the following topics are suggested to be studied in future:

- The optimal orientation of courtyard buildings with sun and prevailing wind in case of using natural heating, cooling, ventilating and lighting;
- The optimal proportion of void (courtyard) to solid (the building) in case of using the courtyard as a sun protector or sun collector based on different climates and latitudes.

The above questions are answered generally in the text, but numerical simulations can address exact proportions for the mentioned questions.

Consequently, although some studies have been done in the field of climatic impacts of courtyard buildings, more investigations are needed to understand why this building shape is still working after thousands of years.

NOTES

1. A peristyle is a columned porch or open colonnade in a building surrounding a courtyard that may contain an internal garden.
2. Cortile is an Italian word which means courtyard.
3. Dar is an Arabic term which means "house."

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