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## The courtyard pattern's thermal efficiency: Limits and significance of impact

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**Abstract:** The courtyard pattern has been advocated as a thermally efficient design for hot regions. Many studies have been yielded the suggestion of re-introducing this building pattern for its thermal efficiency. However, it has not been widely investigated to which extent courtyards actually provide thermal comfort for people. By examining the thermal behaviour of 360 courtyards, this paper investigates the impact of courtyards' geometry and orientation on its thermal conditions and occupants' thermal sensation. Baghdad was used as a case study due to its hot climate and traditional use of courtyards. A comfortable temperature for hot climate defined by a previous study was used to judge the tested courtyards. Calibrated Envi-met simulation models have been used to determine courtyards' thermal conditions. The results show that the most effective design parameter on courtyards' thermal efficiency is the courtyard's Width/Height and the most effective climatic factor is the Mean Radiant Temperature. The thermal efficiency increases by having deep and small courtyards. If properly designed, courtyards can provide 4-7 °C less Globe Temperature than the outdoor temperature, while improperly designed ones can be 20°C higher than outdoor temperature. In all cases, courtyard spaces cannot provide thermal comfort if the outdoor Globe Temperature exceeded 38°C.

**Keywords:** Courtyard pattern, thermal efficiency, thermal comfort, Baghdad,

### 1. Introduction

For the last three decades, the courtyard pattern has been widely investigated and analysed to determine its thermal efficiency. It has been concluded that, when properly designed, the courtyard pattern is more thermally efficient than other building patterns in hot climate regions (Edwards, 2006); (Al-Azzawi, 1984); (Al Jawadi, 2011). However, it is still not clear to which extent it is a thermally comfortable space for the people who are adapted to air-conditioned spaces, which is an essential aspect in assessing the courtyard's thermal efficiency (Ghani et al., 2016). This research focuses on this question. To achieve this, first, courtyard pattern's thermal efficiency, thermal comfort and previous relevant literature were explored. Then, a simulation experiment using Envi-met 4.2 was conducted to determine the thermal conditions for various courtyard configurations.

#### 1.1. The courtyard pattern

By definition, the courtyard pattern consists of a building with an open space in its core, which provides access and natural lighting and ventilation to surrounding indoor spaces (Al-Hafith et al., 2017c); (Soflaei et al., 2017). This building pattern has been used in hot regions for a long period until the introduction of modern architectural styles and construction technologies at the beginning of the 20th century (Al-Hafith et al., 2017b); (Sthapak and Bandyopadhyay, 2014). Since that time, modern building patterns, such as detached and semi-detached buildings, have been used, which rely on mechanical air-conditioning to provide thermal comfort. This has led to an increase in running costs, energy consumption and CO<sub>2</sub> emissions (Foruzanmehr, 2015). In the general quest for environmental solutions,

the courtyard pattern's thermal efficiency has been tested and proven experimentally by many researchers, such as Cho & Mohammadzadeh (2013) in Iran, Al-Masri (2012) in the UAE, Al Jawadi (2011) in Iraq, Manioğlu & Yılmaz (2008) in Turkey and Edwards (2006) in Saudi Arabia. They have shown that the courtyard pattern yields more thermally efficient and less energy consuming buildings than modern non-courtyard patterns.

The thermal efficiency of a courtyard building depends on two main strategies: controlling the buildings' exposure to solar radiation and providing sufficient natural ventilation (Ali and Shaheen, 2013a); (Agha, 2015); (Al-Hemiddi and Megren Al-Saud, 2001). In the courtyard space, shading protects from having heat gain resulted from solar radiation (Shaheen and Ahmad, 2011a); (Al Jawadi, 2011). Natural ventilation, brought about by buoyancy created by warm air rising in reaction to release of accumulated heat in the courtyard's surrounding surfaces, helps to get rid of the heat from the courtyard, and will cause the surrounding indoor spaces' hot air to be replaced by cooler air (Moosavi et al., 2014); (Mohammed, 2010). This thermal behaviour is mostly dependent on the courtyard geometric properties, these are width, length, height and orientation (Muhaisen and Gadi, 2006); (Al-Hafith et al., 2017a). If the courtyard space is improperly designed and has inefficient shading and natural ventilation, the performance of the courtyard building may become less efficient than other possible building patterns (El-deep et al., 2012); (Aldawoud and Clark, 2008); (Ratti et al., 2003).

## **1.2. Thermal comfort**

Thermal comfort is one of the factors that affect people's overall comfort in built environments (Al horr et al., 2016); (Frontczak and Wargocki, 2011). It has also relations with health (ASHRAE, 2005), productivity (Elaiab, 2014), energy consumption (Nicol et al., 2012), CO<sub>2</sub> emissions (Elaiab, 2014), and the use of indoor and outdoor spaces (Chen and Ng, 2012). Thermal comfort has been defined by ASHREA as 'that condition of mind that expresses satisfaction with thermal environments' (ASHRAE, 2005); (Enescu, 2017); (Höppe, 2002). Scholars have shown that this subjective feeling is related to the surrounding environments' features and the human body thermal balance (Enescu, 2017); (Elaiab, 2014); (Höppe, 2002).

Within the framework of this definition, aiming at investigating and determining people's thermal sensation and comfort temperature, scholars have explored the key comfort factors that determine thermal comfort (Nicol and Roaf, 2017); (Passe and Battaglia, 2015). It is well known now that these factors can be classified into two groups: quantitative factors and qualitative factors. The former includes air temperature, air velocity, humidity, Mean Radiant Temperature (MRT), clothing and activity levels (Reiter and De Herde, 2003); (Nikolopoulou, 2011). The other category includes various factors such as people's thermal expectation and past experience, time of exposure to specific conditions, people's potential control over climatic conditions, and people's psychological factors (Aljawabra, 2014); (Nikolopoulou, 2011); (Höppe, 2002).

Aiming for a single measure that combines the effective factors to indicate people's thermal sensation and predict thermal comfort limit, various studies have been done since 1905 and more than 100 indices have been developed (Epstein and Moran, 2006); (Fabbri, 2015). These indices have been introduced and used within the framework of two thermal comfort models: the Static model and Adaptive model (Nikolopoulou, 2011); (de Dear and Brager, 2002). The first model depends fundamentally on the thermal balance between the human body and its surrounding environment, proposing a steady and universal thermal comfort limit (Reiter and De Herde, 2003); (Nikolopoulou et al., 2001). Among the widely

used indices of this model are the Predicted Mean Vote (PMV), the Standard Effective Temperature (SET), the Physiological Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI) (Nikolopoulou, 2011). The second model, argues that thermal sensation is dynamic and cannot be found from the human body balance factors only (Nicol et al., 2012); (de Dear and Brager, 2002). It assumes that people can adapt themselves to their surrounding contextual climate and that people from different places and regions are different in their thermal sensations. (de Dear and Brager, 2002); (de Dear and Brager, 1998); (Nicol, 2004); (Nicol and Humphreys, 2002). Thermal comfort limit is defined in this model by conducting thermal comfort surveys (Nicol et al., 2012); (de Dear and Brager, 2002), and using direct thermal comfort indices that combine a number of climatic factors in one value expressing the temperature felt by people. Among the widely used adaptive indices are Dry and Wet Bulb Temperatures, Globe Temperature (T<sub>g</sub>), Wet Bulb Globe Temperature (WBGT) and Operative Temperature (T<sub>o</sub>) (Song, 2011).

Many of these indices and both of the Static and the Adaptive models are used to define the limits in international thermal comfort standards such as EN 15251, ASHRAE and ISO Standard 55 (Nicol et al., 2012); (Rupp et al., 2015). However, studies have shown that the Adaptive model's prediction is closer to the actual people thermal sensation than the Static model, especially in naturally ventilated spaces. The Static model overestimates people thermal discomfort (Kim et al., 2015); (Nicol et al., 2012), and is not applicable in outdoor and semi-outdoor spaces (Rupp et al., 2015). The main reason behind this is that the Static model does not consider the social and contextual factors, people's adaptation abilities and the dynamicity of environments' thermal conditions (Nicol et al., 2012); (Nikolopoulou et al., 2001). Accordingly, to determine the courtyard space's thermal efficiency, the Adaptive model's indices should be used.

### **1.3. Thermally comfortable courtyard spaces - literature review**

The thermal behaviour of courtyard buildings has been the subject of many studies since the 1980s. The aim of most of this work has been to describe, investigate, analyse and determine courtyard buildings' efficiency in providing thermal comfort. Studies have used different approaches, such as real life measurements, surveys and simulation. This has led to a growing awareness about courtyards' thermal behaviour and the various effective factors (Al-Azzawi, 1984); (Meir et al., 1995); (Nasrollahi et al., 2017). This paper classifies the conducted studies in this field according to their defined aims into three categories:

1. Describing courtyard thermal behaviour: this group includes the earlier studies in this field. Their focus have been to explore and describe the courtyard pattern's thermal behaviour. Literature review or real life measurements have been their main research methods. As an example, an early PhD study was conducted at University College London (UCL) in 1984. It included comparing the thermal conditions of three courtyard houses and three non-courtyard houses in Baghdad during two weeks in summer and winter. The study concluded that, in Baghdad's long and hot summer, courtyard houses provide a more thermally comfortable environment than the modern non-courtyard houses (Al-Azzawi, 1984). Other studies in this group with similar results include El-Harrouni (2015) in Morocco, Al-Jawadi (2011) in Iraq, Sadafi et al. (2011) in Malaysia, Manioglu & Yilmaz (2008) in Turkey and Al-Hemiddi & Megren (2001) in Saudi Arabia.
2. Analysing the courtyard thermal behaviour: this group follows and builds on the previous group of studies. Here, more in-depth attention has been paid to the thermal behaviour of the courtyard pattern. The main aim has been to determine the impact of courtyard's geometry, orientation, construction materials, contextual climate and

openings on its shading and natural ventilation and the resulted thermal conditions (Aldawoud and Clark, 2008); (Soflaei et al., 2017); (Nasrollahi et al., 2017). Studies by Muhaisen (2006) and Muhaisen and Gadi (2006, 2005) widely explored and analysed courtyard shading in different contexts. Their main results included that courtyards get better shading by increasing their height, decreasing their Width/Length ratio and having a specific orientation for each geographical location in correspondence with the sun's angles. These results are supported by other studies, such as Al-Hafith et al. (2017) in Iraq and Soflaei et al. (2017) in Iran. Regarding natural ventilation, it has been found that wide courtyards have more active natural ventilation than narrow ones (Bittencourt and Peixoto, 2001). It has also been found that natural ventilation is affected by courtyard's openings size and location (Rajapaksha et al., 2002); (Soflaei et al., 2016); (Mousli and Semprini, 2016). Having cross ventilation enables higher air flow than if there are opening from all sides (Soflaei et al., 2016).

3. Analysing thermal comfort in courtyard spaces: developments in the available research methods, such as building performance simulation and modern meteorological instruments, have enabled researchers to further advance in this field: relating courtyards' performance to occupants' thermal sensation. Amongst the researchers who have investigated this aspect are Soflaei et al. (2017) in Iran, Martinelli & Matzarakis (2017) in Italy, Nasrollahi et al. (2017) in Iran, Mousli & Semprini (2016) in Syria, Ghaffarianhoseini et al. (2015) in Malaysia, Almhafdy et al. (2015) in Malaysia and Berkovic et al. (2012) in Israel. They have used either simulation tools with thermal comfort indices or real life measurements with thermal comfort surveys to assess courtyard occupants' thermal sensation. In the first case, they have mostly used the Envi-met simulation tool with static thermal comfort indices to assess a range of courtyard configurations. In the second case, they have assessed thermal sensation in a limited number of cases with specific configurations.

According to the literature review presented in this paper, it can be concluded that courtyards can, through passive systems, provide a higher level of thermal comfort for its occupants compared to other building patterns. Shading and natural ventilation have a significant impact on courtyards' thermal behaviour. Using an appropriate courtyard design is essential to get the courtyards' thermal efficiency (Ghaffarianhoseini et al., 2015); (Aldawoud and Clark, 2008, Soflaei et al., 2017);(Nasrollahi et al., 2017). However, there are still knowledge gaps that need to be filled:

1. While the impact of courtyard configurations on shading has been intensively investigated, there has been limited work to investigate the impact of courtyard configurations on its thermal comfort related climatic conditions: air temperature, air velocity, MRT and humidity.
2. There has been no attempt to determine the impact of courtyard configuration on an adaptive thermal comfort index to predict people's thermal perception.

## **2. Research's aim and methodology**

This research aims to analyze the impact of the courtyard space's parameters on its thermal conditions and achieving thermal comfort in hot regions. More specifically, it determines the impact of courtyard's orientation and geometrical parameters on its climatic conditions affecting occupants' thermal comfort.

To achieve this aim, this research used Envi-met 4.2, an outdoor environmental simulation tool, to determine the thermal conditions of 360 courtyard configurations during

summer in Baghdad. This city was used as a case study for its extremely hot and long summer and its long history of using the courtyard pattern. Regarding the Envi-met 4.2 simulation tool suitability and validity, further details are provided in Section 2.3.

### 2.1. Research variables

This research has three kinds of variables: Independent variables, mediating variables and a dependent variable (Fig.1). The former represents the causes, the last one represents the results and the mediating variables represent intervening factors. The impact of the independent variables can be seen on mediating variables before reaching dependent variables. Exploring the subject in this way helps to develop a comprehensive idea of a phenomenon (Creswell, 2014).

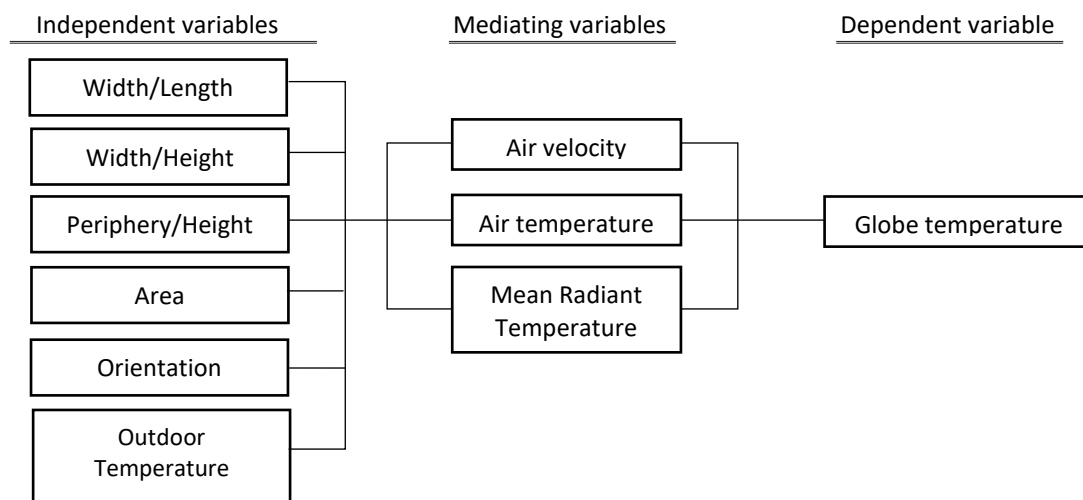


Figure 1. The research variables and their relations

In the research presented in this paper, the dependent variable is occupants' thermal sensation. As the courtyard is a semi-outdoor space (Rupp et al., 2015), the Globe Temperature, an adaptive thermal comfort index, was selected to quantify thermal sensation in the tested configurations. Globe Temperature has been widely used in thermal comfort studies as it has been found that it shows acceptable correlation with the people actual thermal sensation (Toe and Kubota, 2011). As a measurement, it combines the effects of air velocity, air temperature and MRT (Song, 2011). To assess the courtyard ability to provide thermal comfort, a thermal comfort upper limit was defined using the results of a thermal comfort survey conducted by Aljawabra in Marrakech (Aljawabra, 2014). Exploring previous studies showed that the case study in Marrakech, is the closest available study to Baghdad's summer temperature and people culture. According to this study, the maximum Globe Temperature that people may accept in summer is 36°C.

The independent variables are the courtyard's ratios of Width/Length (W/L), Width/Height (W/H), Periphery/Height (P/H), the ground area and long axis orientation. These parameters have been defined as the effective variables on courtyard's thermal conditions (Muhaisen, 2006); (Al-Hafith et al., 2017a). The ground area has been rarely investigated in previous studies, but the research presented in this paper included it in its analysis for the impact of the distance between the subject and the courtyard's surfaces on MRT, which cannot be captured by the other variables (ASHRAE, 2005). Outdoor Globe temperature (Tgout) is the final independent variable, which is uncontrolled and not related to courtyard's configuration, but is essential to have a comprehensive analysis, as the courtyard is a semi-outdoor space. Globe temperature was selected to represent the

outdoor condition because it includes three climatic factors and can be used to make comparisons with this research's thermal sensation index.

Mediating variables are the courtyard's climatic conditions that affect its Globe Temperature, this research thermal sensation index, which are air temperature ( $T_a$ ), MRT and air velocity ( $A_v$ ) (Song, 2011). To have a comprehensive analysis of people's thermal precipitation in courtyards, this research determines the impact of the courtyard configurations on each of these variables. As it is stated in Section 2, Envi-met simulation tool was used to determine each of these three variables in each of the 360 tested courtyard configurations. Then, Globe Temperature was calculated using a special equation, as it is not measurable in Envi-met.

## 2.2. Tested courtyard configurations

In order to study a wide range of the possible courtyard configurations and their relation to thermal efficiency, 360 courtyard configurations were developed and tested. They include six different areas, five W/L ratios, three heights and four orientations, representing most of the possible courtyard configurations (Figure 2.). These 360 options help to give a comprehensive idea of the impact of each of the effective factors on the environmental conditions and thermal perception.

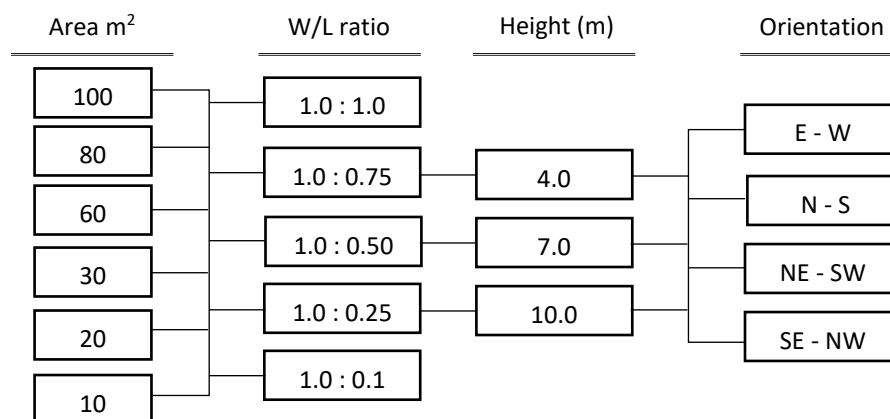


Figure 2. The tested courtyard configurations' variations

## 2.3. The simulation experiment

Envi-met 4.2, a CFD simulation tool, was used to determine the thermal conditions of the selected courtyard configurations. Envi-met simulates the interactions between building surfaces, air and natural elements on a micro scale of urban spaces, such as streets, plazas and courtyards (Berardi, 2016); (ENVI-MET, 2017). It depends on well-based physical and fluid dynamics rules and principles in considering the impact of wide-range effective factors on outdoor spaces' environments. Among the factors that it considers are long and short waves radiation, air temperature, wind velocity, humidity and vegetation (Hedquist and Brazel, 2014); (Malekzadeh, 2009), which are not offered by other similar simulation tools (Taleghani et al., 2015). The software versions before version 4.2 had a number of drawbacks, which included mainly the problem of determining buildings heat storage during the day-time and radiation during the night-time, which led sometimes to inaccurate results (Berkovic et al., 2012); (Hedquist and Brazel, 2014). However, this problem has been solved with the newly introduced improvements on the software during the previous two years (Simon, 2016). Many studies have validated its results by making comparisons between the software simulation results and real-life measurements (Nasrollahi et al., 2017); (Hedquist and Brazel, 2014); (Ridha, 2017).

In order to get true simulation results, the simulation model was calibrated before testing this research's courtyard configurations. For this purpose, simulation results were compared with real life measurements of two courtyard houses in Baghdad obtained from a third party measurement effort (Al-Azzawi, 1984); (Salman, 2016). The reference Baghdadi courtyard houses were modelled in Envi-met, then their courtyards' surfaces properties were fine-tuned until the simulation results became visually similar to the real life conditions (Figure 3). To check the validity of the calibration and the accuracy of the results, a typical equation used in literature for quantifying accuracy was used: Coefficient of Variation for the Root Mean Squared Error (CV-RMSE) (Eq1). This equation gives a percentage showing how close the simulation is to real life conditions. Lower resultant values indicate a better-calibrated model (Bagneid, 2010); (Haberl and Bou-Saada, 1998). According to ASHRAE standard, for hourly data simulation, the simulation model can be declared to be calibrated if the result of this equation is within  $\pm 30\%$  (Bagneid, 2010).

$$CV-RMSE = ((\sum (D_a - D_d)^2 / P - 1))^{0.5} / D_{aa} \quad \text{----- (Eq1)}$$

where :

$D_p$  = the predicted data,  $D_a$  = the actual data,  $D_{aa}$  = the average value of the actual data,  $P$  = the number of data points

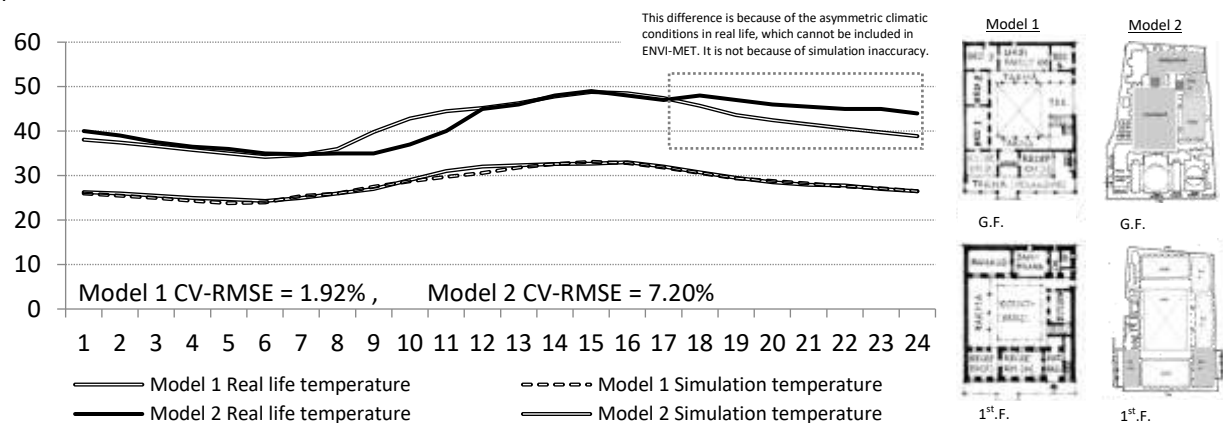


Figure 3. The comparison between courtyard house's real and simulation temperature (to the left), and the plans of the used Baghdadi courtyard house to the right.

A simulation experiment was carried out for Baghdad's climate on the 12th of July, the hottest day, to determine the courtyard performance in the extreme scenario. Hourly climatic data of this day was obtained from unpublished data of the Iraqi meteorological organization for 2016. The conditions and parameters used in the software configuration file are shown in Table 1, which were based on this research's objectives and calibration, and settings used in previous similar studies (Nasrollahi et al., 2017); (Jiang, 2017).

Table 1. The values used in the software configuration file

Simulation parameters	Input value	Material parameters	Input value
Start date	12/07/2017	Thickness	0.30 m
Start time	00:00:00	Absorption	0.80 Frac
Total simulation time	32 (hours)	Transmission	0.00 Frac
Output interval for file	30 (minutes)	Reflection	0.05 Frac
Wind speed	3.1 m/s	Emissivity	1.10 Frac
Wind direction	45	Specific heat	1300.0 J/(kg*k)



Roughness length	0.01	Thermal conductivity	0.30 W/(m*k)
Max Tem. and time	49.8 °C at 16:00	Density	1000.0 kg/m <sup>3</sup>
Min Tem. And time	35.1 °C at 06:00	<b>Note:</b> <ul style="list-style-type: none"> <li>The first six hours of simulation results were not considered as the impact of stored heat in buildings on night thermal conditions is missed.</li> <li>All of the not mentioned software's parameters were kept as default</li> </ul>	
Max Hum. and time	53 % at 06:00		
Min Hum. and time	24 % at 16:00		
LBC (Lateral boundary condntions)	Cyclic		

### 3. The simulation results

The results include the air temperature, MRT and air velocity for each of the tested alternatives. The measurements were taken in the centre of the tested courtyards at 1.5m height, which was considered to represent the courtyards' conditions and the perceived thermal sensation by occupants. The Globe Temperature was determined depending on the obtained values using the Globe Temperature equation (Eq2). The result of this equation was used to determine the temperature experienced by occupants in each of the tested courtyards. Comparing the resulted values with the defined comfort threshold of 36 °C determines how close the courtyards are in providing thermal comfort.

$$T_g = (MRT + 2.35 \times Ta \times (Av)^{0.5}) / (1 + 2.35 \times (Av)^{0.5}) \dots\dots (Eq2)$$

#### 3.1. The courtyards' thermal conditions

Exploring the simulation results shows that all of the cases average daily Globe Temperature is greater than the comfort temperature. The lowest value is 41.7 °C and the highest is 50.3 °C (Figure 4). The graph in Figure 5 shows the hourly Globe Temperature in the five courtyards with the lowest average daily temperature and the highest average temperature. It can be seen that all courtyards are not thermally comfortable during the day-time and comfortable during a part of the night-time. However, the difference in Globe Temperature that results from changing the courtyards' parameters is around 20 °C. The courtyards with the lowest average Globe Temperature are the small and deep ones. The inverse can be said about the courtyard with the hottest average Globe Temperature. Regarding the orientation, the results show that (E-W) and (N-S) orientations offer higher chances to provide more thermally comfortable conditions than the other two orientations.

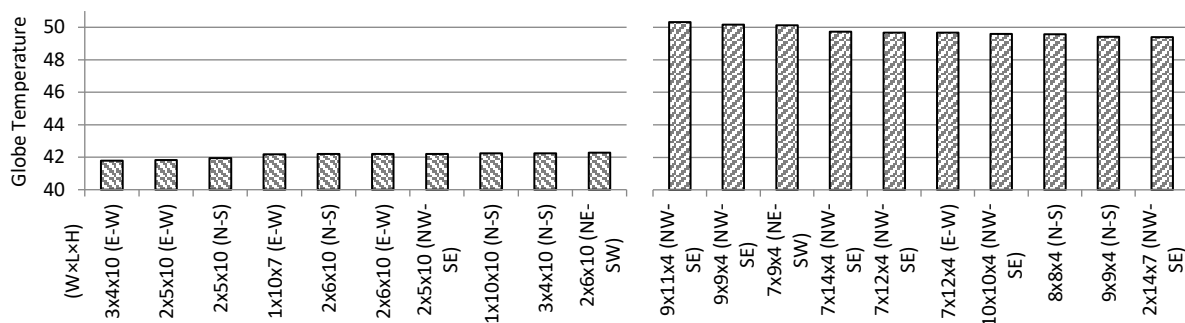


Figure 4. The ten lowest average daily Globe Temperature courtyards (left) and the ten highest average daily Globe temperature courtyards (right).

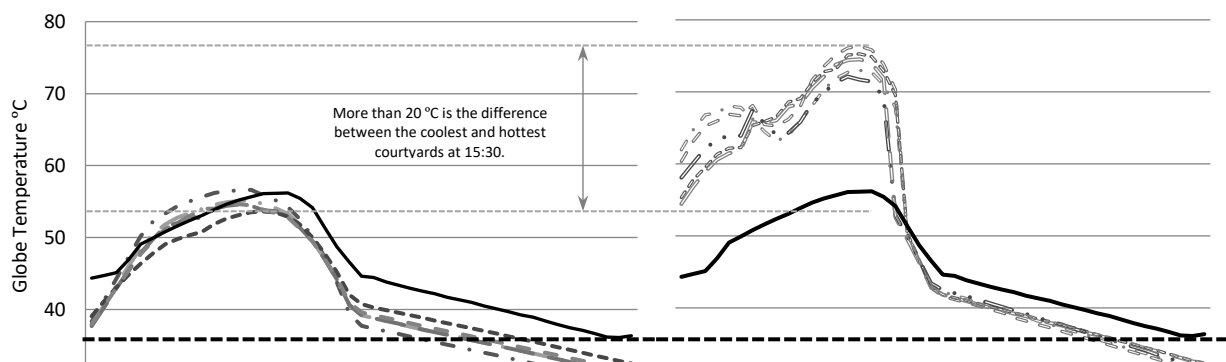


Figure 5. The hourly Globe Temperature in the five most thermally efficient courtyards (to the left) and the worst five courtyards (to the right)

### 3.2. Results analysis

To make useful recommendations and conclusions from the obtained results, it is essential to perform a statistical analysis, which includes regression and correlation analysis.

The results from the correlation analysis in (Table 2) show that there is a statistically significant correlation between all of the research variables ( $P \leq 0.05$ ), except the correlations between courtyards' air velocity and thermal comfort. Regarding the significance of the impact of courtyards' parameters on its thermal conditions, the most effective parameter on its air temperature and MRT is the W/H ratio, while on air velocity; it is the P/H ratio. The most effective courtyard design parameter on thermal comfort is W/H ratio. The most effective climatic parameter on occupants' comfort is the MRT. It is essential also to state that the outdoor conditions, represented here by the Globe temperature, has the most significant impact on occupants' thermal sensation. It has around ten times higher impact than all of the courtyards' design parameters (Figure 6). Regarding the impact of courtyard orientation on its thermal conditions, it was not included in the statistical analysis for being a nominal variable.

Table 2. The results of the correlation analysis

	Statistical Indicators	Air tem.	Air vel.	MRT	Globe temp.
W/L	Pearson C.	0.020	-0.323	0.057	0.063
	Sig. (P-value)	0.011	0.000	0.000	0.000
W/H	Pearson C.	0.056	0.028	0.168	0.160
	Sig. (P-value)	0.000	0.000	0.000	0.000
P/H	Pearson C.	0.043	0.511	0.120	0.099
	Sig. (P-value)	0.000	0.000	0.000	0.000
Area	Pearson C.	0.028	0.389	0.103	0.078
	Sig. (P-value)	0.000	0.000	0.000	0.000
T <sub>gout.</sub>	Pearson C.				0.892
	Sig. (P-value)				0.000
Air tem	Pearson C.				0.736
	Sig. (P-value)				0.000
Air vel.	Pearson C.				0.003
	Sig. (P-value)				0.729
MRT	Pearson C.				0.981
	Sig. (P-value)				0.000
Notes	Sig. : indicates the statistical significance of correlation.				

**Pearson C.:** indicates the strength and direction of the relationship. Positive values indicate positive association between variables and negative values indicate negative association. Higher values indicate stronger impacts.

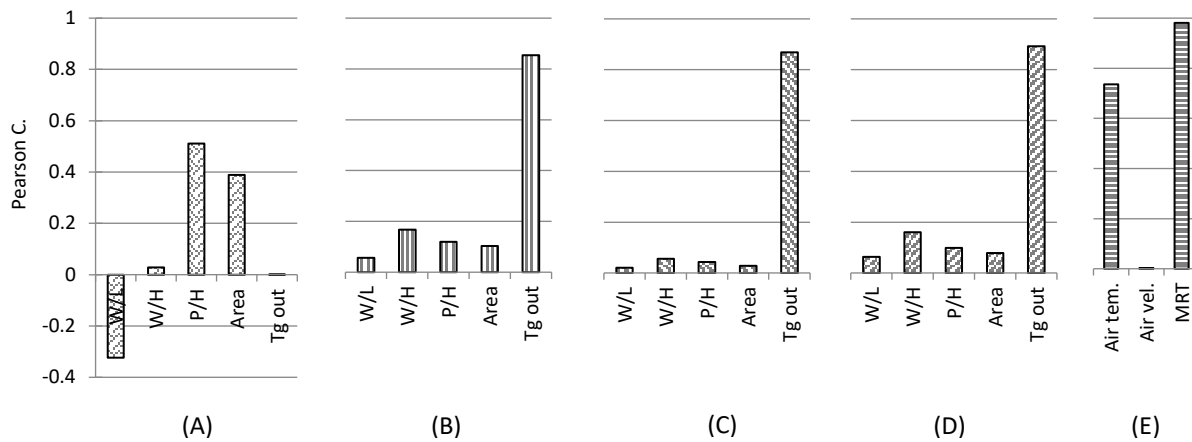


Figure 6. The significance of impact (Pearson C.) of each of the independent variables on Courtyards' air velocity (A), MRT (B), and Air temperature (C). The impact of the independent variables on thermal comfort (D) and the impact of mediating variables on thermal comfort (F)

Regarding the regression analysis, equation 3 was developed to predict people thermal sensation in any given courtyard space in Baghdad, or another location with similar conditions. The explanatory power of this equation (Adjusted  $R^2$ ) is 0.818, which means that 81% of the variation in thermal sensation is explained by the considered variables. From this equation, it can be found that the stated most thermally efficient courtyard from the tested cases can provide thermal comfort if the outdoor Globe Temperature is equal to or less than 38 °C.

$$\text{Courtyard's } T_g = -24.142 + (-0.612 \times W/L) + (3.31 \times W/H) + (0.091 \times P/H) + (-0.12 \times \text{Area}) + (1.47 \times \text{Out } T_g) \quad \dots (\text{Eq3})$$

### 3.3. Results discussion

These results highly agree with what has been concluded in previous literature. On the first hand, similar to this research, it has been concluded by many studies, such as (Aljawabra, 2014); (Ali-Toudert and Mayer, 2006); (Nasrollahi et al., 2017); (Berkovic et al., 2012) and (Nikolopoulou, 2011), that the MRT has the most significant impact on people thermal sensation in hot regions. Accordingly, having less exposure to the solar radiation and less surfaces radiation by having deeper and smaller courtyards will help to have more thermal comfort (Al-Hemiddi and Megren Al-Saud, 2001); (Muhaisen, 2006). This study results also agree with other studies, such as (Rajapaksha et al., 2002); (Soflaei et al., 2016) and (Mousli and Semprini, 2016), regarding the impact of courtyards' width and area on natural ventilation. However, a major difference compared with other studies can be found. Although the results agree with other studies, such as (Berkovic et al., 2012), in indicating a limited impact of natural ventilation on thermal comfort in courtyards, this may seem to imply a major contradiction with the majority of studies, which suggest that natural ventilation is a principal environmental strategy in courtyard buildings (Mousli and Semprini, 2016); (Shaheen and Ahmad, 2011b); (Ali and Shaheen, 2013b); (Agha, 2015). The answer is that this contradiction can be traced to the unrealistic design of openings in the courtyard cases used in the current study and in (Berkovic et al., 2012) study. In the current study, the cases used have no openings, while in (Berkovic et al., 2012) study, the cases have large

opening allowed for solar radiation to access, not just air, which contributes to increasing the courtyards' temperature (Berkovic et al., 2012).

#### **4. Conclusions & recommendations**

The research presented in this paper did a simulation experiment to test courtyards' ability to provide thermal comfort. By taking Baghdad as a case study, it determined courtyards' efficiency in providing thermal comfort and the significance of the impact of each of the courtyards' design parameters on its thermal conditions. Furthermore, it defined the most effective factors on people thermal comfort in courtyard spaces, which all have not been determined in previous literature. The following conclusions and recommendations were drawn from this study's investigation:

1. Courtyards thermal efficiency increases by decreasing the ratios of W/H, W/L, P/H and the ground area, which means having deep and small courtyards.
2. As a semi-outdoor space, the impact of outdoor climatic conditions on courtyards' conditions significantly exceeds the impact of its design parameters.
3. The most effective design parameter on courtyards' air temperature and MRT is W/H ratio, while on air velocity, it is P/H.
4. The most effective climatic factor on people thermal sensation in courtyards is MRT.
5. The most effective design parameter on people thermal sensation in courtyard spaces is W/H ratio.
6. Regarding courtyard orientation, the results show that, for Baghdad and other similar locations, E-W and N-S orientations offer higher chances to provide thermal comfort than NW-SE and NE-SW.
7. The Globe Temperature difference between a properly designed courtyard and improperly designed one is around 20 °C. The highest decrease in Globe Temperature that the courtyard space can offer compared to outdoor temperature is around 4 °C during the day-time and 7 °C during the night-time.
8. Regarding providing thermal comfort, courtyards, without having any passive or active environmental support, cannot provide thermal comfort during summer in hot regions unless the outdoor Globe Temperature is equal to or below 38 °C.
9. For future research, this study recommends determining the impact of other effective factors on courtyards' performance, which might include vegetation and openings. The study also recommends determining the courtyard performance during the whole year and assessing its thermal efficiency using an adaptive comfort model developed for hot regions.

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