Assessing annual thermal comfort extent in central courtyards: Baghdad as a case study

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Abstract

Purpose – Traditional central courtyards have been advocated for being thermally efficient for hot-climate regions. However, exploring previous literature shows that it is not clear to what extent courtyards are truly thermally comfortable. This study determines the level of thermal comfort in residential courtyards in hot-climate regions, taking Baghdad as a case study.

Design/methodology/approach – This study develops a novel Courtyard Thermal Usability Index (CTUI) to quantify the ability of courtyards to provide thermal comfort to occupants. CTUI is the fraction of useable thermally comfortable hours in courtyards of the total occupation hours during a specific period. To operationalise CTUI, the research employs the Envi-met 4.2 simulation tool to determine the annual thermal conditions of 360 courtyards. An adaptive thermal comfort model developed by Al-Hafith in 2020 for Iraq is used to judge simulated thermal conditions and determine CTUI.

Findings – CTUI enables determining the level of thermal comfort courtyards offer to occupants by showing the ratio of the thermally comfortable period versus the occupation period. Results show that, in Iraq, annually, courtyards offer up to 38% comfortable hours out of the total potential occupation hours. The rest of the time the courtyard will not be comfortable, mostly due to overheating. When designing courtyards, the most effective geometric property impacting courtyards' thermal conditions is width/height. The most important microclimatic factor impacting occupants' thermal sensation is mean radiant temperature (MRT). This study can be used to inform designing thermally efficient courtyards for hot-climate regions.

Originality/value – This study presents the first assessment of the thermal efficiency of courtyards in hot-climate regions depending on an assessment of their ability to provide thermal comfort to occupants. The study presents a novel index that can be used to quantify the ability of courtyards to provide a thermally comfortable environment to occupants.

Keywords Courtyards, Thermal comfort, Baghdad, Envi-met simulation

Paper type Research paper

1.Introduction

The traditional courtyard pattern has been widely advocated as an environmentally efficient solution for hot-climate regions (Almumar, 2019; Ali *et al.*, 2013; Edwards, 2006; Sahebzadeh *et al.*, 2020; Hanan and Abumoeilak, 2020). Experimentally, studies have proven that introducing the courtyard space, if it is appropriately designed, can help to provide more thermally comfortable built environments than non-courtyard buildings (Salman, 2016; Al Jawadi, 2011; Kocagil and Oral, 2016). Table 1 lists 17 recent studies as a sample of existing literature demonstrating courtyards' thermal performance.

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Study	Research work and methodology	Results
Akbari *et al.* (2021)	As indicators of thermal comfort in courtyards, this study investigated the shading performance of 10 courtyard houses over a year in Yazd, Iran. The study used the Ecotect analysis simulation tool	Courtyards offer the opportunity to influence the shading conditions during summer and winter, which enables them to provide a higher level of thermal comfort to occupants than other building patterns. The average level of impact over shading in courtyards is 51%
Taleb and Abumoeilak (2021)	This study used the Envi-met simulation tool to determine the thermal performance of four urban spaces: U-shape, linear shape, central courtyard shape and a cluster of four U-shape spaces around a central courtyard space	Results showed the thermal conditions of the examined four spaces vary. Amongst the examined cases, the fourth examined case provided the best thermal conditions with 41.03 °C temperature
Pilechiha *et al.* (2021)	Using the adaptive thermal comfort model and three courtyard houses, this study investigated the impact of occupants' seasonal movement on achieving indoor thermal comfort in courtyard houses in Iran	The study demonstrated that people change their places in traditional courtyard houses around the year to achieve thermal comfort. These houses include spaces that vary in their thermal conditions
Teshnehdel *et al.* (2020)	This study used Envi-met to determine shading and sunlit levels in ten courtyards in Iran, and their impact on thermal sensation. It employed PET and PMV thermal indices	The results of this study show that shading and sunlit levels have a significant impact on thermal comfort and temperature in courtyards
Soflaei *et al.* (2020)	This study used the Grasshopper tool with two plugins to produce 8,600 courtyard forms, and to determine their thermal conditions. The study depended on ASHRAE 55's adaptive model to assess thermal comfort in courtyards	Results showed that thermal comfort in courtyards is significantly affected by courtyards' geometric properties and construction materials
Soflaei *et al.* (2017)	This study introduced a new "shading index" to assess the shading performance of ten courtyards in Iran and to determine shading impact on thermal comfort	Based on international comfort standards, this study determined the period of the year in which shading and sunlit are needed to achieve thermal comfort
Nasrollahi *et al.* (2017)	Using the Envi-met simulation tool, this study determined the PMV and UTCI static thermal indices to assess the level of thermal comfort in 45 courtyard houses in Iran for two days representing typical summer and winter conditions	Courtyards offer five comfortable hours during the early morning and late evening hours in summer, and two hours during the noontime in winter. The thermal performance of courtyards is affected by their geometric properties
Martinelli and Matzarakis (2017)	Using the RayMan model, this study investigated the thermal conditions of five courtyard options in Italy, and assessed the level of thermal comfort they can offer around the year during the daytimes using the PET thermal sensation index	Courtyards in Italy, annually and during the daytimes, offer between 151 and 224 comfortable days. This performance is primarily affected by the geometric properties of courtyards
Mousli and Semprini (2016)	Measured the thermal conditions in a courtyard space in Syria and used ASHRAE 55 standard's adaptive model to determine people's thermal sensation	With the 90% acceptability limits of ASHRAE's adaptive model, the courtyard house offers thermal comfort for 30–50% of the occupation period

Table 1.
Previous literature exploring thermal comfort in courtyards

(*continued*)

Study	Research work and methodology	Results
Salman (2016)	This study depended on ASHREA adaptive thermal comfort standard to assess thermal comfort in two courtyard houses in Baghdad	Courtyards are thermally comfortable during the early morning and evening times in summer, and in the afternoon time in winter
Yasa and Ok (2014)	Using the Fluent 6.3 CFD simulation tool, this study investigated the impact of courtyards' geometry on energy consumption to achieve thermal comfort. The study determined the thermal conditions of seven courtyard models in three cities in Turkey representing three climatic zones, Diyarbakır, Antalya and Erzurum	Through affecting shading and solar radiation, results stressed that the geometric properties of courtyards significantly affect their thermal conditions and energy consumption to achieve thermal comfort. The best courtyard form is the one that provides the highest possible shading in summer and the highest possible radiation in winter
Cho and Mohammadzadeh (2013)	Conducted a simulation experiment using EnergyPlus simulation software. It measured the impact of natural ventilation on the temperature in a courtyard house in Iran	Having efficient natural ventilation in a courtyard house can lead to having up to 5.4 °C temperature difference between inside and outside
Foruzanmehr (2012)	Undertook two surveys in Yazd, Iran to investigate the thermal comfort levels in summer in traditional central courtyard houses	Courtyard buildings do not provide continuous thermal comfortable conditions throughout summer. However, they provide mitigated thermal conditions through passive cooling measures
Al Jawadi (2011)	Measured the temperature in a modern courtyard house in Baghdad	The air temperature in the courtyard and surrounding rooms was, respectively, 6.7 °C and 9.9 °C less than the outdoor air temperature
Manioğlu and Yılmaz (2008)	Measured the temperature in courtyard and non-courtyard buildings in Turkey	The temperature in the courtyard building is 5 °C less than in the non-courtyard one
Al-Zubaidi *et al.* (2008)	Compared two courtyard houses. One of them is of an open courtyard, and the other one is of a closed courtyard	The air temperature in the open courtyard is around 8 °C less than the air temperature in the closed one
Edwards (2006)	Measured the temperature in a courtyard space and surrounding rooms in a courtyard house in Saudi Arabia	Results showed that the temperature difference between outside and inside the courtyard is up to 13 °C

Table 1.

Research work presented in the available literature has included simulation work and surveys and using international thermal comfort indices and models to determine the thermal performance of courtyard spaces. They suggest that courtyards can help to offer more thermally comfortable environments than non-courtyard buildings. They stress that the thermal conditions of courtyards are significantly affected by their geometric properties. Regarding thermal comfort levels in courtyard spaces, studies indicate that courtyards can offer thermally comfortable environments for up to 50% of the occupation time around the year, and the rest are uncomfortable times. However, the results of these studies lack accuracy due to one or more of the following reasons:

(1) International comfort standards are not appropriate for hot-climate regions, as international standards have been developed for regions of different climatic conditions (Eltrapolsi, 2016; Farghal, 2011; Nicol *et al.*, 2012).

(2) Static thermal comfort indices do not provide accurate predictions of people's thermal sensation in courtyards. Static thermal indices overestimate the extent of people's

discomfort in outdoor and naturally ventilated indoor spaces (De Dear and Brager, 2002; Monteiro and Alucci, 2006; Nicol *et al.*, 2012; Pantavou *et al.*, 2013).

(3) The residential courtyard space is a special case of an external or semi-external space. Its location and function make it useable as a private space for regular residential activities, such as eating, sitting or watching television (Al Jawadi, 2011; Khan and Majeed, 2015; Salman, 2016). In addition, its size and design enable occupants to have a level of control over its microclimate conditions, including its air temperature (Ta) and air velocity (Va) (Salman, 2016). Neither of these two aspects is available in ordinary external or semi-external spaces for which the thermal indices used in these studies have been developed. Accordingly, using these indices to determine thermal comfort in courtyards may lead to inaccurate results. Thermal indices provide accurate predictions only for situations and locations where they have been developed (Aljawabra, 2014; Johansson *et al.*, 2014; Nikolopoulou, 2011).

Based on this exploration, it can be concluded that, whilst there is evidence that courtyards can improve the thermal conditions of buildings, accurate results regarding the extent of thermal comfort in residential courtyards are still not available. Accurate assessments of thermal comfort in courtyards can be obtained through determining the thermal conditions of courtyards in a specific region and judging them using thermal comfort thresholds determined for the people and climate of that specific region. This study assesses the level of thermal comfort in residential courtyards taking the hot-climate city of Baghdad, the capital of Iraq, as a case study. This research determines the possible thermal conditions of residential courtyards in Baghdad. It uses an adaptive thermal comfort model developed by Al-Hafith (2020) for Iraq to judge the extent of thermal comfort in courtyards.

2. Research aim and methodology

The overarching aim of this research is to determine the level of thermal comfort courtyards can offer to occupants in hot-climate regions, taking Baghdad as a case study. To achieve this aim, this research adopted a quantitative research methodology. It developed a novel Courtyard Thermal Usability Index (CTUI) to quantify the ability of courtyards to offer thermally comfortable environments to occupants. This index determines the amount of time courtyards offer useable thermally comfortable environments to occupants out of the total occupation time. Accordingly, CTUI is the ratio between thermally comfortable hours and the total number of occupation hours of a specific period, such as a season or a year. The higher the CTUI value, the higher the thermal comfort level in courtyards. Regarding the considered total occupation hours in this study, courtyards are used in residential buildings during the day and evening times to do various domestic activities, but not sleeping. Therefore, the considered daily occupation hours in this research are from 8:00 AM until 10:00 PM (Salman, 2016).

In comparison with the thermal comfort assessment approaches adopted by previous literature (Table 1), CTUI offers a higher level of accuracy in determining the level of thermal comfort in courtyard spaces for three reasons. Firstly, CTUI is to be determined based on the specific thermal comfort thresholds of the region subject to investigation, not general international thermal comfort standards that may lead to inaccurate results (Eltrapolsi, 2016; Farghal, 2011). Secondly, CTUI uses the adaptive thermal comfort model in its assessment, not the static thermal comfort model. The adaptive model has been found by studies to be more accurate than the static model in predicting and assessing the thermal sensation of people in outdoor and indoor naturally ventilated spaces (De Dear and Brager, 2002; Nicol *et al.*, 2012; Yang *et al.*, 2014; Humphreys *et al.*, 2007). Thirdly, the assessment of CTUI depends on considering the thermal comfort limits of people undertaking the domestic activities associated with residential courtyards, not universal limits applied to a wide range of activities that may not be performed by people in residential courtyard spaces. Considering these three factors enable to accurately determine the level of thermal comfort of occupants in spaces, including the traditional central courtyard spaces (Nicol *et al.*, 2012).

To establish CTUI, the possible thermal conditions of courtyards in Baghdad and the thermal comfort thresholds of Iraqis were determined. A set of simulation experiments was conducted to determine the thermal conditions of courtyards. Simulation tools have been intensively used in similar studies as they provide the opportunity to examine buildings in different scenarios and to consider different factors, which may not be applicable in real-life experiments (Almhafdy *et al.*, 2013; Bahar *et al.*, 2013; Seyedzadeh *et al.*, 2020; Pilechiha *et al.*, 2020). Regarding defining Iraqis' thermal comfort thresholds, an adaptive thermal comfort model developed by Al-Hafith (2020) for Iraq was used to judge the simulated thermal conditions of the examined courtyard configurations. To determine CTUI, the number of hours in which courtyards satisfy the thermal comfort thresholds of Iraqis were divided by the total number of potential occupation hours.

The considered adaptive thermal comfort model of Al-Hafith (2020) was developed based on a year-long thermal comfort study. A total of 90 participants from four Iraqi cities, including Baghdad, recorded their thermal votes and the daily thermal conditions of their residential environments, including globe temperature (Tg) and Ta. In total, 6,400 thermal comfort votes were recorded and used to develop a dedicated adaptive thermal comfort model for Iraq. According to this adaptive model, with a 90% confidence level, the lowest Tg accepted by Iraqis in winter is 14.0 °C, and the highest acceptable Tg in summer is 35.0 °C (Figure 1) (Al-Hafith, 2020). This adaptive model shows the specific thermal comfort thresholds of Iraqis around the year, which are different to the thresholds determined by the international American Society of Heating, Refrigerating and Air-conditioning Engineers

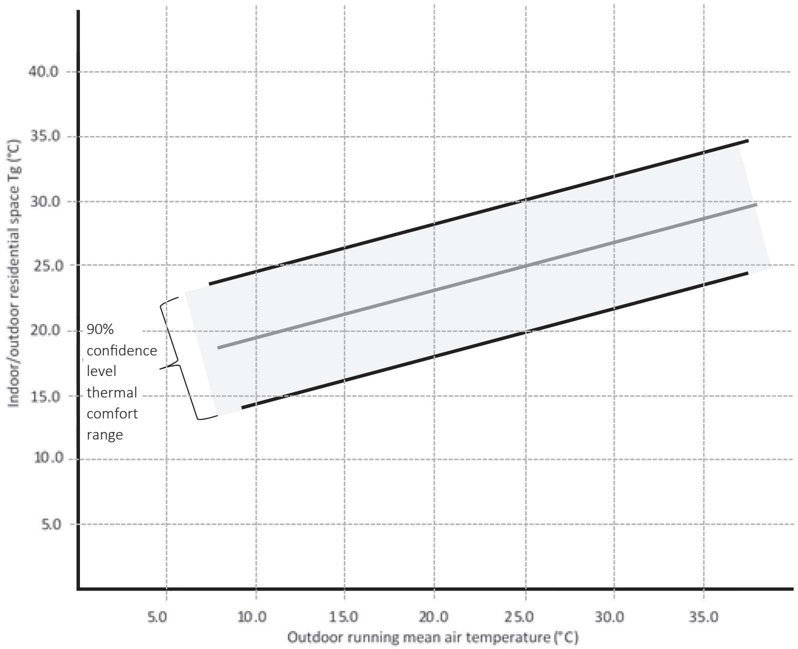


Figure 1.
The adaptive thermal comfort model developed by Al-Hafith (2020)

(ASHRAE) and EN15251's adaptive models. The lowest and highest comfort limits of EN15251's model are 24.0 and 29.0 °C, respectively. ASHRAE's adaptive model sets the lowest and highest comfort temperatures at, respectively, 20.0 °C and 27.0 °C. These differences between the Iraqi model and these two international models, which are American and European models, are due to the differences in the climates and people's thermal preferences between Iraq and the regions where these two international models have been developed (Al-Hafith, 2020).

3. Research process

The research work presented in this paper was conducted in two interrelated stages (Figure 2). The first stage involved conducting simulation experiments to determine the thermal conditions of courtyards in Baghdad. The second stage involved judging these determined thermal conditions of courtyards based on the thermal comfort thresholds of Iraqis as determined by Al-Hafith's adaptive model. The outcomes of these two stages were used to assess the level of thermal comfort that courtyards can offer to occupants using the novel CTUI index developed by this study.

3.1 Stage 1: simulation experiments

A set of simulation experiments was conducted to determine the possible thermal conditions of courtyard spaces in Baghdad. The design and execution of the simulation experiments were as follows:

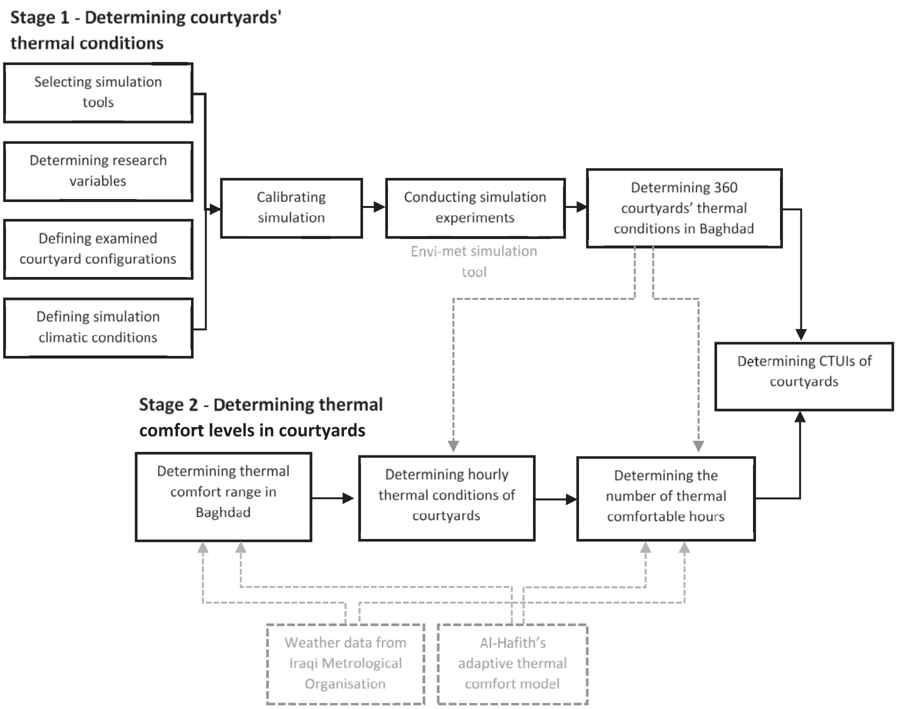


Figure 2.
Research work stages

(1) Simulation tool used: this study conducted an intensive literature review and contacted the support teams of various simulation tools in order to explore available options and to select a tool that serves its objectives. The Envi-met 4.2 simulation tool was selected to conduct the simulation experiments. Envi-met 4.2 is a computational fluid dynamics (CFD) tool that considers the impact of a wide range of influential factors. It simulates the interactions between building surfaces, air and natural elements in outdoor spaces (Berardi, 2016; ENVI-MET, 2021; Malekzadeh, 2009). This simulation tool has been validated and intensively used by previous studies to obtain valid and reliable simulation results for outdoor spaces, including courtyards (Hedquist and Brazel, 2014; Peron *et al.*, 2015; Nasrollahi *et al.*, 2017).

(2) Variables determined in the simulation experiment: there are two categories of variables that were considered when designing and conducting the simulation experiments:

- Courtyard space thermal conditions: this study adopted the globe temperature (Tg) as a thermal comfort index for predicting the thermal sensation of occupants in courtyards. Tg was selected for two reasons. Firstly, it is the thermal index used in the considered adaptive thermal comfort model (Al-Hafith, 2020). Using the same index was essential for making accurate judgements of the extent of thermal comfort in courtyards. Secondly, the measurements of Tg have been found by previous studies to be highly reflecting people's actual thermal sensation (Humphreys *et al.*, 2015). However, the version of Envi-met used in this study does not offer the option of directly determining Tg. Instead, the research used an equation developed by previous literature for this purpose (Moss, 2015). The equation used involves the three microclimatic factors that comprise Tg and significantly affect people's thermal sensation: Ta, Va, and mean radiant temperature (MRT) (Song, 2011; Shooshtarian and Ridley, 2016). These three microclimatic factors were determined using the Envi-met 4.2 simulation tool.

$$Tg = \frac{\mathrm{MRT} + 2.35 \times \mathrm{Ta} \times (\mathrm{Va})^{0.5}}{1 + 2.35 \times (\mathrm{Va})^{0.5}} \qquad \text{(Used equation to determine Tg)}$$

- Courtyard space geometric properties: the thermal conditions of courtyard spaces are significantly affected by their geometric properties, namely courtyard area, width/height (*W*/*H*), width/length (*W*/*L*), periphery/height (*P*/*H*) and orientation (Khan and Majeed, 2015; Muhaisen and Gadi, 2006; Tabesh and Sertyesilisik, 2016; Soflaei *et al.*, 2016). Through the examination of a wide range of courtyard configurations, this study determined the possible range of thermal conditions of courtyards in Baghdad and the impact of altering their geometric properties on the thermal sensation of occupants.

(3) Courtyard configurations examined: 360 courtyards of different geometric configurations were examined (Figure 3). These courtyard forms were developed to represent a wide range of possible courtyards and to enable us to extrapolate other not examined options. The manipulated and examined geometric properties included the following:

- Courtyard area: six different areas were examined ranging from a 10 m^2 courtyard, to a 100 m^2 courtyard.
- Width/Length ratio (*W*/*L*): five different ratios were examined ranging from a narrow courtyard with a 1:10 ratio to a square courtyard with a 1:1 ratio.

- Courtyard long axis orientations: four main geographic orientations were examined, which included north-south, east-west, northeast-southwest and northwest-southeast.
- Height: courtyards with 3, 7 and 10 m heights were examined. These three heights represent the typical height of one-storey, two-storey and three-storey courtyards. Having different heights affects the ratios of Width/Height (*W*/*H*) and Periphery/Height (*P*/*H*).

The 360 options stem from exploring the permutations of these effective geometric properties of courtyards on their thermal conditions:

$$6\,\text{areas} \times 5\,W/L\,\text{ratios} \times 3\,\text{heights} \times 4\,\text{orientations} = 360$$

(4) Baghdad's climatic conditions: four days representing the typical conditions of summer, winter, spring and autumn of Baghdad were identified and used in the simulation. These four days were selected following analysis of climatic conditions of Baghdad using weather data from the Iraqi Metrological Organisation and previous literature (Bilal *et al.*, 2013) (Table 2). No further simulation could have been done due to the limitations of time and resources. Simulating further days would have exponentially increased the time and efforts to conduct the simulation experiments.

(5) Simulation calibration: actual measurements of two typical courtyard houses in Baghdad obtained from third-party measurements were used to calibrate the simulation model (Al-Azzawi, 1984; Salman, 2016). The two typical Baghdadi courtyard houses were modelled and simulated in Envi-met 4.2. The thermal properties of courtyard surfaces were fine-tuned until the simulation results were similar to the real-life conditions (Table 3). The coefficient of variation for the root mean squared error (CV-RMSE) statistical test was conducted to test the validity and the accuracy of the calibrated simulation model. This coefficient gives a percentage

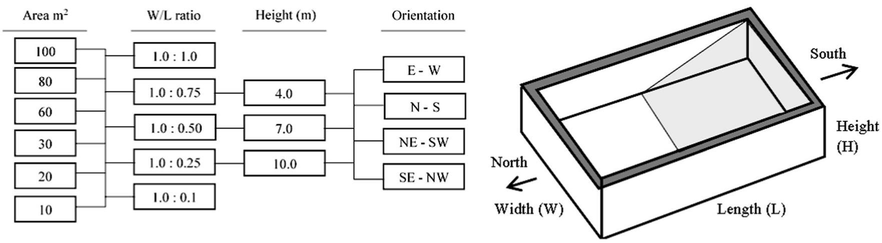


Figure 3. Tested courtyard configurations matrix

Table 2. Selected simulation days' climatic conditions–Baghdad

Season/date	Climatic conditions Air temperature (°C) Min	Max	Humidity (%) Min	Max	Wind speed (m/s)	Direction
Typical winter/21 January	13.6	19.7	68.0	89.0	2.7	East
Typical spring/16 March	21.8	27.0	44.0	51.0	2.0	East
Typical summer/01 August	31.6	46.8	26.0	41.0	1.3	East
Typical autumn/01 October	27.0	38.0	39.0	63.0	2.6	East

showing the accuracy of simulation results in comparison to real-life conditions. Lower resultant values indicate a better-calibrated model (Bagneid, 2010; Haberl and Bou-Saada, 1998). In this study, the comparison showed that the simulation results agree with the actual thermal measurements of the two examined courtyards (Figure 4). The maximum determined CV-RMSE is 0.072, which indicates that the maximum margin of error in the simulated data is 7.2%. According to the ASHRAE standard, for hourly simulation data, the simulation model can be declared to be calibrated if the result of this coefficient is within ±30% (Bagneid, 2010).

(6) Simulation results analysis: data obtained from Envi-met 4.2 was arranged in Excel spreadsheets. IBM SPSS statistics 24 was used to analyse the correlations between the various explored variables. All variables were determined and analysed on an hourly basis over the examined period in the simulation experiments. Hourly analysis of thermal conditions in courtyards allows accurate determination of the period of thermal comfort that courtyards may offer to occupants.

3.2 Stage 2: assessing thermal comfort in courtyards – applying CTUI

This study used the results of its simulation experiments and the proposed adaptive thermal comfort model by Al-Hafith (2020) to determine the annual CTUIs of the examined courtyard spaces. The assessment of thermal comfort in courtyards included four steps (Figure 5):

(1) Determining the daily thermal comfort ranges for Baghdad for a year based on the considered adaptive thermal comfort model and using hourly weather data collected from the Iraqi Meteorological Organisation. In this step, the running mean Ta of each

Thermal property	Value	Thermal property	Value
Thickness	0.30 m	Emissivity	1.10 Frac
Absorption	0.80 Frac	Specific heat	1,300.0 J/(Kg*K)
Transmission	0.00 Frac	Thermal conductivity	0.30 W/(M*K)
Reflection	0.05 Frac	Density	1,000.0 (Kg/M^3)

Note(s): The simulation period length was set to be 32 h, starting at 00:00. The first six hours were not considered in the analysis, as they do not include the impact of the stored heat during the daytime on the thermal conditions of courtyards

Table 3. Thermal properties used in Envi-met 4.2 simulation experiments

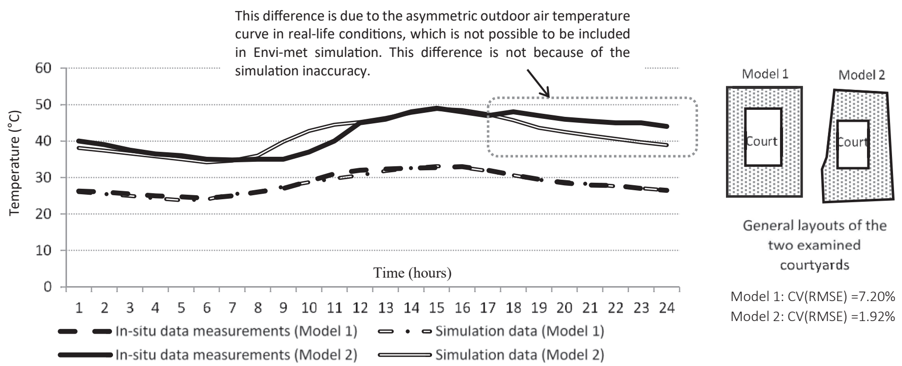
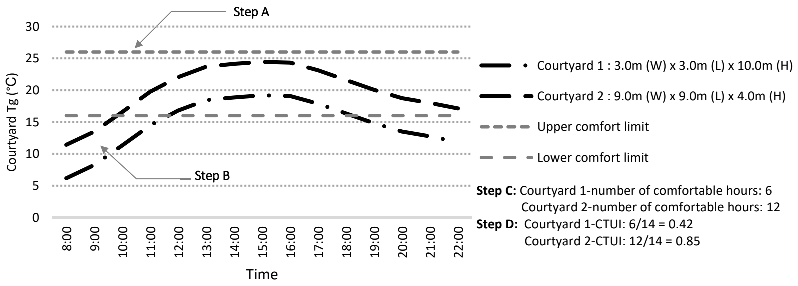


Figure 4. Calibrating Envi-met simulation model



Step B Step A Step C

	Date & time			Courtyard Tg	Daily running mean outdoor air tempeture	Thermal comfort	
2	Month	day	Hour			Lower comfort limit	Upper comfort limit
3	January		08:00	6.93		16	26
4			09:00	9.0105		16	26
5			10:00	12.0765		16	26
6			11:00	15.252		16	26
7			12:00	17.5515		16	26
8			13:00	19.194		16	26
9			14:00	19.632		16	26
10		1	15:00	19.9605	15.3	16	26
11			16:00	19.851		16	26
12			17:00	18.6465		16	26
13			18:00	17.1135		16	26
14			19:00	15.5805		16	26
15			20:00	14.2665		16	26
16			21:00	13.5		16	26
17			22:00	12.624		16	26

Summary			
	No. Of comfortable hours	No. of cold hours	No. of hot hours
Anually	2037	602	2835

Annual CTUI: 2037 / 5474 = 0.37

Step D

Figure 5.
A diagram and a snapshot of the used Excel spreadsheet illustrating applying the four stated steps to determine CTUI

day was determined, and the correspondent thermal comfort thresholds were set as determined by Al-Hafith's adaptive thermal model.

(2) Determining the hourly thermal conditions for each of the examined courtyards to be judged regarding providing thermal comfort to occupants. Using 20,160 data sets produced in the simulation experiments, the research conducted a regression analysis to develop an equation that was used to interpolate the hourly Tg of courtyards for a year. The developed equation enables determining the thermal conditions of any of the examined 360 courtyards for any given outdoor temperature. The equation was considered reliable to determine the hourly Tg of courtyards. The factors included in the equation explain 90% of the changes in Tg in courtyards (Adjusted $R^2 = 0.904$):

$$\text{Coutyard Tg} = -3.638x\left(-0.811 \times \frac{w}{L}\right) + \left(2.808 \times \frac{w}{H}\right) + \left(0.044 \times \frac{P}{H}\right)$$
$$+ (-0.008 \times \text{Area}) + (1.035 \times \text{Outdoor Tg})$$

(Developed equation to determine annual Tg in courtyards)

(3) Determining the total number of thermally comfortable hours per annum for each of the examined courtyards. On a daily basis, and for a year, the research compared the hourly Tg of each courtyard option (determined in step 2) with the daily thermal comfort range in Baghdad (determined in step 1). The hours of temperatures that sit within the comfort range as determined by Al-Hafith's model were determined to be comfortable hours. The hours that are of higher and lower temperatures than the set upper and lower comfort thresholds as determined by Al-Hafith's model were, respectively, set to be hot and cold hours.

(4) Determining the CTUI of each of the examined courtyards through determining the ratio of the total number of thermally comfortable hours (determined in step 3) to the total occupation hours for a year.

These four steps were applied to each of the examined 360 courtyard options to determine their annual CTUIs. Figure 5 shows an example of applying these four steps to determine CTUI.

4. Results

4.1 Courtyards' thermal conditions in Baghdad – simulation results

The results of the simulation experiments show that the examined 360 courtyard forms are of different thermal conditions. Table 4 shows the Tg in summer at 12:00 of a sample of 90 courtyards out of the examined 360 cases. This table demonstrates that the examined courtyards have significantly different thermal conditions with having a Tg as low as 46.0 °C in some cases and as high as 67.0 °C in other cases. Figure 6 shows the hourly thermal conditions in two courtyards in summer. The first courtyard is shallow and large, and the second courtyard is small and deep. In this figure for the same outdoor climatic conditions, there is a significant difference in Tg and MRT between the two courtyards and the Tg follows MRT in its trend. The difference in globe temperature between these two courtyard options is up to 20.0 °C. Ta is almost the same in both courtyards.

These results demonstrate that the courtyards' geometric properties significantly affect their thermal conditions. However, this impact of courtyards' geometry does not include all the three effective microclimatic factors on Tg, but MRT only. Figures 7–9 are graphical representations produced via Envi-met 4.2 demonstrating Ta, Va and MRT in different courtyard forms. In Figure 7, the difference in Ta between different courtyards does not exceed 0.5 °C. Figure 8 shows that there are no or only limited differences in Va between the 30 presented courtyards. However, this is not applied to the case of MRT. Figure 9 shows that, affected by courtyards' geometry, there are high differences in MRT between the presented courtyard options. The deeper and narrower the courtyard, the lower the MRT. The difference in MRT between courtyards is up to 15.0 °C.

Correlation analysis was conducted using the IBM SPSS 24 statistical package to elaborate on the impact of courtyards' geometric properties on Tg (Table 5; Figure 10). Table 5a shows that there is a statistically significant correlation between the geometric properties of courtyards and Tg (p-value < 0.05). However, these geometric properties are not all of the same level in term of their impact on Tg. Table 5 and Figure 10 demonstrate that *W/H* and *P/H* ratios are the most effective geometric properties on Tg in courtyards. The orientation and the rectangularity of the courtyard plan (*W/L*) are of limited impact on Tg. Table 5b shows that there is a significant statistical correlation between Tg and the three effective microclimatic factors (p-Value < 0.05). MRT has the strongest impact on Tg in courtyards (Pearson coefficient 0.979), and Va is of the least impact (Pearson coefficient 0.024).

Based on these results, it can be concluded that the geometric properties of courtyards significantly affect Tg in courtyards. The most significant impact on Tg comes from the impact of the *W/H* ratio on MRT. For any courtyard orientation, the deeper and narrower the courtyard, the lower the MRT, and the lower the Tg. Also, Tg is affected by Ta and Va. However, both of these microclimatic factors are not affected by courtyards' geometry.

4.2 Assessment of courtyards' thermal comfort (CTUI)

This research assessed the extent of thermal comfort in courtyards by developing the CTUI, which is the ratio of thermally comfortable hours to the total annual occupation hours. Figure 11 shows the ranking of courtyards according to their annual CTUIs. In this figure, the highest CTUI level courtyards can offer is 0.38. In other words, in Baghdad, annually, courtyards can offer up to 38% comfortable hours out of the total occupation hours. Regarding the

Table 4. Variation in globe temperature in a sample of 90 courtyards in summer at 12:00

	Geometric properties						Geometric properties				
Courtyard	*W*	*L*	*H*	Orien	Tg (℃)	Courtyard	*W*	*L*	*H*	Orien	Tg (℃)
01	10	10	10	90	61.48	46	10	10	10	45	57.62
02	9	11	10	90	60.39	47	9	11	10	45	57.26
03	7	14	10	90	58.58	48	7	14	10	45	56.24
04	6	17	10	90	59.79	49	6	17	10	45	55.96
05	3	32	10	90	46.22	50	3	32	10	45	46.49
06	10	10	7	90	56.68	51	10	10	7	45	56.64
07	9	11	7	90	56.41	52	9	11	7	45	56.38
08	7	14	7	90	55.00	53	7	14	7	45	55.59
09	6	17	7	90	54.97	54	6	17	7	45	56.02
10	3	32	7	90	53.72	55	3	32	7	45	47.80
11	10	10	4	90	56.31	56	10	10	4	45	56.49
12	9	11	4	90	56.08	57	9	11	4	45	56.25
13	7	14	4	90	55.19	58	7	14	4	45	56.18
14	6	17	4	90	56.75	59	6	17	4	45	57.29
15	3	32	4	90	48.92	60	3	32	4	45	57.42
16	10	10	10	135	64.40	61	9	9	10	90	62.39
17	9	11	10	135	65.75	62	8	10	10	90	61.69
18	7	14	10	135	64.20	63	7	12	10	90	55.72
19	6	17	10	135	63.81	64	5	15	10	90	47.75
20	3	32	10	135	64.43	65	2	28	10	90	45.90
21	10	10	7	135	66.00	66	9	9	7	90	57.88
22	9	11	7	135	66.03	67	8	10	7	90	57.29
23	7	14	7	135	67.72	68	7	12	7	90	58.37
24	6	17	7	135	67.34	69	5	15	7	90	62.10
25	3	32	7	135	58.06	70	2	28	7	90	56.41
26	10	10	4	135	59.55	71	9	9	4	90	57.55
27	9	11	4	135	58.27	72	8	10	4	90	57.39
28	7	14	4	135	56.43	73	7	12	4	90	55.47
29	6	17	4	135	55.35	74	5	15	4	90	56.24
30	3	32	4	135	55.84	75	2	28	4	90	49.09
31	10	10	10	0	61.92	76	9	9	10	135	65.26
32	9	11	10	0	62.76	77	8	10	10	135	65.42
33	7	14	10	0	64.74	78	7	12	10	135	63.50
34	6	17	10	0	66.15	79	5	15	10	135	62.02
35	3	32	10	0	63.52	80	2	28	10	135	64.42
36	10	10	7	0	62.37	81	9	9	7	135	65.61
37	9	11	7	0	62.44	82	8	10	7	135	67.68
38	7	14	7	0	62.26	83	7	12	7	135	65.21
39	6	17	7	0	63.55	84	5	15	7	135	66.46
40	3	32	7	0	64.24	85	2	28	7	135	59.84
41	10	10	4	0	62.19	86	9	9	4	135	60.49
42	9	11	4	0	64.76	87	8	10	4	135	59.96
43	7	14	4	0	64.61	88	7	12	4	135	63.35
44	6	17	4	0	67.36	89	5	15	4	135	59.32
45	3	32	4	0	65.37	90	2	28	4	135	57.08

Note(s): *W*: Width, *L*: Length, *H*: Height, Orien: The angle of the courtyard's long axis in relation to north

uncomfortable period, hot hours represent the main challenge (Figure 12). Occupants may experience, annually, between 4,500 and 3,500 hot hours. The number of cold hours, in the worst-case scenario, does not exceed 1,400 h The CTUI of courtyards and the number of potential cold and hot hours to be experienced by occupants is affected by the geometric properties of courtyards, especially the *W/H* ratio. This is due to the significant impact of this geometric

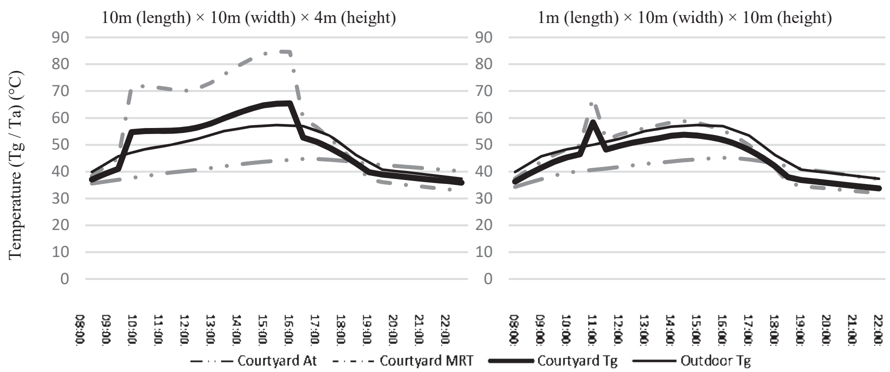


Figure 6.
Summer conditions in warm and cold courtyards

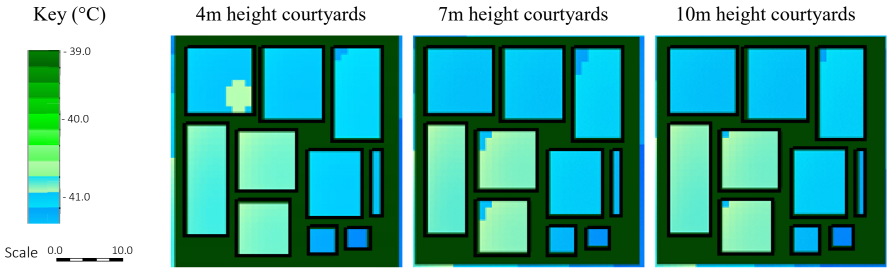


Figure 7.
Air temperature in 30 different courtyards (at 12:00 PM in summer)

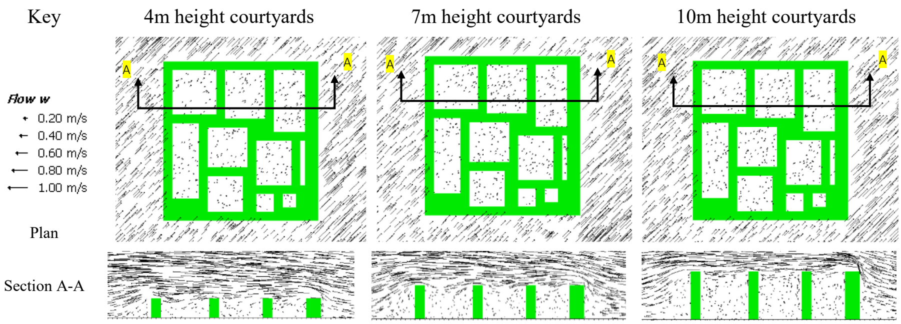


Figure 8.
Air velocity in 30 different courtyards (at 12:00 PM in summer)

property of courtyards on their thermal conditions. CTUI and the number of cold hours increase by decreasing W/H ratio. The inverse is applied to the case of hot hours.

On a daily basis, Figure 13 shows an example of the daily thermal conditions in the most thermally comfortable courtyards amongst the 360 courtyards. The dimensions of this presented courtyard are 5.0 m (*W*) × 6.0 m (*L*) × 10.0 m (*H*). The *W/H* ratio in this courtyard is 0.5, and its CTUI level is 0.38. During the daily occupation hours, this courtyard is comfortable during the daytime in winter, and in the early morning and the evening in spring and autumn. Its cold period is during the first morning hour and the evening in winter. This courtyard is hot during most of the daytime in spring and autumn and the whole occupation time in summer.

5. Discussion

This study presents the first assessment of thermal comfort in courtyards based on a local adaptive thermal comfort model of a hot-climate city and through developing a novel index for this purpose: the CTUI. This index determines thermal comfort in courtyards by determining the ratio of the number of thermally comfortable hours in a courtyard space to the total occupation hours.

The results of this study agree with the studies discussed in Table 1 in that courtyards do not offer continuous thermally comfortable environments to occupants in hot-climate regions; instead, they provide periods of thermal comfort only. On this note, Martinelli and Matzarakis (2017) determined the period of thermal comfort in courtyards in Italy to be 151–224 days per annum. Mousli and Semprini (2016) suggested that courtyards, in Syria, offer a 30%–50% comfortable period out of the total occupation period. These results of the literature highly correspond to the outcomes of this study. However, there are differences regarding the level of thermal comfort in courtyards, and these differences can be traced back to the climatic variations between the examined regions and the adopted assessment approaches. This study suggests that, in Baghdad, the maximum comfort range in courtyards is 38% out of the total occupation hours per annum. This assessment is based on a more accurate approach than the assessment approaches presented in previous literature. Previous studies have depended on either international thermal comfort standards or static thermal comfort indices, both of which cannot provide an accurate assessment of thermal comfort in courtyards. In this study, the thermal conditions of courtyards were

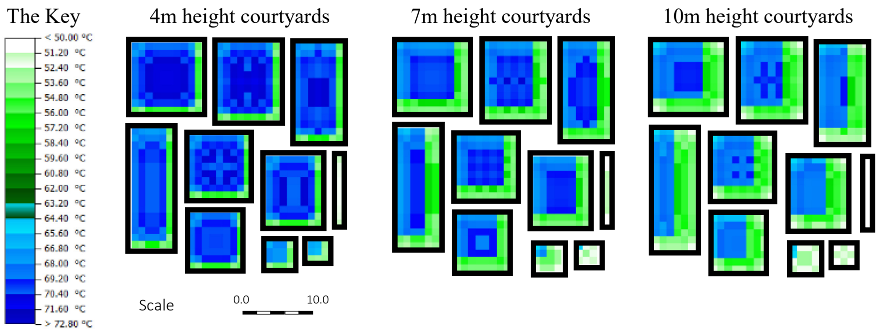


Figure 9. MRT in 30 different courtyards (at 12:00 PM in summer)

Table 5. Correlation analysis between the research variables

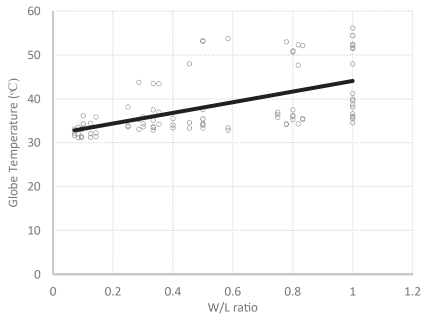
(a) Correlation analysis between globe temperature and courtyards' geometric properties

Statistical coefficient	Courtyard area	Courtyard orientation	*W/L*	*W/H*	*P/H*
Pearson coefficient	0.151	0.047	0.084	0.231	0.158
Sig. (*p*-value)	0.00	0.00	0.00	0.00	0.00

(b) Correlation analysis between globe temperature and the three effective microclimatic factors

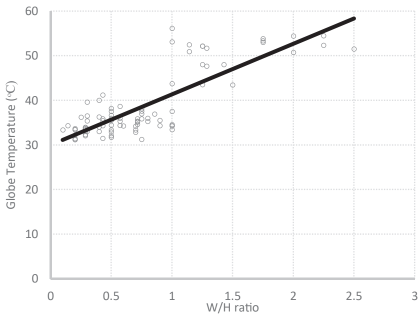
Statistical coefficient	Mean radiant temperature	Air velocity	Air temperature
Pearson coefficient	0.979	0.024	0.861
Sig. (*p*-value)	0.00	0.00	0.00

Note(s): (1) Pearson coefficient is a measure of the strength of the association between the two variables. It ranges between 1.0 and 0.0, and the higher the value the stronger the correlation
(2) Sig. (*p*-value) is a measure of results significance. It ranges between 1.0 and 0.0, and a small *p*-value (typically $\leq$ 0.05) indicates strong evidence of the exiting of the correlation



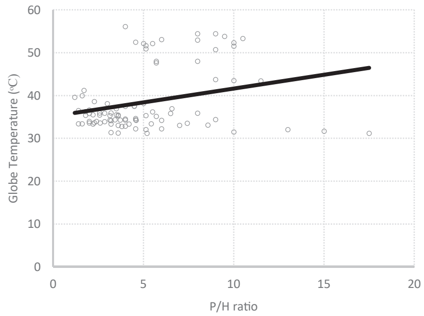
The correlation between the width/length (W/L) ratio and globe temperature

(a)



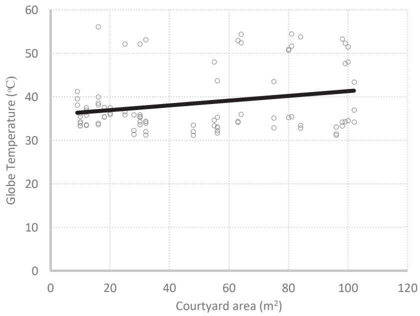
The correlation between the width/height (W/H) ratio and globe temperature

(b)



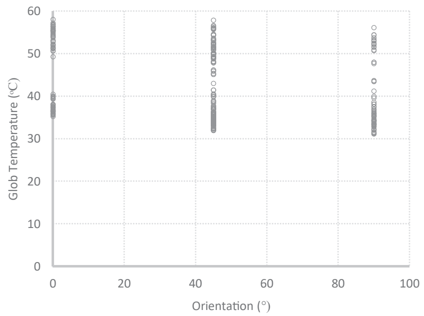
The correlation between the periphery/height (P/H) ratio and globe temperature

(c)



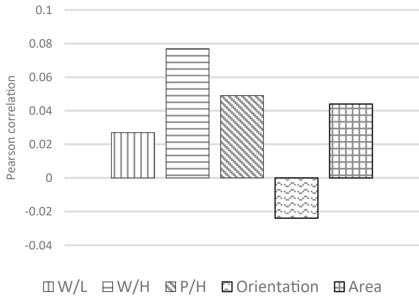
The correlation between courtyard area and globe temperature

(d)



The correlation between the courtyard orientation and globe temperature

(e)



Strength of impact of each of the geometric properties on globe temperature

(f)

Note(s): Presented data is for spring at 12:00 PM - same correlation is applied to other times and other seasons

Figure 10. Impact of courtyard geometry on globe temperature

accurately simulated and their thermal comfort levels, CTUIs, were determined based on an adaptive thermal comfort model specifically developed for Iraq (Al-Hafith, 2020).

Agreeing with previous literature, this study demonstrates that the level of thermal comfort in courtyards and their thermal conditions are significantly affected by their geometric properties. The geometric configurations of courtyards affect their MRT conditions, but not Ta and Va. Studies have shown that, affected by shading conditions, MRT is significantly affected by the horizontal and vertical dimensions of courtyards. Shading increases by increasing the courtyard space's depth, which leads to decreasing MRT. The most effective geometric property on the thermal conditions of courtyards is the *W/H* ratio (Al-Hafith e al., 2017; Al-Hafith *et al.*, 2019; Muhaisen, 2006; Muhaisen and Gadi, 2006; Soflaei *et al.*, 2017). The conclusion that MRT is the most effective factor on the thermal sensation of occupants agrees with thermal comfort studies that have shown that MRT is the most effective factor on people's thermal sensation in external spaces in hot-climate regions (Ali-Toudert and Mayer, 2006; Aljawabra, 2014; Berkovic *et al.*, 2012; Nasrollahi *et al.*, 2017; Nikolopoulou, 2011).

The results of this study can be used by architects and designers to inform their design of courtyard spaces. The outcomes of this study show that designers can influence Tg in courtyards, which correlates directly with the thermal sensation of occupants, through manipulating the geometry of the courtyard. They can make a difference of up to 20.0 °C in Tg by targeting the insolation level and MRT in courtyards. To have a low Tg, designers need to reduce the *W/H* ratio to ensure high shading levels and low MRT. However, this is not applicable to Ta and Va, although these also influence Tg in courtyards. Designers and architects cannot impact Ta and Va by manipulating courtyard geometry. If the aim is to have an impact on Ta and Va, strategies other than manipulating the geometry of the courtyard need to be adopted, such as to invest in a range of passive and active environmental design strategies.

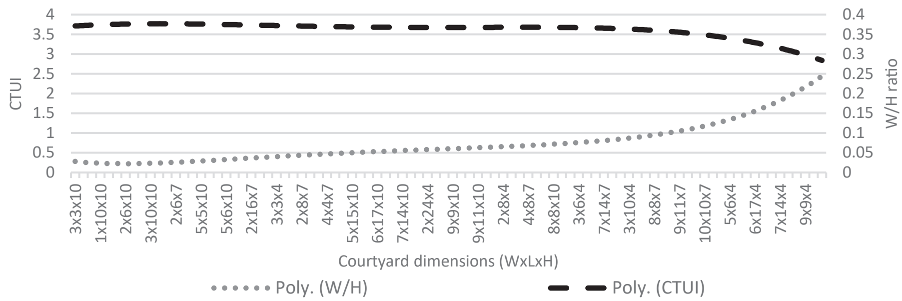


Figure 11.
The correlation between the CTUI and *W/H* ratio

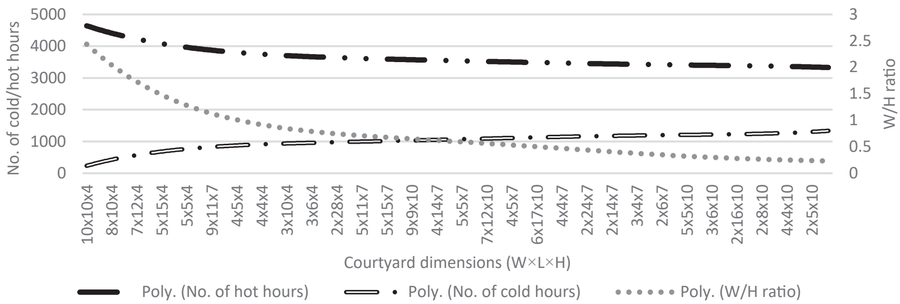


Figure 12.
The correlation between the number of hot/cold hours and *W/H* ratio

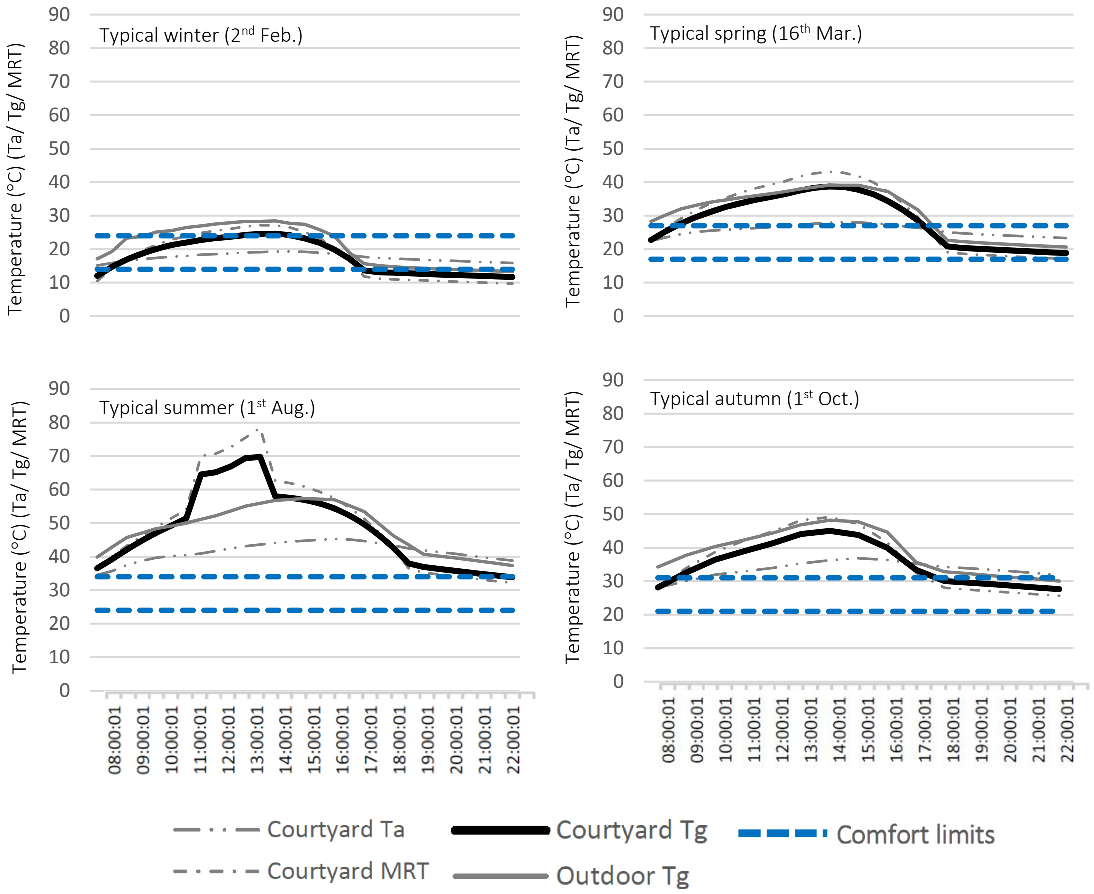


Figure 13. Hourly thermal conditions in one of the most thermally comfortable courtyards around the year

6. Conclusions

This study shows that the courtyard space can provide a level of thermal comfort to occupants in hot climate regions, but not for the whole time. In Baghdad, courtyards, in the best-case scenario, can offer thermally comfortable conditions for up to 38% of the occupation hours around the year. Around 51% and 11% of the annual occupation hours are hot and cold, respectively. On a daily basis, the comfortable hours are during the daytime in winter and the morning and evening hours in spring and autumn. Courtyards are hot in summer and most of the time in spring and autumn, and they are cold during the evening in winter.

The main thermal advantage of the courtyard space is related to its ability to reduce MRT, which is found to be the most effective microclimatic factor on the thermal sensation of occupants (Tg). This thermal advantage can be achieved by manipulating the geometric properties of courtyards, especially the *W/H* ratio. The deeper the courtyard, the higher the shading level, the lower the MRT and the lower the Tg. The difference in courtyards' geometry can lead to a difference in their Tg of up to 20.0 °C. However, this impact of courtyard geometry on its MRT is not applied to Ta and Va. Both of these microclimatic factors affect Tg in courtyards, but they are not affected by the geometric properties of courtyards. Based on these results, it can be concluded that architects and designers can use the courtyard space to offer a level of thermal comfort to occupants. To maximise thermal comfort, they need to reduce the W/H ratio for its significant impact on the resulted thermal conditions. As courtyards are not able to offer total thermal comfort, options to support their thermal performance need to be explored and used when adopting courtyards in buildings. This may include the use of passive or active environmental design strategies.

These conclusions are based on the results of the simulation experiments and the considered adaptive comfort model. Although, typically, simulation predictions are not claimed to be totally presenting real conditions, the results of the current study highly reflect the actual thermal conditions and thermal sensation in courtyards in Baghdad. The comfort limits were determined based on a year-long thermal comfort survey in Iraq that included 6,400 thermal comfort votes from 90 participants. In the simulation experiments, the majority of the effective factors on the thermal conditions of courtyards are implied in the simulation as the simulation model was built depending on two typical courtyard houses in Baghdad.

The results of this study may not be applicable to cities of different climatic conditions compared to Baghdad. Also, the results of this study may not be accurate for courtyard buildings of different thermal properties than the thermal properties of the two employed courtyard houses to build and calibrate the simulation model of this study.

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