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The Impact of Courtyard parameters on its shading level

An experimental study in Baghdad, Iraq

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Abstract

The courtyard pattern has been advocated to be thermally efficient for the hot-arid climatic zone. This paper investigates one of its environmental strategies: shading. By taking Baghdad as a case study, it presents an experimental study, using LightUp Analytics simulation tool, to determine the impact of courtyard geometry and orientation on its shading. The results showed that they significantly affect the shading level. The most effective parameter is the ratio of courtyard width to height. Depending on the results, this paper suggests a regression equation that can predict the shading level of different courtyard forms throughout the year in Baghdad.

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Keywords: Baghdad; Courtyard; LightUp Analytics; shading; simulation.

1. Introduction

The courtyard pattern has been used in most of the hot regions in the world for centuries [1, 2, 3]. But, in most of these regions, it has been replaced since the middle of the 20th century with other modern patterns, such as the detached and row housing patterns, for different reasons. Currently, many studies advocate readopting the courtyard pattern in the current and future buildings in the hot climatic zone for being more climatically responsive and energy efficient than modern patterns. Among these studies are Foruzanmehr [4], Miller et al [5], Ratti et al [6], Manioğlu et al[7], Al Jawadi [8], Soflaei et al [9] and Al-Masri et al [10]. These studies demonstrated the efficient environmental performance of this architectural pattern.

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For instance, Manioğlu et al [7] study presented an experiment showing that in one of the hot summer days in Turkey, the temperature in a courtyard house's room was 22Cº, while in a similar room in a modern western pattern house; it can reach around 33Cº. Al Jawadi [8] study showed that the temperature in a courtyard house in Baghdad can be less by around 9º than the outside temperature. Al-Masri et al [10] compared the energy consumption in a multi-storey courtyard building and a normally closed one in the UAE. The result showed that the courtyard building consumes 6.9% less energy than the other building.

However, studies have shown that to get this efficiency, various factors and parameters should be considered and determined. Otherwise, the courtyard will have negative performance. For instance, Ratti et al [6] study showed that changing the proportions, like the building volume to surface ratio or the courtyard depth, can lead to poor thermal performance. El-deep et al [11] showed that if the courtyard building is situated in a context where it is exposed to the solar radiation from all its sides, its energy consumption will by higher by up to 15% than a similar rectangular non-courtyard building.

Accordingly, to have efficient performance, courtyard buildings should be designed depending on the comprehensive understanding of the courtyard pattern environmental strategies, elements and affecting factors. Basically, the courtyard pattern thermal performance depends on two integrally working strategies: protecting buildings from solar radiation, which includes shading, and natural ventilation [12, 13]. The former implies handling the direct surfaces exposure to the solar radiation to control the heat gain. In summer, the aim is to increase shading to reduce the heat gain and as a result reducing the temperature. While in winter, the aim is to increase the heat gain [14, 13, 9, 15]. On the other hand, natural ventilation helps to reduce the temperature through replacing the hot air with cold one and cooling the building elements. The integrity is implied in that having sufficient natural ventilation is partially related to the first approach as it depends on the pressure differences between the sunny and shaded areas to generate air movement [16, 17]. During the daytime, courtyard buildings are protected from the solar radiation by being attached to the surrounding building blocks [18]. The courtyard, on the other hand, is kept cold, for a specific period, by being shaded. After that, the temperature increases gradually as the solar radiation hits its surfaces. In the night time, the courtyard surfaces radiate their stored energy to the sky [8, 17] and natural ventilation is stimulated by the pressure difference between the hot courtyard and surrounding spaces and the cold outside. The courtyard, at this time, works as a passage for the hot air to be discharged and replaced by cold air. This mechanism helps to reduce the whole building temperature during the night until it reaches its minimum value by sunrise [8,19, 20].

To achieve this performance, a number of elements have been used in the traditional courtyard houses. These elements include, mainly, the courtyard, the wind-catcher, the thick envelope walls, the compact urban fabric and plants and water elements (Fig 1) [21, 17, 8]. Each element has several parameters that affect buildings thermal conditions. Among the main affective factors are the courtyard geometry and orientation, the building volume to external surfaces area, the internal spaces' dimensions, openings size and location and urban compactness (Table1).

Table 1. The main affective factors on courtyard buildings performance

Buildings' elements or features	The effective parameters	The direct impact	Reference
The courtyard	Geometrical properties (Width, length and height) Orientation (the orientation of the courtyard long axis)	Heat gain and natural ventilation	[14, 22]
The internal spaces	Openings size and location The internal dimensions (width, length and height)	Natural ventilation	[3, 23]
The wind - catcher	Orientation and geometrical properties	Natural ventilation	[24, 25]
The building envelope	Envelop thermal mass (construction materials U-value)	Heat gain	[3,7]
The water& planting elements	The ratio of these elements area to the courtyard area	Heat gain and natural ventilation	[9]
The building form	Building volume to external surfaces area	Heat gain	[1]
The building urban context	Building adjutancy and urban fabric compactness	Heat gain and natural ventilation	[3,21]

This research focuses on the impact of changing the courtyard parameters on its shading for its significant impact on the courtyard and the surrounding spaces thermal conditions; having a larger shaded area for a longer time, in summer, can significantly help in improving the courtyard building thermal performance. It helps to have a cooler courtyard for a longer period during the daytime with less heat storage, and reduces surfaces heat radiation during the night time, which might lead to having overall less temperature in the whole building. However, the research also stresses considering the courtyard winter shading, as having high shading with positive impact during summer might lead to having negative performance during winter [16].

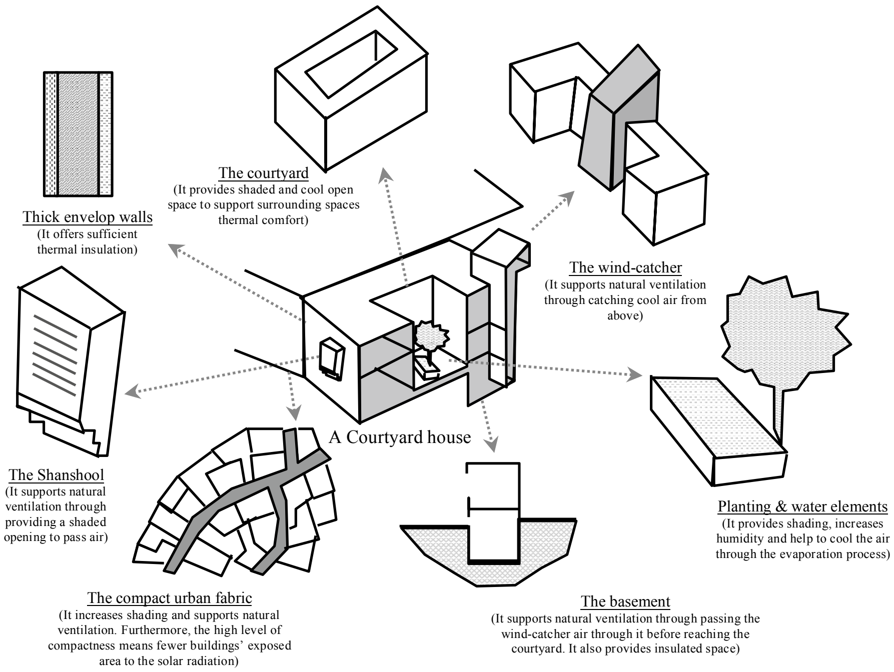

Fig. 1. The courtyard pattern environmental elements
Source: Drawn by the author depending on [17, 21, 7]

2. Research methodology and objective

This research's aim is to show the impact of courtyard parameters on its shading performance and to define the relative impact of each of them. It also aims to suggest a regression equation that can help designers to predict the shading level of different courtyard forms throughout the year.

The research methodology included conducting an experiment to determine the impact of the courtyard various design parameters on its shading. Using Baghdad as a case study, the experiment included simulating the shading in fifty different courtyard forms using LightUp Analytics simulation tool. The result of the simulation included the shaded area percentage in each of the tested courtyard forms. IBM SPSS statistics 23 software was used to determine the correlations between the shaded area percentage and the courtyard design parameters.

3. Defining the research variables

Two kinds of variables affect the courtyard shading (Figure 2). The first one includes external factors related to the sun location in the sky, which is different from one place to another and from time to time. It includes two parameters, the sun azimuth and the sun altitude [26, 27]. This paper considers the maximum altitude angle and the maximum azimuth angle range as measurements of these two parameters to consider the full range of sun location possibilities. The second kind of variables includes internal factors which are mainly two: the courtyard geometry and orientation. The latter parameter, on the first hand, is the orientation of the courtyard long axis, which is expressed in this paper by measuring the long axis rotation angle from the north orientation [13]. The courtyard geometry parameters, on the other hand, include the relation between its various dimensions:

- R1 (W/L): It is the ratio of courtyard width to length [14, 22].

- R2 (W/H): It is called the ‘aspect ratio’. It includes the relation between the court width to height [15, 22].
- R3 (P/H) : it is the ratio of the court periphery to height [14, 22].
- R4 (T/G): The ratio of the top open area to the ground area [22].
- R5 (SH/PL): The ratio of the southern wall height to the perpendicular length [22].

To have efficient shading performance, these parameters should be determined with considering summer efficiency and winter efficiency. The most efficient performance during summer implies increasing the shaded area to reduce the heat gain, while the reverse can be said about winter [26, 14, 13, 9].

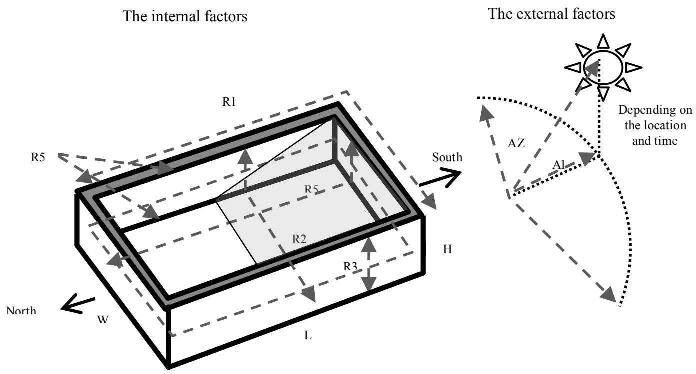

Fig. 2. The variables that affect the courtyard shading level

Several studies have investigated the impact of changing these parameters on the courtyard shading and thermal performance in different geographical locations. Among the widely referred and discussed studies on this subject are the studies that have been carried out by Muhaisen and Gadi. In one of their studies, Muhaisen et al [14], they investigated the impact of changing the courtyard configuration on courtyard buildings cooling loads, with showing the relation with courtyard shading performance. Muhaisen [13] tested the impact of rectangular courtyard dimensions and orientation on courtyards shading in four different locations. In other two studies, Muhaisen et al [28] and Muhaisen et al [29], they investigated the shading performance in courtyards forms other than the rectangular one, which included the polygonal and circular forms. The results of these studies demonstrate that courtyards geometrical parameters and orientation have a significant impact on courtyards shading and buildings energy consumption. They showed that courtyard shading increases when courtyard forms become deeper, which in turn leads to having less cooling loads in summer, but higher heating loads in winter. Accordingly, they stressed on that defining optimum universal ratios and orientation to have efficient courtyards is inapplicable as it depends on the buildings geographical locations and annual climatic conditions. Similar results have been highlighted by other studies, such as Manioğlu et al [30], Soflaei et al [31] and Meir et al [32].

However, none of these studies have investigated the integrated impact of all of these variables and their relative significance. With considering the impact of sun altitude and azimuth, this study aims to determine the impact of all of the courtyard effective parameters on shading and to identify which one of them has the most significant impact on shading.

4. Determining the impact of changing the courtyard parameters

This paper used LightUp analytics simulation tool to define the impact of courtyard geometry and orientation on its shading. The shading level represents the dependent variable while the courtyard two variable parameters and the sun location two parameters represent the independent variables. Baghdad, the capital city of Iraq, was taken as a case study because it has hot climate and a large area of traditional courtyard neighborhoods.

4.1. Generating the courtyard options

Fifty options were generated and simulated. They were approximately the same ground area, around 100m^2, but they included different values of each of the considered parameters. First of all, four options were generated of different 'R1' with 3m height (Fig. 3). Then each of the four options was used to generate nine options with increasing the height by one meter each step. This offers wide-ranging values for R1, R2, R3 and R5. Finally, the first two initial options were used to generate ten forms with partially closed top opening to offer different 'R4' values ranging from 0.9 to 0.5. Each of these fifty options was tested for four different orientations: north-south, east-west, northeast-southwest and northwest-southeast. In other words, the long axis orientation angle from the north was respectively 0º, 90º, 45º and 135º. This represented a total of 200 different possibilities of courtyard forms.

Option1 10.0m x 10.0m R1 (W/L) = 1

Option 2 14.2m x 7.1m R1 (W/L) = 0.5

Option 3 17.4m x 5,8m R1 (W/L) = 0.3

Option 4 31.7m x 3.17m R1 (W/L) = 0.1

Height ranges from 3m to 12m

Fig. 3. The basic considered courtyard options

4.2. Determining the independent variables

All of the 200 defined courtyard forms' independent parameters, the five geometry ones and the orientation one, were determined by doing the required calculations. On the other hand, the two parameters of the sun location variable were taken from Baghdad sun path (Table 2) [26, 27].

Table 2. Baghdad sun angles [26, 27].

Month	Sun angles (º)		Month	Sun angles (º)		Month	Sun angles (º)	
	Max. Altitude	Azimuth range		Max. Altitude	Azimuth angle		Max. Altitude	Azimuth angle
Jan.	38	240-120	May.	78	290-70	Sep.	58	270-90
Feb.	46	255-105	Jun.	80	295-65	Oct.	46	255-105
Mar.	58	270-90	Jul.	78	290-70	Nov.	38	245-115
Apr.	70	280-76	Aug.	70	280-80	Dec.	34	240-120

4.3. Simulating the shading performance

LightUp Analytics was used for the simulation purpose. This software has a valid lighting simulation system and can give the percentage of surfaces' sunlit area [33]. The 15th day of each month was selected for the simulation to represent the whole year solar conditions. The measurements included measuring the percentage of the total sunlit area and shaded area of each option's five surfaces: the courtyard ground and the four surrounding walls (Fig. 4). A total of 11600 measurements were taken, which represented determining the total shaded and sunlit areas percentages of 2400 different cases; 200 options in each of the twelve months.

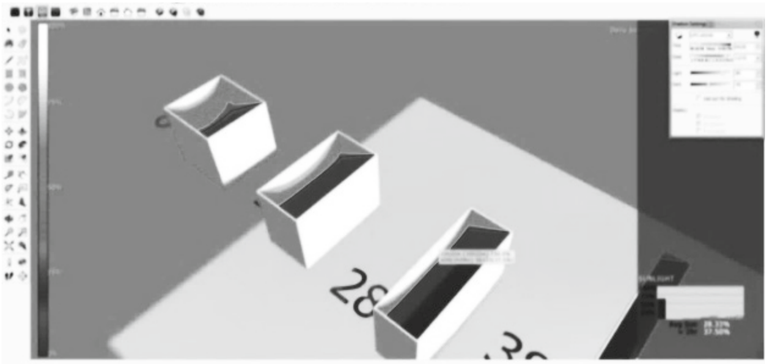

Fig. 4. A screenshot from LightUp Analytics software- Measuring surface sunlit area percentage

5. The results and analysis

The results show the impact of courtyard geometry and orientation on courtyard shading in Baghdad throughout the year (Table 3). They are presented in this section as three divisions: the impact of courtyard geometry, the impact of courtyard orientation and the significance of variables impact.

Table 3. The shading level in January and July, representing winter and summer, in a random sample of forty cases from the tested 200 courtyard forms.

No.	Courtyard design parameters						Surfaces shading (%)		No.	Courtyard design parameters						Surfaces shading (%)	
	R1	R2	R3	R4	R5	Ori.	Jan	Jul		R1	R2	R3	R4	R5	Ori.	Jan	Jul
01	1.0	3.33	13.3	1.0	0.30	N-S	0.65	0.49	21	1.0	1.66	6.6	1.0	0.60	NE-SW	0.78	0.61
02	1.0	1.42	5.7	1.0	0.70	N-S	0.81	0.63	22	1.0	0.90	3.6	1.0	1.10	NE-SW	0.88	0.69
03	1.0	0.83	3.3	1.0	1.20	N-S	0.88	0.72	23	0.5	1.18	7.1	1.0	0.84	NE-SW	0.79	0.64
04	0.5	1.01	6.0	1.0	0.98	N-S	0.79	0.67	24	0.5	0.64	3.8	1.0	1.54	NE-SW	0.88	0.72
05	0.5	0.59	3.5	1.0	1.69	N-S	0.87	0.76	25	0.3	0.96	7.7	1.0	1.03	NE-SW	0.78	0.64
06	0.3	0.82	6.6	1.0	1.20	N-S	0.78	0.69	26	0.3	0.52	4.2	1.0	1.89	NE-SW	0.87	0.73
07	0.3	0.48	3.8	1.0	2.06	N-S	0.85	0.76	27	0.1	0.52	11.5	1.0	1.90	NE-SW	0.81	0.71
08	0.1	0.45	9.9	1.0	2.22	N-S	0.84	0.79	28	0.1	0.28	6.3	1.0	3.49	NE-SW	0.88	0.78
09	0.1	0.26	5.7	1.0	3.81	N-S	0.85	0.81	29	1.0	3.33	13.3	0.6	0.30	NE-SW	0.78	0.70
10	1.0	3.33	13.3	0.5	0.30	N-S	0.80	0.76	30	0.5	2.36	14.2	0.6	0.42	NE-SW	0.77	0.71
11	0.5	2.36	14.2	0.6	0.42	N-S	0.75	0.72	31	1.0	1.66	6.6	1.0	0.60	NW-SE	0.78	0.61
12	1.0	1.66	6.6	1.0	0.60	E-W	0.78	0.61	32	1.0	0.90	3.6	1.0	1.10	NW-SE	0.88	0.69
13	1.0	0.90	3.6	1.0	1.10	E-W	0.88	0.72	33	0.5	1.18	7.1	1.0	0.84	NW-SE	0.79	0.62
14	0.5	1.18	7.1	1.0	0.84	E-W	0.82	0.58	34	0.5	0.64	3.8	1.0	1.54	NW-SE	0.88	0.70
15	0.5	0.64	3.8	1.0	1.54	E-W	0.90	0.69	35	0.3	0.96	7.7	1.0	1.03	NW-SE	0.79	0.63
16	0.3	0.96	7.7	1.0	1.03	E-W	0.84	0.57	36	0.3	0.52	4.2	1.0	1.89	NW-SE	0.88	0.72
17	0.3	0.52	4.2	1.0	1.89	E-W	0.91	0.67	37	0.1	0.52	11.5	1.0	1.90	NW-SE	0.81	0.70
18	0.1	0.52	11.5	1.0	1.90	E-W	0.90	0.56	38	0.1	0.28	6.3	1.0	3.49	NW-SE	0.88	0.77
19	0.1	0.28	6.3	1.0	3.49	E-W	0.94	0.65	39	1.0	3.33	13.3	0.6	0.30	NW-SE	0.78	0.70
20	1.0	3.33	13.3	0.6	0.30	E-W	0.76	0.72	40	0.5	2.36	14.2	0.6	0.42	NW-SE	0.77	0.71

5.1. The impact of courtyard geometry on its shading

The results demonstrate that courtyard shading changes with changing its five tested parameters. (Fig.5) shows that, in all of the four considered width to length ratios (R1), shading increases by decreasing R2 and R3 and increasing R5. This demonstrates the impact of increasing the courtyard height on shading, as each of these three parameters, with fixing the width and length, are totally affected by the courtyard height. For instance, in the square courtyard, R1 = 1, the percentage of the overall shaded area increases from 65% to 88% by decreasing R2 and R3 and increasing R5 as a result of increasing the height from 3m to 12m. The same thing is applied to the other three width to length ratios. They all have their minimum shading with their minimum height and reach their maximum shading level by the 12m height, which is the highest tested height in this research.

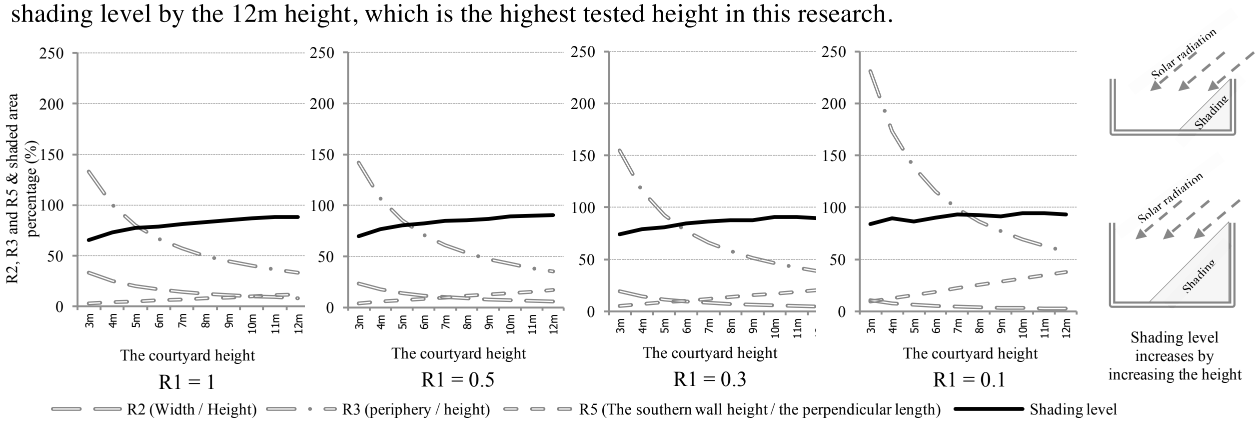

Fig.5. The impact of R2, R3 and R5 on courtyard shading

Regarding the impact of the courtyard upper opening area (R4) on shading, (Fig.6) shows that it affects the courtyard shading in a similar way to the impact of R2 and R3. The tested forms have their minimum shading level with the maximum upper opening area and the maximum shading with the minimum upper opening area.

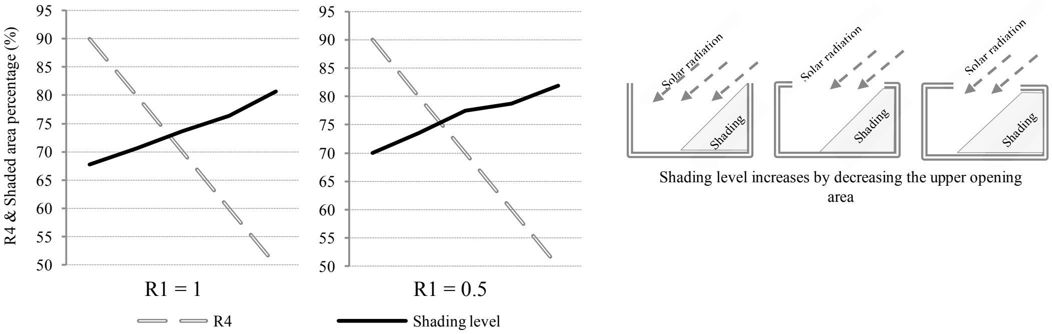

Fig.6. The impact of R4 on courtyard shading

The courtyard shading also increases with decreasing the width to length ratio (R1). (Fig.7) shows that, with fixing all of the other courtyard parameters, the courtyard form has its maximum shading when it has the least R1 and the minimum shading when it has the maximum R1.

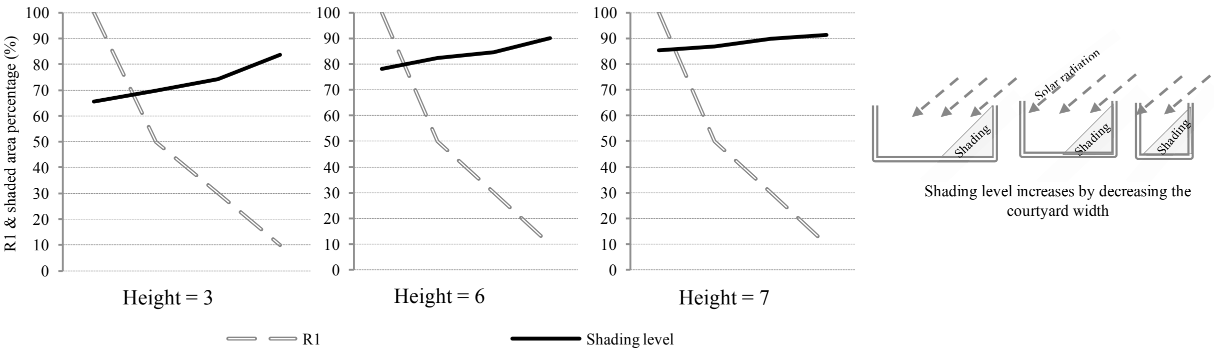

Fig.7. The impact of R1 on courtyard shading

5.2. The impact of courtyard orientation on its shading

Apart from the impact of courtyard geometry on its shading, the results show that courtyard shading is also affected by its long axis orientation. The impact of orientation on shading level increases with increasing the courtyard rectangularity. But, in all of the rectangular forms, the highest shading level is when the long axis is along the east – west and the lowest one is when it is along the north – south. Courtyards with northwest-southeast and northeast-southwest orientations have similar shading levels (Fig. 8).

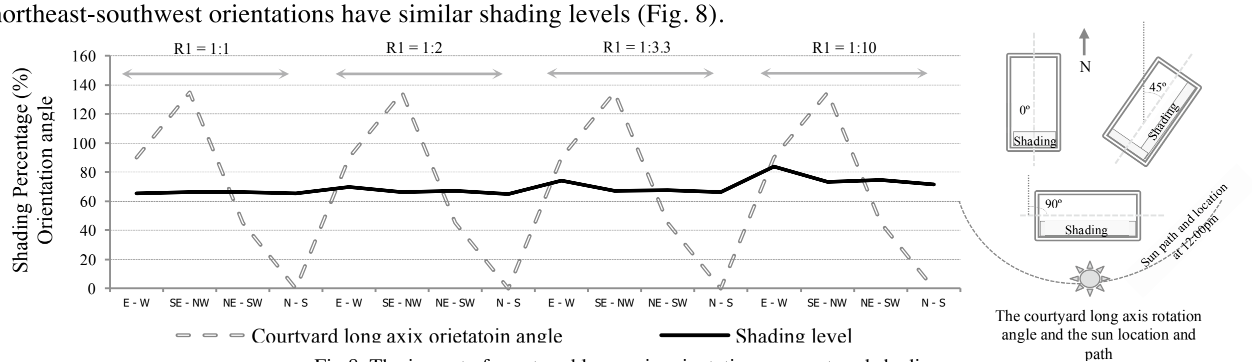

Fig.8. The impact of courtyard long axis orientation on courtyard shading

5.3. The significance of variables impact & the regression model

As each of the tested variables has an impact on courtyard shading, it is of importance to determine the significance of their impact as it indicates for designers where to focus to get the intended shading performance. IBM SPSS statistics 23 was used to analyze the results. The analysis showed that there is a statistically significant correlation between the independent and dependent variables ($P \leq 0.05$). R1, R2, R3 and R4 have negative correlations with the shading level, while R5 has a positive correlation. This means that the shading level increases by increasing R5 and decreases by increasing the other variables. The significance of the independent variables impact in descending order is respectively R2, R3, R5, R1, R4 then the orientation angle (Table 4).

Regarding the orientation, the analysis shows that shading increases by increasing the long axis rotation angle with the north orientation above 0˚ and reaches its maximum with a 90˚ angle. Further increase in the rotation angle leads to a reduction in the shading level until it reaches its minimum with the 180˚ angle. Accordingly, to have a correct analysis of the orientation impact, the included angle cases in the analysis were 0˚, 45˚ and 90˚. The 135˚ and 180˚ angles were not included because including them will indicate contradicted impact of increasing the rotation angle and as a result misleading analysis. 135˚ shading is very similar to 45˚ shading. 180 ˚ shading is totally the same of 0˚ angle. Increasing the angle above 90˚ will have the same impact and strength of decreasing it below 90˚.

Table 4. The correlations between the research variables

		R1 (W/L)	R2 (W/H)	R3 (P/H)	R4 (T/G)	R5 (SH/PL)	Orientation angle 0˚- 90˚	90˚- 180˚	Max. sun Altitude	Azimuth angle range
Shading level	Pearson C.	-0.187	-0.466	-0.439	-0.112	+0.388	-0.076	+0.076	-0.568	-0.564
	(P) Sig.	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000

To provide the ability to predict the thermal performance of various possible courtyard forms, this research used the results to generate a regression model. The same analysis software was used to do a multiple regression analysis. But, it was found that including all of the independent variables in the regression model decreases its explanatory power, the adjusted R^2, as a result of variables multicollinearity. To have a more accurate and stronger model, a regression model was generated for each month and included only R1, R2 and R3. Accordingly, twelve different set of values were determined to be included in a regression model (Equation 1) that can predict courtyards shading level (Table.5). The generated model is valid only for Baghdad, which is this research case study. For other locations the same approach can be considered, but with using the relevant data set

$$The\ shading\ level\ (\%\ of\ the\ total\ surfaces\ area) = A + R1xBR1 + R2xBR2 + R3xBR3 + OrixBori \quad (1)$$

Table 5. The regression equation coefficients

Month	Var.	B	Sig	Adjusted R^2	Month	Var.	B	Sig	Adjusted R^2
Jan A=0.119	R1	-0.70	0.000	0.888	Jul A=0.184	R1	0.032	0.019	0.809
	R2	0.99	0.000			R2	0.093	0.010	
	R3	0.002	0.014			R3	0.004	0.001	
	Ori.	-0.001	0.000			Ori.	0.001	0.000	
Feb A=0.131	R1	-0.066	0.013	0.888	Aug A=0.0.1 68	R1	-0.045	0.018	0.823
	R2	0.109	0.006			R2	0.095	0.009	
	R3	0.002	0.001			R3	0.005	0.001	
	Ori.	0.000	0.000			Ori.	0.001	0.000	
Mar A=0.161	R1	-0.66	0.015	0.861	Sep A=0.145	R1	-0.039	0.014	0.879
	R2	0.117	0.008			R2	0.099	0.007	
	R3	0.001	0.001			R3	0.005	0.001	
	Ori.	-0.0005	0.000			Ori.	0.000	0.000	
Apr A=0.160	R1	-0.50	0.018	0.823	Oct A=0.130	R1	-0.058	0.013	0.896
	R2	0.102	0.009			R2	0.113	0.006	
	R3	0.004	0.001			R3	0.002	0.001	
	Ori.	0.001	0.000			Ori.	0.000	0.000	
May A=0.181	R1	-0.047	0.019	0.811	Nov A=0.126	R1	-0.071	0.013	0.880
	R2	0.096	0.010			R2	0.106	0.007	
	R3	0.004	0.001			R3	0.002	0.001	
	Ori.	0.001	0.000			Ori.	-0.001	0.000	
Jun A=0.178	R1	-0.031	0.024	0.746	Dec A=0.117	R1	-0.066	0.013	0.861
	R2	0.095	0.012			R2	0.094	0.007	
	R3	0.005	0.002			R3	0.002	0.001	
	Ori.	0.001	0.000			Ori.	-0.001	0.000	
Note	Orientation coefficients in this table are for angles increasing from 0˚ to 90˚. For angles above 90˚, the same coefficient values can be used but with inverse sign.								

6. Results Discussion

This study's results highly correspond with the explored previous studies' results in that courtyards configuration and orientation highly affect their shading performance. The courtyard shading level increases by increasing the courtyard rectangularity and height and, in the case of Baghdad, directing its long axis to be along east-west. With considering the impact of shading on courtyards thermal conditions, these results demonstrate how it is essential to consider the impact of courtyard configurations on its shading to design environmentally efficient courtyard buildings. Furthermore, this study's results analysis showed that the explored effective factors on courtyard shading performance have different degrees of impact, which has not been done by previous studies. The most effective factor, in Baghdad, is the ratio of courtyard width to height and the least effective one is the courtyard orientation. A regression equation was established depending on the results analysis, which can be used do predict the shading performance of various courtyard forms in Baghdad throughout the year.

To get efficient environmental performance for both hot and cold periods in Baghdad, this study recommends having a special consideration to balance between the requirements of these two periods to have acceptable conditions for the longest possible period. However, this requires further research work to determine the impact of shading on temperature, which has not been done in this study.

As future studies, this paper recommends investigating the impact of courtyard shading on its temperature to define the required shading limits to have comfortable conditions. In addition, it recommends investigating the other courtyards environmental strategies and other elements impact on courtyard buildings environmental performance, such as the environmental role of natural ventilation and the impact of wind-catchers, vegetation and basements on courtyards thermal conditions.

7. Conclusions

The courtyard pattern has been advocated for being a thermally efficient pattern of hot climate regions. It depends on having a number of efficiently working elements, such as the courtyard, the basement and the windcatcher, to apply two main environmental strategies: controlling buildings exposure to solar radiation, which includes shading, and supporting natural ventilation. Each of its elements has its impact and parameters that affect their performance and, as a result, the whole buildings' thermal conditions. This research investigated the impact of courtyard design parameters on its shading in Baghdad, as shading has a significant impact on courtyard buildings thermal performance.

The investigation demonstrated that courtyard shading is affected by its various geometrical properties and orientation, which have different degrees of impact. But, as a rule, to get a higher shading level, courtyards should be designed to take the deep and narrow forms. Regarding the relative impact of courtyard design parameters on shading, in Baghdad, courtyard shading is mostly affected by the ratio of courtyard width to height, while courtyard orientation is the least effective factor. A regression equation was generated depending on the results to predict the shading performance of various courtyard forms in Baghdad.

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