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Impact of the Courtyard Geometry on Cooling Energy Demand in Arid Zones. Univariate Regression-based Approach.

Boukarta Soufiane

Blida 1 university, Algeria
Institute of architecture and urban planning, ETAP laboratory.
e-mail: boukarta.soufiane@univ-blida.dz

Abstract

Vernacular architecture, often described as architecture without an architect, never ceases to show us the extent to which the building system was linked to its environment and clearly expressed the *genius loci*. This paper looks at the role that courtyard geometry can play as a thermal and energy regulator in traditional houses. To do this, the study is based on a historical reading of the evolution of the courtyard, with the aim of characterising its geometry in terms of its size in relation to the house, its depth, its position (centred or off-centre), its shape and finally its orientation. To assess the performance of each type of courtyard, the study is based on a campaign of dynamic thermal simulations (DTS) carried out under DesignBuilder for the arid climate of the city of Laghouat in Algeria. The results of the study are based on a comparative approach and modelling using univariate linear regression. The best configuration obtained for the courtyard is that of a rectangular courtyard, with a 10% opening ratio, elongated on the axis east-west direction, a central position and a depth of three levels, as this best combines solar gain and shading protection.

Keywords: vernacular architecture, courtyard geometry, energy performance, dynamic thermal simulation, univariate linear regression.

1 Introduction

Vernacular architecture, often defined as architecture without an architect, never ceases to impress us with its potential to adapt to its environment [1]. The accelerated urbanisation that is taking place in Algerian towns and cities is taking place in partial or total denial of the virtues of local architecture in terms of spatial organisation and the materials chosen for construction. This urbanisation is directly involved in the proliferation of energy-guzzling buildings, which play a full part in exacerbating the phenomenon of climate change. Algeria, a signatory to the Kyoto Protocol and the 2015 Paris Agreement, has put in place a national energy management strategy structured by Law 09-99, the implementation of which is based on national energy management plans [2, 3] and whose objective is the gradual introduction of renewable energies (RE) to reach 20% by 2030 [4] and the reduction of energy demand by introducing energy efficiency in the residential, transport, industrial and agricultural sectors. The residential sector alone is responsible for 46% of final energy consumption [5]. Algeria is also committed to reducing its greenhouse gas emissions by 7% by 2030 without financial assistance, and by 20% if Algeria receives financial assistance to do so [4].

The thermal regulations also corroborate the government's goal to reduce energy demand by improving architectural studies via the DTR C3-2, the use of which is only made by architects on a voluntary basis. In line with this purpose to reduce energy demand and the associated greenhouse gas emissions, architectural practice seems to be neglecting the virtues of vernacular architecture, despite the fact that it offers promising ideas for reducing energy demand. Some Algerian researchers have set themselves the goal of demonstrating the virtues of local architecture by promoting the use of local materials in housing design [6] or the microclimatic aspect [7, 8] or by evoking the organisation of interior space as a thermal regulator [9] or by testing the thermal behaviour of architectural elements such as balconies [10]. In another study carried out by Boukarta (2023) [11], the author found that by increasing insulation and even using local materials, energy demand in arid zones remains high for air conditioning. The author concludes that vernacular architecture with its spatial organisation around courtyards and chebaks, covered passageways and other elements of architectural composition common in arid zones can in turn improve the thermal behaviour of the house and reduce the energy demand for air conditioning in arid zones, which account for more than 80 per cent of Algerian territory. In this paper we aim to identify the impact of courtyard geometry on the energy demand of an individual house by considering the case of the arid climate of the city of Laghouat.

2 Literature Review

A review of the scientific literature shows that the courtyard is an architectural element present in ancient civilisations, namely the Egyptian civilisation in the Kahn area in 5000 BC and the Chaldean city of Ur before 2000 BC [12]. Courtyard houses did not appear in the West until later, in cities such as Greece and Rome [13]. Courtyard houses have evolved in line with the lifestyle of the inhabitants and as a climatic response in hot and dry climates [14]. In Italy, for example, the courtyard was transformed into an atrium from 700 AD onwards, the purpose of which was to create a private space [15], while in China the primary houses conceived of the courtyard as a private and meditative space [16]. In Algeria, on the other hand, courtyard houses are available for climatic and social reasons and can be found in almost all Algerian cities with *ksour* or *kasbahs* as their old centre, see Figure 1 below.

A review of the scientific literature has enabled us to characterise courtyards geometry by: (i) Its shape, which is most often rectangular, square or even circular [17]. Tablada et al (2005) [18] have shown that the rectangular shape provides better protection from solar radiation and limits the impact of sand winds; (ii) the scale or size of the courtyard is another distinctive element. The size calculated in relation to the house's area varies from one house to another; (iii) the position of the courtyard may be central or off-centre, or the courtyard may be semi-enclosed, bordered by the house on one side and by enclosing walls on the other [19]; (iv) The depth of the courtyard, which may vary from one region to another. (V) The orientation of the courtyard plays an important role in defining wind movement, solar protection and solar gains [20].

(a) (b)

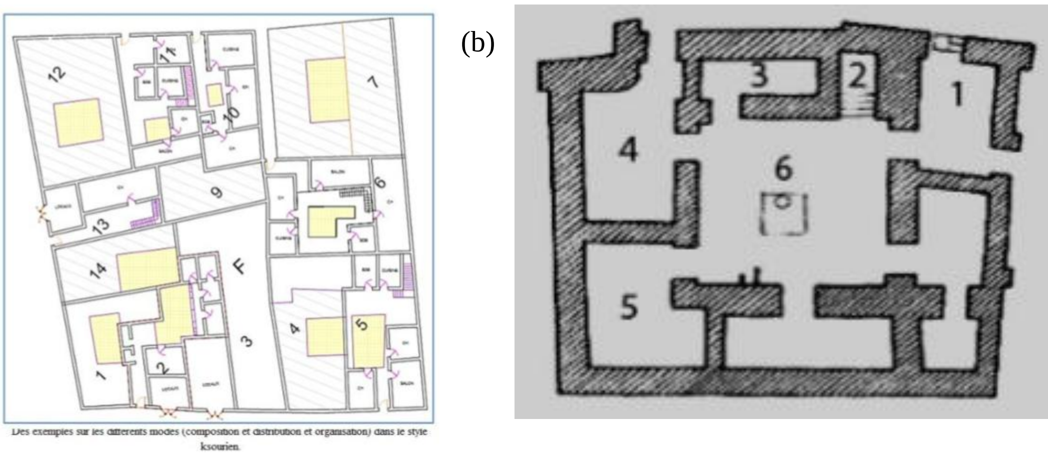

Figure 1: (a) Examples of the different modes of composition and organisation in the ksourien style. Source: PPSMVSS of ksar Laghouat, Algeria. (b) Courtyard house in Mesopotamia. Source: Abass et al: 2016[14].

Research into the role of courtyards has been the subject of several studies around the world since the early 2000s, with the rise of sustainable development principles. The most frequently asked questions concern several aspects of environmental performance, namely energy demand, daylighting [21], natural ventilation [22] and microclimate generated [23]. The energy aspect is the most widely studied and focuses mainly on the summer period, with fewer studies looking at both aspects at the same time. The summer period is the most studied because the courtyard still exists in arid zones and is still an element of architectural composition. Studies of the adaptability of courtyards to the two periods, summer and winter, are few Akbari et al (2021) [24] demonstrated a higher adaptability for the summer period with 73% and 20% for winter, which explains the tendency of researchers to deal only with the summer period. Also, some studies state that courtyards are better adapted to hot climates than cold climates [25, 26]. It is also worth noting that in some climatic regions the trend is reversed, Yaşa et Ok (2014) [27] found that the maximisation of solar radiation is greater for the winter period than the summer period giving a better adaptability of patios to winter than summer.

De la Flor et al (2021) [28] carried out a comparative study using a simulation-based approach between a house with a courtyard and a reference case without a courtyard. They found that the courtyard could improve energy savings by more than 10% and that the geometry of the courtyard is a key parameter for controlling cooling energy demand. Diz-Mellado et al (2023) [29] explored the impact of courtyard geometry on energy demand in the climate of the city of Seville. They found that the temperature gap between the courtyard and outdoor temperature can vary according to the geometry of the patio from 10 to 14°C. And that the geometry of the yard can vary the cooling energy demand from 8 to 18% and by 15 to 22% once the floor level is combined with the orientation. Tabadkani et al (2022) [30] simulated in Grashooper with the environmental plugins ladybug and honeybee several possible combinations of courtyards in Tehran and found that the rectangular shape with an opening of 12% and the best configuration to satisfy summer and winter comfort is obtained for a rectangular patio of 10*5 and 4.5m deep in Tehran. Seddik et al (2024) [31] also studied the impact of the shape of the courtyard with the length-width ratio, the placement of the courtyard in relation to the centre of the houses and in relation to the facades, as well as the axis of orientation in the city of Kharga in Egypt. The study was carried out using DesignBuilder. The results show an energy saving of 18.73% with a rectangular shape at a ratio of 2.5:1 and a positioning of the patio on the south-west façade. Soflaei et al (2020) [32] carried out a parametric study using Grashooper, generating 8,600 cases and combining parameters relating to the geometry of the courtyard, the window to wall ratio and the material chosen for the walls. This study shows that the thermal behavior of courtyard depends initially on the construction materials, and that the depth of the courtyard is more important than its orientation.

The review of the scientific literature suggests that the combined effect of variables controlling courtyard geometry and the comparison between them are missing from the studies. this is why, In the present study, we aim to quantify the impact of courtyards geometry on cooling energy demand by specifying the effects of the parameters considered alone and in combination with each other under arid climatic conditions.

3 Methods

The methodology used in this paper to determine the impact of the courtyard geometry on energy demand is based on a parametric approach aimed at varying the elements characterising the courtyard obtained from scientific literature. Each variation is considered as a case study and the energy requirement for cooling is identified by dynamic thermal simulation carried out using DesignBuilder V.7.The variables considered in this paper are: the size of the courtyard considered by the ratio of courtyard area to ground floor house area (Ac/Ah); the depth of the courtyard considered according to the number of floors in the house; the shape of the courtyard, square or rectangular and finally the orientation which is considered according to the axis running along the courtyard, either North-South or East-West. The parametric variation considered is presented in Table 1 below.

Table 1 : parametric variation applied to selected parameters.

Courtyard parameters	**Variation**
Ac/Ah	10, 20 et 30%
Courtyard depth	Ground floor (3.5m), 1st floor (7m), 2nd floor (10.5m)
Courtyard shape	Square, rectangular
Orientation of the courtyard axis	North-South, East-West

The simulation protocol is designed so that the parametric variations combine to assess the impact of each parameter in relation to the other parameters. In all, a campaign of 27 simulations was run in DesignBuilder. Table 3 shows the parametric variation applied for each simulation and the results of the simulations containing the cooling requirement and solar gain.

The case study is a generic model house with a square shape and 15 m sides (see Appendix A1, Table A1-1). The glazing ratio applied is 10% of the external wall surface and the ceiling height is 3.5m. To simplify interpretation and speed up simulation time, the house is considered as a single thermal zone. The thermal characteristics of the building materials are presented in Table 2 below.

Table 2 : The thermal characteristics of building materials

Construction elements	Heat loss coefficient W/m².k
Exterior stone walls	1.698
High floor, traditional (earthen)	1.778
Low floor on earth	1.778
6mm single glazing	5.778

4 Results and discussion

The climate data used for the simulations covers the period from 2007 to 2021 for the city of Laghouat-Medaghri and was obtained from the climate.onebuilding.org website. The bioclimatic analysis was carried out using the Climate Consultant V6 psychometric diagram developed by the University of California. See figure 2 below. By applying the ASHRAE Standard 55, adaptive thermal comfort model for naturally ventilated buildings, the comfort thresholds are limited to between 18.4°C for heating and 30.6°C for cooling (90% acceptability).

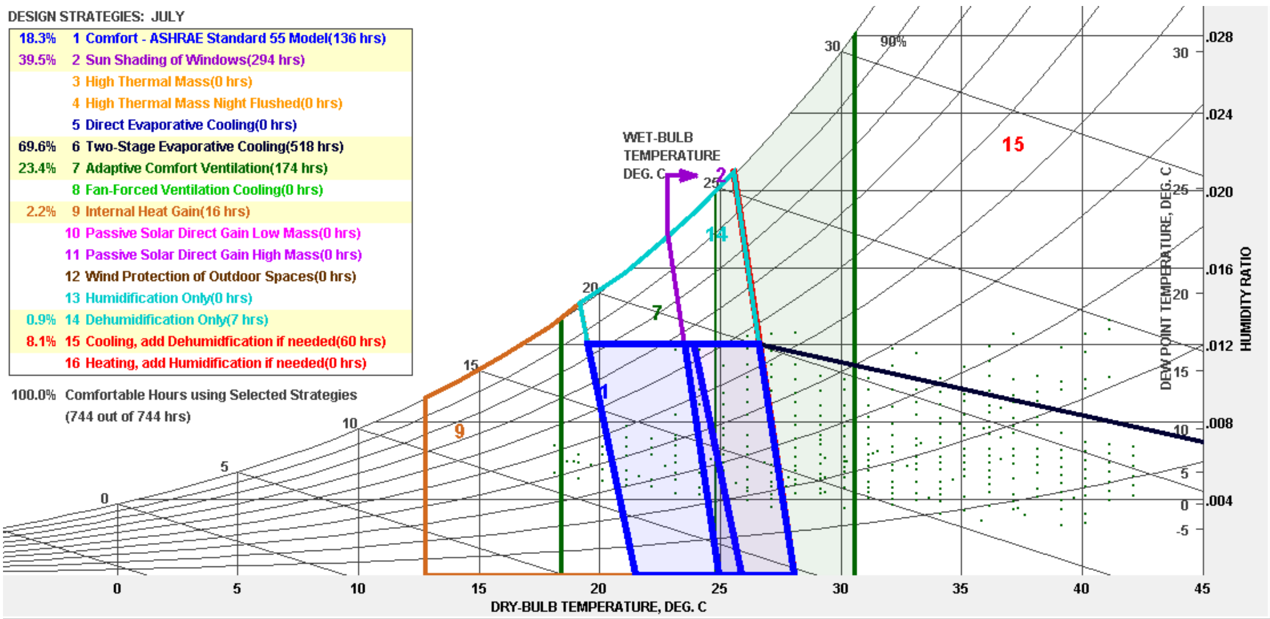

Figure 2: psychometric diagram of the city of Laghouat for the month of July.

The psychometric diagram shows that during the month of July, the climate is only comfortable for 18.3% because of the high temperatures experienced in the city of Laghouat, which can exceed 42°C. With ventilation management, comfort can be improved by 23.4%, while the need for air conditioning remains high at 62.5%. The passive strategies proposed by the model focus mainly on solar protection (nearly 40%) and evaporative cooling (nearly 70%). The role of the courtyard revolves around ventilation and solar protection. In this paper, the courtyard is studied to assess its role in solar protection and its potential for reducing energy demand.

4.1 Presentation of simulation results:

The results of the 27 simulations carried out are presented in the table below, which contains, in addition to the parametric variation applied, the cooling requirement and solar gain calculated by intensity per m².

Table3 : Parametric variation and simulation results

Case	Ac/ Ah	Depth	Shape	Orient	Cooling Kwh	EPI (w/m²)	Solar gain(W)	SG/m²	Dif %
1	10%	GF	Square	Neutral	47,56	234,86	22,51	111,15	8,94
2	10%	GF+1	Square	Neutral	84,77	235,48	42,86	119,06	9,23
3	10%	GF+2	Square	Neutral	119,82	221,89	62,63	115,99	2,92
4	20%	GF	Square	Neutral	48,34	238,73	24,65	121,74	10,73
5	20%	GF+1	Square	Neutral	86,79	241,08	46,48	129,1	11,82
6	20%	GF+2	Square	Neutral	123,49	228,69	67,34	124,7	6,08
7	30%	GF	Square	Neutral	48,02	237,14	26,39	130,31	10
8	30%	GF+1	Square	Neutral	87,39	242,75	49,73	138,14	12,6
9	30%	GF+2	Square	Neutral	123,56	228,82	71,72	132,82	6,14
10	10%	GF	Rectangle	North-South	49,6	244,95	22,88	112,98	13,62
11	10%	GF+1	Rectangle	North-South	85,03	236,19	43,05	119,57	9,56
12	10%	GF+2	Rectangle	North-South	117,93	218,39	62,81	116,31	1,3
13	20%	GF	Rectangle	North-South	50,62	249,96	25,5	125,94	15,94
14	20%	GF+1	Rectangle	North-South	89,45	248,46	47,24	131,21	15,25
15	20%	GF+2	Rectangle	North-South	124,34	230,26	67,95	125,83	6,8
16	30%	GF	Rectangle	North-South	50,72	250,45	27,36	135,11	16,17
17	30%	GF+1	Rectangle	North-South	90,07	250,19	50,45	140,13	16,05
18	30%	GF+2	Rectangle	North-South	126,84	234,89	72,07	133,46	8,95
19	10%	GF	Rectangle	East-West	46,56	229,94	22,07	108,97	6,66
20	10%	GF+1	Rectangle	East-West	81,69	226,91	42,7	118,62	5,25
21	10%	GF+2	Rectangle	East-West	116,41	215,58	62,78	116,25	0
22	20%	GF	Rectangle	East-West	46,79	231,08	24,18	119,42	7,19
23	20%	GF+1	Rectangle	East-West	83,13	230,92	46,24	128,46	7,11
24	20%	GF+2	Rectangle	East-West	120,15	222,5	67,53	125,05	3,21
25	30%	GF	Rectangle	East-West	45,59	225,12	25,78	127,3	4,42
26	30%	GF+1	Rectangle	East-West	83,21	231,13	48,99	136,08	7,21
27	30%	GF+2	Rectangle	East-West	119,54	221,37	71,22	131,88	2,68

SG: solar gain. Dif: the difference in cooling requirement compared with the best case (21 in green).

Based on the results described in Table 3 above, we can identify the role of each parameter on the energy demand for air conditioning. (i) The size of the courtyard, expressed as the Ac/Ah ratio, clearly shows a linear trend: the larger the courtyard, the greater the energy demand. 10% is the ideal scale for the courtyard to reduce its energy demand for air conditioning. This result is explained by the reduction in solar gain. (ii) The depth of the courtyard also makes it possible to reduce the energy demand for air conditioning by reducing solar gain, and GF+2 is the best case. (iii) The shape of the courtyard also helps to regulate solar radiation, and, in fact, the rectangular shape provides better protection than the square shape. (iv) The orientation of the courtyard axis, combined with the shape, scale and depth of the courtyard, provides the best case and reduces energy demand by more than 16%.

4.2 Sensitivity analysis

There are several methods of sensitivity analysis, but for this study we chose the univariate linear regression method because it allows assessing the importance of each parameter in relation to the other variables based on the F statistics. (ii) This method also allows assessing the importance of all the variations by parameter on the energy demand for air conditioning.

The collinearity test is verified if all the variables have a VIF of less than 3 and a tolerance well above 0.2, see Table 4 below. The heteroscedasticity test is satisfied by applying White's test, see Table 5 below. Linearity and normality are also validated; see Figure A1-1 in Appendix A1.

Table 4 : Collinearity statistics

	Tolérance	**VIF**
Ac/Ah	1,000	1,000
Depth	1,000	1,000
Orientation	1,000	1,000

Table 5 : White's test for heteroskedasticity

Khi-carré	**ddl**	**Signification**
27,000	26	**0,409**

The results of the modelling of energy demand for air conditioning gave us an explanatory model with 99.6% accuracy. The details of the model are presented in Table 4 below and the comparison in terms of effect on energy demand is developed from F statistics and the estimated marginal mean of each parameter, see Figure 6 below.

Table6 : Summary of the univariate linear model.

Source	**Somme des carrés de type**	**ddl**	**Carré moyen**	**F**	**Signification**
Corrected model	544,526[a]	18	30,251	101,166	0,000
Constant	1888,609	1	1888,609	6315,804	0,000
Ac/A_h	52,822	2	26,411	88,322	0,000
Depth	230,550	2	115,275	385,498	0,000
Orientation	201,161	2	100,581	336,358	0,000
Ac/A_h * Depth	14,623	4	3,656	12,225	0,002
Ac/A_h * Orientation	17,671	4	4,418	14,774	0,001
Depth * Orientation	27,699	4	6,925	23,157	0,000
Error	2,392	8	0,299		
Total	2435,528	27			
Corrected total	546,918	26			
R^2 = ,996 (R^2 adjusted = ,986)					

Based on the values of F, it seems clear to us that depth is the most important followed by orientation combined with the shape of the courtyard and finally the scale of the courtyard Ac/Ah. See figure 3 below.

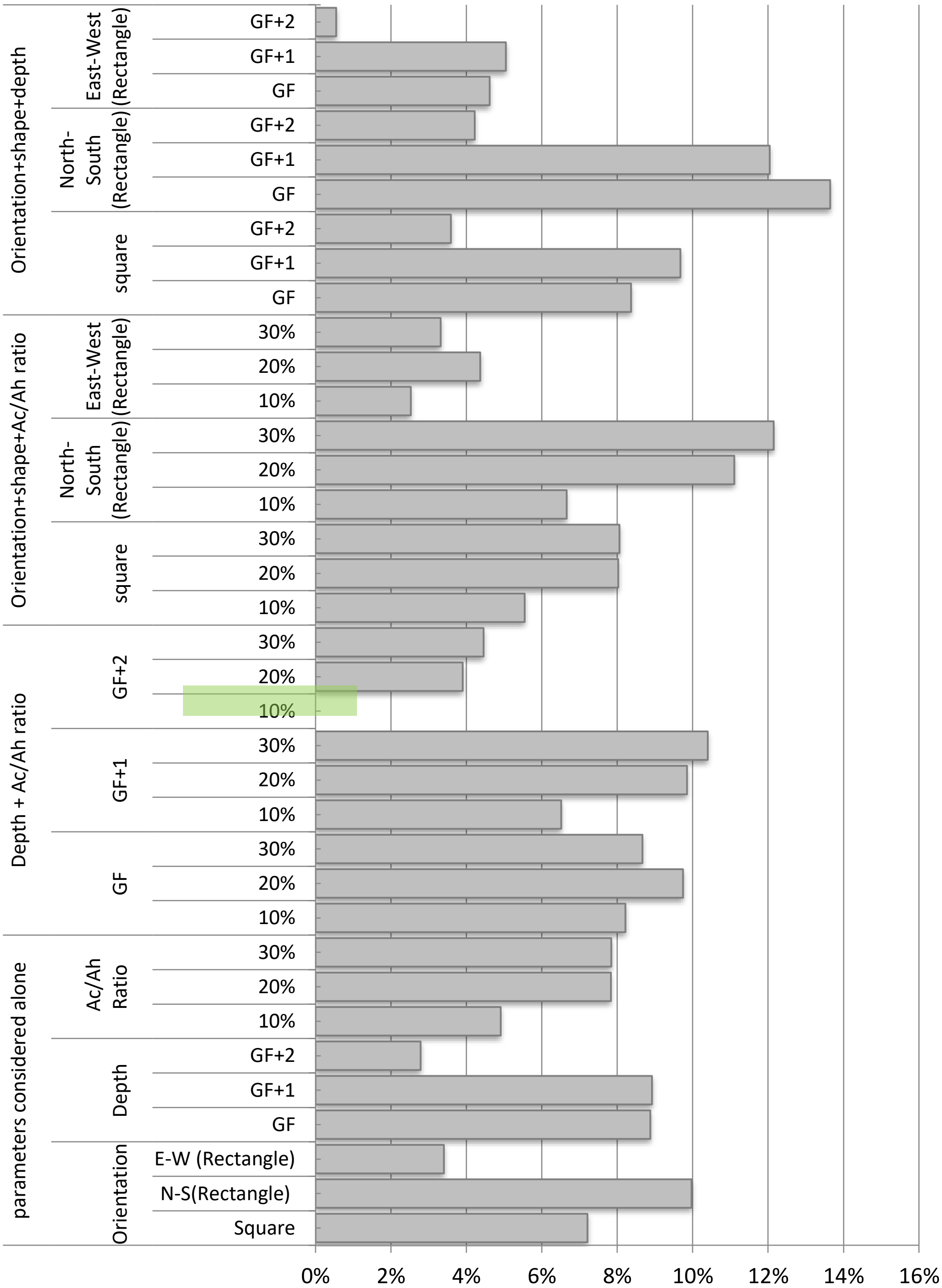

Figure 3: Impact of varying the influencing parameters on the energy demand for air conditioning. In green: the best case considered as a reference.

The impact of the parameters considered alone:
The parameter with the greatest impact on energy demand is the depth of the courtyard, an element which concords with the results of Akbar et al (2021) [24] and Solfei et al (2020) [32] because the best sunshade is achieved inside deeper courtyard. It achieves a performance 2.79% better than the reference case (combining depth with Ac/Ah), but with shallower depths (ground floor and first floor), energy demand rises to almost 9% compared with the reference case. In second place comes the orientation and shape of the courtyard. An east-west orientation of the courtyard axis combined with a rectangular shape, elongated on the same axis; is the best configuration and limits energy demand to 3.40% compared with the reference case. On the other hand, a north-south orientation, even with a rectangular shape, increases energy demand by almost 10%, as it also increases solar gain. The square shape of the courtyard also increases energy demand by almost 7% compared with the reference case. The size of the courtyard, expressed as an Ac/Ah ratio, comes in 4th place, and the most favourable case is a 10% opening with an increase in energy demand of almost 5% compared with the reference case. An opening of 20 and 30% of the courtyard surface will increase solar gains and the resulting energy demand to almost 8% compared with the reference case.

The impact of the courtyard's "depth and size" combination
This combination results in the most favorable case for reducing cooling energy demand, with a depth of GF+2 or 10.5m and a courtyard opening of 10%. The most unfavorable cases are obtained with courtyard opening of 20 to 30% and depths of ground floor to first floor. Energy demand rises to 10.40%. The depth and openness of the courtyard considerably reduces solar gain.

The impact of the "Orientation - shape and the size of the courtyard" combination
The rectangular shape combined with an east-west orientation of the courtyard axis and a 10% opening reduces energy demand by 2.53% compared with the reference case. And even with courtyard openings of up to 20 and 30%, energy demand remains virtually stable, increasing by only 4.3% and 3.7%, because the rectangular shape reduces solar radiation from the south-facing orientation. On the other hand, when the courtyard is elongated along the north-south axis, the opening of the courtyard is more detrimental to solar protection and increases energy demand by more than 12%.

The impact of the combination of orientation, shape and depth of the courtyard
With this combination, it is also possible to achieve the best configuration by combining a 10% courtyard opening with a depth of GF+2 and a rectangular shape elongated along the East-West axis. On the other hand, a North-South orientation of the courtyard axis considerably reduces solar protection and increases the energy demand for air conditioning by almost 15%. The square shape is sensitive to the depth of the courtyard and increases energy demand by up to 9.6% compared to the reference best case.

The results obtained in the present study support the results obtained by other researchers and by the application of other sensitivity analysis methods in the arid regions, as demonstrated by De la Flor et al (2021) [28] and Diz-Mellado et al (2023) [29], Solfei et al (2020) [32] and Akbari et al (2021) [24]. The findings suggest that deep, narrow courtyards are better adapted to warmer climates and the orientation of the courtyard performs well with rectangular east-west elongated courtyards. The explanation for these results lies in two factors, the first is the solar radiation, which is more direct in shallow courtyards and the second is the thermal layering that happens inside the courtyard.

5 Conclusion

The courtyard, as an element of architectural design, has emerged as a regulator of comfort in vernacular houses. This paper examines the importance of the courtyard's influencing geometry parameters on the energy demand for air conditioning. The method of analysis is based on univariate linear regression modelling applied to the results of 27 dynamic thermal simulations. The results show that the geometrical parameters with the greatest impact are the depth of the courtyard, followed by the orientation and shape of the courtyard, and finally the size of the courtyard. The rectangular shape of the east-west-facing courtyard reduces solar gain, and even with a larger courtyard opening, energy demand varies only slightly. The North-South orientation, on the other hand, is very sensitive to the size of the courtyard and its depth, and constitutes the most unfavourable case, since it increases energy demand by more than 15% compared with the reference case.

In the present paper, the role of the courtyard geometry has only been considered for its role as a thermal regulator in the summer period, the winter period could provide ample information on the dimensioning of the influencing parameters. In addition, other parameters can influence the thermal regulation role of the courtyard, such as window to wall ration, envelope materials, the terrain relief, the oasis effect and the compactness of the urban form, as is generally the case in the *Ksours,* ancient cities in southern Algeria. Considering other parameters allow to generate some simple-to-use rules for architects to conceive better eco-friendly housings and limit the energy consumption and the greenhouse gas emissions.

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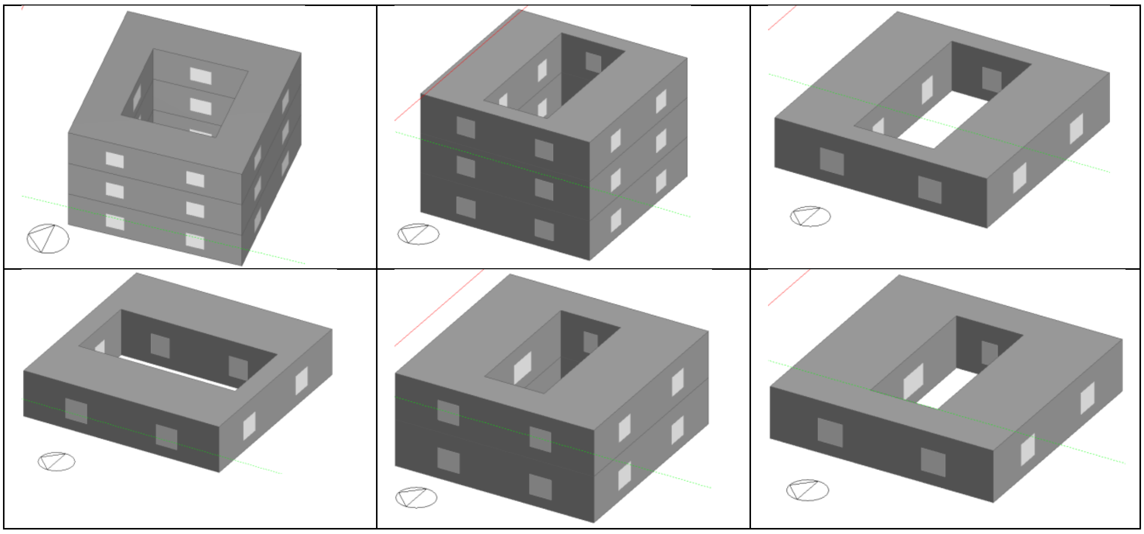
Appendix A1

Table A1-1 : Some examples of courtyard configurations.



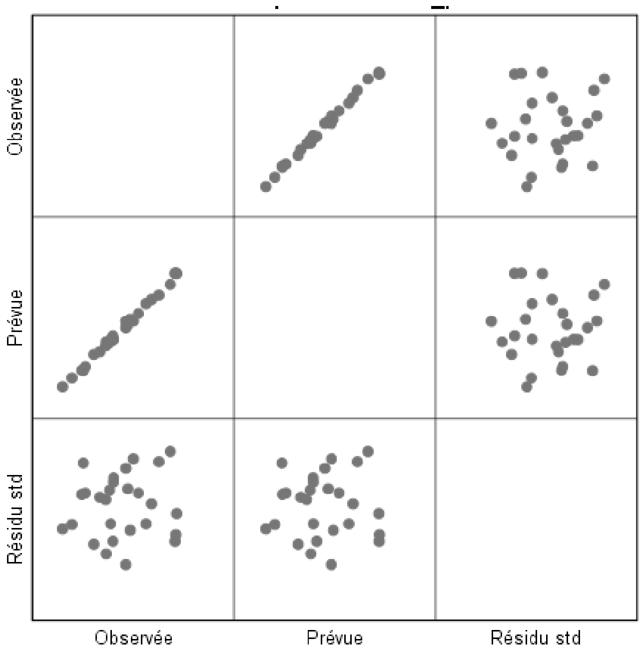


Figure A1-1 : QQ plot and comparison between simulated results and those obtained by the model