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Assessing the impact of courtyards in cooling energy demand in buildings

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ABSTRACT

Sustainable passive design strategies can reduce the energy consumption of buildings. In this regard, inner courtyards act as microclimate modifiers that enhance the perception of comfort in the surrounding environment. The present study, through a pooled analysis of experimental and numerical data, intends to assess the beneficial effect that the courtyards have in reducing the energy consumption of the buildings, especially for cooling demand. Accordingly, a new methodology allowing the use of different experimental data for facades and courtyards in software tools for the assessment of the real energy performance of buildings with courtyards is proposed. Besides, a detailed example of the application of the proposed methodology is performed for two scenarios simultaneously: a case study (considering the courtyard effect on the air temperature) and a reference one (without considering this effect). From the results, it is found that the courtyard reduces the demand for cooling in the spaces bordering it. As expected, the magnitude of the cooling demand reduction is correlated to the floor level, is increased at lower floors in the courtyard building. This relative reduction is up to 11%, being, for the case study analyzed, an average reduction of 7%.

1. Introduction

As it is well known today, buildings are responsible for 36% of global final energy consumption (International Energy Agency, 2019). This huge amount of energy is mainly due to the need for lighting, heating and/or cooling, ventilation and others, depending on the type of building, its use, the thermal quality of its exterior envelope, the state of conservation of the building and its facilities, as well as, of the climate of the locality in which it is located (Santamouris, 2004).

There are several databases in which the actual energy consumption in buildings can be obtained and filtered according to the type of building, the final use of energy, etc. A good example of this is the European Union (EU) Buildings Database (EU Buildings Database, 2019), or the Key World Energy Statistics (KWES) produced by the International Energy Agency (IEA) ("Key World Energy Statistics (KWES) 2018, " n.d.). According to the KWES the total electricity consumption in 2016 was due in 27.1% to the residential sector and 22.2% to the commercial and public services. These are average values corresponding to different countries at different latitudes and climates.

In the specific case of an office, commercial, and general tertiary sector buildings, the climatic factor is less decisive than for residential buildings. As a result, almost at any latitude can be found in tertiary buildings with heating and especially cooling consumptions (Santamouris et al., 1994).

Numerous studies have revealed these consumption trends in buildings. As a matter of the many examples, Gul and Patidar (2015) studied the relationship between the electrical energy demand profiles and user activities for a university building. Karjalainen (2016) emphasized the importance of user awareness in the energy consumption of office buildings and, in consequence, how to reduce this impact thanks to robust design solutions more independent of the user.

In the search for the causes of energy consumption in buildings, different studies indicate climatic reasons, building envelope, building facilities, user behavior, etc. D'Agostino and Mazzarella (2018) presented in their paper and its supplementary material, an overview of the European status concerning energy consumption, as well as, further data about building geometry, costs, envelope, lighting, appliances, and systems. Many efforts have been made to estimate the effect that microclimate modifications have on energy consumption for building conditioning. Sánchez et al. (2008) proposed a method based on the concept of climatic severity.

Given the importance of the energy consumption of buildings, there

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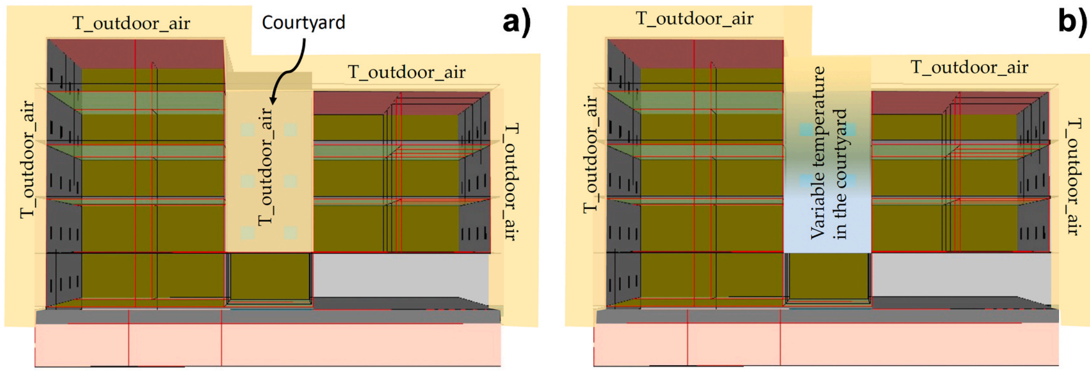


Fig. 1. Main difference between the standard and the proposed methodology for thermal simulation of a building including a courtyard.

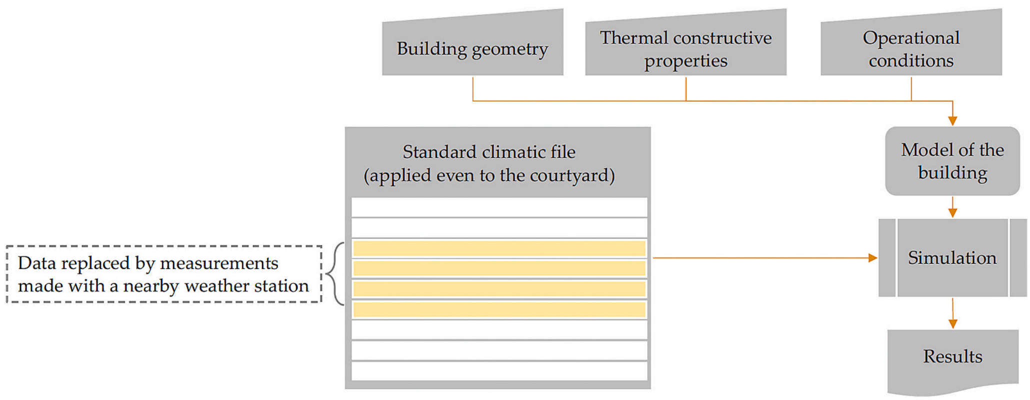


Fig. 2. Flow diagram for the reference case simulation.

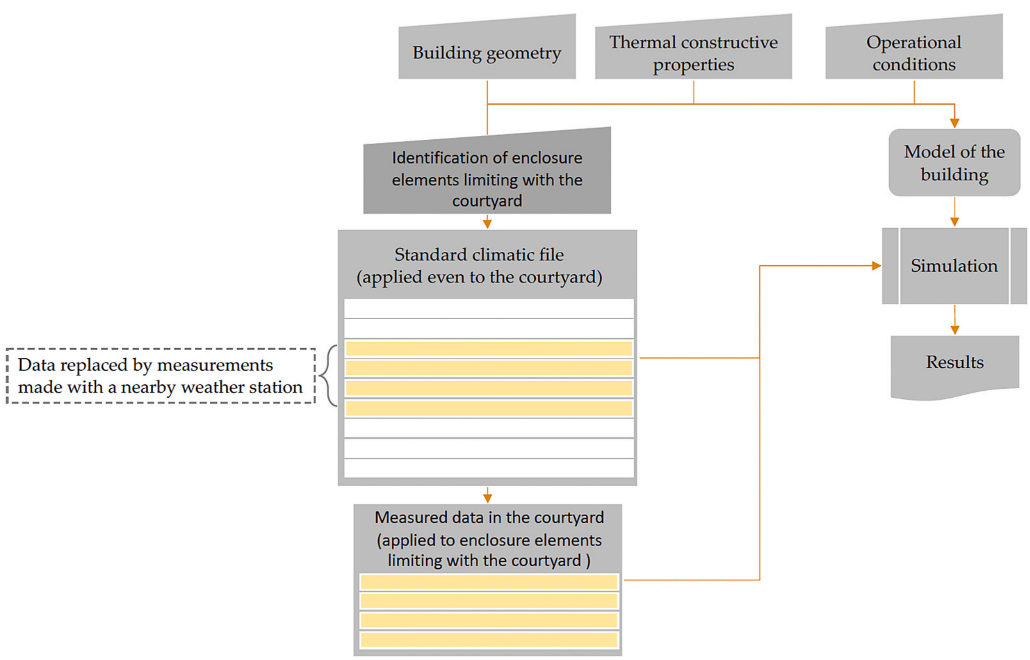


Fig. 3. Flow diagram for the case study simulationc

are regulations to standardize them by establishing limits, on the one hand, and, on the other, promoting low-energy buildings through energy efficiency certificates. Thus, at the European level, the regulations concerning the energy consumption of buildings are the well-known EPBD, which each member country of the European Union has transposed to its national regulation ("DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, of May 19, 2010, on the energy performance of buildings (recast)," n.d.). In the Spanish case, the requirements imposed by the EPBD are included in the Technical Building Code (CTE) (BOE.Orden FOM/1635/2013, 2013), and the

Fig. 4. Location of the IMUS building.

Fig. 5. 3D view of case study.

computer program for the compliance with these regulations is named HULC (Unified Tool LIDER-CALENER, for its acronym in Spanish) (HULC – Herramienta Unificada LIDER-CALENER, 2019). These regulations tend to push towards what has been called the nearly Zero Energy Buildings (nZEB). It is a very ambitious goal and requires that the building design is prepared to require a small amount of energy for its thermal conditioning both in winter and summer. In this sense, passive conditioning systems of buildings, that is, systems that do not require energy consumption or that are negligible, are of particular relevance.

Prieto et al. (2018) explored the energy-saving potential of the best-known passive cooling strategies for commercial buildings in hot climates. They differentiated between passive cooling design strategies and passive cooling systems. Among the former, we have modifications of microclimate, design, and orientation of the building, and measures to reduce internal heat gains based on thermal mass, PCM storage systems or user behavior patterns. Also, within this group, there are actions on elements of facades and roofs, such as insulation, solar control, the size and location of windows, etc. Within the group of passive cooling systems, they grouped the techniques according to the medium that acts as a heat sink, that is, the air, the water, the sky, or the ground. Once focused on the passive strategies, Marino et al. (2017) highlighted the important role of the window to wall ratio in the energy consumption of

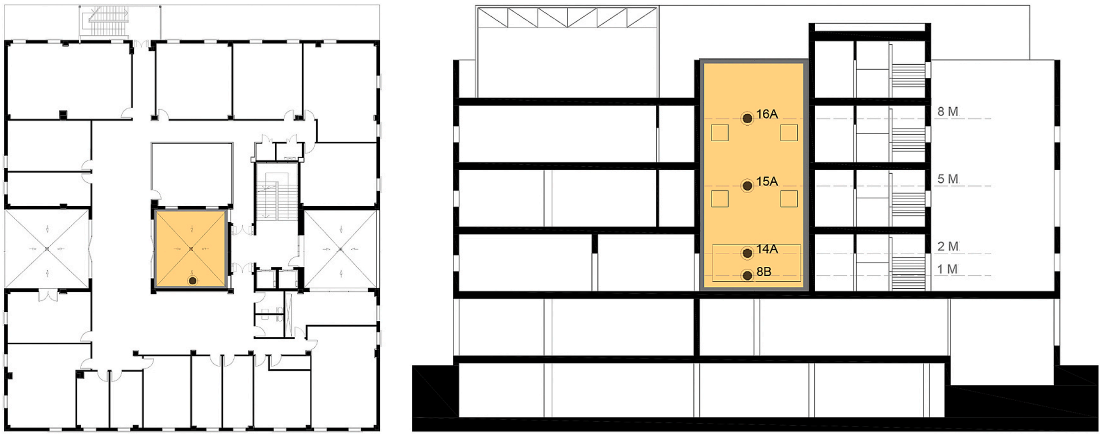


Fig. 6. Sensors location. Plant and section drawings of IMUS.

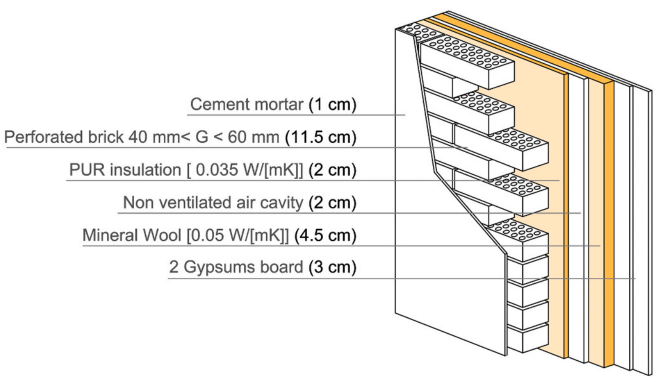


Fig. 7. Construction section of the wall.

the building.

In the particular case of the Mediterranean basin and the Middle East, the vernacular architecture has responded to this need for passive conditioning in climatic conditions of hot summers (Rojas-Fernández et al., 2017), and the best example is the construction of the inhabited places around a central courtyard. The courtyards provide shade to the walls that delimit them, and they are also able to act as a heat sink by cooling the air. This last effect is increased when there are sources of water and vegetation in the courtyard. Rodríguez et al. (2017) conducted several experimentation campaigns to measure air temperatures in courtyards in buildings in localities with a Mediterranean climate. Air temperature drops concerning the outside air were observed and characterized according to the geometry of the courtyard.

Despite the current availability of integrated programs, such as emerging BIM systems, the aptitude showed by most common energy analysis simulation software packages for the modeling of thermal conditions in small-sized outdoor spaces such as inner courtyards is limited (Rojas-Fernández et al., 2018).

But if those responsible for energy policy want to promote this type of solution based on the design of transition spaces such as courtyards, energy regulations should be able to properly evaluate them, and this is the main issue that the authors of this article intend to correct.

Not only does the aforementioned HULC tool lack the possibility of correctly assessing the beneficial effect of the courtyard on the building, but the same can be said of other international tools such as EnergyPlus (EnergyPlusTM, 2019).

For a certain building simulation tool to be able to correctly assess the effect of the courtyard, it would first have to evaluate the improvement of the environmental conditions in the courtyard itself and then evaluate its effect on the building.

For the first objective, that is, the evaluation of the modification of the external climatic conditions, the most widespread program today is the ENVI-met (Bruse, 2004). While EnergyPlus is commonly used for the evaluation of heating and cooling consumption of buildings. In any case, ENVI-met is more useful for large proportions of urban spaces thermal simulations, not being able to predict the microclimatic conditions of small spaces such as courtyards.

Although there is the possibility of using ENVI-met first to generate a climate file and then use it in EnergyPlus, it is not possible to generate different weather conditions outside the building and in the courtyard at the same time, much less if it is wanted to show differences at different heights or specific positions of the courtyard.

The same happens in the case of the HULC tool, and since this is the official/compulsory tool to obtain the energy rating of buildings in Spain, this qualification does not take into account precisely the effect of the existence of courtyards.

Another issue to be addressed is the combined used of experimental and numerical data to assess the energy performance of buildings. In this case, it would be interesting to be able to match experimental data of the outdoor conditions inside and outside the courtyard as input data for the numerical assessment of its effect on the energy consumptions for air conditioning of the building. This use is again out of the current capabilities of the most common energy performance software tools (Crawley et al., 2008).

The first objective of this article is, therefore, to propose a methodology that allows the use of different experimental data for facades and courtyards in software tools for the assessment of the energy consumptions for space heating and cooling of buildings.

Secondly, and thanks to the above, it is intended to value the beneficial effect that the courtyards have in reducing the energy consumption of the buildings, especially by reducing the needs for conditioning in summer.

Finally, this article details an example of the application of the proposed methodology to a real building, the building of the Institute of Mathematics of the University of Seville (IMUS).

2. Materials and methods

The correct evaluation of the influence that the transition spaces, specifically the courtyards, have on the energy consumption for the conditioning of the buildings requires a methodology with two main stages:

2.1. Stage 1: Experimental campaign

To the first stage corresponds the data collection of the real building, and specifically, of the climatic conditions to which the building is

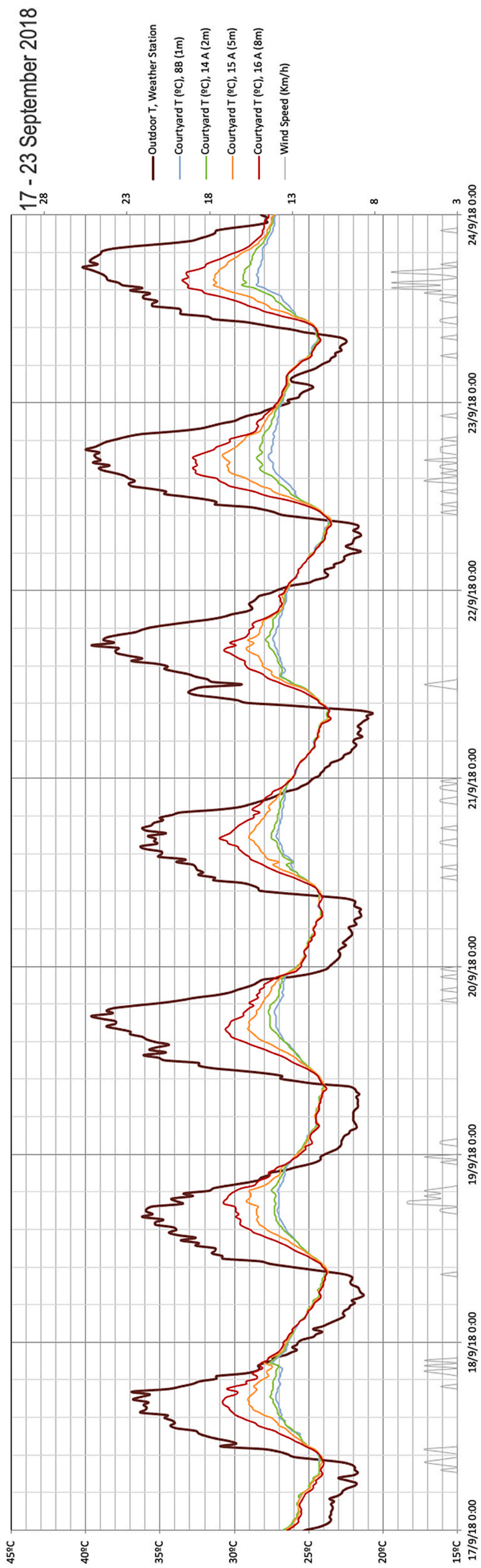


Fig. 8. Courtyard monitoring results graph.

Table 1
Measured variables, technical data of the instruments, and observation parameters.

Situation	Outdoor			Courtyard	
Sensor	PCE- FWS 20			TESTO 174H	
Interval	15 min	15 min	20 min	20 min	20 min
Variable	T[a]		Wind Speed	T[a]	Hr
Accuracy	±1 °C	±5%	±1 m/s	±0.5 °C	±0.1%
Range	−40 a +65 °C	12 a 99%	0 a 180 km/h	−20 a +70 °C	0 a 100%
Resolution	0.1 °C	1%	–	0.1 °C	2%

subjected both in its outer envelope, as in its courtyards. Numerous studies have shown that these conditions can be very different from one place to another, especially in summer, when courtyards act as a heat sink creating a semi-confined space with an air temperature below the outside temperature by several degrees.

The main issues to be taken into account to proceed with the study of the building are:

- **Dates of beginning and end of the experimental campaign**

As the main effect of the courtyard is the reduction of the building's cooling needs, the experimental campaign must be carried out in summer. The duration, meanwhile, must be at least 2 weeks as indicated by the monitoring protocols in courtyards established in previous research (López-Cabeza et al., 2018).

- **Selection of climatic variables to be measured**

The courtyard modifies the climatic conditions in its interior, fundamentally, the solar radiation that reaches each surface, walls and, windows, as well as the temperature of the air. Callejas et al. (2020) calculated the importance of the shading index inside the courtyard. Therefore, in principle, solar radiation should be measured on each surface in the courtyard and the air temperature at different heights and positions within the courtyard in order to detect the thermal stratification in the courtyard (Rivera-Gómez et al., 2019). These data will be used later in the second stage of the methodology proposed in this paper, that is, in building energy simulation programs. In these programs, the calculation of shadows cast by elements of the building itself is very common, but not the modification of the outside air temperature, as explained above. Consequently, the need to experimentally measure solar radiation can be avoided, which will instead be calculated by the simulation tool, while it is still necessary to measure the air temperature.

- **Choice of time between measurements**

Building energy simulation programs usually run with an hourly time step. Experimental measurements must, therefore, be taken in an equal or lower time step. A suitable value is to take data every 15 min as indicated by thermal monitoring protocols in previous research courtyards (López-Cabeza et al., 2018).

- **Sensor positioning**

If solar radiation sensors are used, they must be placed at least one in each orientation and for each floor of the building. The air temperature sensors should be placed on the side of the courtyard that is most protected from solar radiation, to avoid measurement errors. Therefore, they will be located on the north-facing façade. In addition, as indicated by previous monitoring researchs, sensors must be protected with an insulating material and separated 10 cm from the facade so as not to interfere with the data recording (Diz-Mellado et al., 2020). An air

Table 2
Minimum, Maximum daily temperatures and Thermal Gap measured in the courtyard.

Week	ºC	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
1	T_{max}	28,3	26,9	31,1	34,5	35,8	37,4	37,4
	T_{min}	14,2	16,4	14,8	19,2	16,2	17,8	18,7
	TG	2	2,7	2,6	5,6	4,4	5,8	3,8
2	T_{max}	41	40,9	39,1	37,9	36,5	36,8	38,8
	T_{min}	19,3	21,7	19,7	21,1	20,1	21,3	19
	TG	6,5	3,7	5,5	4	3,9	3,1	4,3
3	T_{max}	35,6	31,2	33	33,3	29,3	31,3	27,9
	T_{min}	22	19,9	18,2	18,2	19,6	17,3	17,7
	TG	1,5	0,6	0,8	0,5	1,3	0,5	3,4
4	T_{max}	28,2	31,6	35,3	31,8	33,1	37,6	39,6
	T_{min}	17,7	17,5	17,2	16,6	18,7	18,5	19,6
	TG	1,7	6,4	3,3	1,3	1,3	4,1	5,5
5	T_{max}	37,9	39	31,3	30,4	30,5	30,3	28,7
	T_{min}	20,1	20,5	19,9	19,7	19,3	17,4	16,8
	TG	3,1	4,2	-0,5	0,5	1,7	0,4	-0,5
6	T_{max}	30,1	36,9	38,7	34,8	36,2	37,3	35,4
	T_{min}	17,8	16,7	18,5	19,2	16,9	17,6	18
	TG	1,6	6,9	5	1,5	3,4	4	2,4
7	T_{max}	35,8	36	33,6	35,2	33,8	36,6	34,6
	T_{min}	18,3	18,1	18,7	17,4	17,5	18,4	18,3
	TG	3,2	3	1,6	3,2	2,6	3,8	8,3
8	T_{max}	32,3	35,5	42,4	43,7	45,8	47,3	41,7
	T_{min}	18	17,1	19,4	23,2	24,7	26	25,2
	TG	1,8	3,3	10,1	8,1	10,1	11,2	6,5
9	T_{max}	42	42,5	41,7	35,2	36,2	39,2	40,9
	T_{min}	24,1	23,3	24,1	21,3	18,2	18,5	22
	TG	7,1	7,5	7	0,8	4,4	5	7,6
10	T_{max}	40	35	38,4	35,6	33,8	40,7	44,7
	T_{min}	23,4	21,1	19,3	19,3	20,3	20,3	22,8
	TG	6,4	1	5,4	4,9	4	9,2	10,4
11	T_{max}	42,3	42,7	43,7	43,5	42,9	43,6	40,2
	T_{min}	23,2	23,6	23,6	23,4	23,1	23,1	23,4
	TG	9,3	9,1	10,7	10,8	9,7	10,4	5,8
12	T_{max}	42,2	41,9	41,1	39,5	41,3	43	42,3
	T_{min}	21,7	23,1	21,6	21	21	22,8	23,4
	TG	10	10,5	9,1	9	11,5	11	10
13	T_{max}	42	33	33	33,2	35,9	35,1	31,3
	T_{min}	22,2	20,4	20,4	20	19,8	19,8	20,5
	TG	9,6	3,8	4,9	5,4	7,4	7,3	4,3
14	T_{max}	38,3	39,3	39,3	39,8	37,2	34,1	38,3
	T_{min}	20,4	20,4	22,1	22,6	18,7	18,7	20,2
	TG	9,3	10,3	9,6	10,8	7,5	7,3	11,4
15	T_{max}	37,4	39,2	38,4	41,5	39,3	41,1	42,6
	T_{min}	21,5	22,2	22,2	22,9	22,7	21,8	21,8
	TG	8,9	10,2	9,9	12,7	10,3	12,2	11,8
16	T_{max}	43,4	43,4	39,3	38,5	34,3	35	35
	T_{min}	22,5	22,5	29,6	22,7	22,5	21,2	18,8
	TG	13,6	12,4	9,7	8,5	4,3	6,6	7,7

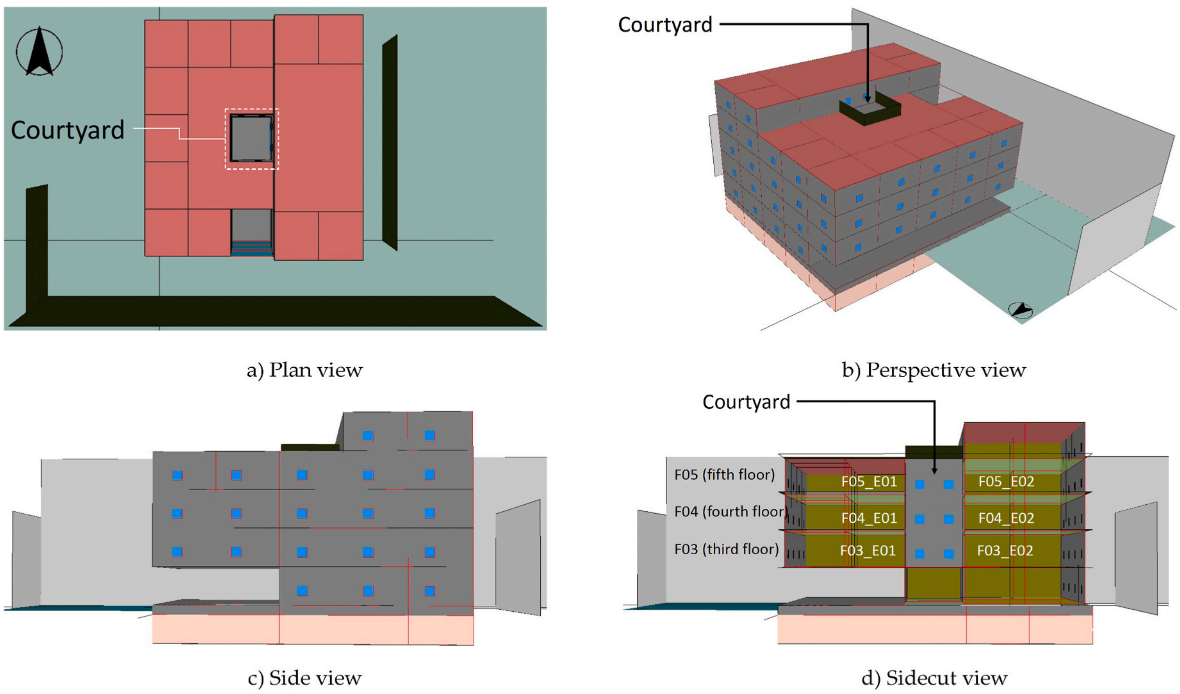


Fig. 9. General view of the graphical model of the building. Grey: exterior elements, red: roof elements, green: interior elements.

temperature datalogger for each floor of the building is sufficient, although the use of more sensors allows the correction of possible measurement errors.

2.2. Stage 2: Numerical study: New methodology proposed

The second stage of the methodology consists of using some experimental measurements as inlet data for the energy performance simulation of the building. The numerical study aims to evaluate the courtyard effect in the building from a thermal point of view.

This paper proposes the use of the official tool for energy regulations in Spain, that is, the HULC tool (" Herramienta Unificada LIDER-CALENER," n.d.). The HULC tool runs with an hourly time step in a transitory state and has passed the tests of Spanish regulations for energy certification software tools (IDAE, 2009a), as well as the well-known IEA Bestest (Judkoff and Neymark, 1995). HULC uses the official climate files provided by the "Ministerio para la Transición Ecológica y el Reto Demográfico (Ministry for Ecological Transition and Demographic Challenge)" which is the entity that in Spain establishes the regulations for the qualification and energy certification of buildings (IDAE, 2009b). This tool, in its latest version, includes the additional capability to modify the boundary conditions of one or more of the elements of the building envelope. Besides, such modification may consist of changing a certain climatic variable, such as the temperature of the air in the courtyard.

The simulation of the building and the use of the additional capabilities in the HULC tool for this study does not follow the standard procedure established for simulation, since in this case some climatic conditions were taken from the measures performed in the experimental campaign, and not from a standard climatic file as it is usually done.

Also, the standard simulation procedure establishes that the boundary conditions of air temperature are the same for all elements of the envelope regardless of whether they limit the courtyard or not. This assumption will be used as a reference case. What is proposed in this study is that different boundary conditions should be used for the elements limiting the courtyard since the courtyard air temperature, in general, is different from that of the outside air. This is the methodology uses in the case study. See Fig. 1.

To evaluate the effect of the courtyard on the building's cooling demand, two simulations were carried out:

- **Reference case**, Fig. 1. a: it consists of a simulation in which it is assumed that in the whole envelope of the building including the courtyard, the air temperature is equal to that of the outside air
- **Case study**, Fig. 1,b: it consists of taking the temperatures measured in the courtyard to use them as boundary conditions for the elements of the envelope that limit with the courtyard, while the other elements of the envelope see the temperature of the outside air.

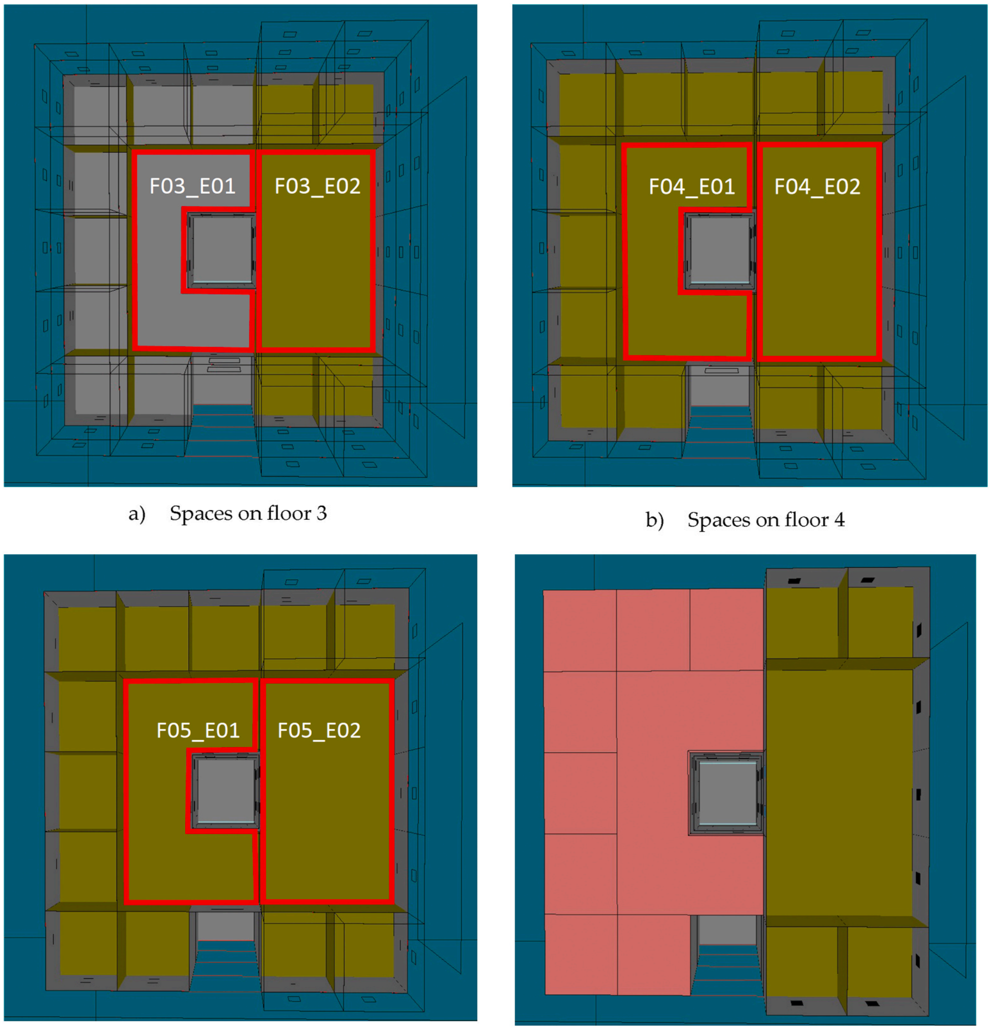
It is convenient to make three clarifications about the procedure followed:

- **The** first is that, since the temperature of the courtyard air is related to that of the outside air, it is necessary to simultaneously measure the temperature of the outside air; which was done using a weather station located on the roof of the building.
- The second is that as was evidenced from the measured data, the temperature of the air in the courtyard varies with height, in consequence for the simulations, different temperatures were assigned to each of the elements of the courtyard, depending on the height in which they were located.
- The third is that, since the experimental campaign does not cover the whole year, to carry out the simulation, the official file of the climatic conditions of Seville was taken, and when there were measured data available they were replaced by the official data.

In Figs. 2 and 3, a flow diagram explaining de basic ideas of the procedure followed shows.

The steps followed to perform the numerical comparison between the reference case and the case study were:

1. Building modeling: in this step, the geometric, constructive, and operational conditions of the building are defined. The different rooms inside the building were named F0X_EYY where "X" refers to the floor number where the room is located and "YY" is a given number for each room.



a) Spaces on floor 3

b) Spaces on floor 4

c) Spaces on floor 5

d) The roof of Spaces on floor 5 and spaces on floor 6

Fig. 10. Spaces limiting with the courtyard. It can be seen that the floor of space E01 of the third floor is in contact with the exterior air. (grey color denotes element in contact with the exterior and green color denotes element in contact with the interior element.

Table 3
Annual cooling demand for spaces bordering the courtyard.

		Accumulated cooling demands			
Floor	**Space**	**Case study (kWh/m2)**	**Rference case (kWh/m2)**	**Absolute difference (kWh/m2)**	**Percentage difference**
Third floor	F03_E01	23.67	25.74	2.07	9%
Fourth floor	F04_E01	18.38	20.17	1.79	10%
Fifth floor	F05_E01	27.62	29.27	1.65	6%
Third floor	F03_E02	15.47	15.96	0.49	3%
Fourth floor	F04_E02	16.09	16.65	0.56	4%
Fifth floor	F05_E02	17.20	17.75	0.55	3%

Table 4
Monthly cooling demand for spaces bordering the courtyard.

Monthly cooling demand and differences for Case Study and Reference Case					jun.	Jul.	Aug.	Sep.	Total
Third floor	F03_E01	Reference case	[kWh/m²]		3.84	5.75	9.94	6.21	25.74
		Case Study	[kWh/m²]		3.43	5.82	9.07	5.35	23.67
		Abs. difference	[kWh/m²]		0.41	-0.07	0.87	0.86	2.07
		% difference			11%	-1%	9%	14%	8%
Fourth floor	F04_E01	Reference case	[kWh/m²]		2.92	4.55	7.67	5.02	20.17
		Case Study	[kWh/m²]		2.60	4.53	6.93	4.32	18.38
		Abs. difference	[kWh/m²]		0.32	0.02	0.74	0.70	1.79
		% difference			11%	1%	10%	14%	9%
Fifth floor	F05_E01	Reference case	[kWh/m²]		4.52	6.90	10.86	6.99	29.27
		Case Study	[kWh/m²]		4.20	6.89	10.19	6.34	27.62
		Abs. difference	[kWh/m²]		0.32	0.01	0.68	0.65	1.65
		% difference			7%	0%	6%	9%	6%
Third floor	F03_E02	Reference case	[kWh/m²]		2.27	3.57	6.22	3.90	15.96
		Case Study	[kWh/m²]		2.19	3.58	6.01	3.70	15.47
		Abs. difference	[kWh/m²]		0.09	-0.01	0.21	0.20	0.49
		% difference			4%	0%	3%	5%	3%
Fourth floor	F04_E02	Reference case	[kWh/m²]		2.43	3.77	6.40	4.04	16.65
		Case Study	[kWh/m²]		2.33	3.76	6.17	3.83	16.09
		Abs. difference	[kWh/m²]		0.11	0.01	0.23	0.21	0.56
		% difference			4%	0%	4%	5%	3%
Fifth floor	F05_E02	Reference case	[kWh/m²]		2.65	4.10	6.74	4.27	17.75
		Case Study	[kWh/m²]		2.54	4.09	6.52	4.05	17.20
		Abs. difference	[kWh/m²]		0.11	0.01	0.22	0.21	0.55
		% difference			4%	0%	3%	5%	3%

2. Modification of the climate file of Seville (Spain): This step consisted of replacing the outdoor air temperature data that the standard climate file has for Seville with the specific data measured during the experimental campaign.

This step does not correspond to the standard simulation procedure when additional capabilities are incorporated. However, in this case, it is necessary to perform it because it is intended to make a comparison between the reference case and the case study using experimentally recorded temperature data.

3. Execution of the thermal simulation of the building with the modified climate file for the reference case.

In this simulation, although the defined building has a geometry that includes the courtyard, the elements (walls and windows) limiting with it, have as contour condition the same exterior temperatures as the rest of elements and in consequence, from the simulation point of view, the courtyard does not affect the thermal behavior of the building.

In the standard use of additional capabilities in the HULC tool, this is the first step to perform the calculation when non-conventional elements are included in the building. Here, the elements limiting with the courtyard are considered as non-conventional elements. This first step is an energy simulation under the standard calculation conditions, that is, on the outer side of the building envelope, all elements have the same climate conditions file.

4. Selection of the walls, windows, and any other envelope element of the building bordering the courtyard.
5. For each of the elements selected in point 4, new outside air temperature is defined. This is the second step of the standard procedure, where the new particular climatic conditions are established.

Because of the air temperature changes with height, the temperature assignment was done as follows:

- Walls and windows of floor 3 (F03_) → Average temperature measured by the sensors located at 2m of height
- Walls and windows of floor 4 (F04_) → Average temperature measured by the sensors located at 5m of height

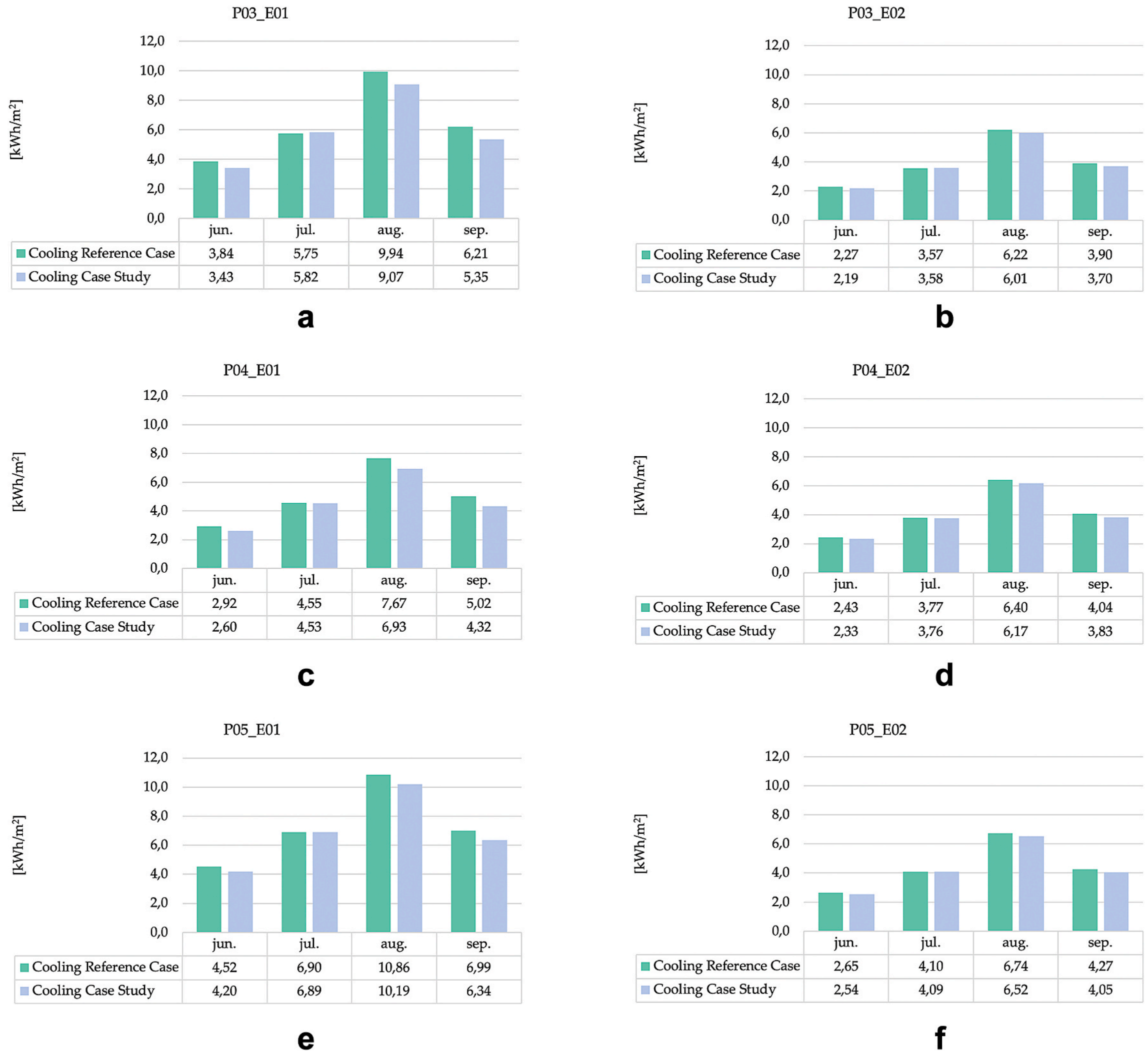


Fig. 11. Monthly cooling demands of spaces bordering the courtyard for the reference case and case study.

Table 5
Specific reduction of the cooling demand due to the courtyard effect.

	Relative reduction in cooling demand	Absolute reduction in cooling demand	Space area	Wall area bordering the courtyard	Wall area ÷ Space area	Specific reduction in the demand of the space per m^2 of wall bordering the courtyard
	[%]	[kWh/m^2]	[m^2]	[m^2]	[-]	[kWh/m^2]
F03_E01	10%	2.7	241	82.0	0.34	8.0
F04_E01	11%	2.3	241	82.0	0.34	6.8
F05_E01	7%	2.2	241	82.0	0.34	6.5
F03_E02	4%	0.6	289	29.2	0.10	6.3
F04_E02	4%	0.7	289	29.2	0.10	7.2
F05_E02	4%	0.7	289	29.2	0.10	7.2

- Walls and windows of floor 5 (F05_) → Average temperature measured by the sensors located at 8m of height

6. The final step is to perform a new energy simulation of the building but with the conditions modified in point 5.

3. Experimental set-up

3.1. Case study

The selected case study is located in Seville, Spain (37°17′01″N 5°55′20″W, elevation 42 m a.s.l.). The climatic conditions of the city, are as follows: is Csa in the Köppen classification (Warf, 2014), characterized by hot and dry summers with mean temperatures of 36 °C in July and mild winters with mean temperatures of 10.9 °C in January. The mean annual precipitation is 539 mm (Resúmenes climatológicos, 2019). The building selected is located in an urban area of a high density of mid-rise constructions. It is a five-story square-floor building with a central courtyard that is the current headquarters of the Institute of Mathematics of the University of Seville (IMUS), see Figs. 4–6. The courtyard façades consist of brick masonry with cement mortar linings

Table 6
Comparison of the accumulated cooling demands in all the spaces that limit the courtyard.

	Case Study Cooling Demand kWh/m^2)	Reference C Cooling Demand (kWh/m^2)	Absolute difference (kWh/m^2)	Percentage difference
Total of spaces bordering courtyard	20.8	22.3	1.5	7%

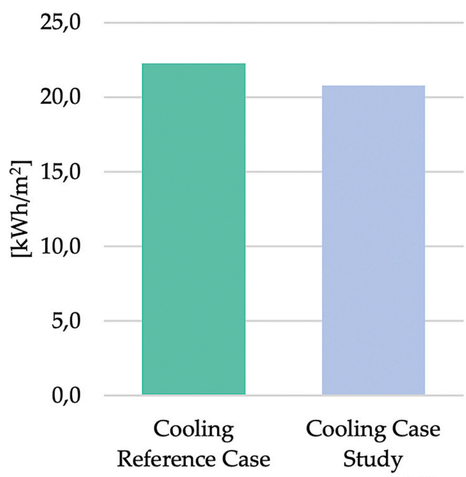


Fig. 12. Comparison of the accumulated demands in all the spaces that surround the courtyard.

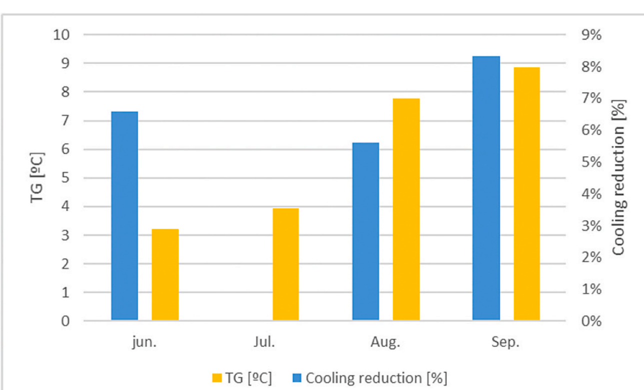


Fig. 13. Monthly Thermal Gap (TG) and average cooling reduction.

and a painted finish (Fig. 7). The global transmittance of the building envelope is U = 0,474 W/m^2K.

3.2. Field monitoring campaign

The monitoring campaign of atmospheric data, in this case, has been extended throughout a whole year; therefore, there are winter and summer data available. The recorded parameters are air temperature, wind direction, and speed of the outdoor of the courtyard, measured by a meteorological station model PCE-FWS 20 located on the roof of the building. Inside the courtyard, air temperature and humidity have been recorded using sensors model TESTO 174H, located in the south façade to avoid direct solar radiation, at 1m, 2 m, 5 m, and 8 m, from the floor, as explained Fig. 8. Table 1 shows the technical specification of the instruments used. As explained in section 2, the need to experimentally measure solar radiation can be avoided, which will instead be calculated by the simulation tool.

4. Results

4.1. Experimental results

The previously mentioned field monitoring campaigns were carried out over sixteen weeks, from June to September (summer time), during which it was possible to detect the thermal behavior of the courtyard alongside the hottest season of the year. Table 2 shows the maximum and minimum daily temperatures, as well as the thermal gap between maximum outdoor temperatures and the simultaneous courtyard ones.

The thermal tempering potential of the courtyard is shown in Table 2. In this study courtyard, thermal behavior can be identified through two different outdoor temperature intervals. In the first case, below 30 °C, the tempering behavior of the courtyard is low with thermal gaps, regarding outdoor temperatures, up to 5 °C. However, parallel to the rise in outdoor temperatures, the thermal tempering potential of the courtyard increases coming to be reached, while outdoor temperatures above 42 °C, a thermal gap up to 12 °C less inside the courtyard.

4.2. Simulation results

The transposition of the Energy Performance of Buildings Directive (EPBD) ("DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, of May 19, 2010, on the energy performance of buildings (recast)," n.d.) has been carried out in Spain through the regulation of the Technical Building Code (BOE.Orden FOM/1635/2013, 2013). This regulation is made up of various sections that, concerning energy efficiency in buildings, can be grouped into sections to limit the energy demands of buildings, sections to promote the efficiency of facilities, and sections to promote energy generation through renewable sources.

Compliance with these regulations can be verified in various ways, the most versatile being the use of the aforementioned LIDER-CALENER Unified Tool ("HULC – Herramienta Unificada LIDER-CALENER," n.d.).

The "HULC" software has been used to perform the simulation of the building, as already said, and from its graphic preprocessor, some views of the modeled building have been taken and shown in Fig. 9.

The spaces that border the courtyard are those shown with a red line in Fig. 10.

The main results of the simulations performed are the cooling demand of the building for the two scenarios considered, that is, reference case and case study.

This section shows a comparison between the two simulations of the main results obtained during the period with experimental data.

Focusing on spaces having at least one wall bordering the courtyard, the results of the accumulated cooling demands are shown in Table 3. It can be seen that the general tendency of the cooling demand is that it is smaller at a lower height of the floor of the building. However, the exception is the space E001 of the 3rd floor, since according to the aforementioned trend, it should have a lower cooling demand than the same space but on the 4th floor. This apparent anomaly explains that the floor of the mentioned space limits with the outside air, see Fig. 10a, having, in consequence, a higher area of heat transfer with the outside than that of the space of the 4th floor, so it is logical that it has a greater cooling demand.

On the other hand, it is observed that the cooling demand for the spaces on the 5th floor is greater. It is a consequence, in part, of the higher air temperature in the courtyard at this height. However, the relative difference with the same space of the previous floor shows a greater variation in the case of space F05_E01 than in space F05_E02. The reason is that the first one has a roof that borders the exterior while the roof of the last one borders another space. See Fig. 10d.

The absolute and relative differences in the cooling demand between the reference case and the case study are analyzed below.

Results of the monthly demands and their corresponding reductions in the demands are shown in Table 4.

It is appreciated that for all spaces, the greatest cooling demands are presented in August, which is a consequence of higher outdoor air temperatures, as can be seen from Table 4. It is also in this month when the absolute differences between the cooling demand of the reference case and the case study are greater. This suggests that the effect of the courtyard is increased in conditions of high outdoor temperature.

On the other hand, the cooling demands in July and September are quite similar but it is observed that the difference between the reference case and the case study is practically zero in July and relatively high in September the highest relative differences occurs in this month. The explanation for this behavior is that, in July in which the experimentation was carried out, the average daily difference between the temperature of the outside air and that of the courtyard was very small, because in this month the nocturnal outdoor temperatures were abnormally low.

A graphic view of the demands for the reference case and the case study can be seen in Fig. 11.

From the previous tables and figures, it can be seen that spaces XXX_E01, have a level of reduction in cooling demand much higher than spaces XXX_E02. This is because the former has a percentage of the area exposed to the courtyard greater than the latter, as shown in Table 5.

To assess the unit effect, that is, per unit of courtyard area in the cooling demand, in Table 5 is shown the reduction in the cooling demand of each space, the area of the spaces, the area of walls limiting with the courtyard and the relations between courtyard area/space area and the specific reduction in demand.

It is observed that the specific reduction in the demand for refrigeration per unit of wall area that borders the courtyard is a value that presents a small variation between spaces, independently of how much wall area is exposed to the courtyard. This result indicates that the effect of the courtyard is approximately uniform in each of its walls regardless of its orientation and the size of the space with which it borders. On the other hand, this result was expected given that solar radiation has little effect on the courtyard walls and the operational conditions of all spaces have been considered equal.

Finally, Table 6 and Fig. 12 show the cumulative results of the cooling demands of the spaces that limit the courtyard as well as the total percentage difference of these spaces.

5. Discussion

In this work, the combination of experimental data and a thermal simulation has proved out to be useful to evaluate the influence of the courtyard on the cooling demand of the building, since in the simulation it is possible to calculate the building with and without the effect of the courtyard on air temperature. The limitation of this methodology is the requirement of the collection of experimental data and for this reason its application is restricted to existing buildings. Hence, it is necessary to develop tools that correctly simulate the behavior of courtyards, and it is at this point where this technique can be highly useful as it can help to validate these models.

For the case study, it was found that the cooling demand would be reduced by including the effect of the courtyard. This reduction, compared with the building without the effect of the courtyard, rise up to values that can reach up to approximately 10% in the rooms located at a middle height of the courtyard and with a high percentage of facade in contact with it. Globally, the reduction in cooling demand obtained is 7% for the spaces bordering the courtyard. Muhaisen and Gadi (2006) found an average reduction of 4% according to a parametric study carried out for courtyards in the city of Rome, which is a value that is located in the same order of magnitude as that obtained in this study.

There is a correlation among daily exterior difference of outdoor temperatures (diurnal thermal range), and the thermal gap between maximum outdoor temperatures and the simultaneous courtyard ones. This correlation is due to the fact that the courtyard acts as a thermal buffer (Fig. 8), Therefore, the greater outside temperature variations, the greater the effect inside the courtyard reducing the maximum temperature.

The difference between the cooling demand of the reference case and the case study depends not only on the thermal gap, but also on the minimum outside temperature. In Fig. 13 it can be seen that, although the thermal gap in July is greater than in June, the savings due to the courtyard are zero. This is related to the fact that, as mentioned in the results section, for the precise month of July in which the experimentation was carried out, minimum nighttime temperatures were abnormally low allowing the building to store cold at night and consequently cancelling the effect of the courtyard in reducing cooling demand.

6. Conclusions

This paper presents a numerical and experimental study on the effect of courtyards on building cooling demands. The city chosen for the studio, Seville, is Csa in the Köppen classification, and is characterized by hot and dry summers.

The monitoring campaigns were carried in summer, from June to September, showing thermal gaps between maximum outdoor temperatures and the simultaneous courtyard ones of up to 12 °C. These monitoring campaigns also reflected that higher thermal gaps occurred with higher outdoor tempertures.

This paper has also served to illustrate how it is possible to combine such experimental results with numerical simulations for assessing cooling demands in buildings. In this way it has been shown that the aforementioned thermal gap within the courtyard has a reducing effect of the cooling demands of the spaces adjacent to it. This, being a beneficial effect of the design of the building, must be taken into account by the buildings energy simulation software tools, especially when, as in the presented case study, it is a software tool for the compliance of thermal regulation code for buildings.

In light of the previous results and, for the analyzed case study, overall it could be concluded that the courtyard reduces the demand for cooling in the living spaces that surround it.

As expected, the magnitude of the cooling demand reduction is correlated to the ratio: the envelope area bordering courtyard divided by the floor area of the space. The greater the previous relationship, the greater the reduction in the demand for refrigeration. This implies that there is a direct interaction between energy-saving and the courtyard's geometry conceived as the relationship between the courtyard's surface and the area of the building façades that surround it. If the courtyard's surface is small compared to the area of the bordering façades, the reduction in the demand for refrigeration is small. On the contrary, if the courtyard's surface is large compared to the area of the façade, the reduction in the cooling demand is high. This relative reduction can exceed 10%, being, for the case study analyzed, an average reduction of 7%.

On the other hand, the specific reduction of the cooling demand, defined as the amount by which the cooling demand is reduced per unit of courtyard envelope remains approximately constant. That is, the floor area of spaces limiting the courtyard, looks to be not effected in the cooling reduction per unit of courtyard envelope. In the case study of this paper, the specific reduction of the cooling demand obtained is approximately 7 kWh/m^2 courtyard envelope.

Authorship statement

Francisco José Sánchez de la Flor: Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Drafting the manuscript, Revising the manuscript critically for important intellectual content; **Álvaro Ruiz-Pardo:** Acquisition of data, Analysis and/or interpretation of data, Drafting the manuscript, Revising the manuscript critically for important intellectual content; **Eduardo Diz-Mellado:** Acquisition of data, Revising the manuscript critically for important intellectual content; **Carlos Rivera-Gómez:** Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Drafting the manuscript, Revising the manuscript critically for important intellectual content; **Carmen Galán-Marín:** Conception and design of study, Analysis and/or interpretation of data, Drafting the manuscript, Revising the manuscript critically for important intellectual content; Authorship contributions Please indicate the specific contributions made by each author (list the authors' initials followed by their surnames).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Apolonio Callejas, I.J., Cleonice Durante, L., Diz-Mellado, E., Galán-Marín, C., 2020. Thermal sensation in courtyards: Potentialities as a passive strategy in Tropical climates. Sustainability. https://doi.org/10.3390/su12156135.

BOE.Orden FOM/1635/2013, 2013. Código Técnico de la Edificación. CTE, Real Decreto.

Bruse, M., 2004. ENVI-met 3.0: Updated Model Overview. System 1–12.

Crawley, D.B., Hand, J.W., Kummert, M., Griffith, B.T., 2008. Contrasting the capabilities of building energy performance simulation programs. Build. Environ. 43, 661–673. https://doi.org/10.1016/j.buildenv.2006.10.027.

DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, of 19 May 2010, on the energy performance of buildings (recast) [WWW Document], n. d. URL. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF, 5.7.15.

D'Agostino, D., Mazzarella, L., 2018. Data on energy consumption and Nearly zero energy buildings (NZEBs) in Europe. Data in Brief 21, 2470–2474. https://doi.org/10.1016/j.dib.2018.11.094.

Diz-Mellado, E., López-Cabeza, V.P., Rivera-Gómez, C., Roa-Fernández, J., Galán-Marín, C., 2020. Improving school transition spaces microclimate to make them Liveable in warm climates. Appl. Sci. https://doi.org/10.3390/app10217648.

International Energy Agency, 2019. https://www.iea.org/fuels-and-technologies/building-envelopes (last accessed October 2019).

EnergyPlus™, 2019. https://energyplus.net/ (last accessed October 2019).

Gul, M.S., Patidar, S., 2015. Understanding the energy consumption and occupancy of a multi-purpose academic building. Energy Build. https://doi.org/10.1016/j.enbuild.2014.11.027.

EU Buildings Database, 2019. https://ec.europa.eu/energy/eu-buildings-database_en?redir=1 (Last accessed October 2019).

IDAE, 2009a. Condiciones de aceptación de procedimientos alternativos a LIDER y CALENER (Madrid, Spain).

IDAE, 2009b. Condiciones de aceptación de procedimientos alternativos a LIDER y CALENER. Anexos (Madrid, Spain).

HULC – Herramienta Unificada LIDER-CALENER. 2019. https://www.codigotecnico.org/Programas/HerramientaUnificadaLIDERCALENER.html (last accessed October 2019).

Judkoff, R., Neymark, J., 1995. International Energy Agency building energy simulation test (BESTEST) and diagnostic method. Natl. Renew. Energy Lab. https://doi.org/10.2172/90674.

Karjalainen, S., 2016. Should we design buildings that are less sensitive to occupant behaviour? A simulation study of effects of behaviour and design on office energy consumption. Energy Effic. 9 https://doi.org/10.1007/s12053-015-9422-7.

Key World Energy Statistics (KWES), 2018. International Energy Agency. https://www.iea.org/data-and-statistics/data-products.

López-Cabeza, V.P., Galán-Marín, C., Rivera-Gómez, C., Roa-Fernández, J., 2018. Courtyard microclimate ENVI-met outputs deviation from the experimental data. Build. Environ. 144, 129–141. https://doi.org/10.1016/j.buildenv.2018.08.013.

Marino, C., Nucara, A., Pietrafesa, M., 2017. Does window-to-wall ratio have a significant effect on the energy consumption of buildings? A parametric analysis in Italian climate conditions. J. Build. Eng. https://doi.org/10.1016/j.jobe.2017.08.001.

Muhaisen, A.S., Gadi, M.B., 2006. Effect of courtyard proportions on solar heat gain and energy requirement in the temperate climate of Rome. Build. Environ. 41, 245–253. https://doi.org/10.1016/j.buildenv.2005.01.031.

Prieto, A., Knaack, U., Auer, T., Klein, T., 2018. Passive cooling & climate responsive façade design exploring the limits of passive cooling strategies to improve the performance of commercial buildings in warm climates. Energy Build. https://doi.org/10.1016/j.enbuild.2018.06.016.

Rivera-Gómez, C., Diz-Mellado, E., Galán-Marín, C., López-Cabeza, V., 2019. Tempering potential-based evaluation of the courtyard microclimate as a combined function of aspect ratio and outdoor temperature. Sustain. Cities Soc. 51, 101740 https://doi.org/10.1016/j.scs.2019.101740.

Rodríguez Jara, E.A., Sánchez de la Flor, F.J., Álvarez Domínguez, S., Salmerón Lissén, J. M., Rincón Casado, A., 2017. Characterizing the air temperature drop in Mediterranean courtyards from monitoring campaigns. Sustainabilty 9, 1401. https://doi.org/10.3390/su9081401.

Rojas-Fernández, J., Galán-Marín, C., Rivera-Gómez, C., Fernández-Nieto, E.D., 2018. Exploring the interplay between CAD and FreeFem++ as an energy decision-making tool for architectural design. Energies. https://doi.org/10.3390/en11102665.

Rojas-Fernández, J., Galán-Marín, C., Roa-Fernández, J., Rivera-Gómez, C., 2017. Correlations between GIS-based urban building densification analysis and climate guidelines for Mediterranean courtyards. Sustain. Times. https://doi.org/10.3390/su9122255.

Sánchez de la Flor, F.J., Álvarez Domínguez, S., Molina Félix, J.L., González Falcón, R., 2008. Climatic zoning and its application to Spanish building energy performance regulations. Energy Build. 40 https://doi.org/10.1016/j.enbuild.2008.05.006, 1984–1990.

Santamouris, M., 2004. Energy performance of residential buildings: a practical guide for energy rating and efficiency, energy performance of residential buildings: a practical Guide for energy rating and efficiency. https://doi.org/10.4324/9781849776059.

Santamouris, M., Argiriou, A., Dascalaki, E., Balaras, C., Gaglia, A., 1994. Energy characteristics and savings potential in office buildings. Solar Energy 52, 59–66. https://doi.org/10.1016/0038-092X(94)90081-C.

Warf, B., 2014. Köppen-geiger climate classification. In: Encyclopedia of Geography. https://doi.org/10.4135/9781412939591.n671.

Resúmenes climatológicos, 2019. AEMET. Gobierno de España. http://www.aemet.es/es/serviciosclimaticos/vigilancia_clima/resumenes?w=0&datos=2 (last accessed October 2019).