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# Unravelling the impact of courtyard geometry on cooling energy consumption in buildings

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ABSTRACT

At present, the energy used for air conditioning in buildings in urban areas accounts for over 36% of total global energy consumption. Energy efficiency has become a critical factor in the urban planning of cities worldwide. Courtyard buildings in hot cities are a prime example of the approach used in traditional vernacular architecture to mitigate the effects of extreme weather. However, given the challenge of guaranteeing accurate modelling of microclimates within these courtyards, their impact on energy demand in buildings has been routinely overlooked by energy certification tools.

This work examines three empirical case studies selected in Seville city (Spain), where temperatures during the summer months are extreme. The case studies selected display distinct geometric variations, and the primary objective of the research is to assess the influence of this geometric factor on the cooling energy demand of the building indoors. To achieve this, a validated methodology combining experimental and numerical data was implemented to evaluate the energy performance of buildings with courtyards. Different simulations were conducted to detect the impact of individual courtyard features. The results show a reduction in cooling demand of 8–18% depending on the geometry of the courtyard. Analysis was also carried out on the influence of the floor level and the orientation of adjacent rooms, revealing differences of 15% and 22%, respectively. The main conclusion of the research is that the use of courtyards as functional devices, paying particular attention to their geometry, is a key factor in the cooling energy demand of buildings.

## 1. Introduction

Urban living conditions are becoming increasingly challenging due to the impact of climate change on the comfort of citizens. In addition, the urban heat island (UHI) phenomenon leads to a significant increase in urban overheating, especially in the warm seasons of the year [1]. Furthermore, urban areas are expected to become increasingly dense and crowded, concentrating more than 70% of the population by 2050 [2]. This issue becomes particularly problematic, especially in locations most exposed to extreme heat episodes, given that according to forecasts, rising global average temperatures will also involve increasingly frequent and longer heat waves [3]. However, reliance on increasing active air conditioning systems is not a suitable solution to this problem, especially taking into account the current energy context [4] and the fact that without the adequate optimization of resources, population growth will exacerbate energy consumption [5].

While buildings located in cities account for a considerable percentage of the world's final energy consumption [6], building obsolescence further increases the amount of energy required to ensure comfort conditions within them [7].

Major international organizations like United Nations (UN) [8], European Union (UE) [9] or International Energy Agency (IEA) [10], encourage energy savings and environmental protection policies through Nearly Zero-Energy Building (NZEB) [11]. In the specific case of Spain, more than 80% of buildings have poor energy-saving standards [12] due to intrinsic variables such as the quality of their thermal envelopes, or extrinsic ones such as the climate outdoors. Different databases, including Key World Energy Statistics (KWES) [13] produced by the International Energy Agency (IEA) [10], calculate a total electricity consumption in residential buildings of more than 27%, which alerts to the high consumption values of the majority of the built sector.

Much of the energy consumption of buildings is caused by the cooling and heating loads due to the poor energy-efficiency status of

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**Nomenclature**

| | |
|---|---|
| *UHI* | Urban Heat Island |
| *KWES* | Key World Energy Statistics |
| *EPDB* | Energy Performance of Buildings Directive |
| *CS* | Case Study |
| *NZEB* | Nearly Zero-Energy Building |
| *IEA* | International Energy Agency |
| *AR* | Aspect Ratio |
| *TG* | Thermal Gap |

most existing buildings [14]. Although in some cases previous research has analysed building geometry, building envelopes and other building installation systems in relation to energy consumption [15], in others, consumption has been linked to user activity [16] or to user awareness of energy consumption [17]. The optimization of parameters related to the building envelope therefore becomes important in order to reduce building energy consumption [18] and to achieve NZEB [19]. This energy consumption of buildings is directly related to the carbon emissions generated, which are continuously increasing [20]. Researchers assessed the possibility of achieving net zero carbon emissions in residential buildings with purely electrical energy consumption [21] and, in NZEB case studies, these emissions were reduced by up to 40% [21].

The regulation of the energy consumption of buildings is executed through the Energy Performance of Buildings Directive (EPDB), which individual European Union (EU) countries consider in their national standards, awarding energy performance certificates. In the case of Spain, the parameters regulated by the EPBD are specified in the Technical Building Code Basic Document on Energy Saving (CTE-DB-HE) [22]. In order to comply with these regulations different computer tools are used, and in Spain the Unified Tool LIDER-CALENER (under the acronym HULC in Spanish) is the official software of choice for calculating building energy performance [10]. HULC unifies in a single platform the previous official software used for the assessment of energy demand and energy consumption and the general procedures for the energy certification of buildings. The HULC tool runs with an hourly time step in a transitory state and has passed the tests of the well-known IEA Bestest [23], as well as, Spanish regulations for energy certification software tools [24]. 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 certification of buildings [25]. This tool includes the additional capacity to modify the boundary conditions (climate variables) of one or more of the elements of the building envelope. The HULC program is commonly used by technicians and researchers in Spain to calculate and simulate the energy behaviour of buildings in Spain [26–28].

New standards are forcing the construction industry to implement measures for the improvement of energy efficiency of buildings. These improvements in turn lead to an increase in construction costs, prompting reluctance among investors and developers who see the economic factor as a major drawback. While improving energy efficiency of buildings is essential for global awareness [29], the simultaneous consideration of energy consumption and economic factors further increases the popular appeal of NZEB [30,31], with different passive cooling strategies explored previously in building design [32]. Aspects such as the microclimate of certain spaces or the orientation [33,34] or materiality of the building [35,36] modify the thermal behaviour of buildings, with varying degrees of heat gains [37]. In the specific case of the Mediterranean climate and its vernacular architecture, the passive conditioning of residential buildings in summer climatic conditions has been guaranteed by constructing the rooms around a central courtyard [38]. The courtyards generate shade, acting as thermal regulators of the buildings and heat dissipators. They also present the advantage of being microclimates that can be controlled, which means that by incorporating different passive strategies such as shade [39], vegetation [40,41], or albedo [42,43] a significant reduction in temperature can be achieved both in the adjacent rooms of the building and in the courtyards themselves [44]. Previous research has monitored numerous courtyards with different geometries with lower outdoor temperatures of up to 15 °C [45]. Although previous literature reviews [46] show the extensive research carried out on courtyard geometry, this parameter has been analysed primarily in terms of the thermal gap (TG) in relation to the outdoor. This TG between courtyard temperature and outdoor air temperature was calculated according to Equation (2).

$$TG = \text{Outdoor Temperature} - \text{Courtyard Temperature} \quad (1)$$

Table 1 below analyses the research carried out on courtyard geometry in terms of the analysed strategy, TG and energy savings.

Most of the research that has so far considered the effect of the courtyard in reducing energy consumption has not assessed the influence of the courtyard geometry on the energy savings of the building. This research aims to establish the influence of courtyard geometry on cooling energy demand.

Although there is a wide range of computer programs available for the energy analysis of buildings, there is a significant research gap since most of them use only one outdoor temperature node and so fail to consider specific microclimates in transitional spaces adjacent to buildings. Moreover, these programs penalise building perforations such as courtyards as they increase the shape coefficient of the building as a whole. The exclusion of the courtyard microclimate in the modelling tools contrasts with the traditional use of them as passive cooling resources. Regulations and energy policies must be able to assess these constructive resources adequately with the aim of encouraging their implementation. The main objective of the present research is therefore to establish a correlation between the reduction in cooling demand generated by courtyards and their different geometries, which will be fundamental to the design of this vertebral space of buildings in Mediterranean cities.

The calculation methodology for assessing courtyards in the energy certification of buildings in Spain using the HULC tool has been published previously by the authors of this research [80]. The main novelty of the present work is the use of a validated calculation methodology to detect the extent of the influence of courtyard geometry on the cooling demand of buildings in order to suggest a set of possible design guidelines for the optimization of courtyards in new buildings, also considering existing courtyards in building energy certification protocols. The study limitations are related to a specific climate, a small set of case studies and the calculation tool used, that complies with UE regulations.

## 2. Materials and methods

Through the use of the HULC tool, this study aims to evaluate the reduction in cooling energy demand of building indoor spaces adjacent to courtyards with varying geometries. HULC, the official energy certification tool for buildings in Spain, can assign specific outdoor and indoor conditions to individual elements within the building. This software allows the selection of different parameters, among others: the selection of constructive features of walls, windows or, even, other elements of the building envelope surrounding the courtyard to modify the air temperature in contact with each element. This feature is particularly valuable for this research as specific temperatures can be assigned to elements located within courtyards and can also be modified by incorporating experimental data on air temperatures in both the courtyard microclimate and the surrounding environment.

The analysis carried out in this research focuses on three case studies of buildings with courtyards in Seville (Spain) which are located within the same urban environment and climatic zone, and include courtyards with similar construction systems and window percentages. A weather

**Table 1**
State-of-the-art review of geometry in courtyrads.

| Authors/Year | Courtyards geometry case studies | Ref | Cooling Approach | |
|---|---|---|---|---|
| | | | Thermal Gap (TG) | Energy Savings |
| Z. Zamani et al. (2018) | Literature review | [38] | • | |
| L. Huang et al. (2016) | Traditional dwelling buildings in Lhasa (China) | [47] | • | |
| A. Ghaffarianhoseini et al. (2015) | Different courtyard building types (Malaysia) | [48] | • | |
| F. Soflaei et al. (2017) | Traditional houses (Iran) | [49] | • | |
| J. Rodríguez-Algeciras et al. (2018) | Houses in historical centre (Camagüey, Cuba) | [33] | • | |
| N. Nasrollahi et al. (2017) | Traditional houses in Shiraz (Iran) | [50] | • | |
| A. S. Muhaisen (2006) | Simulated coutyards | [51] | • | |
| M. S. Guedouh et al. (2017) | Different Buildings in Biskra (Algeria) | [52] | • | |
| M. Taleghani et al. (2015) | Different courtyards (Netherlands) | [53] | • | |
| X. Xu et al. (2018) | Museum in Yixin (China) | [54] | • | • |
| S. Cindel et al. (2018) | Open places and models | [55] | • | |
| D. H. C. Toe et al. (2015) | Traditional Malay Houses (Malaysia) | [56] | • | |
| M. A. Cantón et al. (2014) | School Building in Mendoza (Argentina) | [57] | • | • |
| M. Taleghani et al. (2014) | Block dwellings (Netherlands) | [58] | • | • |
| G. Maniolu et al. (2015) | Simulated coutyard | [59] | • | • |
| A. Almhafdy et al. (2013) | General Hospital (Malaysia) | [60] | • | |
| A. S. Muhaisen et al. (2006) | Simulated coutyards | [61] | • | |
| F. Soflaei et al. (2016) | Traditional courtyard houses (Iran) | [34] | • | |
| A. Qaid et al. (2014) | Single courtyard. Putrajaya Boulevard (Malaysia) | [62] | • | |
| L. Martinelli et al. (2017) | Different courtyards (Italy) | [63] | • | |
| E. Yaşa et al. (2014) | Courtyard with different shapes (model) | [64] | • | • |
| A. Aldawoud (2008) | Simulated coutyard | [65] | • | • |
| J. Rojas-Fernández et al. (2017). | Residential and tertiary buildings in Andalucia (Spain) | [66] | • | |
| A. S. Jihad et al. (2016) | Simulated courtyard (Morocco) | [67] | • | • |
| X. Ma et al. (2019) | Dao He Old Block inTaizhou (China) | [68] | • | |
| S. Berkovic et al. (2012) | Single courtyards in Beer-Sheba (Israel) | [69] | • | |
| M. A. Del Rio et al. (2019) | Dwelling in Kumagaya (Japan) | [70] | • | |
| H. A. Abdulkareem (2016) | Traditional house in Baghdad (Irak) | [71] | • | |
| X. Du, R. Bokel et al. (2014) | Yang's House (China) | [72] | • | |
| N. Al-Masri et al. (2012) | Simulated buildings in Dubai (EAU). Review | [73] | • | • |
| P. Moonen et al. (2011) | Simulated coutyards | [74] | • | |
| X. Yang, Y. Li et al. (2012) | Simulated coutyard | [75] | • | |
| A. S. Muhaisen et al. (2006) | Simulated buildings in Rome (Italy) | [76] | • | • |
| A. Almhafdy (2015) | Different courtyards building (model) | [77] | • | |
| C. Rivera-Gómez et al. (2019) | 20 Spanish courtyards (Spain) | [45] | • | |
| Diz-Mellado et al. (2020) | School courtyard in Seville (Spain) | [35] | • | |
| Diz-Mellado et al. (2021) | Cases study in Cordoba (Spain) | [39] | • | |
| Apolonio-Callejas et al. (2020) | Brazilian courtyards (Brazil) | [78] | • | |
| Diz-Mellado et al. (2021) | Machine Learning in Courtyards (Spain) | [79] | • | |
| De la Flor et al. (2021) | Case study in Seville (Spain) | [80] | • | • |
| López-Cabeza et al. (2021) | Cases study in Cordoba (Spain) | [81] | • | |
| J. Lizana et al. (2022) | Case study in Seville (Spain) | [37] | • | • |
| López-Cabeza et al. (2022) | Cases study in Seville (Spain) | [36] | • | |
| Galán-Marín et al. (2022) | Andalusian courtyards (Spain) | [44] | • | |
| Diz-Mellado et al. (2022) | Spanish courtyards (Spain) | [82] | • | |
| Diz-Mellado et al. (2022) | Urban analisys (Spain) | [83] | • | • |
| López-Cabeza et al. (2022) | Spanish courtyards (Spain) | [46] | • | • |

station was used to accurately capture the local thermal conditions outdoors, nearby the courtyards, and monitor the outdoor air temperatures, while air temperature in the courtyards was measured with sensors placed at different heights.

The HULC simulation tool was used to perform a detailed calculation of shading within the courtyards, but it does not take into account the microclimate generated by the courtyards in its calculations. To determine the influence of the courtyards' microclimate, three simulation models are established as shown in the attached diagram (Fig. 1) and described in detail in section 2.3. The first model (A) serves as a reference case, with the same outdoor air temperature applied to all non-built spaces and without considering the shading calculation. The second model (B) includes the same conditions as the first but also considers the shade generated within the courtyards. The third model (C) varies the air temperature data within the courtyards based on the temperature data recorded in the courtyards. This process determines the impact of the courtyards on the cooling demand of each building, as well as the influence of the shading provided by the courtyards. Finally, the influence of the courtyards' geometry on energy savings is determined by comparing the results of the three simulation models, each with a specific geometry.

### 2.1. Climate and case studies description

This research has analysed three case studies – three dwellings with an interior courtyard – located in the city of Seville, in southern Spain.

The city of Seville is affected by summer heat waves which, according to the IPCC, will become more abundant in the coming decades [84]. The climate is characterized as hot, with high temperatures in summer. The city, with a characteristically hot dry climate with low rainfall and hot summers, is classed as Csa according to the Köppen classification [85]. According to the Spanish CTE standard [22] the city of Seville is a B4 climate zone, with high summer temperatures and mild winters. B4 is the highest rating in Spain for summer conditions.

The case studies are located in a built-up urban area, surrounded by similar constructions. The courtyards were selected based on their different geometries (Fig. 2) in order to ascertain the influence of this parameter on the cooling demand. Previous research confirms the

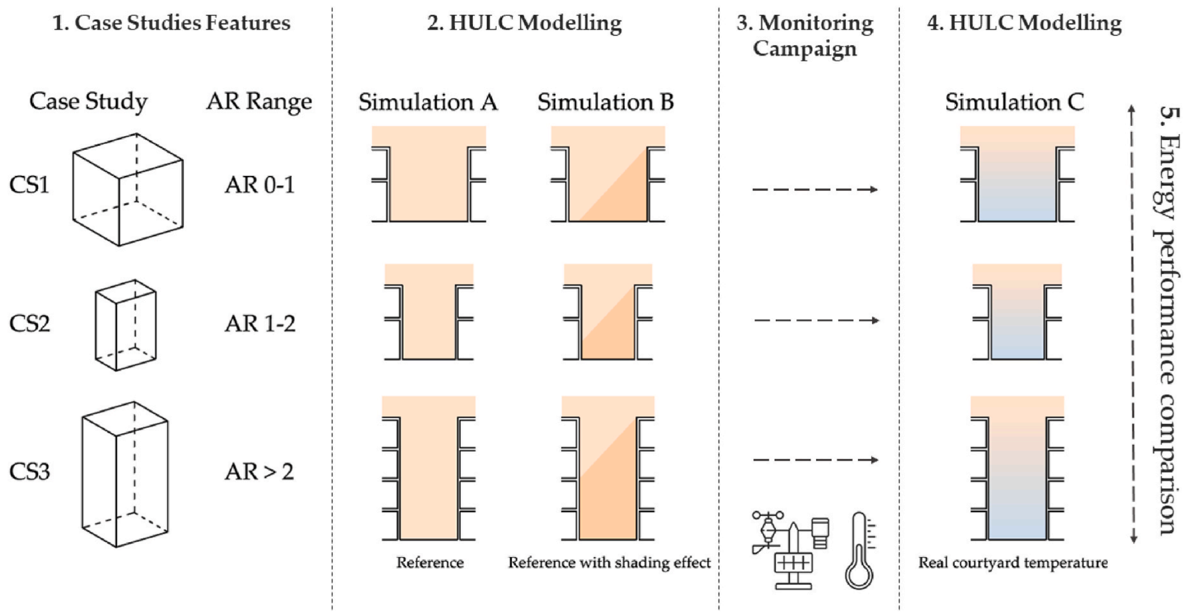


**Fig. 1.** Overview of the methodological assessment.

importance of geometry in the microclimate of the courtyard, defining geometry as the ratio between the height (H) and width (W) of the courtyard, known as AR (Equation (2)). Each courtyard is defined by ARI and ARII, one for each side of the courtyard (Table 2).

$$AR = H/W \tag{2}$$

According to previous research, 93% of the existing courtyards with surface areas greater than 15 and 30 $m^2$ in Seville have an AR between 0 and 3, with this percentage increasing as the surface area increases [66]. Two of the three courtyards are surrounded with a veranda. This is perimetral in CS1 and covers three out of the four courtyard façades in CS2, being the East façade (facing West) the non-protected one as a result of some refurbishment works.

The courtyard façades are brick masonry (11,5 cm) with cement mortar cladding (1 cm) and painted finish. The same envelope conditions were selected for the three case studies so that these conditions were matched in the simulation and the study was focused on the influence of the courtyard. Inside the cavity wall, 2 cm non-ventilated cavity + 6 cm of glass wool panels thermal insulation, covered by plasterboard (3 cm). The overall transmittance of the envelope established for the three case studies is $U = 0.474\ W/m^2K$.

### 2.2. Field monitoring campaign

The monitoring campaigns in buildings with courtyards were carried out in the summer months, when the cooling energy demand is most important. Although the case studies were simultaneously monitored over a period of several months, the representative sample selected is a two-week period, in line with previous research [45].

The data required for the simulation model is limited to the air temperature in the spaces to be modified, such as courtyard and outdoor temperature. Given that the microclimate in the courtyard reduces the outdoor air temperature, as also observed in previous studies, outdoor and courtyard temperature data were monitored.

For the outdoor temperature, a portable weather station model PCE-FWS 20 (Fig. 3a) (Table 3) was placed on the roof of the buildings, an exposed environment with no nearby walls which could alter the actual data. The temperature in the courtyards was recorded using data logger models TESTO 174 T and TESTO 174H (Fig. 3b and c) (Table 3), located on the south façade of the courtyard, which is north-facing and receives no direct sunlight that might overheat these data loggers.

The data loggers, placed 10 cm from the wall so as not to perceive the surface temperature, were also protected from the elements with insulating material, thus guaranteeing the ventilation of the system. In order to analyse thermal stratification the courtyard temperature in the courtyard was recorded at different heights based on its geometry.

Outdoor and courtyard air temperature data were monitored simultaneously at 15-min intervals, shorter intervals than the 60-min period used in simulation tools.

Other values which can affect the courtyard temperature, such as direct solar radiation or shaded areas caused by the different façades or walls, were not measured as the simulation programs take them into account.

### 2.3. Simulation

In the research, three simulations were performed for each of the three case studies using HULC. These simulations were carried out taking into consideration the energy regulations in Spain, where the case studies are located. HULC, which is qualified a suitable tool for the energy certification of buildings, uses official climate files provided by the institution in charge of establishing the regulations for the energy certification of buildings. These climate files are generic for each area of Spain and take into account the data recorded by the official body, usually in the periphery of the city.

The simulation was carried out in the warmer months under cooling conditions. As the UHI effect is not normally considered, the outdoor air temperature in contact with the buildings is also higher in the summer months, when the city heats up. However, the HULC tool allows the modification of the boundary conditions of each building envelope surface modelled for the simulation. Thus, air temperature can be modified, both in the envelope in contact with the outdoors and in the courtyard envelope.

By default, the software sets the air temperature from the official climate file for the entire outdoor environment in the simulation, without taking into account the actual outdoor temperature at the site or the TG produced by the courtyard microclimate. Taking this into consideration, the simulation is performed by varying the standard data, which are replaced with those recorded in the experimental campaign.

- **Simulation A (Reference):** the climate file is modified with the recorded outdoor temperatures monitored in the experimental

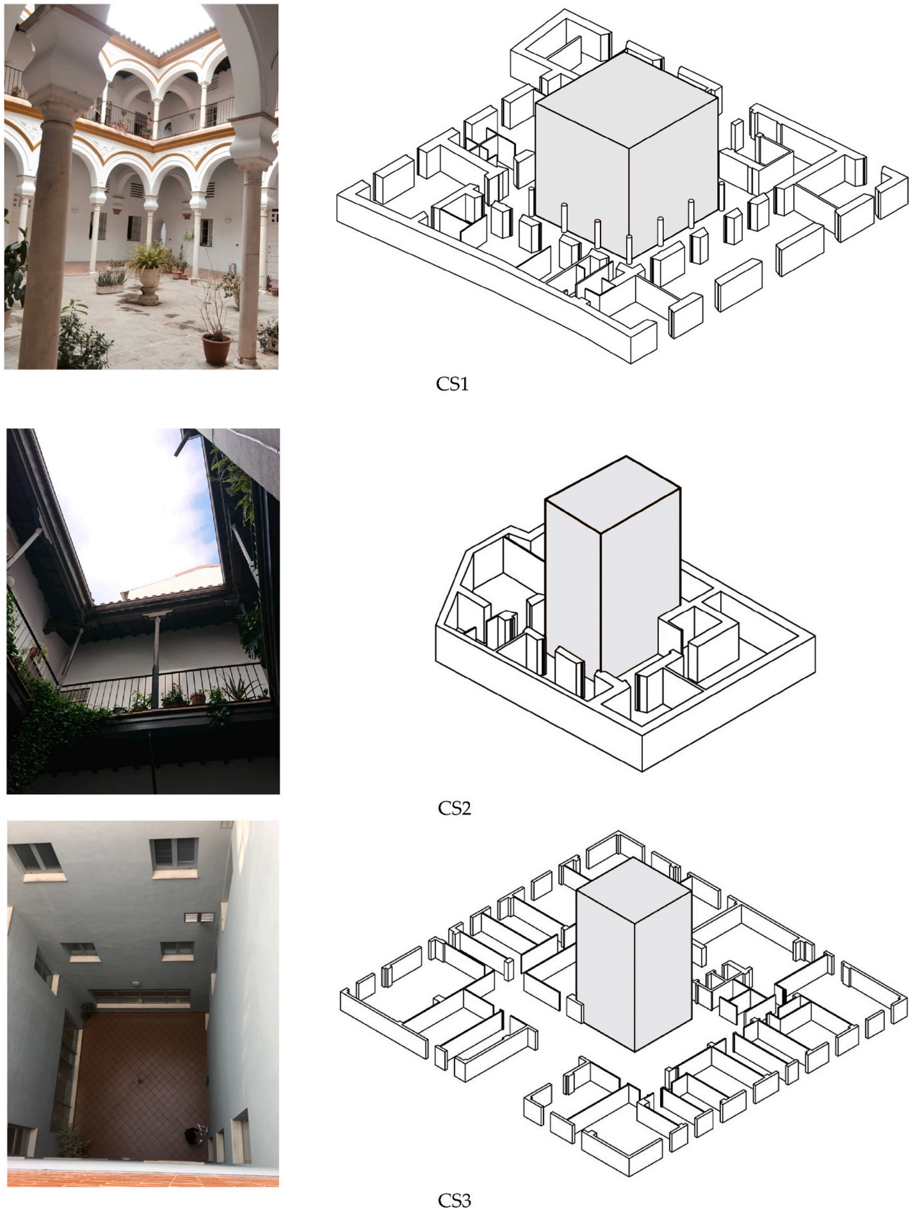


**Fig. 2.** Pictures and volumetric scheme of the different cases study.

**Table 2**
Geometric and climatic data of the case studie set.

| Courtyard | City | Length | Latitude | Climate Zone | Surface | Dimensions | | Hight (m) | AR I | AR II |
|---|---|---|---|---|---|---|---|---|---|---|
| **CS1** | Sevilla | 37° 23′ 52″ | 5° 59′ 46″ | B4 | 81,0 | 9,0 | 9,0 | 8,5 | **0,95** | **0,95** |
| **CS2** | Sevilla | 37° 23′ 52″ | 5° 59′ 46″ | B4 | 22,4 | 5,6 | 4,0 | 8,5 | **1,50** | **2,12** |
| **CS3** | Sevilla | 37° 21′ 32″ | 5° 59′ 14″ | B4 | 48,2 | 7,3 | 6,6 | 14,0 | **1,92** | **2,12** |

campaign. The boundary conditions remain the same for the whole building envelope.

- **Simulation B (Reference with shading effect):** the climate file used is the one monitored outdoors, but the calculation of shade generated by the courtyard produced by the simulation tool is taken into account.
- **Simulation C (Real courtyard temperature):** the temperature file is modified taking into account the monitored values of outdoor temperature and courtyard temperature, modifying the boundary conditions on the courtyard façades. Given the existence of thermal stratification in the courtyard measured in the experimental campaign, the boundary conditions on the different floors of the buildings have been varied.

The procedure followed for the modelling generation has been established in the following two main stages: 1. Building model generation. This stage has also included the definition of the conditions of use, geometry or construction systems used in its envelope, as well as the interior compartments that define the rooms. 2. Model simulation. Once modelled, the reference case (simulation A) was simulated, detecting a specific cooling demand for the months analysed. 3. Replacement of the standard climate file by in situ monitoring. In this phase, the climate file

(a) (b) (c)

**Fig. 3.** Location of the measurement instruments. a) wather station PCE-FWS 20, b-c) data loggers TESTO 174 in CS2 (b) and CS3 (c).

**Table 3**
Technical data of the measurement instruments.

| Situation | Sensor | Variable | Accuracy | Range | Resolution |
|---|---|---|---|---|---|
| Outdoor | PCE-FWS 20 | Dry bulb Temp. | ±1 °C | −40 to +65 °C | 0.1 °C |
| | | RH | ±5% | 12–99% | 1% |
| | | Wind | ±1 m/s | 0–180 km/h | – |
| Courtyard | TESTO 174H/T | Dry bulb Temp. | ±0.5 °C | −20 to +70 °C | 0.1 °C |
| | | RH | ±0.1% | 0–100% | 2% |

of the city was modified by replacing the default outdoor air temperature data with the data monitored by the portable weather station used in the experimental campaign. Subsequently, simulation B was performed considering the shade generated by the geometry of the courtyard. 4. Modification of the climatic boundary conditions including monitored data of the courtyard microclimate. Finally, thermal data of the envelopes in contact with the courtyard were modified, varying the climate data file exclusively in the selected surfaces, establishing specific climatic conditions (simulation C), and obtaining the real cooling demand of the building (Fig. 4).

This simulation process follows the steps set out in a previously published research methodology. The steps performed for the process were as follows.

- Building modelling: using the planimetry of the building as its basis, the geometric, constructive and operating conditions are defined for each individual case study. The interior rooms are modelled according to the actual layout for each floor of the individual case studies.
- Modification of the climate file: the data of the climate file used by default in the program are replaced with the data obtained from the weather stations located on the roofs of individual case studies during the monitoring campaign. This is not in line with the standard simulation procedure when additional capabilities are incorporated in HULC. However, the calculations of this simulation program use data from the default climate file with historical data measured in the periphery of the city. For this reason, the climate file is modified to ensure the accuracy of the data.
- Simulation A is run with the conditions set out above. In this case, the case studies are modelled with the geometric, construction and operating characteristics defined. However, all envelope elements share the same outdoor climate conditions. The courtyard then, does not affect when simulation A is run.
- Simulation B is run with the same conditions as simulation A, but taking into account the shade generated by the geometry of the courtyard.
- For simulation C, all elements of the building envelope bordering the courtyard are selected to modify their climatic conditions. New climatic conditions are established specifically for each of the parts of the building envelope bordering the courtyard, modifying the air temperature according to the experimental results. For this purpose, the thermal stratification values measured in the courtyards have been taken into account. Once these parameters are established, the new energy simulation of the building is carried out.

## 3. Results

The results of this research are shown in two separate sections. The first focuses on the experimental results of the monitoring campaigns and aim to analyse the tempering potential of the individual case studies. The second presents the results of the simulations carried out in HULC in order to assess the beneficial effect of courtyards on the reduction of the cooling demand depending on geometry.

### 3.1. Experimental results

The experimental results of the monitoring campaigns for both the outdoor and the courtyard average temperature data are simultaneously shown in Fig. 5. As the data represented were monitored at 15-min intervals the graphical representation shows a degree of irregularity.

The tempering potential of the courtyards and the importance of their geometry are confirmed thanks to the simultaneous representation of results. As indicated by previous studies, the dependence of the courtyard microclimate on the outdoor environment is remarkable. In addition, the influence of the geometry on the tempering potential of the courtyard can be seen in Fig. 5, while Table 4 provides a representation of TG.

Fig. 6 shows the data of the monitoring campaign for the day with maximum outdoor temperature in each of the case studies. Each graph shows different curves corresponding to the outdoor temperature (black curve) and to the temperature in the different levels of the courtyard (coloured curves) to detect thermal stratification.

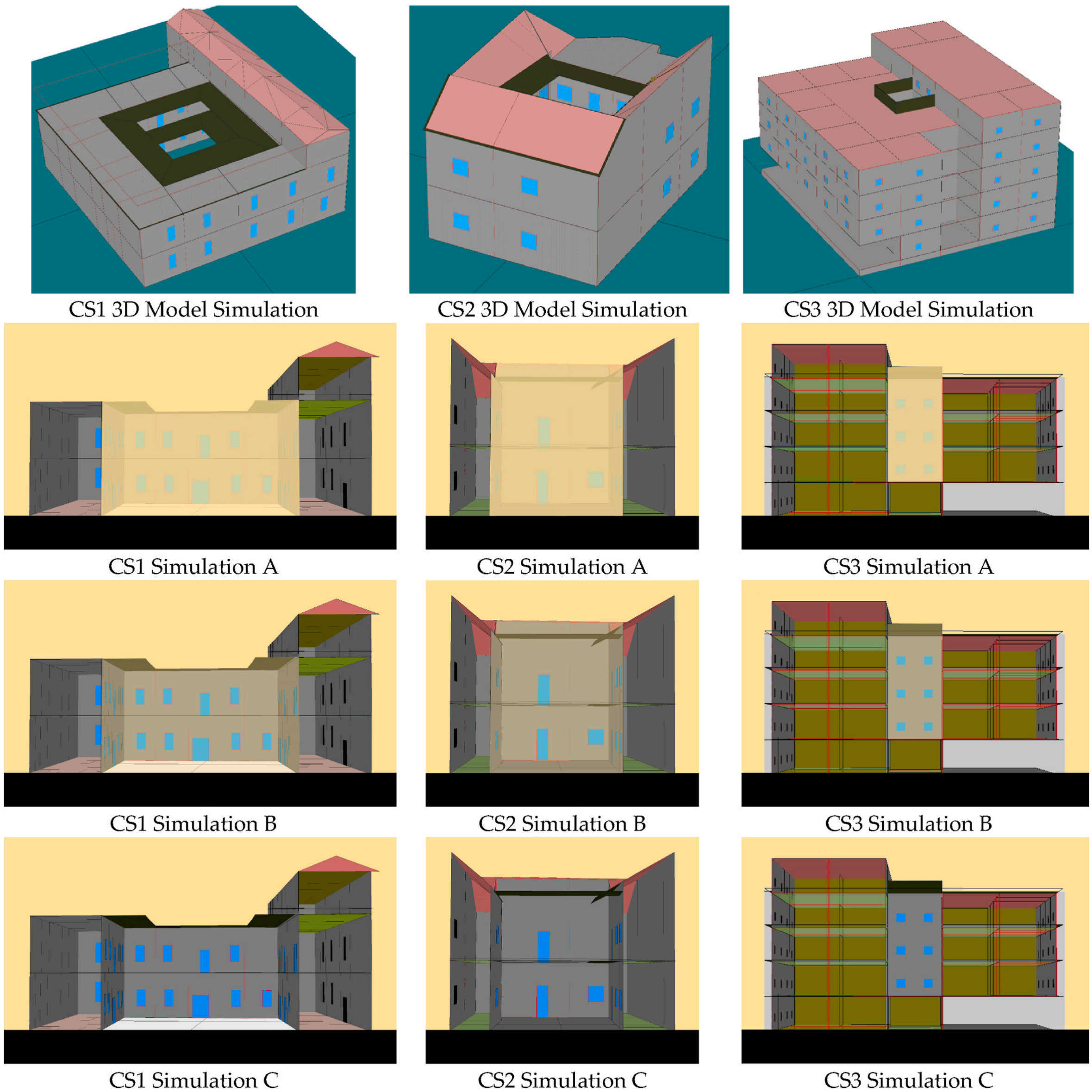


**Fig. 4.** Different views of case studies analysis and modelling.

The TG between the courtyard and the outdoors exceeds 10 °C in the case with the most unfavourable geometry, while this figure increases to 14.4 °C in the case with the highest AR. The greatest TG occurs when the outdoor temperature is higher, so that the tempering potential of the courtyard increases depending on the geometry and the outdoor temperature.

### 3.2. Simulation results

The results of the simulations performed for each experimental case study, showing cooling energy demand and energy savings, are presented in Tables 5–7 and Fig. 7. Simulations A, B and C are represented simultaneously, with simulation A being considered as the energy saving reference value.

The simulations have been performed for each case study, with the lowest energy saving results in CS1, with the lowest AR (8%), and the highest energy saving results in CS3, with the highest AR (18%).

## 4. Discussion

### 4.1. Influence of courtyard's geometry

The influence of the geometry of the courtyards on their tempering potential has already been demonstrated by previous research [45]. This research corroborates the increase in TG between the courtyard and the outdoor climatic conditions during the experimental campaigns and analyses the influence of geometry on energy savings.

The results show an increase in TG of almost 4 °C between the selected case studies with different geometries. The simulations performed, taking into account the courtyard geometry itself and the shading it generates (Simulation B), indicate energy savings of 7–17% compared to Simulation A, which does not take into account the shading

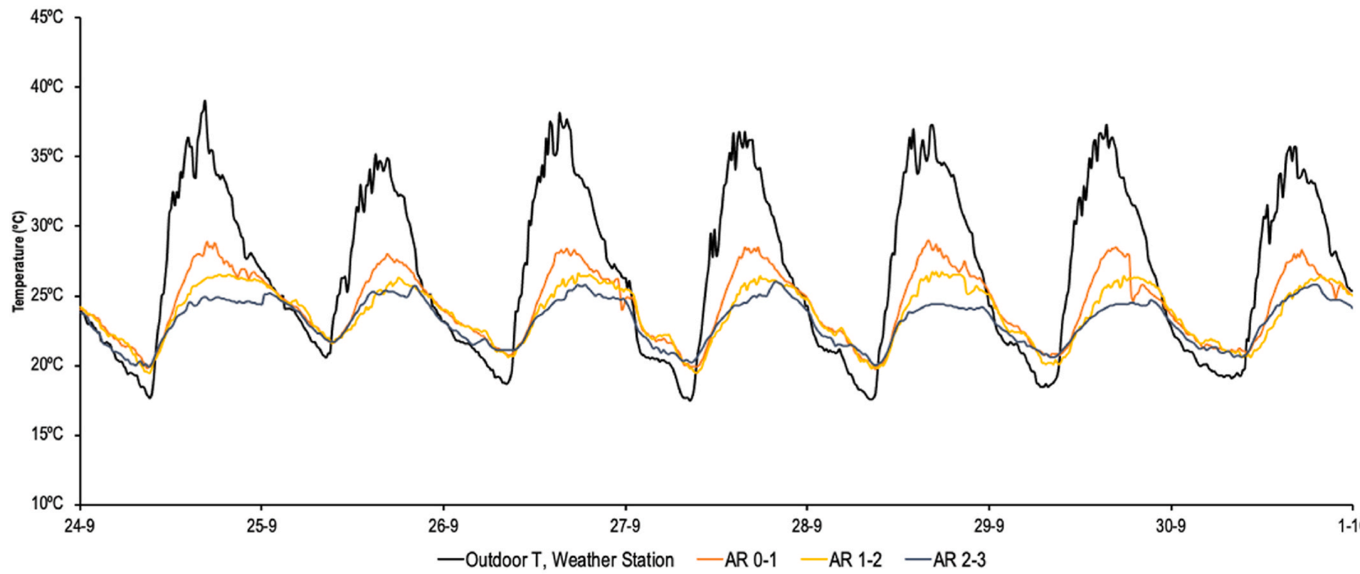


**Fig. 5.** Experimental results.

**Table 4**
Experimental result. Thermal Gap (TG).

| | Maximum Outdoor Temperature | Courtyard Temperature | TG |
|---|---|---|---|
| CS1 | 39 °C | 28,5 °C | 10,5 °C |
| CS2 | 39 °C | 26,2 °C | 12,8 °C |
| CS3 | 39 °C | 24,6 °C | 14,4 °C |

generated by the courtyard geometry. The energy savings increase by an additional 4% when the monitored courtyard temperatures are introduced in Simulation C (Fig. 8).

Fig. 8 simultaneously shows the thermal gap, the energy demand and the energy savings for each case study. Depending on the geometry of the case studies used, energy consumption between different case studies can be reduced by up to 10%. This result establishes a direct correlation between courtyard geometry and the TG and the percentage of energy savings produced. The higher the AR, the higher the TG, and the greater the energy savings in the building due to the courtyard. This effect, which depends on parameters such as the level or orientation of the rooms adjacent to the courtyard, is analysed below in detail.

### 4.2. *Influence of the floor level*

The thermal stratification in the courtyards is a relevant parameter shown by previous studies on courtyard thermodynamics [45]. In this research, the percentage of energy savings for the different floors of the building has been analysed, taking into account the three simulations A,

**Table 5**
Cooling demand simulation results CS1.

| | Cooling Demand ($kWh/m^2$) | Absolute difference ($kWh/m^2$) | Percentage difference |
|---|---|---|---|
| Simulation A | 26,77 | – | – |
| Simulation B | 24,85 | 1,92 | 7% |
| Simulation C | 24,57 | 2,20 | 8% |

**Table 6**
Cooling demand simulation results CS2.

| | Cooling Demand ($kWh/m^2$) | Absolute difference ($kWh/m^2$) | Percentage difference |
|---|---|---|---|
| Simulation A | 32,79 | – | – |
| Simulation B | 29,04 | 3,75 | 11% |
| Simulation C | 27,90 | 4,89 | 15% |

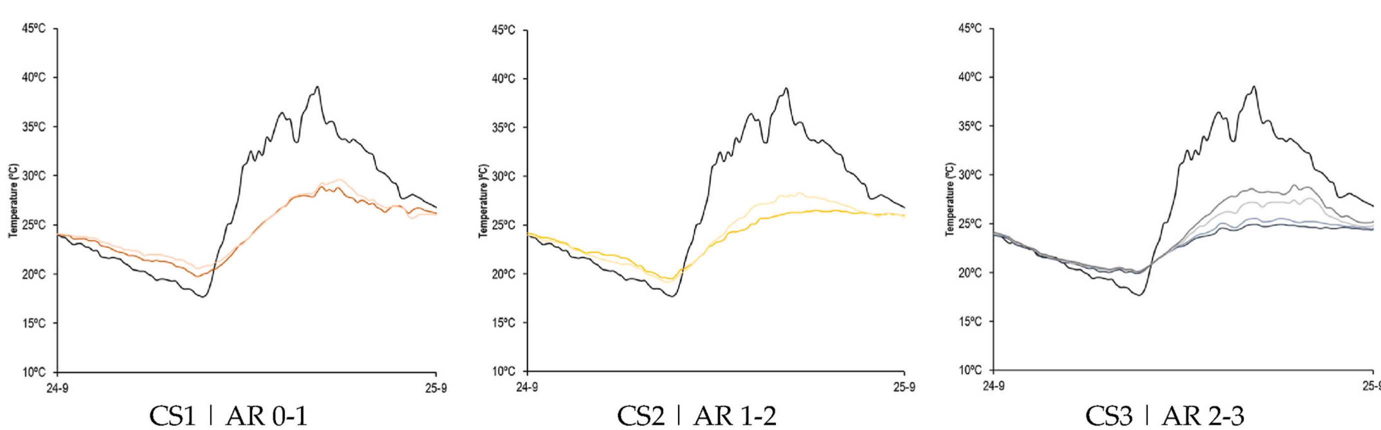


**Fig. 6.** Data field monitoring campaign.

**Table 7**
Cooling demand simulation results CS3.

| | Cooling Demand (kWh/m$^2$) | Absolute difference (kWh/m$^2$) | Percentage difference |
|---|---|---|---|
| Simulation A | 21,34 | – | – |
| Simulation B | 17,74 | 3,60 | 17% |
| Simulation C | 17,59 | 3,75 | 18% |

B and C. Fig. 9 shows the cooling energy demand (Fig. 9a) and the energy savings of the courtyard (Fig. 9b) at the different floors (F) of each case study (ground floor, 1st floor, 2nd floor and 3rd floor).

The results show higher cooling energy savings at the lowest levels of all case studies. The difference in terms of percentages of energy savings is 9% in CS1, 12% in CS2 and 15% in CS3. Again, the depth and geometry of the courtyard greatly influence the cooling demand of the building, due to two factors. The first is solar radiation, which is more direct on the upper floors, as the geometry of the courtyard itself generates shade on the lower levels. The second factor is the thermal stratification that occurs inside the courtyard.

### *4.3. Influence of the orientation and perimeter veranda on courtyards*

For an analysis of the influence of orientation and perimeter verandas on the courtyards of the case studies, only CS1 and CS2 are considered, as CS3 has no perimeter verandas.

The cooling demand of the rooms adjacent to the courtyard was analysed for each of the orientations. The results show little influence on the north-facing façades, while the east and west façades are the most influenced in terms of cooling energy savings. This is the result of the higher levels of direct radiation they receive during the first and last hours of the day if the shading generated by the courtyard itself is not taken into account. The results are shown in Fig. 10.

The influence of the perimeter verandas is significant. In CS2, the savings in cooling demand, as expected, are not as great for the West façade due to the absence of a perimeter veranda in this courtyard façade, unlike in the other three orientations. The percentage of energy savings, which varies depending on orientation, totals 13% in CS1 and 22% in CS2.

## 5. Conclusions

The current climate emergency has prompted extensive interest from international bodies, which are legislating with a view to mitigating the effects of climate change. Excessive global energy consumption linked to buildings in cities must be controlled and, in order to do so, buildings must become more efficient and energy efficient. Based on the analysis of the results, it can be concluded that an appropriate design of courtyards in buildings is crucial to improve their energy efficiency performance. However, it is important to note that the potential energy savings are contingent on proper management of the courtyard microclimate by users during free running building periods.

This research assesses the cooling demand saving capacity that can be achieved in buildings depending on courtyards and their geometry. In the three case studies evaluated in the city of Seville, southern Spain, field campaigns were carried out to measure environmental parameters both inside and outside the courtyards. The courtyards achieved a TG of 10.5 °C when the AR was smaller, reaching 14.4 °C when the AR was

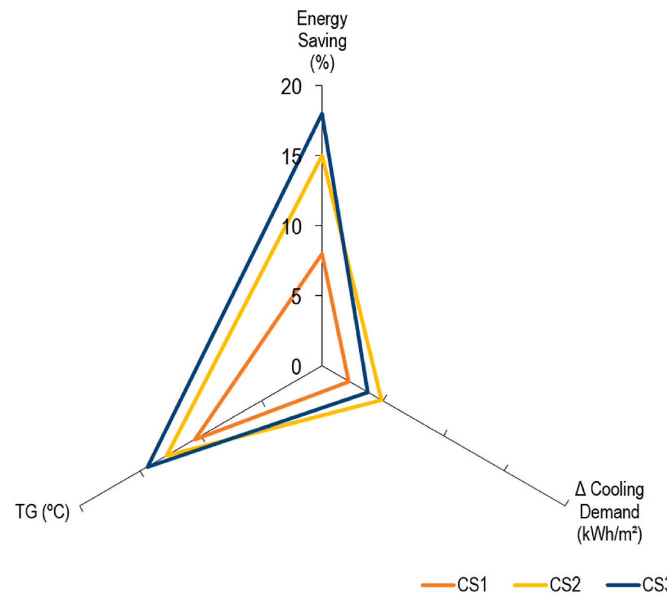


**Fig. 8.** Comparison of results as a function of courtyard geometry.

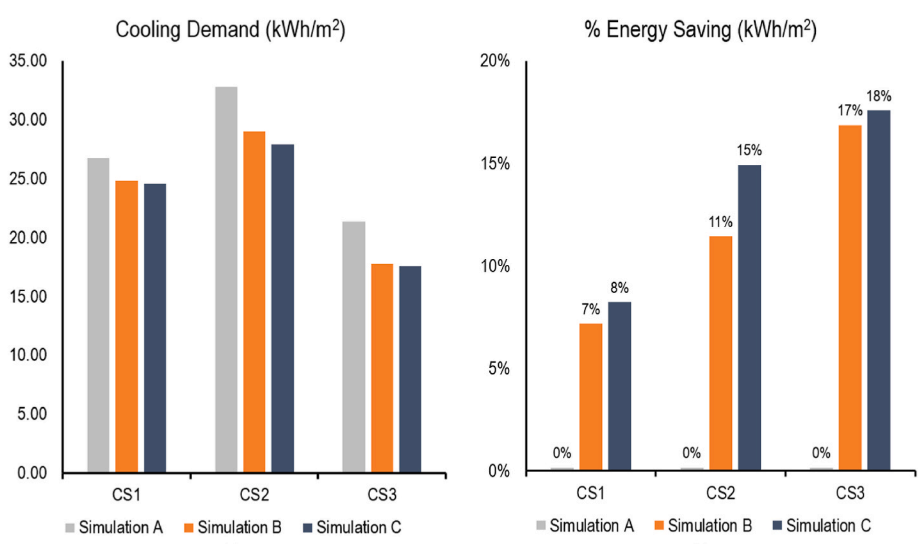


**Fig. 7.** Simulation results. Cooling Demand (a) and Energy Savings (b).

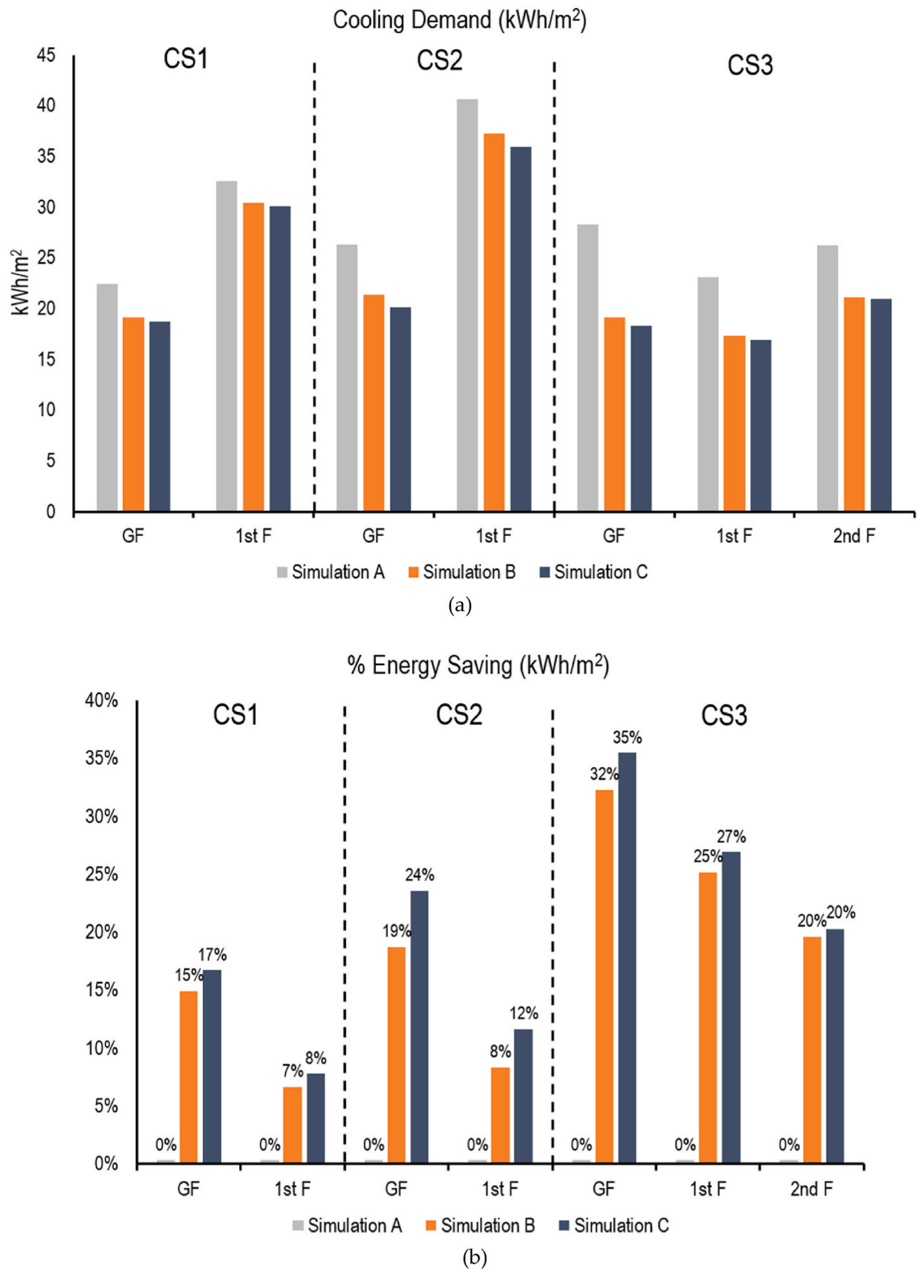


**Fig. 9.** Simulation results. Influence of the level.

higher. Subsequently, the three case studies were simulated with the energy certification tool for buildings in Spain, HULC. Three different simulations have been carried out: the first one (A) does not take into account the effect of the courtyard, which it considers as an outdoor environment; the second (B) takes into account the shading generated by the geometry of the courtyard; while the third one (C) takes into account the thermal values inside the courtyard previously monitored.

The results in percentage savings in cooling demand were 8% in the case study with the most unfavourable geometry (lowest AR), reaching 18% in the case study with the most favourable geometry (highest AR). In addition, the influence of the level of cooling energy demand savings has been evaluated according to the floor level of the building. The difference between floor levels ranges from 9% in CS1, with the lowest AR, to 15% in CS3, with the highest AR. Finally, a comparison of the levels of cooling demand savings was carried out according to the orientation of the façades adjacent to the courtyard, providing results of 13% in CS1 and 22% in CS2, with the beneficial influence of the perimeter veranda detected in both case studies. It is noteworthy that an optimal aspect ratio of a courtyard can not only promote energy savings in a building, but also enhance the phenomenon of thermal stratification, which may result in significant energy savings of up to 35% on the ground floor for CS3. These geometric modifications are interlinked with the potential constraint of wind to impact the microclimate of the courtyard.

The key research of this contribution is the possibility to evaluate the influence of the courtyard microcrimate as a consequence of its geometry, in terms of energy savings. This was domne by means of using a software tool (HULC) that allows to modify specific microclimate variables in the different facades of the building.

To sum up, this research concludes that the geometric design of courtyards in buildings, and their presence as a vertebral space in buildings, is of major importance to the energy demand for cooling in buildings. Hence for, it should be considered in order to evaluate their energy demand. In future research, the number of case studies can be

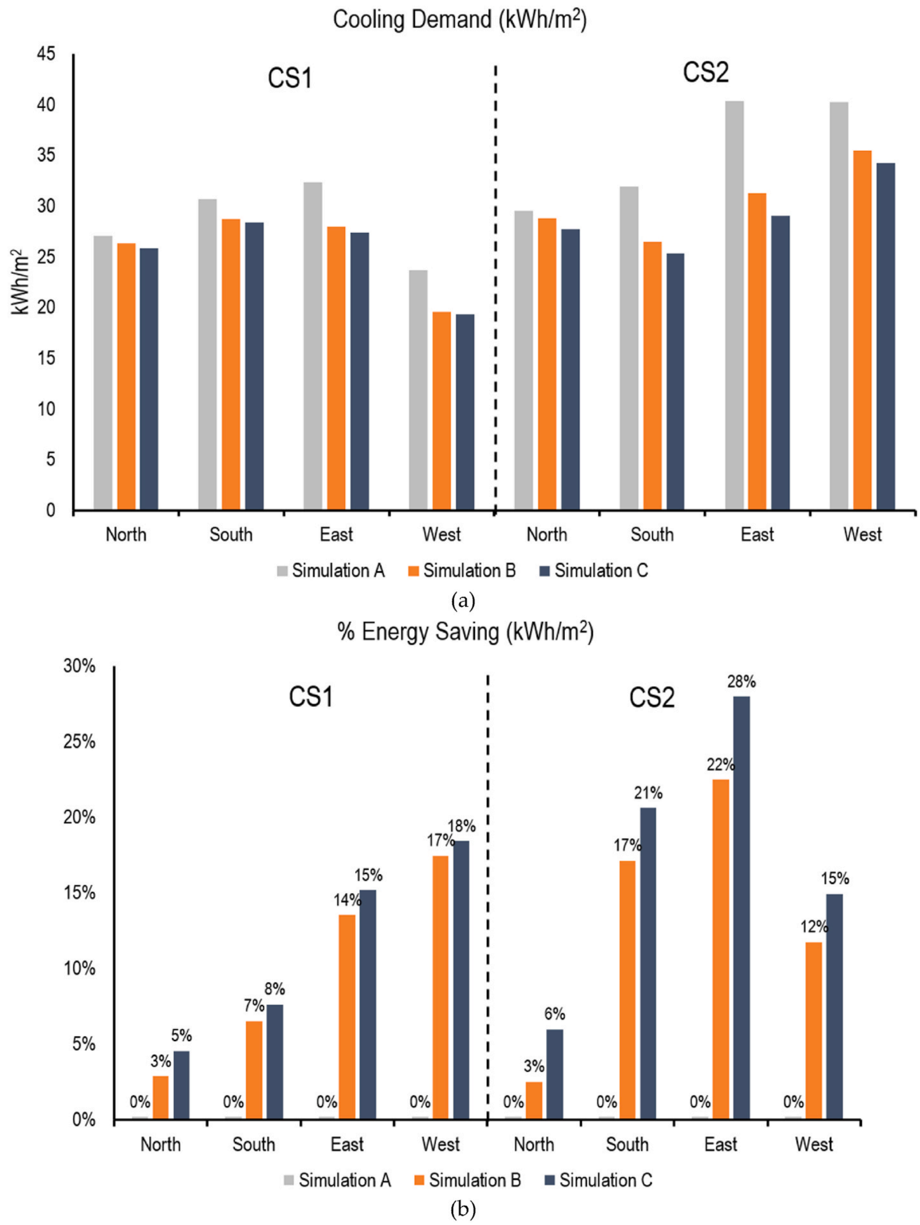


**Fig. 10.** Simulation results. Influence of the orientation and perimeter veranda on courtyards.

increased, as well as the inclusion of different climate zones or other simulation tools to compare and improve the results. While the annual examination of the microclimatic interplay between a courtyard and the outdoor climate, and its implications for potential energy savings in a building, requires further investigation, the findings of the current research underscore the importance of integrating the assessment of courtyard microclimate into conventional building energy performance evaluation frameworks. Public Administrations must be encouraged to implement this passive resource in energy certification tools in order to appropriately assess building performance.

## CRediT authorship contribution statement

**Eduardo Diz-Mellado:** Writing – original draft, Visualization, Validation, Software, Investigation, Data curation. **Álvaro Ruiz-Pardo:** Writing – review & editing, Validation, Software, Formal analysis. **Carlos Rivera-Gómez:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Francisco José Sanchez de la Flor:** Writing – review & editing, Supervision, Formal analysis. **Carmen Galán-Marín:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

## 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.

## Data availability

Data will be made available on request.

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