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Thermal comfort modelling and empirical validation of predicted air temperature in hot-summer Mediterranean courtyards

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ABSTRACT
Courtyards are a passive strategy to improve the energy performance of buildings. However, the accurate simulation of courtyards' thermodynamic performance in the early design stage is still challenging, even though there has been an emergence of new methods to assess outdoor simulation. This paper tests a novel workflow using the Ladybug Tools that uses CFD for outdoor temperature and comfort simulation of courtyards and is suitable for the early stage of building design, comparing the results with monitored data and simulated data from ENVI-met. Results show high accuracy in the prediction of temperature from Ladybug Tools with error ranges from 3.8–7.5%, which is lower than with ENVI-met. In terms of comfort, the simulated Universal Thermal Climate Index values differ by up to 10°C between ENVI-met and the Ladybug Tools. The results show a significant improvement towards the design of the courtyard in the search for net-zero energy buildings.

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KEYWORDS
Courtyard; microclimate; outdoor thermal comfort; building simulation; Ladybug Tools; ENVI-met

1. Introduction

The last report from the Intergovernmental Panel on Climate Change (IPCC) predicts with high confidence an increase in global temperatures of at least 1.5°C above pre-industrial levels during the twenty-first century unless a deep reduction in CO_2 and other greenhouse gas emissions occur in the coming decades (IPCC 2021). Considering that global warming is sped by anthropogenic greenhouse gas emissions (IPCC 2021) and buildings are responsible for approximately 36% of CO_2 emissions in the EU (European Commission 2020), buildings have an important role in the reduction of greenhouse emissions.

The Urban Heat Island (UHI) effect (higher urban temperatures in comparison to rural areas) is exacerbated by global warming. The UHI effect has a direct relationship with urban compactness and the energy performance of buildings (Santamouris et al. 2001). The reduction of energy demand for buildings and the promotion of outdoor comfort strategies to prevent overheating are two ways to tackle the problem of the UHI effect. This should be considered both at the city scale and the building scale. The Directive 2010/31/UE, EPBD, of the European Parliament, related to the energy performance of buildings (European Commission 2010), amended by the Directive (EU) 2018/844 (Directive 2018), is one example of actions policy-makers have taken at the building scale. However, in terms of outdoor comfort, no counterpart can be found, maybe in part due to the lack of specific tools to evaluate and predict these parameters. Nevertheless, the 2030 Agenda for Sustainable Development adopted by all United Nations Member States in 2015 developed the 17 Sustainable Development Goals (SDGs) (United Nations 2015). Among them, SDG 11: 'Sustainable cities and communities' directly relates to the necessity to make cities more resilient to climate change, including outdoor areas.

Buildings can help to improve outdoor thermal comfort in hot climates because they regulate solar radiation and wind speed (Huang et al. 2017). One of the traditional passive strategies that have been used around the world by different cultures to improve comfort both indoors and outdoors, is the use of courtyards in buildings. Here, 'courtyard' refers to any open space surrounded by walls or buildings. The microclimate generated in courtyards provides a thermal buffer from the outdoor space, reducing energy losses from the surfaces that are in contact with the outdoor air and decreasing the energy consumption of the conditioning systems (Xie et al. 2020). Furthermore, the space in the courtyard is often more thermally comfortable than the exposed outdoors, especially in hot and dry climates, providing semi-outdoor spaces that are usable for more of the day or year. This strategy has many

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benefits for health, community closeness, vitality of users and, indirectly, for energy savings, since the more time people spend outdoors, the lower the energy demand indoors (Lai et al. 2014).

1.1. Thermodynamic simulation of courtyards

The benefit of the courtyard can be explained in terms of thermodynamic effects that occur within it, i.e. convection, stratification, and flow patterns, related to the temperature of the surfaces and the wind flows created by their geometry (Rojas, Galán-Marín, and Fernández-Nieto 2012). Extensive monitoring campaigns in existing literature (Rivera-Gómez et al. 2019) have demonstrated beneficial thermal tempering in courtyards of up to 15°C. Several factors can influence these thermodynamic effects (Abdulkareem 2016) as follows. The geometry of the courtyard and its orientation determine the solar radiation that reaches the wall and floor surfaces (Yang, Li, and Yang 2012); the albedo of the walls (the fraction of radiation reflected by the surfaces) affects the temperature of the walls and the diffuse radiation in the courtyard; the sky view factor affects the potential for radiative cooling to the night sky (Lai, Maing, and Ng 2017); vegetation and water cool through evapotranspiration (Ghaffarianhoseini, Berardi, and Ghaffarianhoseini 2015); and shading devices or other shading elements also affect the radiation that reaches the surfaces of the courtyard (Lopez-Cabeza, Galán-Marín, and Rivera-Gómezs 2020). The adequate design and combination of all these factors could lead to enhanced performance of the courtyard as a passive conditioning element of buildings.

1.1.1. Energy performance tools

The numerous factors that affect the performance of courtyards and the interrelations that occur between them make predicting their performance very challenging without a suitable simulation tool. Currently, many tools can predict the energy performance and thermal comfort of indoor spaces in buildings (Choi 2017). These tools have been used to predict the influence of courtyards on energy consumption (Asfour 2020) and indoor comfort (Soflaei et al. 2017). These two studies applied DesignBuilder, which uses the open-source computational model EnergyPlus (Crawley et al. 2001), to obtain simulation results. However, all these studies are underestimating the thermal benefits of courtyards, given that this kind of software is not able to simulate the microclimatic conditions that occur outdoors, thus the temperature in the courtyard is assumed to be the same as outside. This same problem has been detected using other energy simulation tools such as TRNSYS (TRNSYS 2020). When analyzing the impact of urban geometry on the energy consumption of buildings, if the microclimate is not included, this software can lead to inaccuracies (M'Saouri El Bat et al. 2021). In this sense, some tools have been recently developed to account for the urban form on the energy consumption of districts. CitySim can quantify the energy demand at the urban scale, with a higher spatial resolution (Walter and Kämpf 2015). However, it still relies on microclimate simplifications.

1.1.2. Computer fluid dynamics (CFD) tools

Tools to simulate outdoor spaces are few, although in recent years there has been an emergence of new software methods that are able to simulate with some accuracy the microclimatic performance of outdoor spaces (Mauree et al. 2019). The advances in computation resources allow for the use of CFD to gain accuracy. According to Lam et al. (2021), the most used in the last years for the analysis of outdoor thermal comfort is ENVI-met, a software specialized in urban microclimate simulation using CFD. This software has been used for courtyard microclimate simulation in several studies (Ghaffarianhoseini, Berardi, and Ghaffarianhoseini 2015; Berkovic, Yezioro, and Bitan 2012; Forouzandeh 2018; López-Cabeza et al. 2018). While ENVI-met is valuable for being the only software that unifies the simulation of most of the outdoor variables that influence the microclimate (See Section 2.3.1 for more information), it presents some limitations. First, the CFD simulation has a large computational cost (Toparlar et al. 2017), thus making it difficult for most users to analyze periods longer than a few days. The second disadvantage of ENVI-met derives from its simulation assumptions and simplifications (Huttner 2012). The only turbulence model that ENVI-met uses by default is known to overestimate the flow around buildings (Forouzandeh 2018). In addition, the radiation model is known to overestimate the long wave radiation budget within areas with colder surfaces such as courtyards. The inaccuracies of ENVI-met simulating small-scale courtyards have been previously reported (López-Cabeza et al. 2018).

For that reason, some researchers prefer the use of CFD-specific tools to simulate outdoor microclimates. OpenFOAM and FreeFem++ are open-source software, lacking graphical user interfaces, but with flexibility that enables their use through the implementation of other software. Open FOAM has been used in previous research to simulate wind flows at the urban scale (Kastner and Dogan 2020). FreeFem++ has been used to simulate courtyard buildings in a coupled process to handle geometry in a user-friendly way (Rojas-Fernández et al. 2018; López-Cabeza et al. 2021). ANSYS Fluent is not open source but it has been widely used for many purposes, one of them being the simulation of wind flows

Table 1. Simulation tools and workflow capabilities.

	Energy demand	Outdoor comfort	Urban environmental conditions	CFD	Open source
(a) Software					
UWG (Bueno et al. 2013)			●		●
SOLWEIG (Lindberg, Holmer, and Thorsson 2008)		●	●		●
Energy Plus (Crawley et al. 2001)	●				●
CitySim (Walter and Kämpf 2015)	●	●	●		●
TRNSYS (TRNSYS 2020)	●				●
ENVI-met (ENVI-met)		●	●	●	
OpenFoam (OpenFOAM)				●	●
FreeFem++ (FreeFEM)				●	●
ANSYS Fluent			●	●	
Autodesk CFD (Autodesk 2021)		●	●	●	
DesignBuilder (DesignBuilder 2021)	●	●		●	
(b) Hybrid workflows					
ENVI-met + Energy Plus (Yang, Li, and Yang 2012)	●	●	●	●	
Ladybug Tools (Mackey et al. 2017; Elwy et al. 2018; Soflaei et al. 2020; Evola et al. 2020)	●	●	●	●	●
UMI (Reinhart et al. 2013)	●	●	●		●
ENVI-met + TRNSYS (Perini et al. 2017)	●	●	●	●	
Ladybug Tools + ENVI-met (Fabbri et al. 2017)	●	●	●	●	

in outdoor spaces (Blocken, Carmeliet, and Stathopoulos 2007) and ventilation of buildings through courtyards (Padilla-Marcos, Feijó-Muñoz, and Meiss 2015). These software programs usually achieve higher accuracy, but their results are difficult to incorporate into the early design phase, which may be helpful for designers. Autodesk CFD (Autodesk 2021) is a software that can be considered CFD specific but oriented to the early design stage. It calculates comfort indexes using the Finite Element Method. However, it has not been validated for outdoor simulations (Naboni et al. 2019; Willis 2018). DesignBuilder (DesignBuilder 2021) also have a CFD module that includes some simplifications to make it accessible for designers.

1.1.3. Alternative non-CFD methods

The huge amount of time that is required to analyze long periods of time using CFD has been addressed by other software tools that reject CFD methods in favour of faster ones to predict the urban microclimate. For example, the Urban Weather Generator (UWG) is based on energy conservation principles, and it computes a rural profile and then uses an urban boundary layer model to obtain air temperature values for the urban site (Bueno et al. 2013). Another example is SOLWEIG, which simulates spatial variations of 3D radiation fluxes and mean radiant temperature (MRT) in complex urban settings (Lindberg, Holmer, and Thorsson 2008), variables that directly affect thermal comfort. This software was able to simulate a reduction in the Mean Radiant Temperature of courtyards due to their self-shading capacity (Wallenberg et al. 2020). All these tools avoid the use of CFD in their simulations to reduce computation time, however, the use of CFD usually provides higher accuracy in small-scale microclimates such as courtyards, whose performance is very affected by thermodynamic effects.

1.1.4. Hybrid workflows

From a building designer's perspective, we argue that the method to analyze courtyards should fulfil the following requirements. First, it should be a method easy to implement in the early design stage of a project. This means that results and design should be easily connected and allow for many iterations quickly (Graham et al. 2020). Second, to achieve accuracy, the method should include CFD simulation to calculate the microclimatic effects in the courtyard knowing the outdoor conditions (Toparlar et al. 2017; Blocken et al. 2011). Third, the method should also include the interrelation that happens between buildings, soil, air, and vegetation, something that has been difficult to implement until recently given the complexity of connecting their dynamic effects. Fourth, the method should be able to evaluate comfort and include the energy demands of buildings. Finally, ideally, the software should be open source so users can understand and even improve the functioning of the simulation. Table 1(a) summarizes the software previously described and indicates which of the desired characteristic they meet.

It can be seen that using one single software is not possible to meet all these desirable characteristics for simulating a courtyard. Given this situation, some researchers have created workflows that link different tools in order to obtain more desirable results. These hybrid workflows, i.e. workflows in which software outputs become inputs for another software, are gaining attention. Table 1(b) includes a summary of some of the hybrid workflows previously used by other researchers. Most of them consist of a combination of ENVI-met to provide the CFD accuracy with other tools to provide the energy demand such as EnergyPlus (Yang et al. 2012) or TRNSYS (Perini et al. 2017).

More recently, the development of Ladybug Tools, a set of open-source plugins for Grasshopper that link the graphical user interface to other simulation modules such as EnergyPlus, Radiance, or Daysim, is gaining attention. Such tools have some advantages such as the implementation of desired characteristics into one interface, specifically developed for designers, and being open-source (O'Neill 2012). Soflaei et al. (2020) have used the Ladybug Tools to analyze the impact of courtyard design variables on thermal comfort, using a parametric analysis testing 8600 alternatives. Natanian and Auer (2020) used a similar workflow to optimize urban form under three performance indicators: energy load, daylighting, and thermal comfort. They included the UWG plug-in to implement the urban climate in a simplified way. Results showed that the building with courtyard typology achieved the optimal combination across the tested criteria. However, they also emphasized the necessity of including numerical models to accurately predict microclimatic conditions and recommended further validation. In another study, researchers included a CFD module for the Ladybug Tools (Natanian et al. 2020) to simulate wind microclimatic conditions in the urban environment; however, they did not use CFD simulation to account for temperature microclimatic variations, variables that are important in the performance of courtyards. Mackey et al., developers of the Ladybug Tools, published a study analyzing a workflow they designed using their tools for urban microclimate simulation and stated in the 'Limitations and future work' section that '… the surface temperatures from the EnergyPlus simulation were not used to inform the 36 CFD simulations … Needless to say, future research should still include a validation of this method against fully-integrated engines as well as empirically measured climate conditions of the urban environment' (Mackey et al. 2017), which is the gap we are trying to overcome with this paper.

1.2. *Aim and objective*

In this current state of the art, our study aims to (1) build upon this workflow using Ladybug Tools to include the CFD plug-in Butterfly (Ladybug Tools Butterfly), which links to OpenFOAM, to simulate not only wind flow but also temperature variations inside the courtyard with higher accuracy than other tools, and (2) to verify the results contrasting with monitored data. To our knowledge, this is one of the first few studies that analyze the Ladybug Tools including CFD calculations of temperature variations inside a courtyard and compares the results with monitored data. We analyze these tools from a designer's perspective, using currently available components in the tools, assuming that users lack the knowledge to program new components or change advanced settings. Thus, we analyzed the suitability of using the tools in their current state of development for use in the early design stage. Our research includes two steps. First, we validate the tools by comparing temperature simulation results to both a validated tool for this purpose, i.e. ENVI-met, and monitored data. Second, we analyze users' comfort in courtyards via both tools in order to compare results. With this procedure, we provide a tested method of computer simulation of thermodynamic effects in courtyards.

This method is especially relevant for climates where heritage has traditionally established elements such as small courtyards as a passive strategy for environmental cooling, creating microclimates that facilitate the quality of life and comfort of residents. This method can improve energy simulation of such buildings by including multinodal outdoor data, aiming to contribute to the design of climate resilient buildings in a future of climate change projections.

2. Materials and methods

2.1. *Case studies*

We selected three different courtyards to monitor and simulate in this study, see Figure 1. The main criterion for the case study selection was a variety of geometries in the same climatic conditions but sharing the same wall albedo and similar orientation, in order to maintain similar characteristics for all the non-geometric parameters that affect courtyard thermodynamics. Two of the courtyards are located in Córdoba (4°46′21.9"W, 37°53′29.58N, elevation 106 m a.s.l) and the third is in Seville (37°17′01′′N 5°55′20′′W, elevation 42 m a.s.l). Both cities are nearby in the south of Spain, and share the same climate, defined as Csa according to the Koppen classification (Kottek et al. 2006), specifically, hot dry summers with temperatures reaching above 40°C, mild winters and little mean precipitation throughout the year.

The geometry of the courtyards is defined by their Aspect Ratio (AR), the relation between their height and width (see Equation (1)) and the Sky View Factor (SVF) which is the ratio of the sky that can be directly seen from a specific point to the whole hemispheric sky which would be seen without any elements blocking the view (see Equation (2)). Here, it has been graphically calculated using Ladybug (shadingMaskII

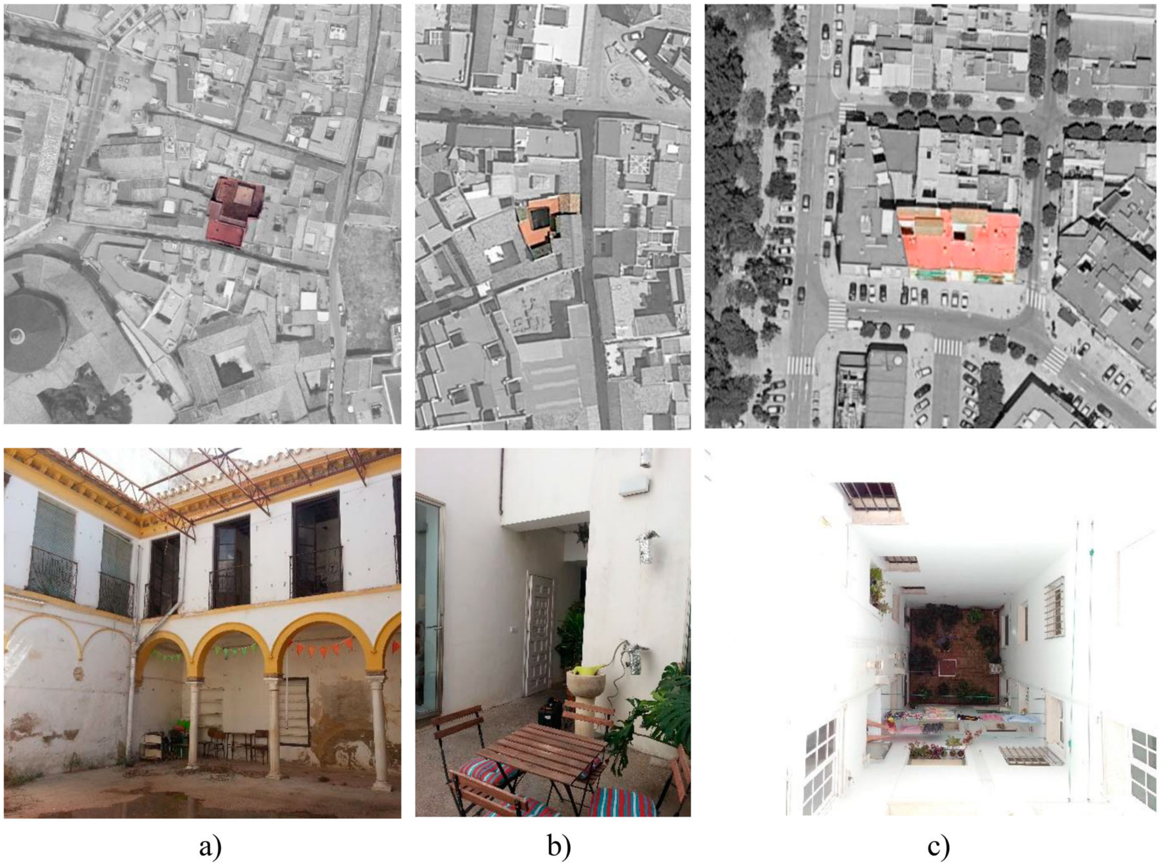


Figure 1. Location within the urban fabric and photographs of the selected case studies. (a) Case 1 (b) Case 2 (c) Case 3.

component).

$$AR = \frac{\text{Height}}{\text{Width}} \quad (1)$$

$$SVF = \frac{\text{Visible Sky Portion}}{\text{Total Hemisphere}} \quad (2)$$

A rectangular courtyard has two AR, one per each one of its directions, while the SVF is a single value per courtyard. The geometrical information of the courtyard is only complete via a combination of the two parameters (AR and SVF). The three cases selected correspond to the most representative aspect ratios and building construction techniques in the Mediterranean region of Spain (Rojas-Fernández et al. 2017), aiming to expand the conclusion of this study to as many typologies of building as possible.

Case 1. This is a residential building in the city centre of Cordoba, in an area of high compactness close to the historic quarter of the city. It is a two-story traditional courtyard house with a nearly square courtyard surrounded by an arcade on three of its four sides. The building is currently unoccupied. The walls, which include windows in the three arcaded sides, are coated with white lime, and the ground is covered with light concrete.

Case 2: This is a two-story house with a small courtyard in the same dense area of the city centre of Cordoba. The courtyard's walls include large windows on the lower level and small windows on the upper level. The coating is cement mortar painted white.

Case 3: This multifamily residential building is located in a dense area of Seville. It is a six-story building and the courtyard studied is used mainly for ventilation and illumination of interior areas; thus, it has the highest AR of the three courtyards studied. The wall's coating is cement mortar painted white.

The geometries of the three courtyards are defined in Table 2, and represented in Figure 2, where the sensors position is also displayed.

2.2. Monitoring

The monitoring campaign took place during the summer (June to September) of 2017 in all cases, looking for high temperatures that can reach up to 45°C. This time of the year was chosen since previous research has shown it to be when the tempering effect of courtyards is the highest (Rivera-Gómez et al. 2019). We selected one day for each courtyard with a similar peak temperature to compare the simulation results. These days are the 20th of August for Case 1, the 19th of August for Case 2, and the 16th of June for Case 3.

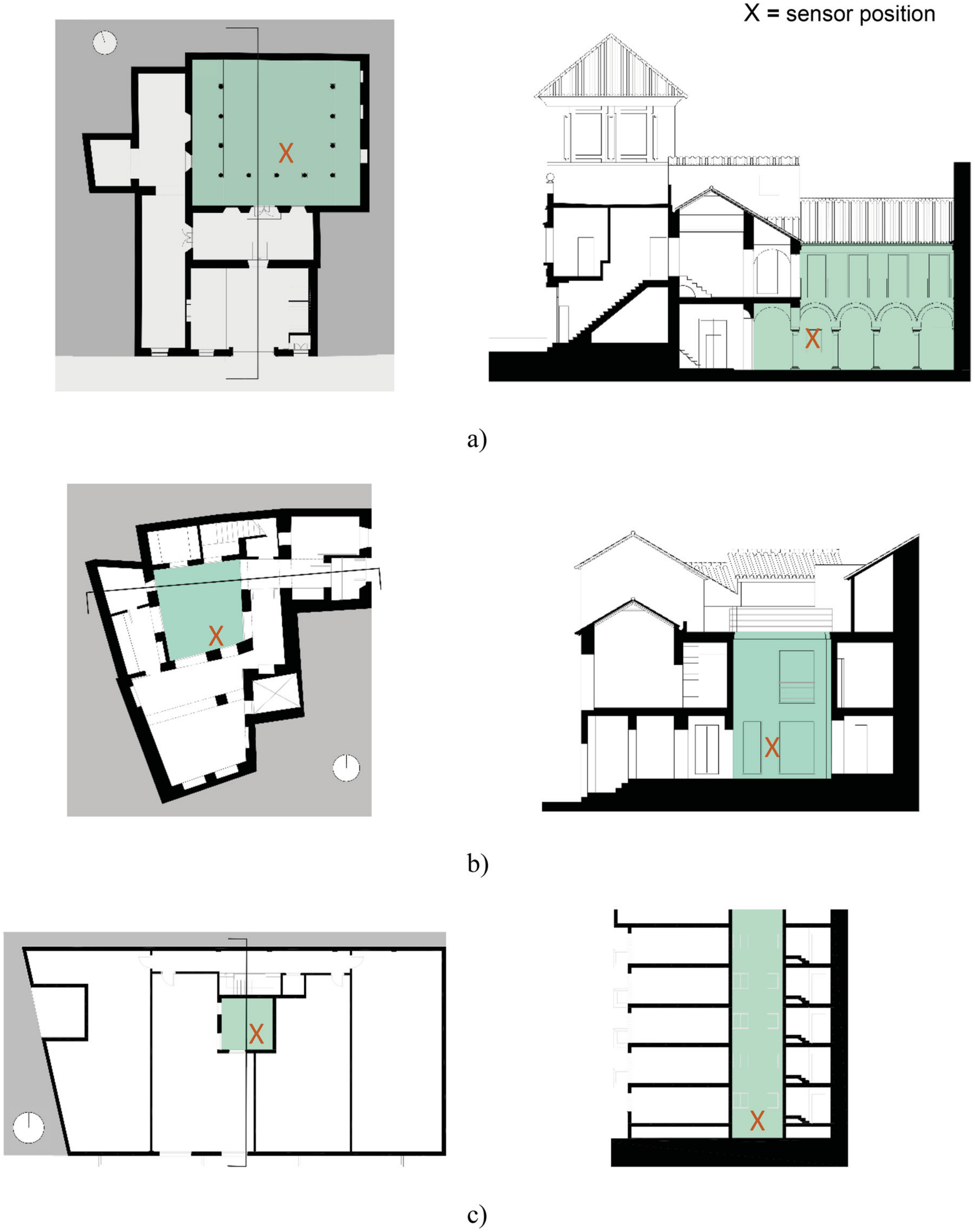


Figure 2. Sensors position in the courtyards (left), in plan and section (right). (a) Case 1 (b) Case 2 (c) Case 3.

Table 2. Geometric characteristics of the courtyards.

Courtyard	Width (m)	Length (m)	Height (m)	AR(Axis 1, Axis 2)	3D Sky View Factor	Albedo (Wall, Ground)
Case 1.	7.8	8.4	6.8	0.9, 0.8	0.17	0.7, 0.4
Case 2.	4.5	4.5	7.0	1.5, 1.5	0.07	0.7, 0.4
Case 3.	3.5	3.5	16.0	4.6, 4.6	0.01	0.7, 0.4

Table 3. Technical data of the measuring instruments.

Location	Sensor	Variable	Accuracy	Range	Resolution
Courtyard	TESTO 174H	Dry bulb Temp.	±0.5°C	−20 to +70°C	0.1°C
		RH	±0.1%	0–100%	2%
Outdoor(2 m above the roof)	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	–

Table 4. Description of the model geometry for each case.

Parameters	Case 1	Case 2	Case 3
Number of grid cells	92 × 86 × 30	121 × 112 × 30	106 × 74 × 30
Size of the cells (m) (*x,y,z*)	1 × 1 × 1	0.5 × 0.5 × 0.5	1 × 1 × 1
Telescoping factor	12% after 15 m height.	12%. Start at 10 m height.	12%. Start at 18 m height.
Nesting grids	3	3	3
Model orientation (degrees clockwise from north)	15	0	0

We recorded outdoor air temperature, relative humidity, and wind speed/direction on-site using a portable weather station model PCE-FWS 20 placed at the roof of each case study. The weather station was placed 2 m from the roof surface to reduce the effects of building heat. Inside the courtyard, air temperature and relative humidity were monitored at a height of 1.5 m above the floor, i.e. the height at which people inhabit the space, using sensor model TESTO 174 H. The sensors were located in the south façade (facing north) and protected with a ventilated and reflective shield to avoid solar radiation. Table 3 shows the technical data of the instruments and Figure 2 shows the sensors' position inside the courtyard.

2.3. *Simulation*

Here, we evaluate the accuracy of the simulation outputs of two different workflows in predicting the dry-bulb air temperature inside the courtyards. Then we measure the importance of this accuracy in terms of predicting outdoor comfort. In this section, the two workflows and their set-up are described and represented.

2.3.1. *ENVI-met simulation workflow*

ENVI-met is a widely validated CFD software for the analysis of urban microclimates, given its capacity to analyze small-scale interaction between soil, water, air, vegetation, and buildings at different scales. It is designed with a typical horizontal resolution from 0.5 to 10 m and a typical time frame of 24–48 h with a time step of 1–5 s. It provides a large variety of data but requires time and computational power. Although previous studies have stated that for small spaces such as courtyards this software shows less accuracy than in larger spaces (López-Cabeza et al. 2018), this limitation is compensated by other advantages such as the possibility of including water and vegetation influences in the simulation. ENVI-met solves the Reynolds-averaged non-hydrostatic Navier-Stokes equations for each grid in space and for each time step. The model used by the software to predict the turbulence in the air is the so-called 2-equation Turbulence Kinetic Energy (TKE) model (Webpage ETI). The numerical discretization scheme is the orthogonal Arakawa C-grid (Arakawa and Lamb 1977) and the numerical method is the Finite Difference Method to solve the multitude of partial differential equations (PDE) and other aspects in the model. The simulation requires an initialization time to provide accurate data, which is why here a total of 36 h have been simulated and the first 12 h have been discarded, as suggested by other researchers (Forouzandeh 2018; Salata et al. 2016). The model geometry of each case study is described in Table 4 and the main input variables are shown in Table 5.

Given that ENVI-met has been previously proven not to be grid independent (Crank et al. 2018), our modelling follows the recommendations of previous research about grid size, context domain, and model size for manageable computer power requirements (López-Cabeza et al. 2018; Darvish, Eghbali, and Eghbali 2021). In this sense, the model includes the context of the courtyard itself and the building to which it belongs. Figure 3 shows the ENVI-met models for the three case studies and the grid configuration and context.

2.3.2. *Ladybug Tools simulation workflow*

The LadyBug Tools are a set of plugins for Grasshopper that allows the connection between different validated simulation software such as EnergyPlus (energy simulation), OpenFOAM (CFD simulation), or Daysim (daylighting analysis) to the graphical user interface of the modelling tool Rhinoceros (Sadeghipour Roudsari, Pak, and Smith 2013). In Grasshopper, a script to link the results of one tool to one another needs to be designed to make use of all the programs in one single interface, providing great flexibility and increasing the possibilities of the

Table 5. Main input variables in ENVI-met for each case.

		Case 1	Case 2	Case 3
Meteorological	Air temperature and relative humidity	Hourly data in Table A1.	Hourly data in Table A1.	Hourly data in Table A1.
	Wind speed and direction	0.3 m/s – 270°	2 m/s – 270°	0.6 m/s – 200°
	Specific humidity at 2500 m	4.5 g/kg	4.5 g/kg	4.5 g/kg
	Roughness length	0.1 m	0.1 m	0.1 m
Building	Wall Material (as from ENVI-met library)	Wall-moderate insulation	Wall-moderate insulation	Wall-moderate insulation
	Roof Material (as from ENVI-met library)	Roofing Tile	Roofing Terracotta	Roofing Terracotta
Soil	Initial Temperature, RH:			
	Upper Layer (0–20 cm):	20°C, 50%	20°C, 50%	20°C, 50%
	Middle Layer (20–50 cm):	16°C, 60%	16°C, 60%	16°C, 60%
	Deep Layer (50–200 cm):	12°C, 60%	12°C, 60%	12°C, 60%
	Bedrock Layer (below 200 cm)	12°C, 60%	12°C, 60%	12°C, 60%
	Material (from ENVI-met library)	Concrete pavement light	Concrete pavement light	Concrete pavement light
Simulation	Start Simulation Day *(DD.MM.YYYY)*	19.08.2017	18.08.2017	15.06.2017
	Start Simulation Time *(HH:MM:SS)*	12:00:00	12:00:00	12:00:00
	Total Simulation Time (hours)	36 h	36 h	36 h
	Save Model State (min)	30 min	30 min	30 min

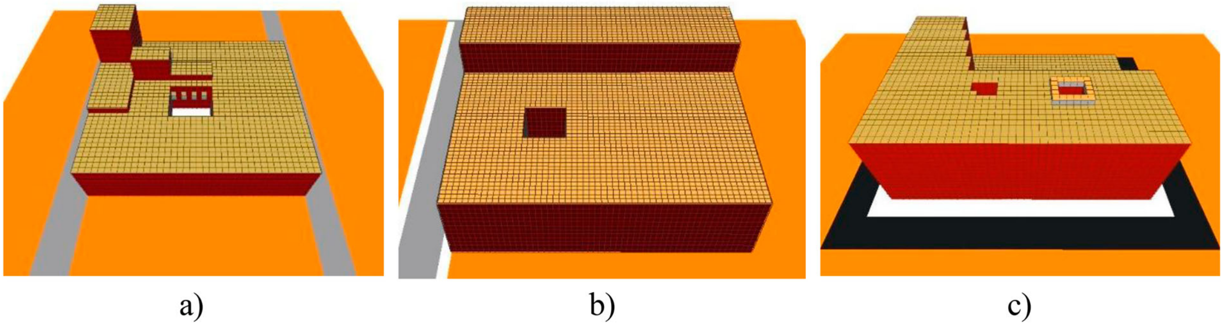


Figure 3. ENVI-met model of the case studies. (a) Case 1 (b) Case 2 (c) Case 3.

simulation. Given that the tool is open source, and is continuously being improved, some capabilities like the simulation of trees and vegetation have been recently included (Chokhachian and Hiller 2020). In this paper, a novel script has been specifically designed for courtyards' microclimate simulations. For that reason, it needs validation, which is done comparing results to measured data. Courtyard performance is radically different to outdoors environments, given that wind flows are not as important as in exposed exteriors, and convection flows generated by the temperature of the surfaces can substantially affect the microclimate. That is why, in this study, we used the OpenFOAM plugin in Ladybug Tools that includes a heat transfer solver to perform CFD simulation using surfaces temperature as boundary conditions, allowing the software to calculate air temperature variations inside the courtyard, in contrast to previous studies where the air temperature was not simulated.

Our workflow is diagrammed in Figure 4. The Ladybug tools utilized are represented by their icons: Ladybug, Honeybee and Butterfly. Here, monitored weather data was input to Ladybug, the climate analysis tool. These data are displayed in Appendix Table A1. The geometry was modelled in Rhinoceros, a 3D modelling software commonly used by architects and designers. Honeybee linked to EnergyPlus performed the energy analysis to provide the temperature of the surfaces of the walls of the courtyard, and the mean radiant temperature that is necessary for the comfort calculation (details for the energy simulation are shown in Appendix Table A4). Finally, combining the monitored data and the surface temperature data, Butterfly performed the CFD calculation that provided the courtyard temperature. That is the temperature that was compared to the monitored temperature in the courtyard to validate the workflow.

Butterfly linked the grasshopper interface to OpenFOAM software to perform the CFD calculation. The model was defined for each case following the general recommendations for best practices in CFD simulation of urban environments (Franke et al. 2007; Franke et al. 2004). The domain's inlet, top, and lateral boundaries have been placed at least 5H away from the building model, with H being the height of the building. The outlet is placed 15H away from the building. For the mesh definition, the *blockMesh* utility is used for the background mesh and *snappyHexMesh* to snap the background mesh to the building geometry. The mesh was further refined with three or four levels of refinement within an area around the courtyard building. This resulted in a mesh with 2.5×10^6, 2.3×10^6, and 2.0×10^6 cells in Cases 1, 2, and 3 respectively. Figure 5 shows images of the mesh in each case. For more information

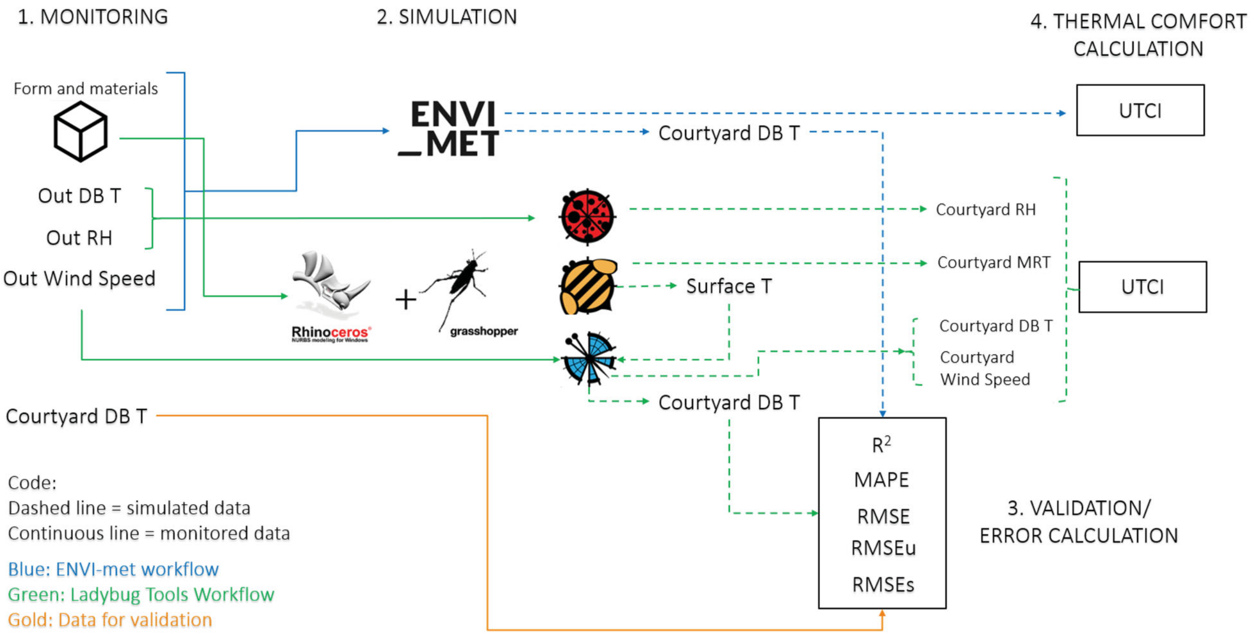


Figure 4. Flowchart showing how different inputs and outputs relate to the simulation tools and validation. DB T = dry bulb temperature. RH = Relative Humidity.

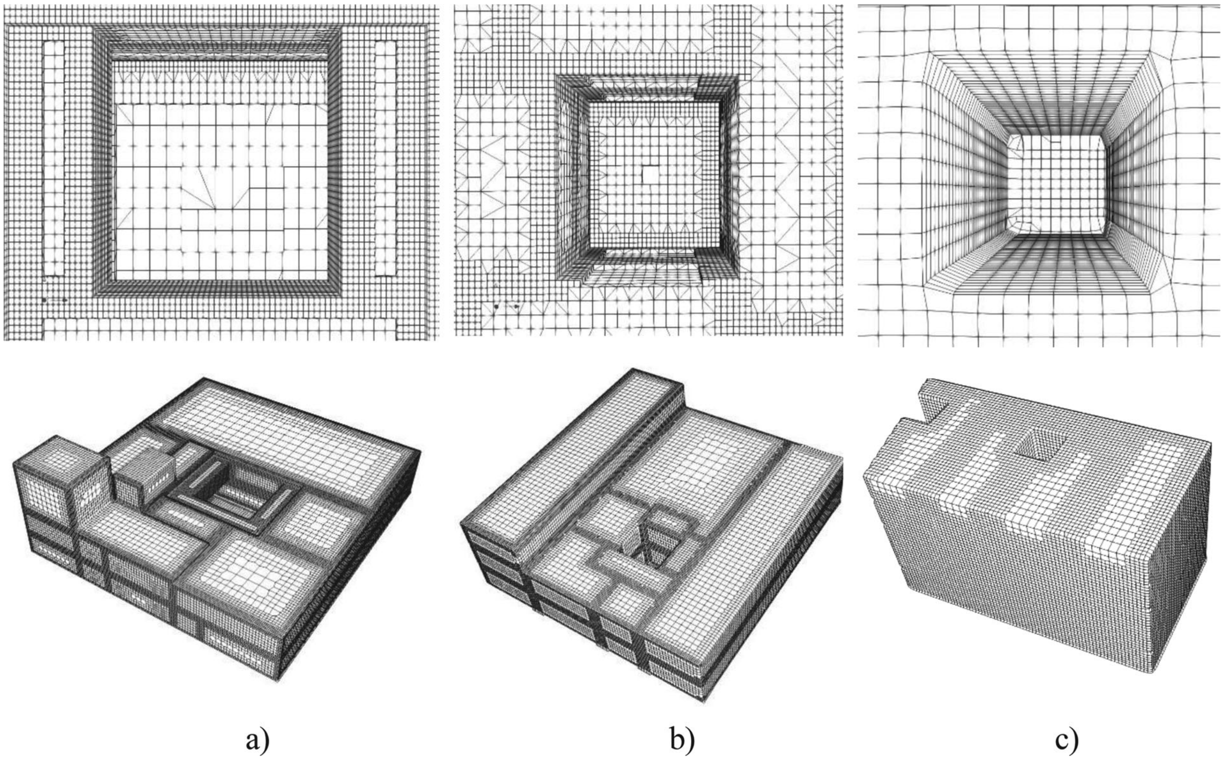
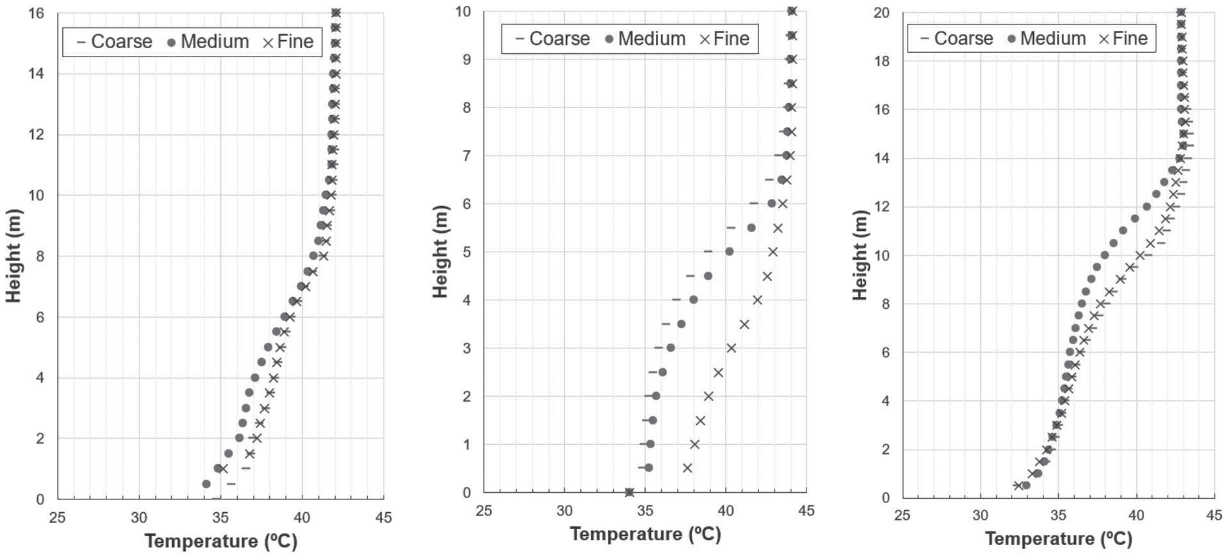


Figure 5. Ladybug Tools models' grid. (a) Case 1 (b) Case 2 (c) Case 3.

about the construction of the domain and the boundary conditions see the Appendix.

This meshing is selected after a process of grid sensitivity analysis performed with different levels of refinement. Three levels of grid refinement were tested (coarse, medium, and fine) with a linear factor between cells of 1.5. Figure 6 shows the results of temperature at different heights in a vertical line in the centre of the courtyard in the three levels of refinement in each case. In Case 1, the average percentage error between the coarse and the



a) b) c)

Figure 6. Simulated results of temperature along a vertical centre line of the courtyard model for the grid sensitivity analysis. (a) Case 1, (b) Case 2, (c) Case 3.

medium is 1.8% and between the fine and the medium is 1.4%. The same values are 1.2% and 3.9% in Case 2 and 2.4% and 1.8% in Case 3 respectively. Based on these results, we conclude that the grid dependency is acceptable in the three cases, and we selected the medium grid refinement in order to avoid the huge computational time required for the finer meshes.

The solver used is called buoyantBoussinesqSimpleFoam. This is a steady-state solver for buoyant, turbulent flow of incompressible fluids that uses the Boussinesq approximation (OpenFOAM), and the SIMPLE (Semi-Implicit-Method-Of-Pressure-Linked-Equations) coupling velocity-pressure scheme (Holzmann 2017). The RNG k-epsilon turbulence model was used. An upwind finite volume method is considered using OpenFOAM. Namely, the divergence terms are discretized by the bounded Gauss linear Upwind method, cell limiters for the gradient approximations are considered and a linear interpolation. Initial parameters for the simulation are shown in Appendix Table A2. The boundary conditions for the domain limits, inlet and outlet, and the building geometry are detailed in Table A3 in the Appendix.

2.4. *Comfort calculation*

Once the workflow was validated, we used it to analyze comfort in the courtyards. The comfort parameter selected was the Universal Climate Thermal Index (UTCI), since it has become a common index used by meteorologists globally (McGregor 2012). UTCI considers air temperature, mean radiant temperature (MRT), wind speed and relative humidity, as well as other factors such as clothing, age, weight, and height of the average population. The index gives a 'feels like' temperature that falls into a scale that indicates thermal stress.

We calculated the UTCI results using the Outdoor Comfort Calculator component in Ladybug (Outdoor Comfort Calculator) which adapts the original Fortran code (UTCI) to Python. The inputs needed are air temperature, wind speed, mean radiant temperature and relative humidity. Results from the two workflows were compared to highlight the importance of the simulated air temperature on comfort.

3. Results

The results section is divided into three parts. First, we show the monitoring results of each campaign, then, the temperature results of each workflow used to validate the simulations and finally, the comfort simulation results provided by each workflow.

3.1. *Monitoring results*

The monitoring campaign results are shown in Figures 7–9, one per case study. Graphs display the monitored outdoor temperature, the courtyard temperature recorded at 1.5 m above the floor and the thermal gap between them, defined as the difference in temperature between the outdoor and the courtyard. It can be seen that there were days when the outdoor temperature goes over 40°C in all case studies and one of them per case are

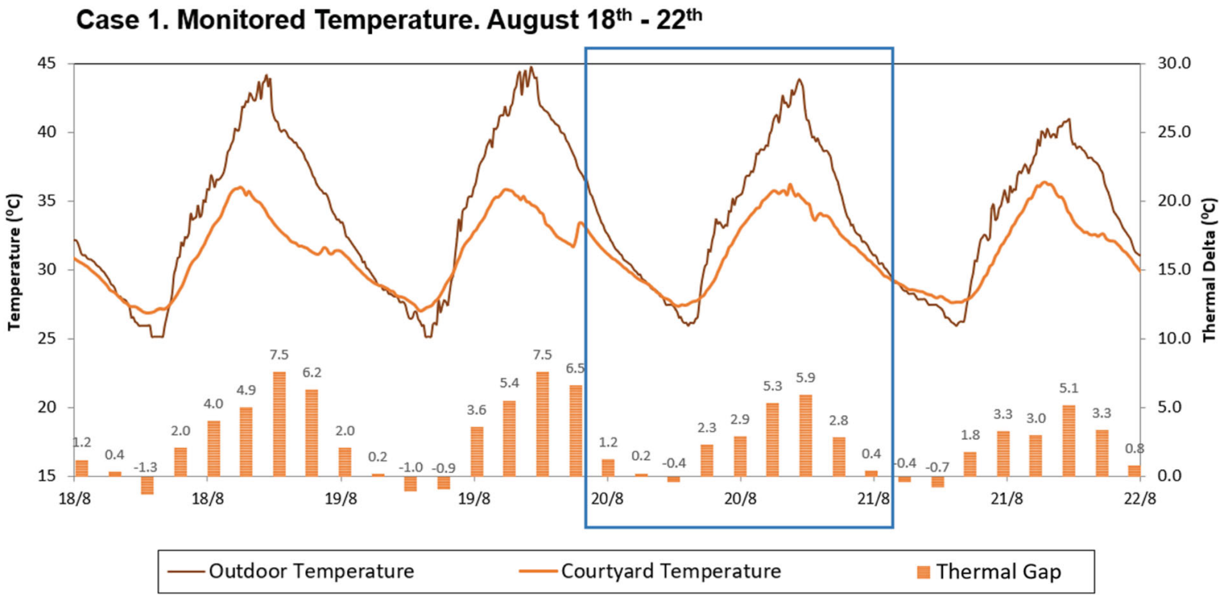


Figure 7. Monitored air temperature and thermal gap in Case 1 from 18 to 22 August.

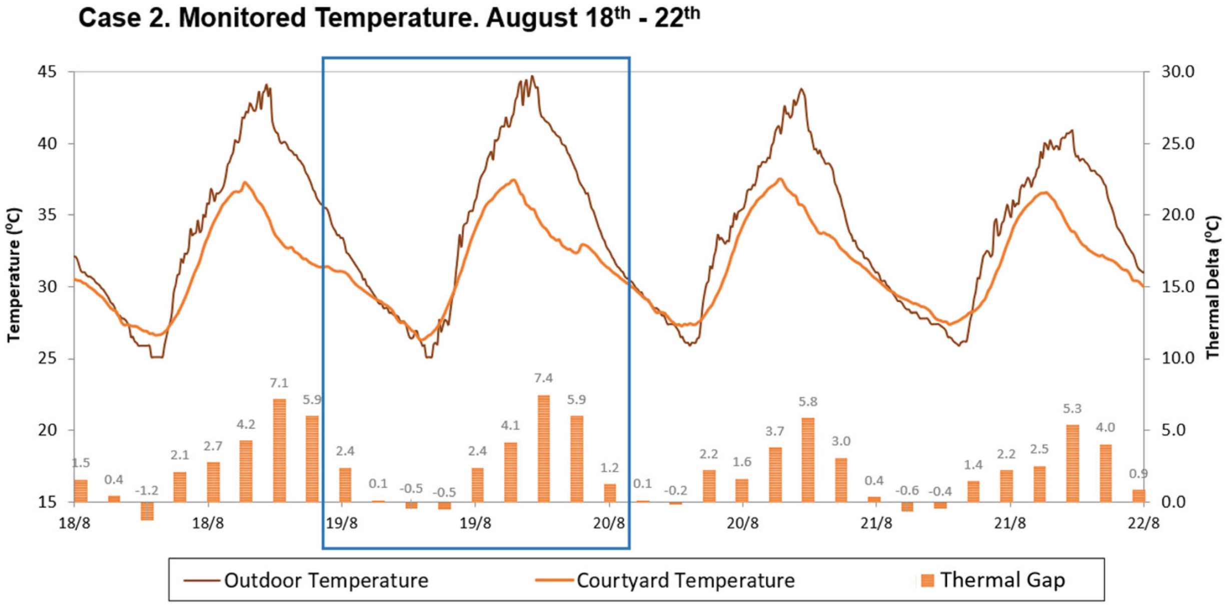


Figure 8. Monitored air temperature and thermal gap in Case 2 from 18 to 22 August.

chosen to be simulated. Selected days are marked in a blue box in Figures 7–9.

The maximum temperature inside the courtyards was always lower than the outdoor temperature, demonstrating the tempering effect of the courtyards. On the selected days, the highest thermal gap at peak outdoor temperature corresponded to the highest AR for the selected courtyards. That is to say, the thermal gap in Case 1 (AR = 0.9) at 18:00 h was 5.9°C, in Case 2 (AR = 1.5) was 7.4°C at the same time, and the highest delta was in Case 3 (AR 4.5), up to 10.8°C.

Another effect displayed in all the cases is an overheating produced during the night. At that time, the temperature of the courtyard was always warmer than the outdoor temperature. This effect is especially pronounced in Case 3 (where the temperature delta between courtyard and outdoors reached −5.6°C at 6:00 am one day) and is explained by the deeper geometry. This shape makes it difficult to ventilate the courtyard during the night and, thus, the heat is released to the environment at a slower pace.

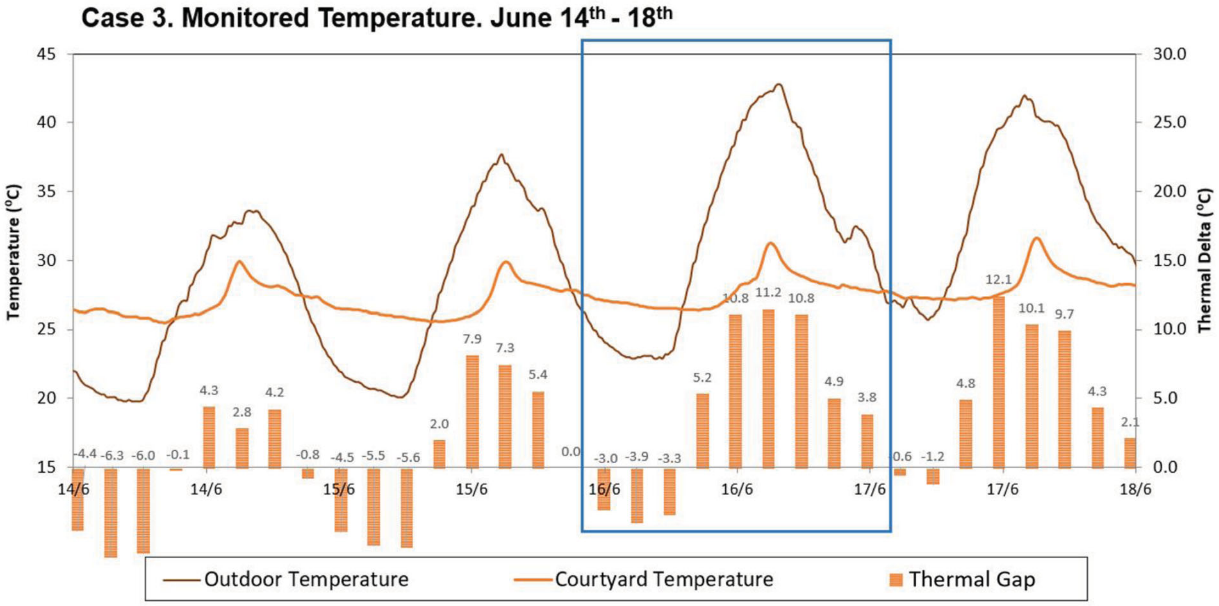


Figure 9. Monitored air temperature and thermal gap in Case 3 from 14 to 18 June.

3.2. Simulation temperature results and software validation

This section summarizes the results of the temperature provided by each workflow. These are the results that we compared to the monitored result previously shown to validate the process. Simulated temperature was recorded at the same height where the sensors were placed for monitoring, 1.5 m above the courtyard floor.

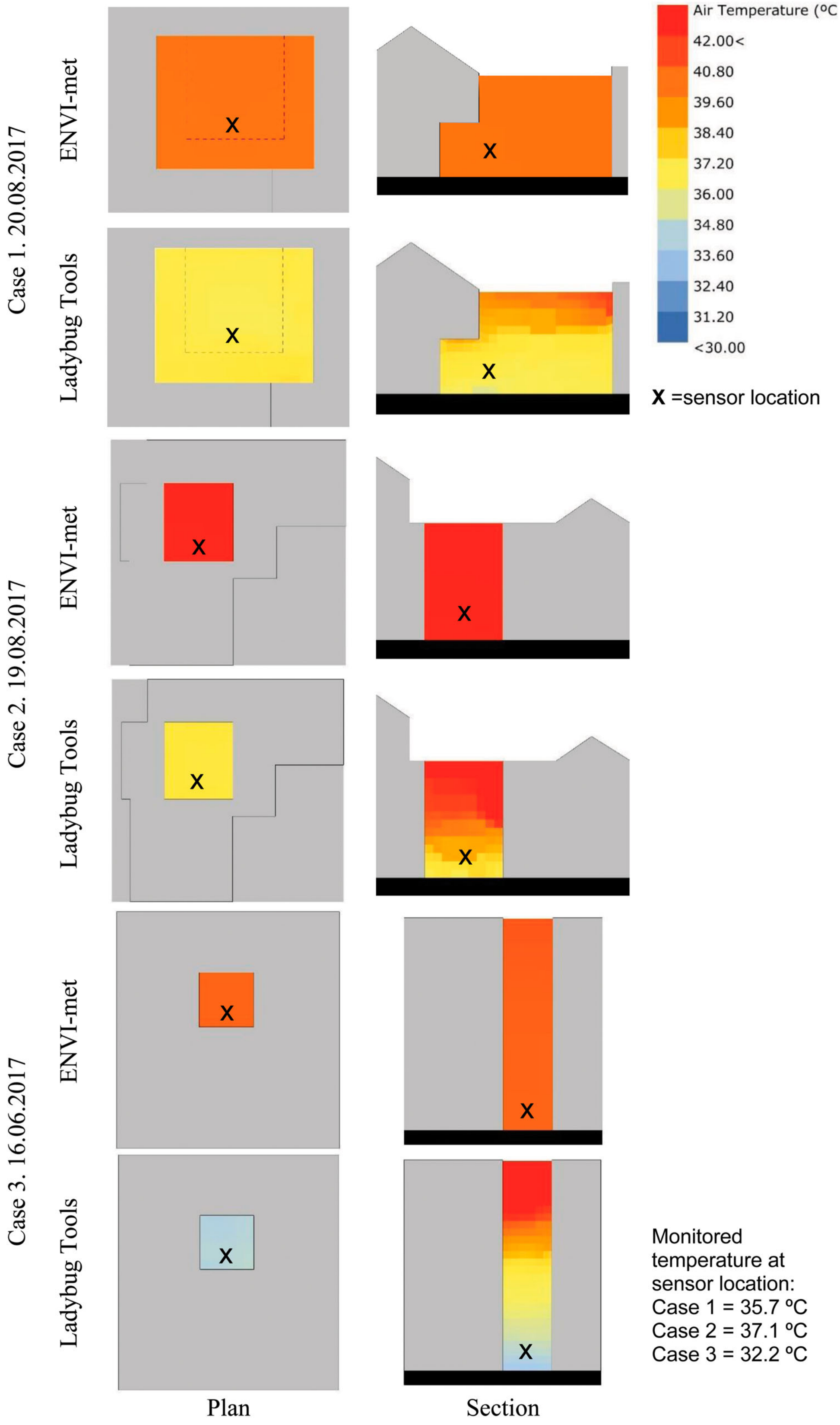
Figure 10 shows the simulated temperature at 16:00 h, which was the peak outdoor temperature in two cases, and close to the peak in the other. The images show that ENVI-met results were always higher than the Ladybug Tools results. Figure 11 shows the hourly temperature evolution in each simulated case. All simulation workflows reproduced courtyard temperatures lower than the outside when the outdoor temperature was at its peak. However, the Ladybug Tools workflow was always closer to monitored results, providing the lowest courtyard temperature of the two workflows. During the night, both workflows simulated the overheating effect of the courtyards, except the ENVI-met simulation of Case 1. Overall, the Ladybug Tools simulation results were always closer to the monitored results.

Temperature simulation results at 1.5 m above the floor at each courtyard are numerically compared to monitoring results in order to validate the accuracy of the two simulation workflows. The statistical parameters used are the Coefficient of Determination (R^2), the Root Mean Square Error (RMSE), Systematic Root Mean Square Error (RMSEs), Unsystematic Root Mean Square Error (RMSEu) and Mean Absolute Percentage Error (MAPE). The values that are desired are: $R^2 \rightarrow 1$, RMSE $\rightarrow 0$, RMSEs $\rightarrow 0$, RMSEu $\rightarrow$ RMSE, MAPE $\rightarrow 0$. An explanation of these metrics can be found in (Armstrong and Collopy 1992). The results calculated for each one of the simulations are displayed in Table 6.

The values obtained for RMSE, RMSEs, RMSEu, and MAPE show that Ladybug Tools simulation workflow has higher accuracy than ENVI-met. MAPE reaches 14.38% in Case 3 of ENVI-met simulation, while the highest MAPE of the three Ladybug Tools simulations is only 7.55%. RMSE ranges from 2.61–5.22 in ENVI-met and only 1.37–2.29 for Ladybug Tools. These error parameters are represented in Figure 12 and show better accuracy in the Ladybug Tools simulation. In contrast, for the Coefficient of Determination, all the cases from ENVI-met are closer to the value 1 desired. However, this coefficient has been reported to be insufficient and unreliable by itself by some authors (Willmott 1982), thus, this study considers these values less significant than the other parameters.

3.3. Comfort results

In this section, we used the workflows to calculate the UTCI index in the three courtyards and compared the results. As explained in section 2.4, the UTCI considers not only temperature but also humidity, wind speed and mean radiant temperature (MRT) in the courtyard. From monitored results and simulation results, we know that the wind speed was very low in the courtyards, so its influence on the UTCI index is limited. However, the influence of the MRT is important and is manifested in



X =sensor location

Monitored temperature at sensor location:
Case 1 = 35.7 ºC
Case 2 = 37.1 ºC
Case 3 = 32.2 ºC

Figure 10. Air temperature results at 1.5 above the ground, shown in plan and section, from ENVI-met and Ladybug Tools workflows at 16:00 h.

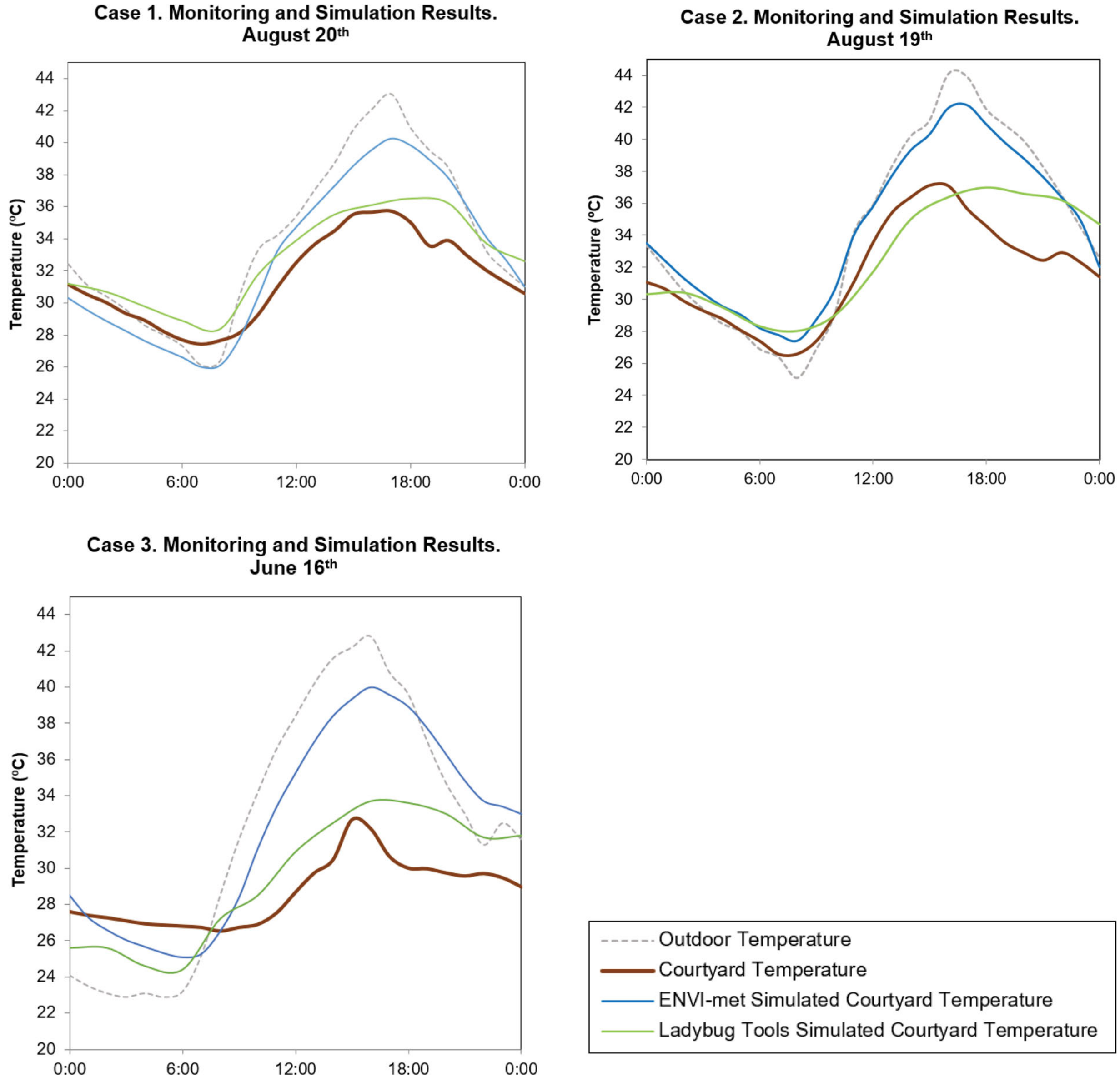


Figure 11. Temperature comparison of monitoring, ENVI-met, and Ladybug Tools workflows results.

Table 6. Quantitative evaluation of the simulation's performance for the courtyard temperature output.

		AR	R^2	MAPE (%)	RMSE (°C)	RMSEu (°C)	RMSEs (°C)
ENVI-met simulation	Case 1	0.9	🟩 0.96	6.85	2.61	3.96	1.42
	Case 2	1.5	0.92	8.74	3.46	🟧 5.54	🟧 2.20
	Case 3	4.6	0.84	🟧 14.38	🟧 5.22	6.76	1.66
Ladybug Tools simulation	Case 1	0.9	0.94	🟩 3.81	🟩 1.37	2.41	🟩 1.12
	Case 2	1.5	🟧 0.73	5.07	2.00	🟩 2.41	0.96
	Case 3	4.6	0.78	7.55	2.29	3.09	1.03

Legend: 🟩 Best result of each parameter between the two simulations
🟧 Worst result of each parameter between the two simulations

Figure 10, which shows the UTCI simulated by the two workflows.

Figure 13(a) shows UTCI results in Case 1 at four different hours of the day (8:00, 12:00, 16:00, and 20:00 h). The sun hit the walls and floor of the courtyard providing a higher value in the UTCI in some parts of the courtyard at 12:00 and 16:00 h, because of the overheating of the surfaces and solar radiation. The arcade of the courtyard had a positive effect, manifested by the lower UTCI in the areas under the arcade, which was providing shading.

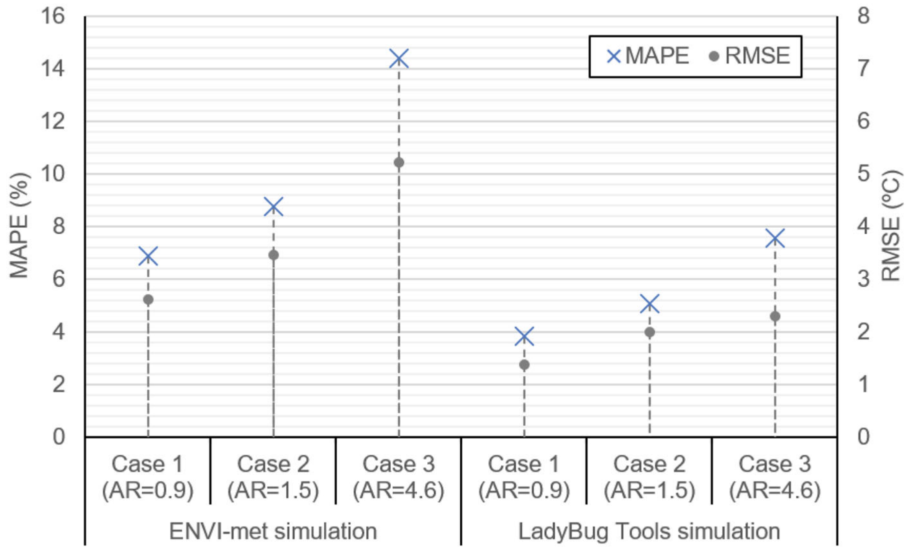


Figure 12. MAPE and RMSE results for each simulation.

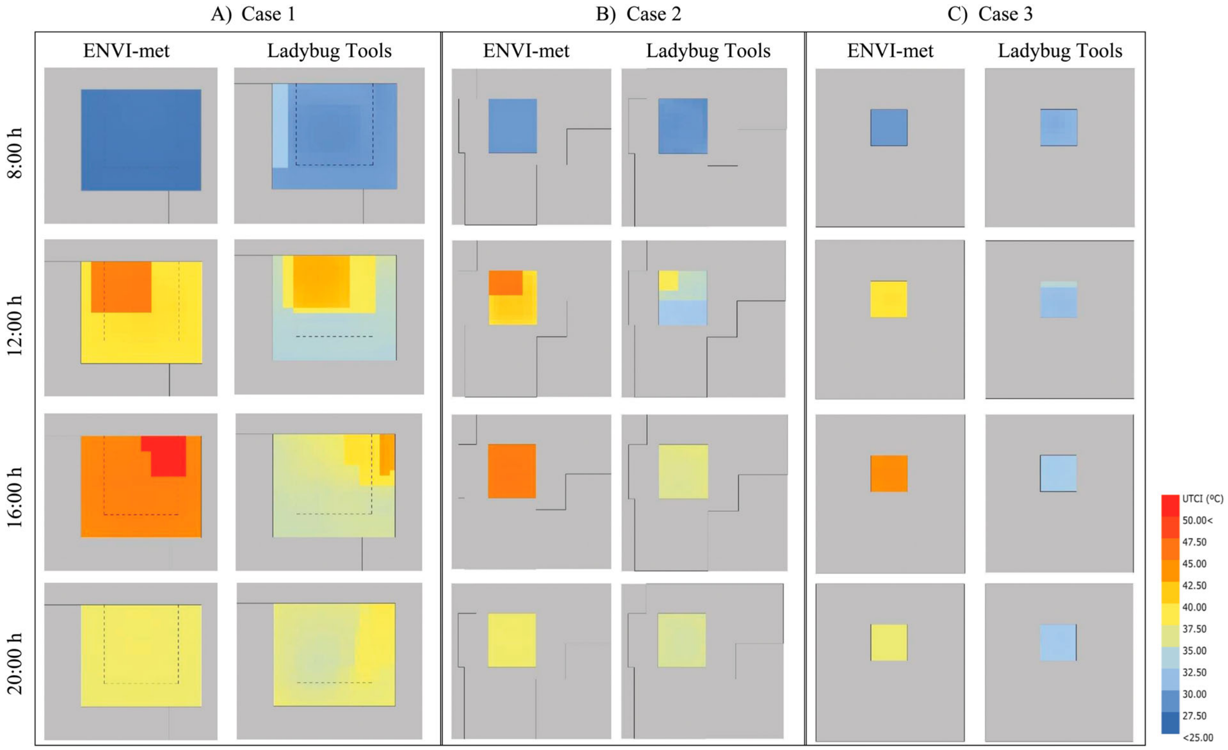


Figure 13. UTCI results at 1.5 m above the ground from ENVI-met and Ladybug Tools workflows. (a) Case 1. (b) Case 2. (c) Case 3.

The difference between shaded areas and sunlit areas was up to 5 UTCI degrees. Values provided by ENVI-met were higher than Ladybug tools except for the night hours.

Figure 13(b) shows the same UTCI results but for Case 2. This courtyard is deeper than Case 1 but still was receiving solar radiation, manifested by the higher UTCI difference in the courtyard at 12:00 h. For the rest of the hours, the UTCI values were homogeneous in the courtyard. The values provided by ENVI-met were always higher than the Ladybug Tools results. The former reached 47 degrees while the latter only reached around 40 degrees where the sun reached the surfaces of the courtyard.

Finally, Figure 13(c) represents Case 3. This is the deepest courtyard, and the sun never reached the lowest level of the courtyard. This effect was manifested by the absence of sudden changes in the UTCI value in the courtyard at any time. In fact, the UTCI provided by the Ladybug Tools was relatively constant during the whole day. ENVI-met results varied more and were higher in the afternoon and lower in the early morning.

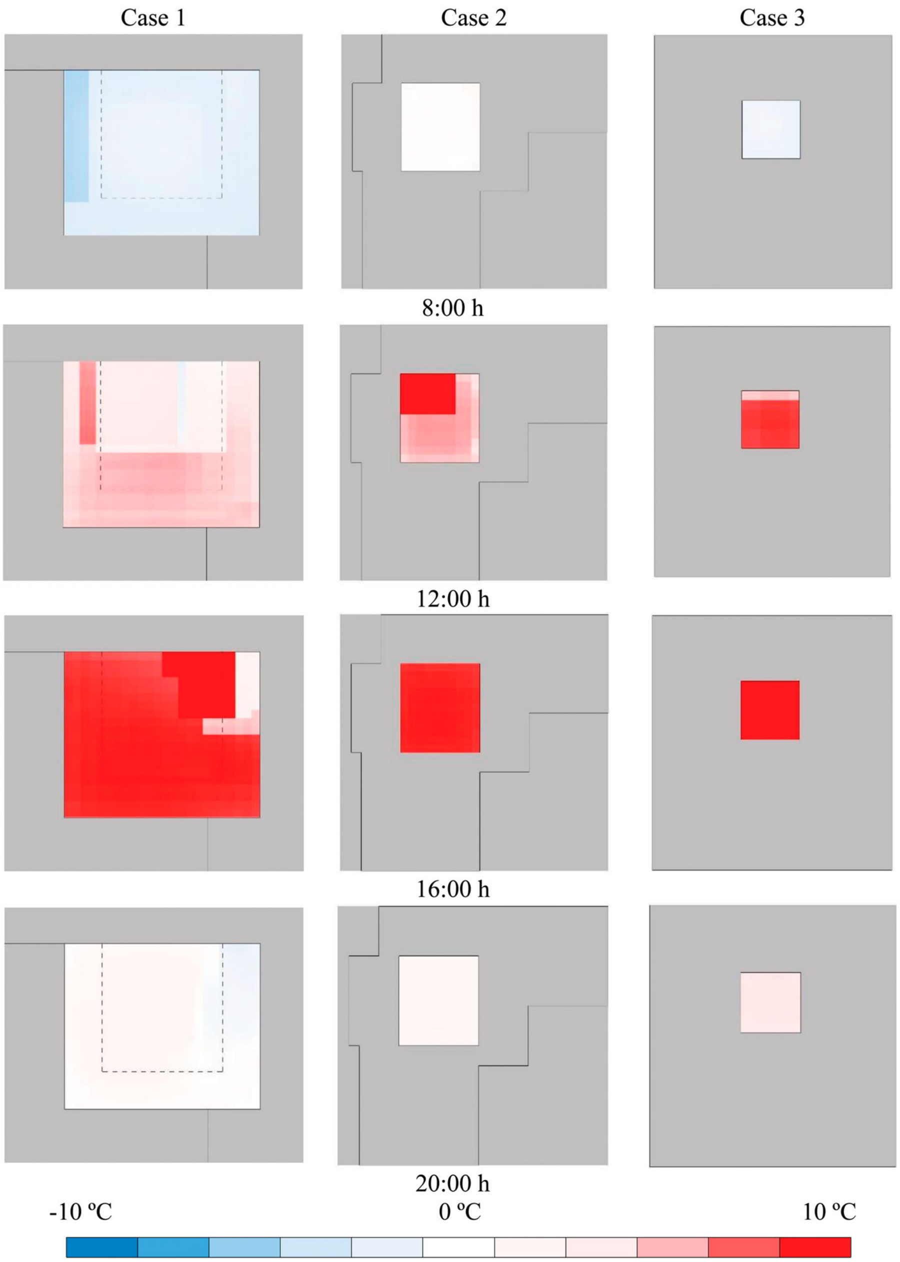


Figure 14. UTCI difference between the ENVI-met and Ladybug Tools workflows at 1.5 m above the ground (Blue = ENVI-met results lower; Red = ENVI-met results higher).

In general, it can be seen that the UTCI values in the courtyard were generally higher than the temperature simulated before, especially during the afternoon, when the sun was high and solar radiation hit the walls and the floor of the smaller AR courtyards.

Figure 14 shows the difference between the UTCI values provided by ENVI-met and Ladybug Tools at different hours in the courtyards. Blue colour shows areas where the UTCI provided by ENVI-met is lower than Ladybug Tools, and red colour show areas where the results provided by ENVI-met are higher. Early morning hours UTCI results from ENVI-met are slightly lower than the same data provided by Ladybug Tools, as can be seen at 8.00 h graphs in Figure 14. The rest of the hours, ENVI-met values are higher than Ladybug.

The greatest differences occur in the afternoon hours of the day, in the shaded areas of the courtyards. In Figure 14, this time is represented by 12:00 and 16:00 h. It is also when temperature results from simulations diverge the most. However, the difference in the UTCI index is even higher than the difference in temperature. While the temperature difference between the two workflows reaches 6°C, the UTCI difference reaches values higher than 10°C.

4. Discussion

4.1. Simulation temperature results

Here, we discuss the results obtained from the temperature simulations from the two methods. From the statistical variables calculated in section 3.2, it is concluded that the Ladybug methodology provides results closer to monitored data than ENVI-met in all three cases. Both methods are actually using the RANS turbulence model with the Boussinesq approximation, so the difference between the results needs to be explained by aspects outside the solution algorithm such as the definition of the boundary conditions or the grid resolution. The CFD model grid in the Ladybug method is finer than in ENVI-met, given the inability of ENVI-met to model grids smaller than 0.5 m. This is because this software is specialized in simulating larger urban areas, where 0.5 m is small enough. Also, the method to obtain boundary conditions differed in the two methods. ENVI-met utilized a simplified method to simulate the building temperatures that affect the surface temperatures in the courtyards. In contrast, the ladybug simulation is performing a whole building energy simulation in EnergyPlus that might obtain more accurate results that later influence the courtyard results. In contrast, this higher accuracy of the surface temperature is reduced by the fact that each calculation is performed by different software, and there is only a one-direction flow of information (from the energy simulation to the CFD) and not an iterative back-and-forth communication Therefore, the CFD results that may affect the energy simulations are not considered in the Ladybug Tools method.

Another interesting characteristic is that, for both simulation workflows, the higher the aspect ratio, the lower the accuracy of the simulated temperature at the 1.5 m height. That is to say, the more beneficial the courtyard, in terms of thermal tempering, the less accurate the simulated results. This is mainly seen from MAPE and RMSE results, as shown in Figure 12. In both workflows, the values obtained for Case 1 are lower than the values for Case 3. One possible explanation for this situation is that in deeper courtyards, the temperature is more influenced by the inner conditions of the building than in shallower courtyards, where the microclimate is mainly affected by the outdoor conditions and solar radiation. Given that this workflow is specialized in simulating outdoor conditions, it is more accurate for lower AR than higher AR. To gain accuracy in the latter case, a closer analysis of the functioning of the building needs to be performed and simulated. If the building is not mechanically conditioned, then the temperature of the courtyard will affect the temperature inside the building and vice versa, suggesting that an iterative simulation approach may be needed for maximum accuracy.

Another interesting difference between the results from the two methods is that Ladybug shows temperature stratification and ENVI-met does not, as can be seen in the Section views of Figure 10. From monitored data, we can say that Ladybug is more accurate than ENVI-met in predicting the temperature at 1.5 m, but in this study, there is no data to prove that the stratification is also happening. However, logic suggests that, since there is a monitored difference between the 1.5 m courtyard temperature and the temperature at 2 m above the roof, some form of a temperature gradient between the two locations does exists. Also, previous studies with courtyards have described this phenomenon, especially in deeper courtyards (Rojas, Galán-Marín, and Fernández-Nieto 2012). The upper part of the walls in the courtyard receives a higher solar radiation throughout the day, warming them up more than the lower surfaces, thus the air closer to these upper parts of the courtyard might be warmer than the lower levels of the courtyard. The simulation of this stratification phenomenon needs to be further studied because it can be especially relevant in deep courtyards, where the difference in the temperature between the lower and the upper part of the courtyard can reach a few degrees Celsius, which might affect the energy simulation results of the building.

4.2. UTCI results comparison

Section 3.3 showed that the differences between the results from the two methodologies were even larger in the calculation of the UTCI than air temperature, reaching 10°C difference at some points. The higher difference could be explained by other factors that intervene in the UTCI. Given that the wind speed is almost null at the lowest level of the courtyards, and relative humidity values are not extreme in this climate, we conclude that the mean radiant temperature is increasing the difference. Each workflow has its way of simulating the MRT. ENVI-met uses the equation of Bruse (1999) and the temperature of each building surface viewed from the target point is assessed as a weighted temperature. It does not use the Sky View Factor, and it considers building temperatures in a simplified way. In contrast, the Ladybug Tools simulate MRT computing the surface temperatures from EnergyPlus simulation and the view factors studied with raytracing. It also considers the sky temperature. Previous research (Naboni et al. 2017) comparing results from both software shows that ENVI-met tends to provide higher MRT values for summer temperatures than Ladybug Tools. This could explain the differences, but further research needs to be done in order to analyze which tool is more accurate in terms of MRT.

4.3. Considerations for the use of the methodologies in early-stage design

In the previous subsection, we have seen that the lack of accuracy of each tool has different reasons based on the calculation method and interrelation of information and the solver. In this section, we analyze the limitations of each tool from a practical point of view, considering the initial objective of this study: evaluating their use as design tools in the early-stage design. In this sense, we divide the analysis into three different aspects that may be desirable for this purpose: computation time, ease of use, and accuracy.

4.3.1. Computation time

The simulation time depends on many factors such as the model size or the computer performance. This study was done with an 8-core CPU and 16 GB RAM computer, which may be a typical computer in the design world. The time needed in the two workflows was similar for a 24-hour simulation (approximately 15 h average for the three models). However, there is a major difference that makes the Ladybug Tools workflow more suitable. It is a steady-state solver that needs to be calculated hour by hour, in contrast to the ENVI-met workflow that is a transient solver that calculates all the hours in one run. This gives the possibility for Ladybug to calculate only some hours that may be of interest for the design (e.g. extreme temperatures, or specific occupation hours), which makes the simulation time shorter. Another factor that may improve speed is the fact that Ladybug Tools import the results directly to Rhinoceros, which is the software already used by many designers, thus reducing the time to shift from one tool to another to analyze the results. Some plug-ins do exist for grasshopper that can read ENVI-met results and incorporate them into the Rhinoceros interface, although we found some of the analyzing capabilities of the software reduced in this process.

4.3.2. Ease of use and access

Here, we analyze the workflows from the perspective of a designer, not an expert in CFD or programming who may consider he problems explained here to be expected challenges in this field. ENVI-met is found to be much more stable than Ladybug Tools. This means that typical problems such as lack of convergence or crushing of the simulation are more common in Ladybug than in ENVI-met. However, while the reduced freedom for defining the ENVI-met grid and running the simulation makes the solver much more stable, this also have resulted in lower accuracy in the courtyard cases. This can be a problem for a non-expert user of the tool, although some general recommendations can reduce this problem.

On the other hand, the connection between the simulation software and the design software is relatively easy in Ladybug, especially for those designers that are already familiarized with the Grasshopper tool. Finally, one major advantage of the Ladybug Tools is that it is a free software package available for everyone, while ENVI-met is a commercial tool that requires a paid subscription to be fully available.

4.3.3. Accuracy

The accuracy of the results has already been analyzed and from a designer's perspective, both tools may be fit for purpose. Estrella Guillén, Samuelson, and Cedeño Laurent (2019) coined the term 'design significance' to describe when differences in simulation results would likely change, not only simulated metrics, but also the resulting design decisions. In this sense, both tools may provide results that can beneficially inform the early design process by reproducing general relationships between design options and physical outcomes. However, the Ladybug workflow has a major limitation in some situations; specifically, it is unable to simulate the evapotranspiration effect of water and vegetation. Nevertheless, we have observed that the large community of open-source developers for Grasshopper tools add capabilities relatively rapidly. This may be an advantage for the Ladybug Tools over ENVI-met, given its non-open-source code.

4.4. Limitations of the study

This study presents some limitations. Those related to each methodology given the software limitations have already been described. Regarding the representativeness of the results, the study analyzes three case studies in two specific urban **typologies** (historic **single-family houses with courtyard** in the city centre in cases 1 and 2 and mid-rise multifamily building in the case 3) in the hot summer of the Mediterranean climate. This means that, although the results can be extended to similar geometries in the same climate (and this covers a large number of existing courtyards), different urban configurations in different climates can present different behaviours. Furthermore, one aspect that is influential to courtyard performance, especially for those with a low aspect ratio, is wind speed, and this study has been performed under low wind speeds as typical for inland summer in the south of Spain. Thus, further study would be needed to be done to cover other climates (specifically cold, humid, or windy climates), typologies and courtyard configurations.

Moreover, the implication of the urban context has to be analyzed in depth specially for larger courtyards where the surrounding context can have a bigger influence.

5. Conclusion

This paper provides a validated method for computerized simulation of thermodynamic conditions of courtyards in the warm Mediterranean climate, using the Ladybug Tools. Responding to the scarcity of such methods, this one meets the desirable characteristics discussed in Section 1. Specifically, its implementation using the Ladybug Tools for Grasshopper, makes it easy to implement in early design. This workflow can: compute CFD simulation (to improve accuracy), link to energy simulation, provide comfort results, and be further improved through an open-source community.

The method has been validated through comparison of results with monitored data and simulation data from another validated software for outdoor simulation, ENVI-met. Via the monitored data, we demonstrated the tempering potential of three courtyards in the south of Spain. This potential is related to geometry, the deepest courtyard producing the highest thermal gap of the three courtyards, reaching 11.2°C difference between the outdoor air temperature and the courtyard air temperature. We tried to simulate that tempering effect using both methods, ENVI-met and Ladybug Tools. Compared to the measured temperature, ENVI-met simulations had a MAPE from 6.85% to 14.38%, and an RMSE from 2.61°C to 5.22°C, versus a MAPE from 3.81% to 7.55% and an RMSE from 1.37°C to 2.29°C with the Ladybug Tools. Therefore, the Ladybug Tools workflow showed higher accuracy in our research which was explained in terms of grid definition and boundary conditions.

Once the workflow was validated, we used the two methodologies to provide UTCI for outdoor thermal comfort and compare the results. Both methods provide a lower UTCI in the deepest courtyard, and an improvement of comfort in the shaded areas of the courtyard. However, ENVI-met provided UTCI values more than 10°C higher than the Ladybug Tools in the afternoon hours, although the values during the night and early morning were relatively similar. Considering that temperature results provided by the Ladybug Tools are closer to monitored data, we conclude that Ladybug UTCI results are closer to reality. This result seems logical given the more sophisticated method of computing MRT in the Ladybug Tools.

This study is limited to one climate (Mediterranean) and one kind of open space (courtyard), although results are representative of a large number of courtyard buildings in the Mediterranean region given the range of aspect ratios analyzed and the typical construction materials. Nevertheless, the method proposed can be implemented in other climates and open spaces, although future research should also validate these situations. Another future step is the coupling of the method with energy simulations in order to quantify the benefits of microclimates on the energy consumption of buildings.

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Appendices

Appendix 1

Table A1. Simulation inputs of outdoor air temperature and relative humidity from monitoring campaigns.

	Case 1. (20/08/2017)		Case 2. (19/08/2017)		Case 3. (16/06/2017)	
Hour	Outdoor Temperature (°C)	Relative Humidity (%)	Outdoor Temperature (°C)	Relative Humidity (%)	Outdoor Temperature (°C)	Relative Humidity (%)
0:00	32.4	35	33.4	25	24.1	67
1:00	31.1	39	31.9	31	23.5	74
2:00	30.4	42	30.5	36	23.1	76
3:00	29.6	45	29.4	41	22.9	79
4:00	28.6	47	28.5	44	23.1	78
5:00	28.0	50	28.0	44	22.9	74
6:00	27.3	49	26.9	50	23.2	75
7:00	26.1	52	26.4	50	25.2	76
8:00	26.4	52	25.1	53	28.5	74
9:00	30.4	43	26.9	45	31.6	63
10:00	33.3	38	29.2	40	34.2	50
11:00	34.2	36	34.2	31	36.6	36
12:00	35.4	32	35.9	22	38.4	31
13:00	37.1	28	38.3	12	40.2	23
14:00	38.7	24	40.2	10	41.6	11
15:00	40.8	20	41.2	10	42.2	10
16:00	42.1	10	44.1	11	42.8	11
17:00	43.0	12	43.9	12	40.8	10
18:00	40.9	10	41.9	10	39.6	10
19:00	39.5	11	40.9	10	37.0	11
20:00	38.4	22	39.9	11	34.7	18
21:00	35.7	28	38.3	12	33.0	23
22:00	33.2	33	36.5	10	31.3	23
23:00	32.0	36	34.5	31	32.5	23

Table A2. OpenFOAM simulation parameters.

Parameter	Case 1	Case 2	Case 3
Air temperature and relative humidity	See Table A1		
Building surface temperature	Outputs from Honeybee simulation		
Wind speed	Log-law profile (See Appendix 2)		
Wind speed at reference height (10 m)	1 m/s.	2 m/s.	1 m/s.
Wind direction	270°	270°	270°
Turbulence model	RNG k-epsilon		
Turbulent kinetic energy	0.1 m^2/s^2		
Turbulence dissipation rate	0.01 m^2/s^3		
Reference Temperature	33°C		
BlockMesh cells	250 × 100 × 20	270 × 90 × 20	180 × 90 × 30
Refinement levels	4	4	3

Table A3. OpenFOAM boundary conditions (types).

	Buildings and Box Boundaries	Outlet	Inlet
alpha	alphatJayatillekeWallFunction	zeroGradient	zeroGradient
epsilon	epsilonWallFunction	inletOutlet	fixedValue
k	kqRWallFunction	inletOutlet	fixedValue
nut	nutkWallFunction	calculated	calculated
P_rgh	fixedFluxPressure	fixedValue	zeroGradient
T	fixedValue	zeroGradient	fixedValue
U	fixedValue	inletOutlet	fixedValue

Table A4. Ladybug Tools energy simulation parameters.

Parameter	Value
Conditioned	No
Zone loads: Lighting (W/m^2)	Case 1 = 0. Case 2 = 10. Case 3 = 10.
Occupancy (People/m^2)	Case 1 = 0. Case 2 = 0.03. Case 3 = 0.03.
Equipment (W/ m^2)	Case 1 = 0. Case 2 = 3.87. Case 3 = 3.87.
Schedule	EnergyPlus Midrise Apartment Schedules
Material prop.: Walls	$U = 0.45$ W/m^{2}K
Roofs	$U = 0.85$ W/m^{2}K
G. Floors	$U = 1.44$ W/m^{2}K
Windows	$U = 2.36$ W/m2 K, SHGC = 0.73
Infiltration (m^2/s m^2)	Case 1 = 0.0006. Case 2 = 0.0002. Case 3 = 0.0003.
Shading	None applied
Floor height	3.5 m

Appendix 2. Atmospheric boundary conditions definition in Ladybug Tools

The definition of the boundary conditions in Ladybug Tools has followed a process that is described here. Given the impossibility of defining automatically an atmospheric boundary layer in the inlet of the domain for the heat transfer solver in Ladybug (we must remember that the Butterfly plugin only incorporates two solvers from OpenFOAM and its functionalities are limited), it has been done manually. A wind tunnel has been modelled following literature recommendations for its dimensions. The inlet surface has been divided into different parts to which it will be assigned a wind speed velocity, in order to define a logarithmic wind profile all together (see Figure A2). The discretization of the different surfaces and velocities has been done every 0.2 m/s speed increase of the wind profile. The wind profile has been calculated following the logarithmic equation as follows:

$$u = \frac{u^*}{k} ln\left(\frac{z - d + z_0}{z_0}\right)$$

$$v = w = 0$$

where u = Ground-normal streamwise flow speed profile [m/s]; v = Spanwise flow speed [m/s]; w = Ground-normal flow speed [m/s]; u^* = Friction velocity [m/s]; k = von Kármán constant [–]; z = Ground-normal coordinate component [m]; d = Ground-normal displacement height [m]; z_0 = Aerodynamic roughness length [m].

The friction velocity u^* is defined as follows:

$$u^* = \frac{u_{ref}}{k} ln\left(\frac{z_{ref} + z_0}{z_0}\right)$$

where u_{ref} = Reference mean streamwise wind speed at z_{ref} [m/s]; z_{ref} = Reference height being used in u^* estimations [m].

Figure A1 shows an example of the wind speeds defined at different heights for a wind profile generated for a wind speed of 2 m/s at a reference height of 10 m. Figure A2 shows the computational domain in the Ladybug Tools model. The domain was defined following the general recommendations for best practices in CFD simulation of urban environments (Franke et al. 2007; Franke et al. 2004). The domain's inlet, top, and lateral boundaries have been placed 5H away from the building model, with H being the height of the building. The outlet is placed 15H away from the building.

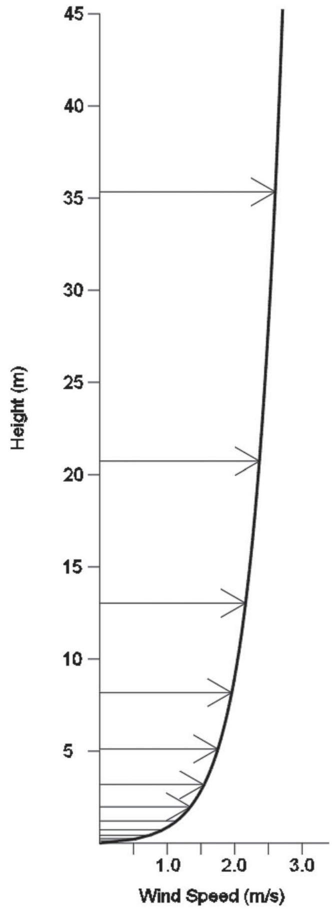

Figure A1. Wind profile in Ladybug Tools models for a wind speed of 2 m/s at 10 m height.

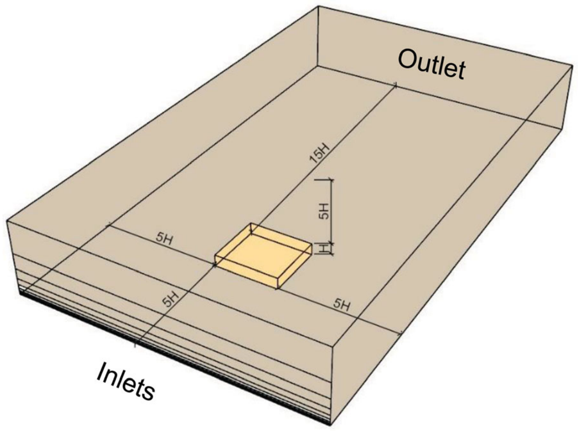

Figure A2. Computational domain in Ladybug Tools models.