Outdoor Microclimate Influence on Building Performance: Simulation Tools, Challenges, and Opportunities

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Abstract This chapter reviews the different approaches that currently exist to evaluate outdoor microclimates and their influence on building performance. Considering specific outdoor microclimates in building design flow can enable additional passive cooling strategies to mitigate climate risks in buildings and cities, improving their resilience capacity under extreme heat events. The available methods are defined and compared through different case studies of buildings with an inner courtyard, a traditional microclimate for passive cooling in hot climates. The results show the advantages and disadvantages of the different approaches and highlight the high interest in hybrid simulations coupling building energy simulation (BES) and computational fluid dynamics (CFD) tools for early design stages.

Keywords Courtyard microclimate · Heat mitigation · Urban heat island · Urban simulation · Climate-resilient design · Climate responsive design

1 Introduction

Buildings have an important role in minimizing climate change, given that they are responsible for approximately 40% of energy consumption in the EU [1] and 35% in the world and increasing [2]. Furthermore, they not only affect climate at a global scale but also at a local scale through the urban heat island effect (the higher urban temperatures in the city in comparison to rural areas), which is related to urban compactness and energy performance of buildings [3]. In the last decade, regulations that aim to reduce the energy consumption of buildings have been developed, especially in Europe. The European Directive 2018/844 of the European Parliament is one example [4], conducting net zero energy consumption requirements for buildings.

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Researchers have studied the cost-effectiveness of different energy-saving measures for many years through building simulation tools and computer technology. However, there are still many challenges to be considered in ensuring high quality and useful building simulations: the importance of weather data selection, the need to include passive performance and thermal comfort indices in design processes, and the consideration of the potential benefits of specific microclimates on building performance. This last point is critical since these microenvironments have been proven to provide thermal benefits to buildings, especially in hot and warm climates. Enclosed courtyards are spaces surrounded by buildings and open to the sky. Their geometry, materials, water, vegetation, or shading elements produce thermodynamic effects that help to temper the extreme outdoor conditions. However, the courtyard performance is not considered in the existing building energy simulation (BES) tools and procedures [5]. This is due to two facts: It needs multi-outdoor climate conditions, which is not an option in most BES tools, and courtyard performance is hard to compute, given the multiple factors that have a role in it. The research aims to identify and compare existing and new procedures to account for the benefits of these specific microclimates, discussing advantages and drawbacks, and highlighting future needs toward a more accurate climate-resilient design process.

In the next section, a review of existing tools and approaches is shown, and in the rest of the chapter, some case studies using different approximations are analyzed, providing some challenges, opportunities, and recommendations.

2 Existing Tools and Approaches Review

Currently, different approximations to estimate the energy performance of buildings are available. They can be divided into two groups: white box models, which are based on the laws of physics that govern a system (e.g., conservation of mass, energy, and momentum) [6, 7], and black box or data-driven models which are based on statistical methods using machine learning [8]. For the simulation of outdoor microclimate, both models have been used.

White box models

Physics-driven models were the first to be developed, and most of the existing tools and methodologies rely on this approach. BES and computational fluid dynamics (CFD) are two of the main numerical approaches in this area:

- Building Energy Simulation Tools (BES)

BES estimates the physical parameters in one single node per zone, representing a uniform profile of parameters in the region. This allows for long-term unsteady analysis although it simplifies too much, and the differences in the area represented by a single node cannot be considered. For that reason, outdoor simulation can be done only in a simplified way. Some examples of software of this kind are EnergyPlus, TRNSYS, or DesignBuilder, among many others. These tools have been used to predict the influence of semi-outdoor spaces on energy consumption and indoor comfort. However, these models underestimate the potential benefits of these spaces, given that BES tools cannot simulate the microclimatic effects that occur outside. The temperature in the transitional space is assumed to be the same as outside, which is inaccurate most of the time. A study analyzing the impact of urban geometry on the energy consumption of buildings using TRNSYS concluded that if the microclimate is not included; this software can lead to inaccuracies [9]. In the last years, some tools, such as CitySim or UMI, have been specifically developed to account for the urban form on the energy consumption of districts. However, they still rely on microclimate simplifications.

- Computational Fluid Dynamic Tools (CFD)

In contrast to BES, these tools account for the whole volume of the space being considered, which is meshed in a few thousand to a few million control volumes, and the conservation equations are then applied to each of them. The basic that uses the CFD approach is the resolution of the Navier–Stokes's equations which can be solved using finite element or finite volume methods for each control volume. This means that this approach requires considerable computing power to analyze unsteady states for a longer period than one day. However, they achieve high accuracy in the results.

COMSOL Multiphysics, ANSYS FLUENT, OpenFoam, or FreeFEM++ are some of the many choices of CFD tools available. They provide a variety of numerical solutions, which are not limited to building simulation. For the specific case of urban microclimates, the most widely used CFD software is ENVI-met. It can analyze small-scale interactions between soil, water, air, vegetation, and buildings at different scales. This software has renounced some of the broader capabilities of non-specific CFD tools to simplify the simulation analysis process. For example, the meshing options in ENVI-met are greatly limited.

- Hybrid workflows

There are currently many approaches that combine BES and CFD approaches to take advantage of the benefits of each one. In the hybrid workflows, one software outputs become inputs for another software. The aims of combining tools are diverse. First, to achieve higher accuracy in the simulation predictions. Second, to improve the workability of these tools to make them appropriate for the different design phases. Third, to add some other capabilities to the simulation from one tool, for example, the calculation of comfort indexes. For this reason, the hybrid workflows generally combine one BES tool with CFD software or comfort-calculation-specific tools. For example, EnergyPlus or Trnsys are combined with ENVI-met in many studies [10–12], or with Ladybug Tools [13–16], which are a set of plugins for Grasshopper that link the simulations engines, such as EnergyPlus or TRNSYS, with climate analysis, CFD procedures, and some comfort components.

Black box models

This approach, also called data-driven models, is based on statistical predictions using machine learning techniques. No physical model is required, but only large sets of input data to train a selected machine learning model to obtain the predicted outputs. Nowadays, these methods are recognized for their exceptional performance describing the overall behavior of a system based on its input–output relationship without needing any physical knowledge.

Machine learning methods can be classified into supervised or unsupervised. In supervised models, the learning is based on input–output pairs to guide the process. Examples used in building simulation are the artificial neural network (ANN) or the support vector machine (SVM). In unsupervised learning methods, there is no outcome, and the goal is to describe the associations and patterns among a set of inputs. Unsupervised methods are more practical and promising in discovering novel knowledge given limited prior knowledge than supervised methods. For this reason, it is preferred in mining building operational data, when many inputs are not known.

Despite a large amount of research into data-driven models, recently, its application by professionals of the building sector is more limited, and no specific simulation tool is based on this modeling approach. Still, they are a promising tool with many advantages that will be later analyzed. The following section shows some case studies using each of the previously described methods for the simulation of courtyard buildings.

3 Courtyard Simulation Studies

In this section, different examples of courtyard performance simulation are analyzed. The case studies selected share the same general methodology, which is represented in Fig. 1. First, a monitoring campaign is carried out to gather weather data used as

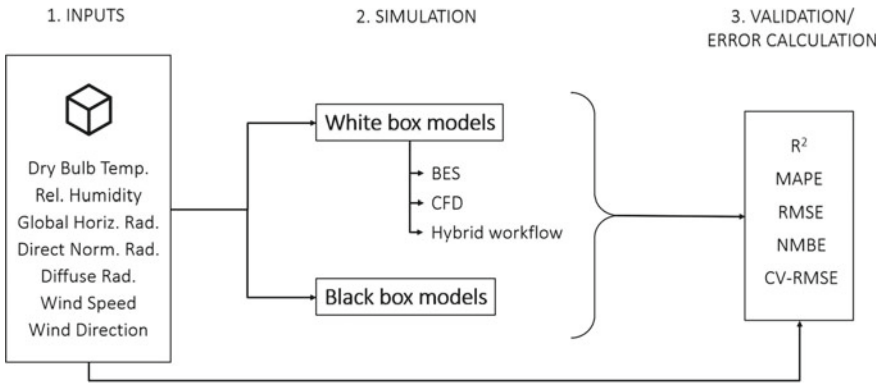

Fig. 1 General workflow methodology followed in all the case studies

inputs for the simulations and courtyard data to validate the simulations. Then, the simulations are performed, each case using one of the previously described tools or approaches. Then, statistical parameters are calculated in order to measure the accuracy of the simulations and validate the results. The section is structured according to the classification previously used.

BES

Many researchers have used building energy simulation to analyze the performance of courtyard buildings [17, 18]. However, few studies have considered the courtyard as a different microclimate to outdoor conditions. This means that the benefits of the courtyard in these simulations are limited to the self-shading that the courtyard provides to the building. Recent studies have acknowledged that the courtyard has a singular microclimate, totally different to the outdoor climate, and they have found a way to include multi-nodal outdoor conditions in the simulations. Lizana et al. [5] quantified the effect of an inner courtyard microclimate on building performance using TRNSYS. The case study was analyzed with two outdoor weather conditions, an inner courtyard, and a local urban climate, as the most realistic case. Then, the building performance was compared to three single outdoor weather conditions associated with the urban climate, weather data from a rural station, and a typical year weather file. The selected case study was a dwelling unit on the sixth floor of a multifamily building in Seville, with one façade to an inner courtyard and the other to the outdoor. The outdoor and inner courtyard environments were monitored using weather stations and data loggers to get information for the microclimatic conditions. The building was numerically modeled as a multi-zone in TRNSYS. Information about geometry, external shadings, constructive elements, internal gains, infiltration, natural ventilation, thermal bridges, and internal heat capacity was required by the software. Surfaces linked to the courtyard microclimate were numerically modeled as an equivalent resistance layer with a boundary condition linked to the courtyard temperature, where courtyard solar radiative and convective gains were previously obtained and introduced per zone. An iterative calibration process was performed using the monitored air temperature data in four rooms and the standard statistical indices for model validation recommended by ASHRAE Guidelines [19] (Table 1). The results were analyzed using two building performance indicators, illustrated in Fig. 2: the percentage of indoor discomfort hours in free-running conditions (Fig. 2a) and the cooling energy demand using an idealized cooling system (Fig. 2b).

The results showed that the simulation considering two outdoor microclimates (the local weather file and the courtyard) mitigates severe hot hours by 88% compared

Table 1 Statistical indices for model validation following ASHRAE Guidelines

	NMBE (%)	CV-RMSE (%)	R^2
Bedroom 1	−2.0 (<±10%)	3.9 (<30%)	0.77 (>0.75)
Bedroom 2	−0.5 (<±10%)	2.0 (<30%)	0.93 (>0.75)
Bedroom 3	−1.5 (<±10%)	3.0 (<30%)	0.84 (>0.75)
Corridor	−1.2 (<±10%)	3.5 (<30%)	0.76 (>0.75)

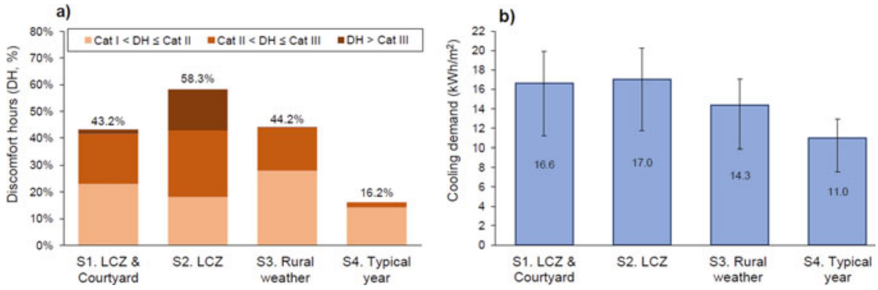

Fig. 2 Discomfort hours and cooling demand results per simulated scenario in [5]

to the simulation with only the local climate. The discomfort hours were reduced by 26% during the measured period. Additionally, it can be noted in Fig. 2 how the comfort period in the courtyard microclimate (S_1) is similar to the simulation where the rural weather file is used. These results demonstrate that the courtyard benefits the building and can mitigate extreme urban heat events.

In terms of cooling energy balance, the courtyard was able to reduce the impact of urban overheating by 15%. This is very influenced by cooling-related occupant behavior patterns, as shown in the bars chart (Fig. 2b), with the possibility of a reduction up to 29% in the case of a low energy consumption pattern.

Another study aimed to quantify the benefits of the courtyard in terms of cooling demand reduction in a building in Seville (Spain) [20]. This time, the simulation was performed with the Spanish BES software HULC and using a university office building with a courtyard as a case study. In this study, only two scenarios were analyzed: a reference case, in which it was assumed that the air temperature throughout the whole building envelope was the outside monitored temperature (Fig. 3a) and the proposed methodology, varying the boundary conditions in the courtyard according to the monitoring campaign (Fig. 3b), thus, considering the effect of the courtyard on air temperature.

The results showed a reduction of the cooling demand in the simulated case considering the monitoring results in the courtyard that reached 10% in adjacent rooms located on the ground floor of the courtyard. For the whole building, the cooling demand obtained was 7% in the spaces adjacent to the courtyard. The variation in cooling demand reduction according to the level of the room is because of the characteristic stratification effect of the courtyards (Table 2).

The results from these studies emphasize the importance of selecting an accurate weather file in the simulation. Local climate weather file increases discomfort hours and cooling demand in comparison to the scenario with the rural weather file, which is not considering the urban heat island effect. Moreover, the unsuitability of the typical year weather file to evaluate the climate resilience of buildings is demonstrated. The analysis of climate resilience building design requires the use of weather files that includes the extreme events that will happen more often in the future. It is also demonstrated how it is needed to include multi-nodal outdoor conditions in order

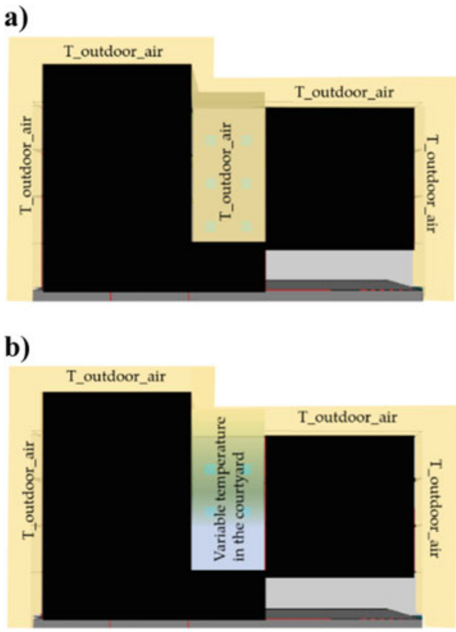

Fig. 3 Section of the building showing the boundary conditions considered in the reference case **a** and the proposed methodology, **b** for thermal simulation of a building including a courtyard

Table 2 Accumulated cooling demand reduction in the case study by Sanchez de la Flor et al. [20]

Room	Case study (kWh/m^2)	Reference case (kWh/m^2)	Absolute difference (kWh/m^2)	Percentage difference (%)
Third floor room 1	23.67	25.74	2.07	9
Fourth floor room 1	18.38	20.17	1.79	10
Fifth floor room 1	27.62	29.27	1.65	6
Third floor room 2	15.47	15.96	0.49	3
Fourth floor room 2	16.09	16.65	0.56	4
Fifth floor room 2	17.20	17.75	0.55	3

to account for the benefits of passive strategies associated with urban microclimate strategies, such as the use of courtyards. However, this is not straightforward for two reasons. First, the introduction of different boundary conditions for the building envelopes in the simulation has been possible following different assumptions, which are even not possible in other tools. And second, in these studies, the courtyard temperature introduced had been previously monitored, but for the energy simulation of the early design, this is not possible. Courtyard temperature needs to be also simulated, which is impossible using BES software. For that reason, other kinds of tools are needed, which are discussed in the following sections.

CFD

Computational fluid dynamic is needed when accuracy is required in the simulation of courtyards, given the thermodynamic effects that govern their performance. Inside a courtyard, not only geometry is a deterministic factor but also the thermal properties of the surface materials, the presence of vegetation, shading, water, etc. They influence the thermodynamic effects inside, associated with the temperature stratification, convection, and flow patterns [21], which are impossible to predict without CFD software.

Several studies use CFD software to predict the thermodynamic performance of courtyard buildings. One of them is ENVI-met, maybe the most widely used for urban microclimate analysis [22]. The suitability of this software for the simulation of inner courtyards is analyzed by Lopez-Cabeza et al. [23], contrasting simulation data with monitoring results. The objective of this study was to find a tool that can predict the temperature of courtyards accurately to be used in the energy simulation of buildings. Three case studies with different aspect ratios[1] were analyzed, all of them located in Seville. Monitoring data from the weather station were used as inputs for the simulations, and the courtyard temperature to validate the results. The three case studies were modeled in ENVI-met, following other researchers' recommendations. Then, results were numerically evaluated using the coefficient of determination (R^2) and the root mean square error (RMSE) as statistical parameters.

Results indicated that ENVI-met was able to simulate a reduction in the temperature inside the courtyards. However, the difference between outdoor and courtyard temperature was much higher in the monitoring campaign than in the simulation results, as shown in Fig. 4. The statistical parameters, reported in Table 3 shows that although outdoor temperatures showed high accuracy, the courtyard temperatures did not, and the RMSE reached 3.35 °C.

The results state that ENVI-met accuracy when simulating small inner courtyards is not enough to consider the results in a building energy simulation. The lack of accuracy of the software can be due to different factors: the insufficient resolution of the software for the scale of this kind of spaces and simplification done by the software in terms of radiative fluxes [24]. Moreover, another problem of the software is the large amount of computational power required and the time needed to simulate a short period. This makes it impossible to couple ENVI-met results with a whole-year simulation in a BES software in an acceptable time.

For these reasons, other CFD options have been analyzed. One of the reasons why ENVI-met takes so long is the large amount of data it provides, much of it not required for the later energy simulation of the building. For that reason, one

[1] The aspect ratio is the relation between the width and the height of the courtyard, following the equation AR = Height/Width.

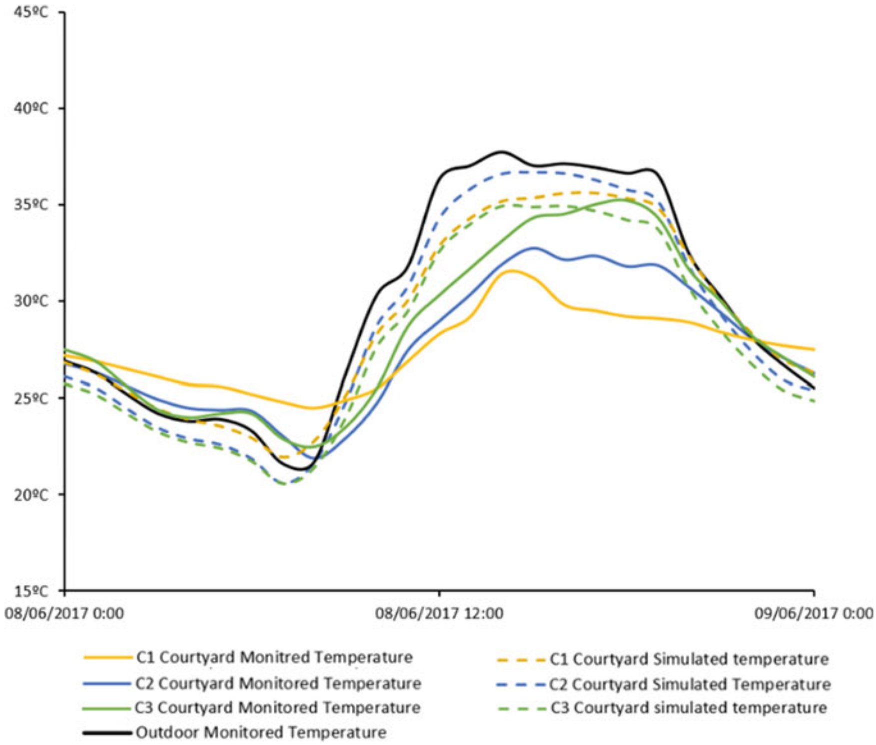

Fig. 4 Monitored and simulated air temperature outside and inside the courtyards in the three case studies by Lopez-Cabeza et al. [23]

Table 3 Statistic parameters for the validation of the simulations with ENVI-met

	R^2	RMSE (°C)
Case 1	0.84	3.35
Case 2	0.88	2.92
Case 3	0.93	1.52

option to make CFD calculation faster is to design a numerical model that optimizes the courtyard calculation. That is done by Lopez-Cabeza et al. [25], developing a new methodology for the simulation of courtyards, coupling a CFD model with a system of equations at the walls to calculate the surface and inner wall temperatures, providing an accurate courtyard thermal performance evaluation. The results were contrasted to monitored data in order to validate the model. The novel coupled model for courtyard simulation was computed using the FreeFEM++ software and validated in a case study located in Seville. Moreover, the results were compared with the simulation performed by other CFD software, in terms of accuracy in the air temperature inside the courtyard predictions and computational time. This last one is another critical indicator, especially if the simulation results are used in annual

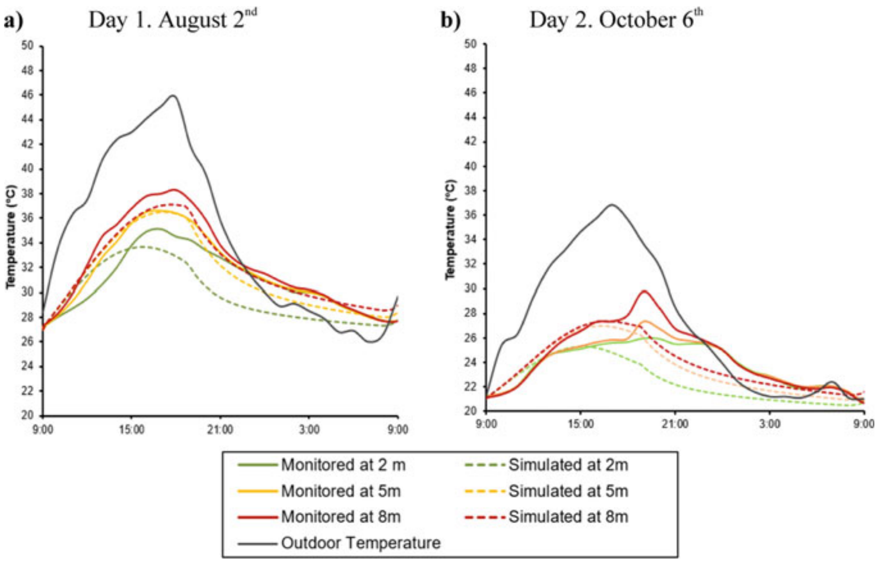

Fig. 5 Air temperature simulation results using FreeFEM++

Table 4 Statistical parameters for the validation of the simulation using FreeFEM++

Date	R^2	RMSE (°C)	CV (RMSE) (%)	NMBE (%)
August 2nd, 2018	0.88	1.19	3.75	1.72
October 6th, 2017	0.64	1.59	6.59	3.69

performance simulation or early design. Two different days were simulated, one in August and another one in October, to test the model under different solar positions and weather conditions.

Simulation results showed high accuracy in reproducing the thermal patterns inside the courtyard. The model was able to predict a thermal gap[2] close to monitoring data and the stratification effect inside the courtyard, which is the variation of temperatures at different heights (Fig. 5). The statistical parameters for error calculation were the best of the three simulation methodologies used in this courtyard, as shown in Table 4. This methodology was also the fastest in terms of simulation time, requiring only a few minutes for a simulation that other software required hours.

This study showed a methodology that is very promising in comparison with other previously analyzed. However, it needs to be further tested and coupled with modeling and visualizing software in order to make the process accessible for designers. The simulation time is very short in comparison to other CFD methods, given that the methodology is designed and optimized for the simulation of temperature and wind

[2] Thermal gap is defined as the difference between the outdoor temperature and the temperature inside the courtyard, as follows: TG = $T_{outdoor}$ -$T_{courtyard.}$

patterns inside the courtyard. Thus, no other results are consuming time and computational resources. The model is also limited to the courtyard space, also reducing the size of the mesh being calculated.

Hybrid workflows

The coupling of BES and CFD tools has been studied by different researchers, to combine the advantages of each other. It can be argued that from a designer perspective, a methodology of courtyard simulation should fulfill some requirements. The method should be easy to implement in the early design stage of projects; CFD is highly recommended to achieve accuracy, including the interrelations between building, soil water, and vegetation; moreover, it should be possible to measure comfort indexes and energy consumption in buildings; finally, it would be ideal if the method is open source to understand the process behind the calculations. With all those requirements, it can be said that using one single software is not possible. A hybrid, or a combination of software, is required.

Lopez-Cabeza et al. [26] developed and validated a methodology for the simulation of courtyards in buildings that combines BES and CFD simulations using the Ladybug Tools. The aim was to simulate the temperature of courtyards in a suitable way for the early design of buildings. The results achieved higher accuracy than other existing methodologies. The study developed a script that included a CFD simulation with the Butterfly plugin in Grasshopper to combine courtyard temperature results with outdoor comfort analysis in Ladybug. The workflow is represented in Fig. 6. It was applied in three case studies of building with courtyards of different geometries, and the results were compared with monitored data to validate them.

The results of air temperature inside the courtyard obtained from the simulation are shown in Fig. 7. These values were then used to obtain the Universal Thermal Climate Index, an outdoor comfort index that can be understood as the "feels like" temperature equivalent to the environmental conditions. Monitoring data were used

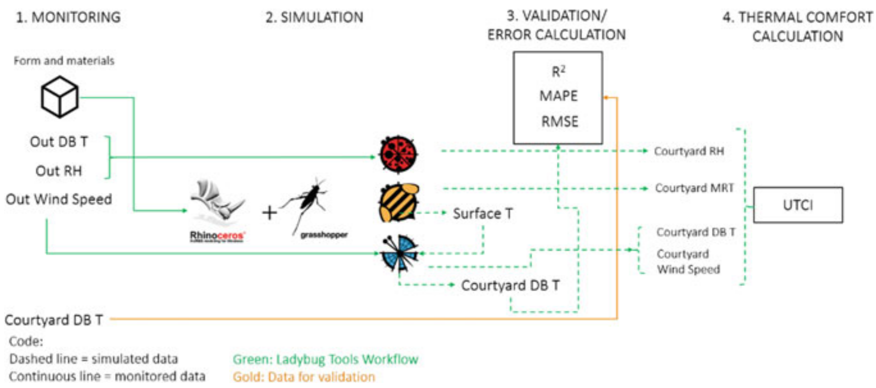

Fig. 6 Hybrid simulation workflow proposed by Lopez-Cabeza et al. [26] (DBT = Dry bulb temperature. RH = Relative humidity. UTCI = Universal Thermal Climate Index)

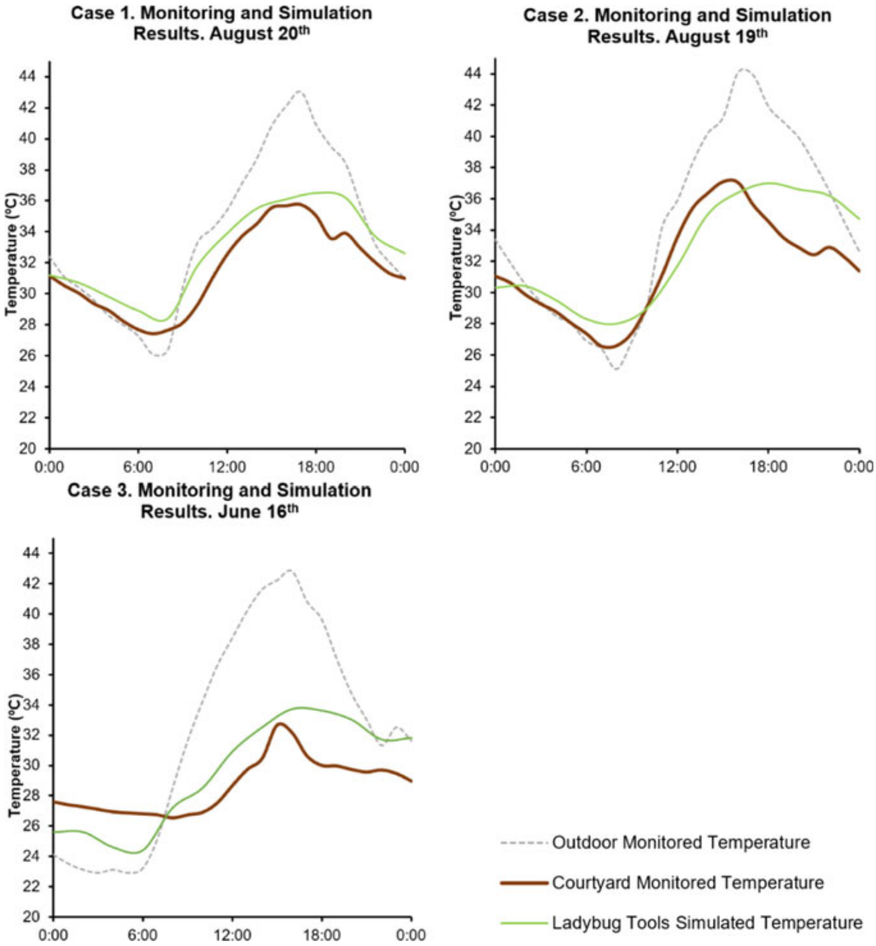

Fig. 7 Hybrid simulation results for the three case studies by Lopez-Cabeza et al. [26]

to validate the simulations, obtaining a mean absolute percentage error from 3.81 to 7.55% and a root mean square error from 1.37 to 2.29 °C (Table 5), results that can be considered highly accurate in comparison with other studies and methodologies.

Table 5 Statistical parameters for the validation of the simulation using Ladybug Tools

	AR	R^2	MAPE (%)	RMSE (°C)
Case 1	0.9	0.9	3.81	1.37
Case 2	1.5	0.7	5.07	2.00
Case 3	4.6	0.8	7.55	2.29

This methodology was analyzed following three criteria: accuracy, computational resources, and ease of use and access.

- Accuracy: The simulation methodology proposed achieves good accuracy in the cases analyzed. However, it has one major limitation, which is that it is not possible to include the evapotranspiration effect of the vegetation. There is no Ladybug Tools component able to do that. On the other hand, given that is an open-source software supported by a large community, this shortcoming may be overcome soon.
- Computational resources: Simulation time depends on many factors in terms of computational resources and simulation configurations. This method requires a long simulation time similar to other CFD software like ENVI-met (a few hours are required to simulate a whole day). However, it has one advantage: Given that it is a steady-state solver, it does not need an initialization time to get accurate results. This means that the simulation can focus on specific hours (e.g., extreme temperatures or specific occupation hours), making the simulation time shorter. This is not possible with transient solvers like ENVI-met, which need to calculate all the hours in a run. Moreover, the possibility of connecting all the results in one interface (Grasshopper) and their visualization in the Rhino interface used for design makes the process much suitable for the early design stage of projects.
- Ease of use and access: The use of the Ladybug tools has one advantage for the design, the easy connection between the simulation software and the design software, especially for people already familiarized with the Grasshopper tool. Furthermore, there is a major advantage with many other tools: All the simulation software used are open source and free, thus available for everyone.

Data-driven method

Although some of the physical models provide accurate results for the simulation of courtyards, their main disadvantage is the impossibility of calculating long periods using CFD without spending a long simulation time. BES and CFD calculations time differ enormously (from minutes to hours). For that reason and trying to make the prediction of courtyard performance easier, the use of data-driven models has been also analyzed. Diz-Mellado et al. [27] aimed to implement an accurate machine learning methodology to predict thermal patterns in courtyards accurately based on their geometry and outdoor temperature. The study trained the algorithm with the monitored data of 32 other case studies using the support vector regression method and MATLAB interpolations. Using the library of data predicted by machine learning, the temperature inside two other courtyards was forecasted according to their climatic zone and geometry. The simulation was validated contrasting results with monitored data. Figure 8 shows an example of the results obtained in the temperature prediction. The simulation showed good accuracy, particularly on days with higher outdoor temperatures.

This research evaluated the errors in the two case studies for validation, one with monitored and predicted temperatures similar to the outside (CS1) and the second case study with a larger thermal gap to the outside (CS17). The graphic on the left

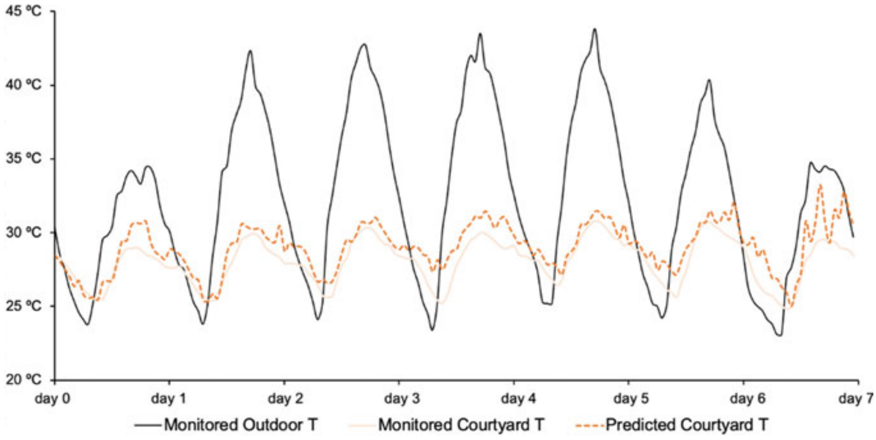

Fig. 8 Example of air temperature simulation results from the data-driven model by Diz-Mellado et al. [27]

(Fig. 9a) corresponds to the relative error of the predicted thermal gap and is always under 8%, and the graphic on the right (Fig. 9b) corresponds to the relative error of the predicted temperature inside the courtyard, providing results under 0.1% in the two cases.

The values confirm that the strategy used is quite accurate compared to other, more computationally expensive CFD model simulations. In addition, the results show more accuracy than other existing commercial tools. The root mean square error (RMSE) of this investigation is in a similar range to the values obtained with the CFD model in FreeFEM++ described before (1 °C) and lower than in other commercial tools that are around 3 °C. The new methodology proposed for the ML

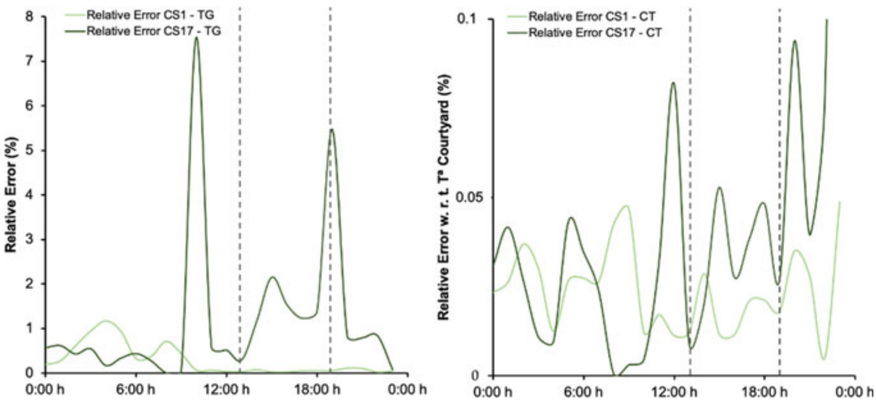

Fig. 9 Relative error calculated for the validation of the data-driven methodology by Diz-Mellado et al. [27]

method in this research is helpful for developing design tools capable of modeling the complex microclimate of semi-outdoor spaces such as courtyards without the complexity of defining a physical model. Other advantages of using ML techniques are related to the identification of fundamental variables, simplifying the calculation process, and better accuracy by including a more significant amount of training datasets.

4 Discussion of Challenges and Opportunities

The previous section analyzed different approaches to simulate the thermal performance of buildings with courtyards. From that analysis, some general conclusions about the strength and weaknesses of each methodology are discussed here:

- BES models are the tool commonly used to simulate the energy performance of buildings. The nodal approach allows for quick computing time when simulating dynamic evolutions throughout the whole year. However, BES models cannot be used to analyze outdoor microclimate influence on building performance if that data are not manually included as boundary conditions. This means that BES needs to be coupled with other simulation approaches that can predict microclimates in order to measure their influence on the building performance. For that reason, the use of hybrid workflows is needed when analyzing passive strategies to enhance the resilience of buildings facing climate change.
- CFD allows performing a detailed analysis of fluxes inside and outside a building on a small scale, being one option to obtain the microclimate data to be coupled in the BES simulations. However, this methodology has some weaknesses. First, these tools are difficult to implement without previous knowledge of fluid dynamics. Some of them are easier but rely on simplifications, leading to a lack of accuracy. And they require a high computation time. We have seen that it is possible to optimize the simulation model for specific simulations, but this has not been implemented yet in a tool accessible to the public, so currently, programing knowledge is also required to do this.
- Data-driven models are a promising alternative to CFD models for the prediction of courtyard performance based on ML. They have another advantage, which is the possibility of being applied even without detailed information of the model. However, their accuracy depends on the quality of the training datasets, and large and representative data are required. This is a novel approach that is currently limited to researchers with programing knowledge of ML.

This analysis highlighted how the best choice depends on the objectives of the analysis and the available data. For example, when speed and easily accessible feedback is needed for the early design, hybrid options using currently available tools are probably the best option. However, research is still needed to improve the connectivity among tools. On the other hand, data-driven models could be the best option if an analysis is to be done about an existing building from which there is not much constructive information. Being this said, future research on this field should still focus on some essential challenges that are not yet overcome:

- The integration of evaporative effects on the simulations is limited to very few software applications currently available for professionals, like ENVI-met. This means that the evapotranspiration effect of vegetation and the evaporative cooling of water are not being considered in many other tools, but experimental research shows that they are effective passive strategies against urban heat. For that reason, it is important to work on this issue to improve our analysis of urban mitigation strategies.
- The simulations can be further optimized, aiming to reduce computational time and increase accuracy in all methods. For the data-driven models, improving the datasets to train the algorithm or developing other ML techniques applied to urban microclimates is ways of future research. For the CFD and hybrid methods, much research exists that can be applied to the development of new CFD algorithms. As an example, reduced-order modeling (ROM) is a strategy that provides reductions of several orders of magnitude in the computational cost of numerical simulation of parametric design processes and problems. This is an option to reduce computing time that is currently under research [28].
- Finally, although many options and tools have been presented here, better accessibility to the professional sector is still required. Some methodologies are still not incorporated into existing commercial or open-source tools accessible for architects, designers, or city planners. Others require advanced knowledge that makes them difficult to apply practically. This is a problem that needs to be addressed in order to transfer research knowledge into society.

5 Conclusion

This chapter presents an overview of the different methods to simulate outdoor microclimates and their influence on building performance. They were tested, discussed, and compared through various case studies based on a very common microclimate, the traditional inner courtyard. Although the examples presented in this chapter focused on courtyards, these methodologies apply to a large variety of small-scale or medium-scale urban outdoor spaces capable of generating microclimates.

The results demonstrate the lack of capabilities of current building energy simulation (BES) tools to consider the benefits of these specific microclimates on building performance. Furthermore, despite different computational fluid dynamics (CFD) software that can predict the performance of these urban environments, the high computational effort and the lack of accuracy limit its potential application for preliminary design stages.

The analysis in different case studies also shows how multi-nodal outdoor climate simulations considering these microclimates can present high benefits in building performance. These specific microclimates can solve the problem of the urban overheating effect, for example, mitigating peak daytime temperatures. The consideration of these benefits in design workflow can enable additional passive cooling strategies in the building design, and BES tools should be improved to account for them.

In this sense, the potential of hybrid simulations coupling a variety of software (BES and CFD) has been described and tested, presenting a novel promising approach to combine the benefits of different methods in early design stages. However, it is still essential to enable better accessibility to the professional sector to promote a better climate change adaptation of the built environment. The optimal integration of these microenvironments in urban planning can enable new actions to mitigate climate risks in cities and buildings. From a practical view, the most important issue is to make it simpler to incor-porate the microclimate data in decision-making processes. Only then it will be possible to broader analyze urban resilience strategies under climate change projections.

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