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Simulation workflow for considering the outdoor microclimate in building energy modeling.

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Abstract

In order to accurately analyze building energy performance, it is important to take into account the outdoor microclimate. However, this can be challenging when different microclimates affect the same building using existing simulation tools. This study proposes a method to combine a Computational Fluid Dynamics (CFD) tool for microclimate simulation and a Building Energy Simulation (BES) tool for energy performance analysis within the Grasshopper interface. The method was tested in a case study involving a courtyard, which is a well-known example of microclimate affecting buildings. Results showed that considering the microclimate can significantly alter simulation results, reaching differences of 11% in energy transmitted through exterior wall, and 18% through the windows, the most affected elements, in some rooms. The total energy load of the room generally increased in the upper level of the house and was reduced in the lower level. This study is particularly relevant for practitioners in Spain, where the BES software used is required by the government for energy certification of buildings.

Keywords: Microclimate simulation; Building energy modeling; Courtyard; Coupling simulations.

1. Introduction

The looming climate crisis has brought many challenges to cities around the world, including threats to the environment, public health, and infrastructure due to rising temperatures. In response, policymakers and city planners have been exploring various mitigation strategies to address these challenges. Urban geometry can improve the performance of the city through the generation of microclimates that can mitigate the urban heat island effect (the higher temperature found in the city compared to the surrounding rural areas). One example of these beneficial microclimates is the use of courtyards. These spaces, open areas surrounded by buildings, can keep lower temperatures during the day than those found outside, due to the thermodynamic effects that provide them with a tempering capacity (Rojas et al., 2012). Previous research has found that the temperature difference between the courtyard and the outdoors can reach up to 12ºC in some cases (López-Cabeza, et al., 2022).

However, implementing effective mitigation measures requires accurate tools to predict their impact on the performance of buildings and the urban environment (Mauree et al., 2019). Simulation tools would allow planners to test the effectiveness of different mitigation strategies under various scenarios. However, existing simulation tools often fail to account for the effects of microclimates, leading to inaccurate predictions and difficulties in the implementation of mitigation measures (Lizana et al., 2021). Therefore, improving the accuracy of simulations and developing tools that incorporate microclimate data is crucial for effectively addressing the climate crisis in urban areas.

This paper aims to explore the challenges and limitations of existing simulation tools and proposes a novel approach that addresses some of these gaps by incorporating microclimate data into the energy simulation of buildings, in the specific context of the energy certification of buildings according to Spanish regulations. The method is tested in the simulation of a building with a courtyard, to account for the effect of the microclimate of the courtyard on the performance of the building.

2. State of the art

There are different kinds of numerical simulations applied to the built environment. Building energy simulations (BES) and Computational Fluid Dynamics (CFD) simulations are the most used (López-Cabeza, et al. 2022).

- BES models calculate the physical parameters in one single node per zone, which represents a uniform profile of data in that region. This is the approach of the tools used to predict the energy use intensity of a building. The problem is that for the outdoor conditions, they only consider one single weather file, thus the microclimate generated around buildings is not considered. Some of the existing tools in this group are EnergyPlus (U.S. Department of Energy, 2021), TRNSYS (*TRNSYS : Transient System Simulation Tool*, n.d.), or HULC (*Herramienta Unificada LIDER-CALENER*, 2022).
- CFD models can quantify spatial variations in a volume, meshed in control volumes where the equations are applied. These models solve the Navier-Stokes equations using the finite element or finite volume numerical methods. They can simulate microclimate variations, but they also require huge computational power and time. Some of the existing tools are ANSYS FLUENT, OpenFOAM (*OpenFOAM User Guide*, n.d.), FreeFEM++ (*FreeFEM*, n.d.), or ENVI-met (*ENVI-Met*, n.d.) for urban simulations.

The different characteristics of these two groups make them difficult to combine in one single workflow for simulations, although it is required in order to compute microclimate effects on building energy simulations. This approach linking different tools is called Hybrid, and has been a recent focus among the research community (Rodríguez-Vázquez et al., 2020). By coupling BES and CFD tools it is possible to improve the results and capabilities of the analysis. However, some problems regarding the simulation time and input-output workflow of the data still need to be addressed. Some of the most common coupling methods use the Grasshopper interface to link different software. In this paper, a CFD workflow for the simulation of courtyard microclimate using the Ladybug Tools is linked with the Spanish Energy simulation tool HULC in Grasshopper. These two tools are described as follows:

- The HULC software is a tool for certifying building energy performance that is provided by the Spanish government to comply with the Spanish Technical Building Code (CTE) (Ministerio de Fomento (Gobierno de España), 2017), which is a regulation that was developed to meet European Union standards. The software uses DOE-2 (*DOE2.Com Home Page*, n.d.) as its simulation engine, which is a well-known tool that meets IEA's Bestest requirements (Judkoff & Neymark, 1995). HULC works by simulating a transitory state with an hourly time step, and it has the additional capability to modify the boundary conditions of one or more elements of a building's envelope. However, it does not calculate specific outdoor microclimates on its own. Instead, it relies on externally calculated or monitored data to incorporate this information into the building simulation. As a result, this additional capability is not very useful in practice since outdoor microclimates require other CFD simulation tools that are not always known by users. This is the problem that the coupling proposal in this work aims to address.
- The Ladybug Tools (LBT) (*Ladybug Tools | Home Page*, n.d.) are a collection of plugins for Grasshopper that enables various engines to operate in one interface. This allows for climate analysis, energy simulations, or CFD simulations to be run and for the outputs of one tool to be connected to another. All results can be imported and visualized in the Rhinoceros interface, making it a very useful tool for early-stage design projects. The LBT is gaining popularity in the research community because the code can be continuously updated and improved.

Previously, the LBT have been used to analyze outdoor microclimates. In a recent study by Lopez-Cabeza et al. (López-Cabeza, et al., 2022), a script was developed using the LBT to evaluate the outdoor microclimate of transitional spaces in buildings, such as courtyards. They were able to predict the thermal tempering potential of courtyards and analyze thermal comfort in that outdoor environment using LBT components that linked the model with the CFD tool OpenFOAM. The proposed method in this work aims to link the microclimate simulation conducted by LBT with the energy simulation in HULC, using Rhinoceros' graphical interface and its parametric tool Grasshopper. This novel method will allow to account for different outdoor climatic conditions in one single building simulation, which is required for energy certification in Spain.

3. Materials and Methods

3.1. Simulation workflow

The methodology for the simulation couples the Building Energy Simulation (BES) tool HULC with the Computational Fluid Dynamics workflow in Ladybug Tools used by Lopez-Cabeza et al. (López-Cabeza, et al., 2022) for the microclimate simulation of courtyards. The two tools are linked using Grasshopper components with Python code that allows the interconnection of the tools in terms of model geometry and inputs-outputs needed for each simulation. The workflow is diagramed in **Figure 1**. The process is controlled from the Grasshopper interface, making it quite easy-going. Some steps are still defined in the HULC interface, those marked as "HULC" in the diagram.

The process starts with a model that can be built in Rhinoceros, and then imported to Grasshopper and exported to HULC. Then the microclimate of the courtyard is simulated at two different hours of the day, those corresponding with the maximum and the minimum outdoor temperatures. The rest of the hours are interpolated in order to speed up the CFD simulation. Then, a script in Python extracts the information and builds the files to export the data to HULC in the format that it requires. These data are used to modify the Initial conditions files (ICF) from HULC (one file per surface facing the courtyard) into Modified Condition files (MCF), which are then used to perform the BES simulation including the courtyard microclimate.

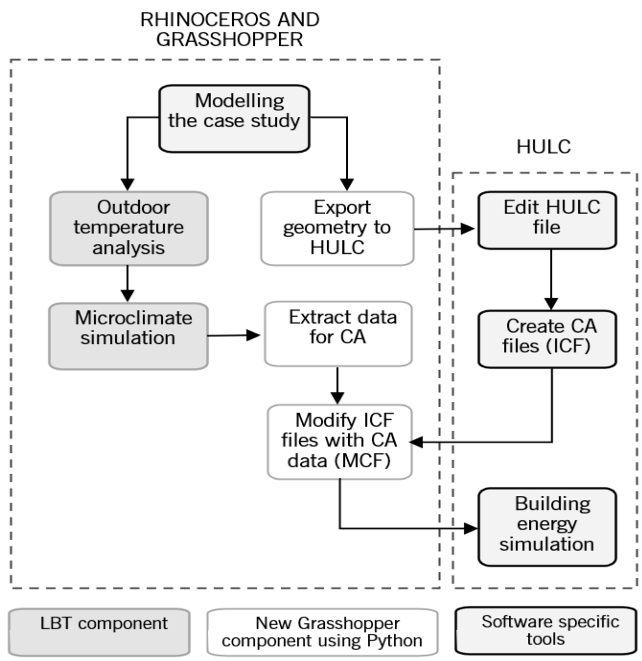
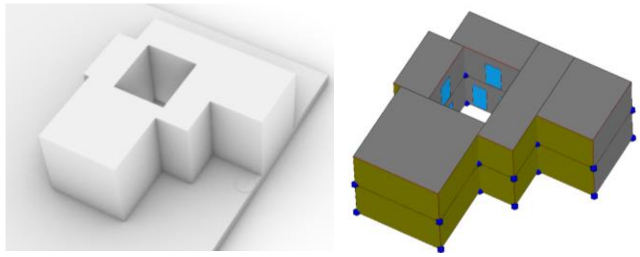


Figure 1. Coupling workflow microclimate simulation using Ladybug Tools and HULC.

3.2. Simulation setup

To start the simulation, a case study was modelled in Rhino and exported to HULC as shown in **Figure 2**. The weather file for the simulation was constructed using monitored data from August 2017. The simulation model defines different parameter settings such as the shadings in the windows, the materials used in construction, internal heat sources, the ventilation schedule and heat loss due to thermal bridges. The software used to analyze the building follows standard regulations for residential buildings, including default schedules for occupancy and internal heat sources.



a) Rhinoceros model b) HULC model

Figure 2. Models of the case study in the different software used.

3.3. Performance evaluation

To test the performance of the workflow, a building was modelled as conditioned to obtain the energy demand to achieve comfort standards. To analyze the influence of the microclimate on the performance of the building, the results of the workflow described are compared with the simulation of the HULC software without including the courtyard effect, which is the standard simulation setup. The comparison between the two models is performed based on three parameters: the results of the total energy load in August, the energy transmitted through the walls and the energy transmitted through windows of the rooms facing the courtyard, all measured in watts per square meter. In addition, the percentage variation between the two simulations of the three variables is also shown.

4. Results and Discussion

4.1. Case Study

The focus of this study is a single-family house located in the city center of Cordoba (at coordinates 4°46'21.9''W, 37°53'29.58N, and an elevation of 106 meters above sea level). This particular case study was selected due to the significant impact of the microclimate of its inner courtyard on the home's performance. The courtyard measures 4.5 m by 4.5 m and has a height of 6.5 meters. Through monitoring, it was found that temperature differences around 7.5ºC existed between the outdoor area and the courtyard during extreme heat temperatures. Moreover, due to the use of traditional construction systems, the residence is more susceptible to external environmental factors than modern constructions. The layout of the house can be found in **Figure 3**. The simplification of the rooms modeled in Rhinoceros is shown in **Figure 4**.

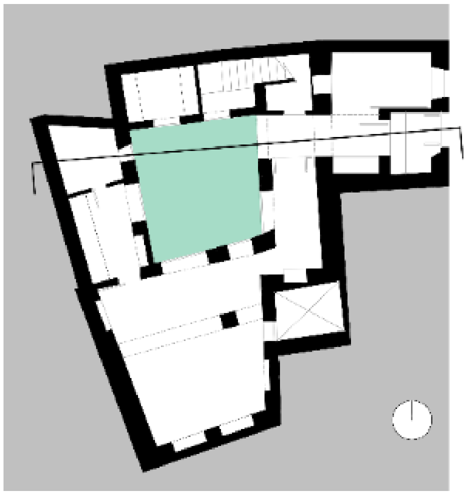


Figure 3. Plan view of the house.

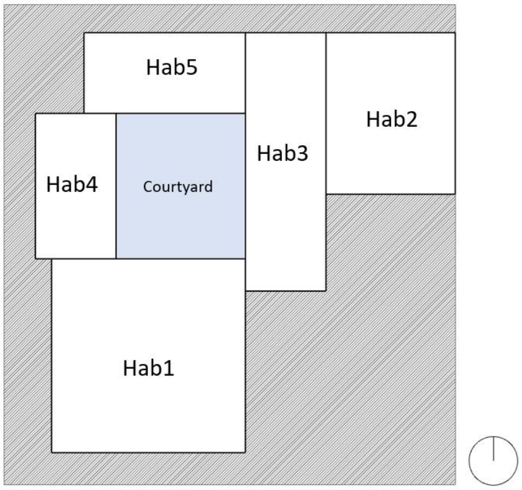


Figure 4. Model room's distribution.

4.2. Microclimate simulation results

This section shows the results of the microclimate inside the courtyard on one of the simulated days. **Figure 5** shows the hourly outdoor temperature and the mean courtyard temperature simulated at the two levels of the house, after the interpolation of the simulation at the extreme hours of the outdoor temperature (9:00 and 17:00 hours). Plotted on the graph, it can be seen that the courtyard achieved a tempering effect of the outdoor temperature close to 9ºC (from 44ºC recorded outdoors to 35ºC recorded in the lower level of the courtyard), being slightly lower in the upper level due to the stratification effect in the courtyard. During the night, the courtyard overheats, reaching higher temperatures than in the outdoors.

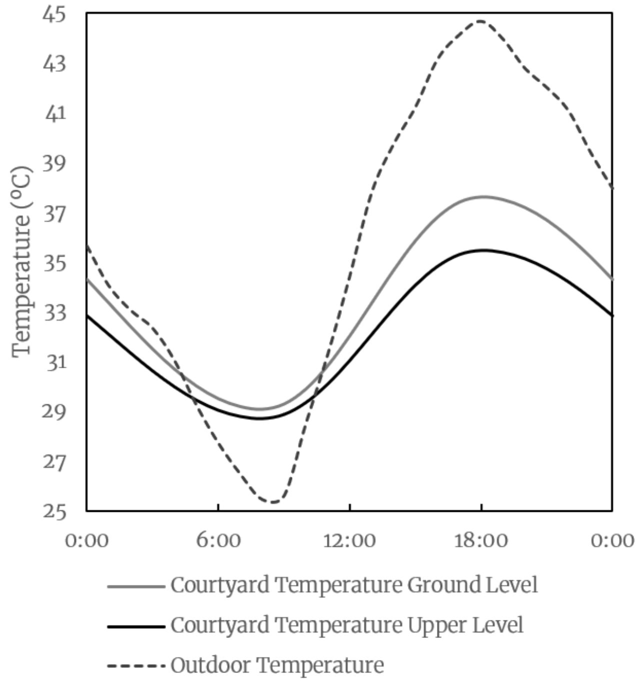


Figure 5. Hourly outdoor air temperature and courtyard interpolated mean air temperature at the two levels of the house.

4.3. Energy transmission results

The total energy transmitted through the exterior walls of the rooms facing the courtyard in the period analyzed is shown in **Figure 6**, for the simulation considering the courtyard and the one not considering it. The consideration of the microclimate reduced the total energy transmitted in the rooms of the ground floor (P0) and increases the transmission in the upper floor (P1) except for Room P1_Hab5, which is facing south. This room, together with P0_Hab4 (facing east) and P0_Hab5 (facing south) are the most benefited by the microclimate effect.

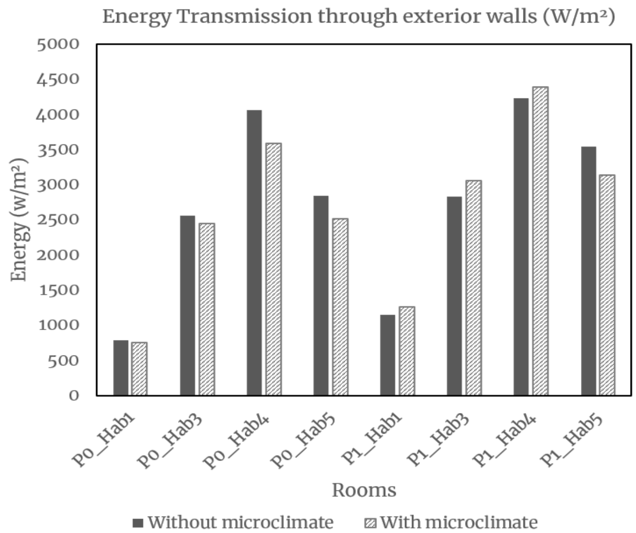


Figure 6. Energy transmitted through exterior walls per room facing the courtyard in the period analyzed.

The energy transmitted through the windows is shown in **Figure 7**. The pattern is the same as in the walls, but the differences between the consideration of the microclimate or not are larger. This means that the lower the thermal resistance of the surfaces facing the courtyard, the most important the consideration of the microclimate is. In this case, the rooms facing South are the most benefited by the courtyard (Hab5).

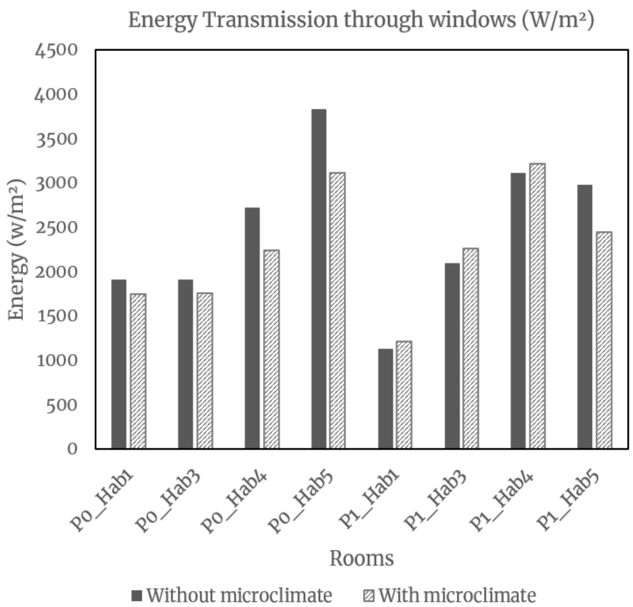


Figure 7. Energy transmitted through the windows per room facing the courtyard in the period analyzed.

4.4. Total energy load results

The total energy load profile of each room is represented in **Figure 8**. This includes not only energy transmitted through exterior walls and windows, as shown before, but also by the other surfaces of the rooms and the internal loads, infiltration, and ventilation loads. Despite the other load considered, the pattern is the same as shown previously: the rooms on the ground floor reduced their total load if considering the microclimate and the rooms on the upper level, except for P1_Hab5, increased their load. This can be explained by the higher temperature in the courtyard at the upper level in comparison with the lower level, joined with the overheating effect during the night, which in sum makes the consideration of the courtyard slightly detrimental.

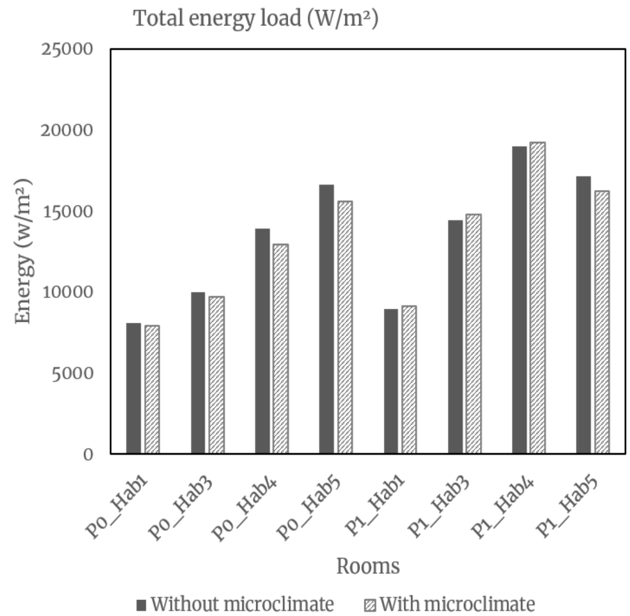


Figure 8. Total energy load per room facing the courtyard in the period analyzed.

4.5. Implications of the results

The comparison of the results between both scenarios, considering and not considering the courtyard microclimate is shown in **Figure 9** in terms of percentage variation. It shows that the differences in energy transmitted by walls ranged between -11.5% to 10.2%, by windows ranged from -18.7% to 8.1%, and the total load difference ranged from -7.0% to 2.6%. The results obtained are aligned with previous research accounting the energy demand variations of a building considering the courtyard microclimatic effect (Sánchez de la Flor et al., 2021). These differences are significant enough to emphasize the need to include the microclimate effect of the courtyard on the energy simulation of buildings. Furthermore, they manifest the need to optimize the performance of the courtyard to avoid overheating during the night which is harming the performance of the courtyard. This could be done by allowing ventilation in the courtyard during the night. This will be analyzed in further research on this topic. It would be also interesting to perform a sensibility analysis of the influence of the constructive solution of the walls facing the courtyard.

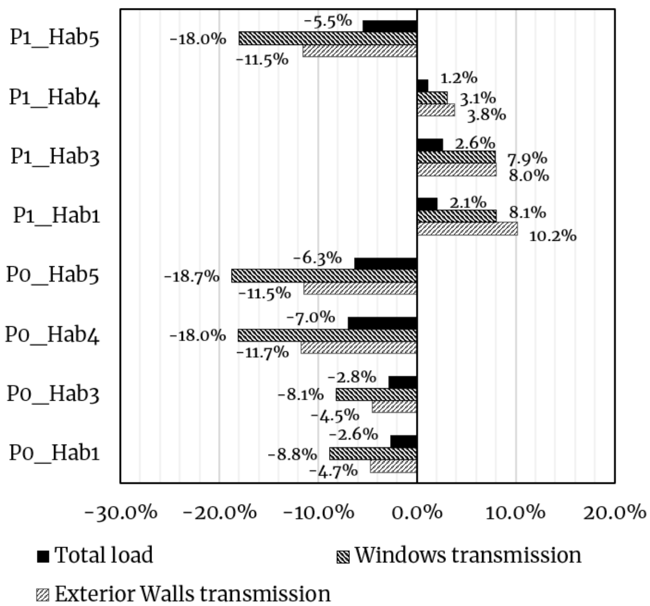


Figure 9. Total energy load, wall and window energy transmission variations between the case considering the microclimate and the case not considering the microclimate.

The presented methodology in this paper is still in its early stages and is undergoing refinement and testing in some case studies. This methodology provides a practical way to incorporate microclimates into energy simulation and certification in Spain using the HULC software's additional capacities tool. The software's capability to account for microclimates is otherwise limited. The case study demonstrated the significant impact of microclimates on indoor temperatures, particularly in extreme weather. The findings suggest that hybrid methods, such as the one presented in this work coupling CFD with BES, are necessary to achieve more accurate simulations.

To further improve this methodology, the introduction of Grasshopper components is necessary to provide complete control of the process in a single interface. Additionally, the HULC software's additional capabilities are limited to air temperature modifications. To achieve more accurate simulations, microclimates should be incorporated in terms of wind speed, heat transfer coefficients, and ventilation loads. This can be especially important in free-running buildings for enhancing thermal comfort.

5. Conclusion

In this paper, a methodology to couple a Computational Fluid Dynamics (CFD) simulation workflow with a Building Energy Simulation (BES) tool to incorporate microclimates in energy simulations of buildings is proposed. The method was implemented using the Ladybug Tool workflow for CFD simulation and HULC software for BES, which is provided by the Spanish Government for energy certification of buildings. The authors explained the linking process between the two tools and demonstrated the practical use of this methodology through a case study with a courtyard. The case study highlighted the significant impact of microclimates on energy transmission through building elements and the total energy load of the different rooms, reaching variations up to 18% in some cases.

The paper also pointed out the limitations of the current methodology and suggested further improvements, such as introducing wind speed, heat transfer coefficients, and ventilation loads in addition to air temperature variations for more accurate simulations. The design of some Grasshopper components to provide complete control of the process in a single interface is still needed. In addition, validation of the methodology contrasting the simulation with monitored data is needed. Despite the limitations, the proposed methodology shows promise for practical use in energy simulation and certification in Spain. The methodology can provide more accurate simulations by incorporating microclimates, which can have a significant impact on thermal comfort and energy demand.

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