Abstract
The consideration of the outdoor microclimate in building energy simulation is needed in order to ensure accuracy in building energy analysis. However, it presents a challenge especially when different microclimates affect the same building, given the capabilities of the existing simulation tools. This work proposed a method to couple a Computational Fluid Dynamic tool for the microclimate simulation and a Building Energy Simulation tool for the energy performance analysis within the Grasshopper interface. It is tested in a case study with a courtyard, a well-known case of microclimate affecting buildings. The results show that the consideration of the microclimate can greatly change the results of the simulations. The indoor temperature on extremely hottest days was reduced up to 1.5°C and the transmission of energy through the walls changed by up to 38% in some of the rooms of the house. This work is especially relevant for practitioners in Spain, where the BES software used is required by the government to perform the energy certification of buildings.

Highlights
• A method to couple CFD and BES simulation tools is provided
• OpenFOAM and HULC software are linked using the Grasshopper interface
• The method is tested in the analysis of a building with a courtyard
• The consideration of the courtyard reduces air temperature inside the building in free running mode up to 1.5°C

Introduction
Building energy certification is required by standards and regulations with the objective of limiting the consumption of buildings, given the importance of reducing energy budget and CO₂ emissions in the current situation of climate change projections (IPCC, 2021). There are many challenges to be addressed to improve the accuracy of building simulations (Lizana et al., 2021): the relevance of the weather data selected for the simulation, incorporating passive performance and thermal comfort indicators into design processes, and taking into account the possible advantages of outdoor microclimates on building performance are among them. This last option needs the introduction of other kinds of tools, apart from the traditional Building Energy Simulation (BES) tools in order to provide this kind of data.

The possibility of providing an easy method to include the specific microclimatic conditions in the energy simulation and certification of buildings means an important advance in the simulation field for different reasons: the benefits of microclimates, such us courtyards’ thermal tempering performance, experimentally demonstrated in many studies, could be finally considered in building simulation in practice, allowing for the introduction of passive strategies that were not sufficiently accurately included in the simulations before. This helps to design more energy-efficient buildings and reduce energy consumption. Furthermore, the possibility of using CFD simulations in an easier-to-use way for designers is another advantage. The coupling of BES and CFD tools has been addressed by previous researchers (Rodríguez-Vázquez et al., 2020), although none of the methods is implementable without difficulties. Some of the main problems to overcome in the coupling process derive from the different approximations between the two types of simulations. They have different time steps, and there is an important difference between the power requirements for the simulations before. This helps to design more energy-efficient buildings and reduce energy consumption. In addition, existing BES tools do not provide an easy way to incorporate differences in the boundary conditions of the elements.

In the Spanish context, the Technical Building Code (CTE) (Ministerio de Fomento (Gobierno de España), 2017) includes the requirements imposed by the European Directive (Directive (EU) 2018/844 on the Energy Performance of Buildings, 2018), and HULC is the computer software offered for compliance. The HULC tool includes the additional capability to modify the boundary conditions of one or more of the elements of the building envelope. This is important in order to introduce the microclimate effects that some passive conditioning strategies, such as courtyards, produce around the buildings (up to 8-12°C less temperature than outdoors) (Rivera-Gómez et al., 2019). However, this software does not have a plugin to calculate specific microclimates, it is only able to incorporate externally calculated or monitored data. This means that this additional capability is in practice not very useful, given that outdoor microclimates require CFD simulation tools not always known by the users.
This paper aims to propose a coupling method to calculate the outdoor microclimatic conditions to allow more automated linking with the HULC simulation using just one interface in Grasshopper. This method is specifically developed to be used by practitioners in Spain, where the HULC tool is provided by the government to practitioners in order to address the building certification requirements.

**Methods**

This method couples the Building Energy Simulation (BES) tool HULC with the Computational Fluid Dynamic (CFD) tool OpenFOAM using the interface of Rhinoceros and Grasshopper and the plugins of Ladybug Tools. The method is developed as a set of components for Grasshopper, a popular parametric design platform, to link the mentioned tools' outputs and input the results in the same graphical interface. This section explains each of the tools that are linked and how the coupling method works.

**HULC tool description**

The HULC (acronym of Unified Tool Lider-Calener in Spanish) (Herramienta Unificada LIDER-CALENER, 2022) software is the energy certification tool provided by the Spanish Government to comply with the Technical Building Code (CTE), the regulation that Spain has developed to address the European Union regulations regarding building energy performance. HULC is based on the simulation engine DOE-2 (DOE2.Com Home Page, n.d.), a well-known tool that meets the requirements of the well-known IEA Bestest (Judkoff & Neymark, 1995). HULC runs with an hourly time step in a transitory state and includes the additional capability (CA) to modify the boundary conditions of one or more of the elements of the building envelope. However, this software does not calculate specific outdoor microclimates, it is only able to incorporate externally calculated or monitored data to include this information in the building simulation. This means that this additional capability is in practice not very useful, given that outdoor microclimates require other CFD simulation tools not always known by users. This is the problem that is addressed in the coupling proposal in this work.

**LBT description**

The Ladybug Tools (LBT) is a set of plugins for Grasshopper that link different engines in the same interface, allowing it to run climate analysis, energy simulations or even CFD simulations and link the outputs of one tool to another, and import all the results to visualize in the Rhinoceros interface. This means that it is a very suitable tool for the early design stage of projects, and it is gaining attention from the research community given the possibility to continuously update and improve the code.

This tool has been previously used for the analysis of outdoor microclimates. Lopez-Cabeza et al. (López-Cabeza et al., 2022) developed a script using the Ladybug Tools (LBT) to analyse the outdoor microclimate of transitional spaces in buildings and applied it to courtyards. They were able to predict the thermal tempering potential of courtyards and analyse thermal comfort in that outdoor environment using the LBT components that link the model with the CFD tool OpenFOAM. The objective of the proposed method in this work is to link the microclimate simulation performed by LBT with the energy simulation in HULC, using the graphical interface of Rhinoceros and its parametric tool Grasshopper.

**Description of the coupling method**

This section explains the coupling process of LBT and HULC in the Grasshopper interface. It was designed with the idea of reducing as much as possible the need for changing from one software interface to another, being able to do most of the simulation directly from the Grasshopper interface. This is not completely achieved in the current state of the methodology, although what is left can be easily incorporated and this work is a proof of concept of that. The most complex part was the communication between the two software in relation to the geometry of the case study, which had to be modelled in Rhinoceros and exported to HULC. To achieve that, several blocks of code in Python components in Grasshopper were written. The workflow structure is diagrammed in Figure 1.

![Figure 1. Coupling workflow for CFD and BES tools using LBT and HULC.](https://doi.org/10.26868/25222708.2023.1550)
The geometry of the case study is modelled using the Rhinoceros CAD software and imported to Grasshopper (GH) (Figure 2) using some LBT components. It is also possible to directly model using GH, especially for parametric analysis. Solids or polysurfaces are supported, representing the spaces in a simplified way, following the rules of LBT analysis.

**Figure 2. Rhinoceros and Grasshopper interface. Import of geometry into Grasshopper.**

- The first step before the simulation of the microclimate of the courtyard is the analysis of the weather file. This is done to find maximum and minimum outdoor temperatures and when they happen. These two hours per day will be selected to perform the outdoor CFD simulation, in order to speed up the simulation time of the CFD. The rest of the hours will be interpolated.
- The CFD simulation of the microclimate is performed using the LBT workflow described.
- A Python code is written to interpolate the results of the temperature at the maximum and minimum temperatures between the different hours of the day given that the HULC software needs hourly data.
- While the HULC tool requires one data per hour and surface of the building as boundary conditions, the LBT CFD simulation provides spatial results outdoors. A code in Python extracts that information from the CFD simulations (which have multiple points per HULC surface) and stores the information in the appropriate format to copy it later in the CA files.
- The most complex part of the workflow is to export the geometry from Rhinoceros into HULC (Figure 3). Each software has its language to define the model, thus, a Python code was created to read the geometry in Rhinoceros and translate it into HULC language. At this stage, the code only exports geometry. The material properties of the constructions still need to be defined in the HULC interface. However, this is something that could be added in the future. At the moment, changes in building construction, openings, systems and the location of the case study need to be defined in HULC.

**Figure 3. Completed model in HULC.**

- Once the model is complete, the CA files are generated in HULC. Each of the surfaces of the building that is going to have their boundary conditions changed is selected and an Initial Conditions File (ICF) is generated. This file contains information about the surface, including outdoor boundary conditions such as radiation, or air temperature.
- The ICF files need to be modified with the temperature data simulated with the CFD simulation and already stored in GH. This is automatically done through a Python piece of code that creates the Modified Conditions Files (MCF) (Figure 4).

**Figure 4. Modified Condition Files created using Python code in Grasshopper interface.**

- The MCF files are imported into HULC, and the energy simulation is run.
- All the information generated by HULC can be imported into the GH interface using Python code to be represented and analysed using the LBT.

**Results**

This section presents the results of the proposed methodology applied to a case study located in Cordoba. An objective evaluation of the potential of the use of the tool by practitioners is presented in the discussion.

**Case study**

The case study is a single-family house located in the city centre of Cordoba (4°46’21.9”W, 37°53’29.58”N, elevation 106 m a.s.l). This case is selected for the clear implications of microclimates on its performance. The house has an inner courtyard, 4.5 x 4.5 m wide and 6.5 m height, which has been monitored, providing differences in temperature between the outdoor and the courtyard up...
to 7.5°C at outdoor extreme heat temperatures. In addition, traditional construction systems in the house make it more influenced by outdoor conditions than new constructions. A distribution of the house is presented in Figure 5.

![Plan and section of the case study building](image)

**Figure 5. Plan and section of the case study building.**

**Simulation setup**

The weather files included in the HULC tool correspond to the climate zones in Spain and are one of the main limitations of the tool, given that they are not updated with current rising temperature conditions yet. For that reason, in this case, the weather file has been built using monitored data in the year 2017 in the city of Córdoba, more accurate in the simulation of current weather conditions. The modelling of the case study includes geometry, external shadings, constructive elements, internal gains, infiltration, natural ventilation, thermal bridges, and internal heat capacity. Operating schedules and internal gains are maintained as default in the software for residential buildings, following the regulation standards. The building is modelled as free running, without the consideration of conditioning systems, in order to analyse the effect of microclimate on indoor temperatures.

**Performance evaluation**

To analyse the possibilities and effectiveness of the methodology proposed, the results compare the HULC simulation without using the CFD simulation of the microclimate with the results using the proposed methodology coupling the BES and the CFD tool. Results are shown in terms of differences in indoor air temperature, and energy loads for the month of August, given that the use of courtyards is more important in the warmest months.

**Microclimate simulation**

The CFD simulation of the courtyard was run for the maximum and minimum temperature hours, 9 am and 5 pm, every day. Figure 6 shows the results of the simulated temperature in the courtyard at 5 pm on one of the warmest days. The rest of the hours were interpolated following a sinusoidal evolution. Figure 7 shows the results for the mean value at each of the two levels where the data was extracted for the BES simulation. The outdoor temperature that day reached 43 °C, while the microclimate of the courtyard maintained a maximum mean temperature of 37°C on the first floor and 35°C on the ground floor, a considerable benefit for the thermal performance of the house.

![LBT results of the air temperature of the courtyard at 17 hours.](image)

**Figure 6. LBT results of the air temperature of the courtyard at 17 hours.**

**Indoor air temperature results**

The results of the comparison of indoor air temperature with the consideration of the microclimate of the courtyard and without the consideration of the microclimate are shown in Figure 8 for one week with extreme outdoor temperatures. The east and west rooms of the house are shown, as they are the most and least affected by the influence of the microclimate.
The figure shows that the consideration of the microclimate generally reduces the indoor air temperature of the house. The west rooms (which have the courtyard façade facing east) are the most benefited from the microclimate, reaching up to a 1.5 °C difference. The rooms on the ground floor also have a higher difference than rooms on the first floor for the same orientation, which is a consequence of the stratification effect of the temperature in the courtyard. Another interesting fact that the graph shows is that the maximum indoor temperature occurs close to midnight. This can be explained by the great inertia that the walls of the house have, given that the traditional construction system is rammed earth that has a high thermal mass, but low insulation.

Energy loads results

The energy transmission per square meter of the room through walls and windows (the most affected elements by the microclimate of the courtyard), as well as the total energy load, are presented in Figure 10 and Figure 10 for the same rooms analysed before. It can be seen how the effect of the microclimate influences the results differently on the two floors and depending on the orientation of the room. On the ground floor (Figure 9), R3 in the east had an increase in heat transmission through walls and windows lower than R4, in the west. The total load, considering the rest of the elements, also increased heat transmission. Given that the building is in free running mode and the outdoor temperature in the courtyard is lower than before, the heat transmitted to the outdoors increases.

On the first floor, the results are slightly different. On this floor, the temperature in the courtyards is not as low as on the ground floor, and it is also important to consider the overheating effect during the night. For that reason, in these rooms, the heat transmission through walls and windows generally decreases with the consideration of the microclimate and the total load increases the heat transmitted inside the house.

Table 1 shows the percentage of change in each of the previously shown rooms per floor where the importance of the introduction of the microclimate is shown, reaching differences up to 43% in the energy transmitted in some elements.
Table 1. Percentage difference between the simulation considering the microclimate and not considering the microclimate.

<table>
<thead>
<tr>
<th>Room</th>
<th>Exterior Walls</th>
<th>Windows</th>
<th>Total load</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0_R3</td>
<td>30%</td>
<td>43%</td>
<td>4%</td>
</tr>
<tr>
<td>P0_R4</td>
<td>29%</td>
<td>30%</td>
<td>18%</td>
</tr>
<tr>
<td>P1_R3</td>
<td>38%</td>
<td>9%</td>
<td>24%</td>
</tr>
<tr>
<td>P1_R4</td>
<td>10%</td>
<td>1%</td>
<td>18%</td>
</tr>
</tbody>
</table>

Discussion

The process presented in this work is still a proof of concept that is being refined and tested in some case studies. This workflow allows the practical use of the additional capacities tool in HULC for the introduction of the microclimates in the energy simulation and certification in Sapin. Otherwise, this capability of the software is rather limited. In the case study presented, the effect of the microclimate of a courtyard in a house under extreme temperatures shows important differences if not considered. This indicates that CFD-BES coupling is needed in order to achieve more accurate simulations.

Further improvement of this methodology requires the introduction of Grasshopper components that allow complete control of the process in one single interface. In addition, the additional capabilities of the HULC software are only modified in terms of air temperature. To achieve more accurate simulations, the microclimate should be also introduced in terms of wind speed, heat transfer coefficients and ventilation loads, which may be an important factor to increase thermal comfort, especially in free-running buildings. However, just with the changes in this work, the air temperature inside the rooms decreased up to 1.5°C, an important amount both, in terms of comfort and in terms of energy demand.

Conclusion

This paper proposed a method to couple a CFD simulation tool in LBT with a BES tool, HULC, which is provided by the Spanish Government to perform the energy certification of buildings according to regulations. This method allows the introduction of microclimates around the building to provide more accurate simulations. This work has described the linking process and the possibilities are presented in a case study with a courtyard, where the effect of the microclimate of the courtyard reduces indoor temperatures up to 1.5°C in free-running mode on some of the hottest days of the year. Differences in energy transmission through some elements can be as high as 43%. This work is a proof of concept and the methodology still needs to be further refined to provide even more accurate simulations.

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References


