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Comparison and validation of two simulation workflows for courtyard microclimates

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ABSTRACT: The simulation of urban microclimates in a way that is flexible enough to be included in the early design stages is still a problem to be solved. Furthermore, the necessity to find a balance between accuracy, provided by the use of CFD software requiring high computational power, operational speed and integration with the modelling tool, is an even more complex challenge. Accordingly, this research investigates the use of the Ladybug Tools, a set of plugins for Grasshopper that links analysis and design, in a hybrid workflow, to simulate the thermodynamic performance of courtyards, a transitional space of buildings that is proven to be a passive design strategy to reduce energy consumption. The results show that the hybrid workflow has a similar accuracy to the integrated CFD tool analyzed, but having the advantage of using the same design interface. It also provides the transparency of an open-source software and the possibility of improving the result in further research.

KEYWORDS: Courtyards, Outdoor Simulation, ENVI-met, Ladybug tools, Validation.

1. INTRODUCTION

The design of outdoor spaces in cities is becoming an important area of research due to the potential of these kind of spaces in reducing the Heat Island Effect, increasing the thermal comfort of citizens. At a smaller scale, outdoor spaces such as courtyards can also create microclimates inside the buildings that help increase thermal comfort and reduce energy consumption [1]. Courtyards are considered a traditional passive strategy that has been widely used in many cultures [2]. The performance of a courtyard depends on many variables such as geometry, orientation, materials, existence of vegetation and water bodies or wind. Our role as designers is to combine them to provide the best possible scheme. Nowadays, apart from traditional best practices, we can also use simulation tools that predict their performance.

However, there is a very limited number of tools that designers can use to analyze the performance of these spaces during early design. The large number of factors that determine their performance makes it necessary to employ very powerful software that uses CFD calculations, which results in more accurate data but excessive computation time. One such tool is ENVI-met [3], a widely validated software that uses CFD to simulate microclimates in urban scenarios. It is able to account for the interaction between buildings, vegetation, air, and soil, at a wide range of scales, from the urban scale to the building scale. It provides a huge amount of data in each simulation for all the mentioned elements, requiring a lot of computational power and time, making it unsuitable for early design.

As a result, this research aims to adapt and test a hybrid simulation workflow using the Ladybug tools for Grasshopper, previously analyzed by other researchers in the analysis of outdoor spaces [4], [5], against an integrated software widely validated, as it is ENVI-met, applying both methods to the smaller scale of courtyards. The objective is to analyze whether the hybrid workflow results are accurate enough to be used instead of the more time-consuming integrated software in order to incorporate its use in early design.

The performance of the simulation is analyzed in terms of air temperature at different levels of the courtyard and the thermal delta that the courtyard is able to provide in comparison with the outdoor temperature. This thermal delta is defined as the difference between the outdoor temperature and the courtyard's temperature. Since the courtyard generally provides a beneficial cooling effect in the hot-arid climate, a higher daily thermal delta means a better thermodynamic performance of the courtyard, providing higher thermal comfort and lower energy consumption in the building.

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2. MATERIALS AND METHODS

2.1 Courtyard description

The selected case study is located in Sevilla, (Spain 37°17′01″N 5°55′20″W, elevation 42 m a.s.l), which is Csa in Köppen classification [6], characterized by hot dry summers and mild winters. The building selected is a school distributed around an 11.0 x 7.0 m courtyard with an 8.9 m height. The walls are 40% glazed and 60% covered with white cement mortar. The most characteristic elements in the courtyard are two palm trees that provide some shadow, modelled as cubic shapes inside the courtyard (see Figure 1).

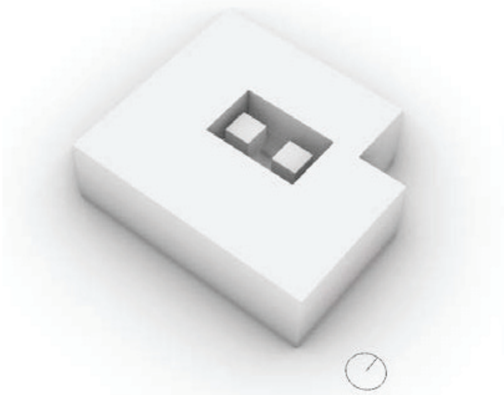

Figure 1: Model of the courtyard.

2.2 Monitoring

The courtyard is monitored during a whole week in summer, between the 4th and the 9th of June, when the weather is hot and dry. Air temperature, wind speed, and direction outside the courtyard are recorded by a weather station model PCE-FWS 20 to obtain the input data for the simulations. Air temperature and humidity are measured inside the courtyard at 1.5 m height, using sensor model TESTO 174H, to compare the data with simulation results. Only one representative day (June 8th) is selected for data comparison to simulated results. Table 1 shows the characteristics of the instruments used.

Table 1: Technical data of the measurement instruments.

Sensor	Variable	Accuracy	Resolution
TESTO 174H	Drybulb Temp.	±0.5 °C	0.1 °C
	RH	±0.1%	2%
PCE-FWS 20	Drybulb Temp.	±1 °C	0.1°C
	RH	±5%	1%
	Wind	±1 m/s	-

2.3 Integrated Software Simulation

Measured data are compared to simulated data using two different workflows in order to evaluate their performance. The first workflow consists of the use of ENVI-met, which integrates the simulation of all the interdependent parameters of the air, wind, radiation, surfaces etc. In addition to the aforementioned computational power and time limitations that it needs, studies suggest that the accuracy of the software when it is used to simulate small-scale courtyards is not good [7]. Table 2 shows the main inputs for the ENVI-met simulation. The monitored outdoor temperature and relative humidity, as well as the mean wind speed are used as boundary conditions for the simulation.

Table 2: Input variables for ENVI-met

Air temperature /Relative humidity	Monitored data.
Wind speed and direction	0.83 m/s - 135°
Specific humidity at 2500 m	4.5 g/kg
Roughness length	0.1 m
3D tree	Palm
Walls/Roof Materials	Mortar / Tiled
Initial conditions for soils	Upper Layer: 293K
Materials: Concrete and Soil.	Middle Layer: 289K
	Deep Layer: 285K
Start Simulation Day (DD.MM.YYYY)	07.06.2017
Start Simulation Time (HH:MM:SS)	07:00:00
Total Simulation Time (hours)	40h
Save Model State (min)	30 min

2.4 Hybrid Simulation Workflow

The second workflow is a hybrid approach using the Ladybug tools, a set of environmental plugins for Grasshopper that connects various validated simulation engines such as EnergyPlus, OpenFOAM, Radiance or Daysim into the same graphical interface, allowing designers to change the design according to the environmental performance of the model. This method calculates the different factors that intervene in the microclimate separately. Honeybee will run Energyplus for surface temperatures and Radiance for solar radiation. Butterfly will run OpenFOAM for CFD analysis. The outputs of each model are used as inputs for another. Again, outdoor monitored temperature, humidity and wind speed are inputs in the simulation. This kind of workflow has been tested and validated by other authors in urban areas [4], [5]. This research aims to validate it on the smaller scale of courtyards. The main difference from the method applied in other studies is the use of a solver that includes buoyancy forces and surface temperatures in the CFD study, given their importance in courtyards. Here, the OpenFOAM heat transfer solver, called buoyantBoussinesqSimpleFoam, is used. This is a steady-state solver for buoyant, turbulent flow of incompressible fluids that uses the Boussinesq approximation, which means that the air density is considered constant [8]. The workflow described is represented in Figure 2.

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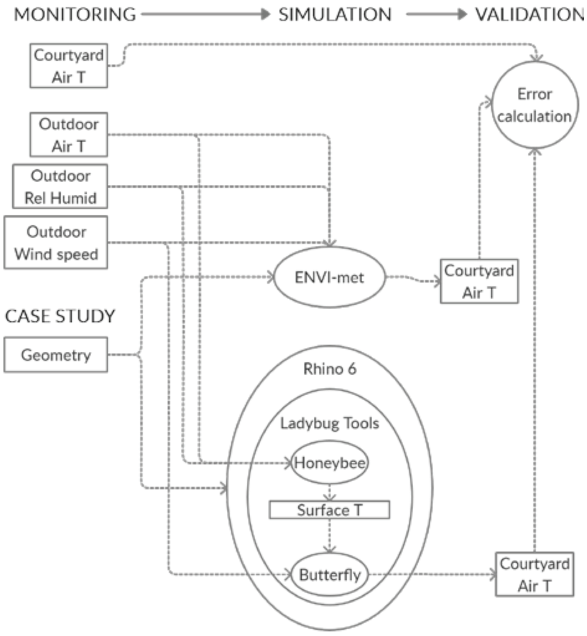

Figure 2: Flowchart showing how different inputs and outputs relate to the simulation tools and validation. T = drybulb temperature.

3. RESULTS

3.1 Monitoring results

Figure 3 shows the monitored temperatures inside and outside the courtyard on the selected representative day, the 8th of June. The maximum outdoor air temperature rises to 37.7 ºC at 14.00 hours and inside the courtyard, it is 33 ºC at 3.5 m high and 31.9 ºC at 1.5 m, providing 5.8 ºC of thermal delta. Maximum thermal delta during the day is 7.4 ºC at noon. In the night, temperatures in the courtyard are slightly higher than in the outdoors: an overheating of 1.4 ºC happens at 7.00 hours.

Another interesting monitored effect in the courtyard is the stratification that happens at different heights. During the day, differences of up to 3 ºC are observed between the lower level at 1.5 m and the higher at 3.5 m.

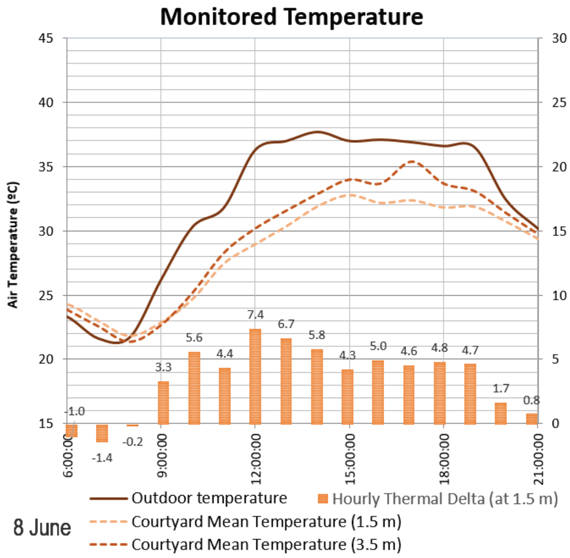

Figure 3: Monitored temperature on the 8th of June.

3.2 ENVI-met simulation results

ENVI-met simulation results are shown in Figure 4, where it can be seen that although the software is able to predict a reduction in the temperature inside the courtyard, the thermal delta is much smaller than in monitored results (maximum calculated thermal delta of 2.0 ºC at 14.00 hours). It is also quite constant throughout the day, in contrast to the monitored data where differences at different hours are noticeable and early-morning overheating in the courtyard is observed.

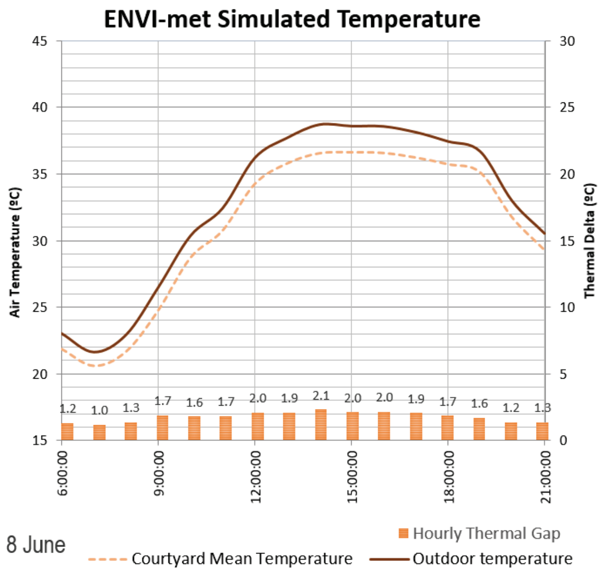

Figure 4: ENVI-met simulated temperature on the 8th of June.

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3.3 Hybrid Workflow simulation results

Final results of courtyard temperature from the integrated workflow are shown in Figure 5. The maximum thermal delta using this tool is 2.4ºC at 14.00 hours. It is also much lower than the monitored delta. However, the courtyard temperature curve correlates better with the monitored one, showing different thermal delta at different hours of the day, being able to predict also the overheating that occurs in the courtyard during the night.

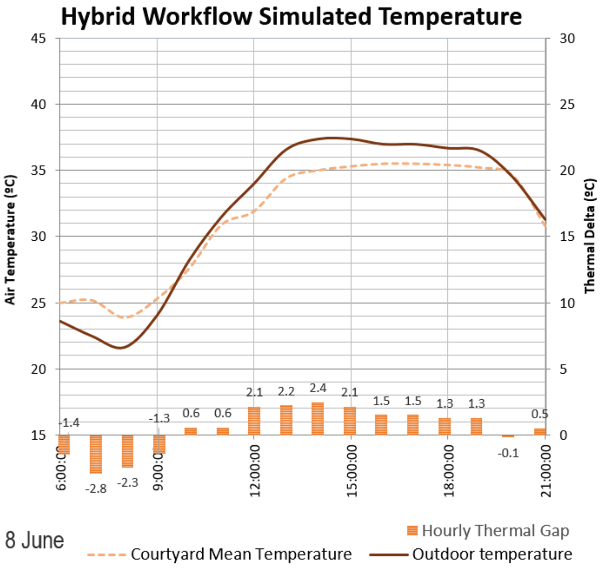

Figure 5: Hybrid Workflow simulated temperature on the 8th of June.

4. DISCUSSION

The temperature distribution inside the courtyard at 14.00 h from the two different workflows is shown in Figure 6 and Figure 7. This is the time when the simulation provides the maximum thermal delta. It can be seen that the temperature simulated by the hybrid workflow is lower than in ENVI-met, and it is more homogenous inside the courtyard at the same level. On the other hand, ENVI-met is not able to show the stratification inside the courtyard at different levels, while the simulated workflow is able to simulate a temperature difference of up to 2.5ºC between the lower and the higher level of the courtyard. This stratification effect has been proven to occur in courtyards of this size by our previous research [9].

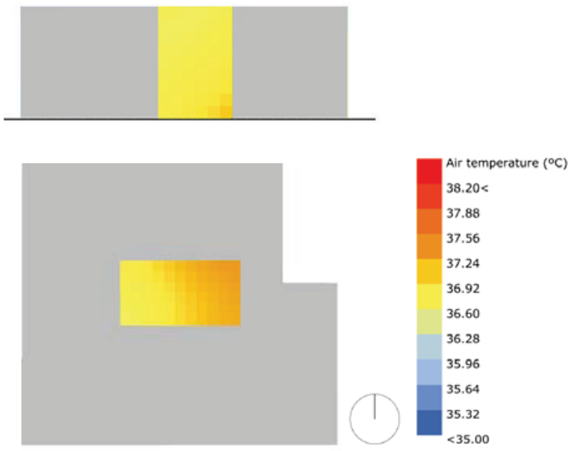

Figure 6: ENVI-met simulated air temperature at 1.5 m above the ground of the courtyard at 14.00 h of June 8th.

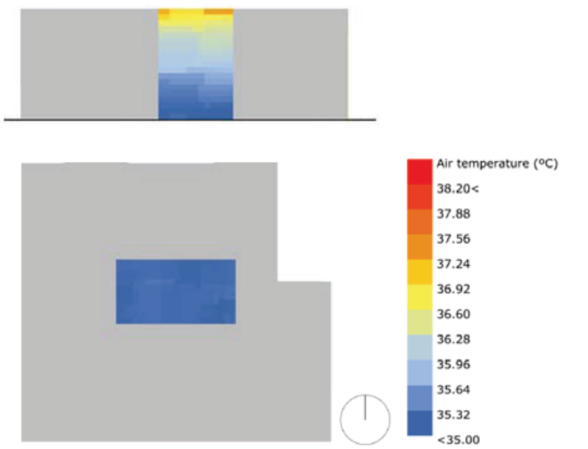

Figure 7: Hybrid Workflow simulated air temperature at 1.5 m above the ground of the courtyard at 14.00 h of June 8th.

The numerical results obtained from the two different simulation workflows are compared with the results from the monitored data using the following statistical parameters: coefficient of determination (R^2) and the Root Mean Square Error (RMSE) which, in order for a model to be considered reliable, must tend to the following values: $R^2 \rightarrow 1$, RMSE $\rightarrow 0$. These values are calculated with the mean temperature at 1.5 m from the floor of the courtyard and the outdoor temperature. Table 3 shows the values for each of the simulations.

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Table 3: Quantitative evaluation of the simulations performance

		R^2	RMSE (°C)
ENVI-met simulation	Outdoor	0.99	0.84
	Courtyard	0.88	3.54
Hybrid workflow simulation	Outdoor	0.96	1.16
	Courtyard	0.97	2.95

ENVI-met shows better results for the outdoor temperature, while the hybrid workflow simulation is better in simulating the courtyard temperature, which is our real objective. The coefficient of determination of 0.97 of the proposed workflow is higher than 0.88 from ENVI-met. The Root Mean Square Error is also 0.5 °C lower. These results validate the use of the hybrid workflow in the design process.

This process also has multiple advantages that are not provided by the use of ENVI-Met.

- The hybrid workflow involves the use of open source software, (although it still needs Rhino, which is not free but is already used by many designers). The open source software means that there is more flexibility and transparency about the process that is being followed, and there are ways to optimize the simulation in the different steps. This is not possible with ENVI-met, that follows its own solvers in an obscure "black box" that cannot be modified.
- The hybrid workflow is much faster and is not restricted to the simulation of one whole day to obtain accurate data. It can be simulated hour by hour. This shorter time needed to have results allows their integration in the early design process, characterized by fast changes in the project.
- Importantly for early design, although the hybrid workflow uses many different simulation tools, the Grasshopper interface links all of them to the same geometry –namely, the designer's own 3D model.

However, there is one disadvantage of the hybrid workflow. It is not easy to include the effect of evapotranspiration of the vegetation or water features, which may be important elements in some courtyards. This factor is one of the main advantages of ENVI-met. However, the flexibility of the hybrid workflow and the open source characteristic of the software involved, make it possible to include the vegetation in the solver in the future. The improvement of the accuracy of the results is also something that needs to be studied.

5. CONCLUSION

This study aims to investigate the 'goodness of fit' of the simulation results to the measured data in courtyards, using a hybrid workflow that uses the modelling interface that a designer might be using for the design, which allows a good connection between the simulation results and the early design to make decisions. It is not limited by a long time of simulation to have results and they have shown that the hybrid workflow is valid and has multiple advantages.

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