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OUTDOOR COMFORT SIMULATION OF COMPLEX ARCHITECTURAL DESIGNS: A REVIEW OF SIMULATION TOOLS FROM THE DESIGNER PERSPECTIVE

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ABSTRACT

The expanding design interest in outdoor comfort design is today supported by a few software tools. Given their different user-friendliness, modelling environments and simulation engines, a rational inquiry is how they are integrated into the digital design flow of architects and urban planners, which may include complex forms developments. Preliminary work is conducted to select architect-friendly tools that support the analysis of urban microclimate. A minimum set of criteria (amongst them the use of 3D models, the capability of calculating Mean Radiant Temperature and visual graphical outputs) led to the pre-selection of CitySim Pro, ENVI-met, Autodesk Thermal CFD, Grasshopper plug-ins Honeybee / Ladybug.

The complex modelling experiment is conducted by simulating the outdoor thermal comfort of the space underneath the Rolex Learning Centre in Lausanne with each of the tools above. The paper describes and compares the principles, the procedures and the resources needed to prepare sound models that reduce the time of computation without compromising the quality of results.

The potential applicability of tools in design is finally discussed from a user's point of view. The tools' capability of creating a 3D complex geometric model, or of importing one from a typical architectural tool, such as Rhino, is studied. Furthermore, it is debated how models can be used in the broader digital environment.

INTRODUCTION

Design choices alter local environments by influencing a series of thermodynamic phenomena, which impact in a substantial way human thermal comfort (Anon 2017). This makes it imperative to focus on microclimate design to raise people's health and wellbeing (Santamouris & Kolokotsa 2016; ONU 2014). Because of the dynamic nature of the urban environment, it is still difficult to quantify and manage the physical variables that play a role in urban microclimates (Robinson 2011). In the last decade, the scientific community has become increasingly interested in outdoor comfort analysis, and a few modelling tools are today available to predict microclimatic conditions (Coccolo et al. 2016a). It is thus a challenge to model the outdoor comfort quality of design options (Coccolo et al. 2016a, Balslev et al. 2015, Matzarakis et al. 2014, and Ng et al. 2015).

Urban and Architectural Designers are becoming aware of the need of designing the microclimate (Naboni 2014a). Still, the potential users are confronted with the dilemma of choosing a suitable Outdoor Comfort Simulation tool. Architects and urban planners are challenged with the selection of tools that fit in their "digital ecosystems", being these either BIM-based or Rhino/Grasshopper ecosystem (Mackey & Roudsari 2017).

Whilst the integration of environmental analysis and building simulation into the design process is a topic discussed mainly at the building scale (Bleil de Souza 2012; Attia et al. 2012), this is not the case for the outdoor microclimatic scale. Old claims, such as "Tools developers rarely state the tool's capabilities and limitations" (Reinhart et al. 2006), are even more relevant in a nascent field as the one of outdoor simulation. Outdoor comfort calculation tools and their capabilities were assessed in previous research (Naboni et al. 2017a; Naboni et al. 2017b), what was not discussed yet, is their usability by designers, architects and urban planners, for the modelling of geometrically complex spaces.

The critical contribution of this paper is thus to describe the principles of complex models development seen from a user's perspective. The description encompasses the analysis of the different tools that are able to assess outdoor comfort in light of their integrability in a design process and their integration in commonly used digital modelling ecosystems.

The potential users of microclimatic modelling tools are in some cases confronted with a lack of specific information about the tools' capabilities of being implemented in their practice (Naboni et al. 2017a; Naboni et al. 2017b). Information about tools interoperability with modelling environments, geometric input type, responsiveness to design modifications and simulation time is thus studied. However, the readability of results, the exportation of results for further analysis, the computational flexibility and the accuracy, are not discussed in this paper as already discussed in previous publications (Naboni et al. 2017a; Naboni et al. 2017b).

Four microclimatic tools were selected for this study: CitySim-Pro (Kaempf 2009), ENVI-met (Bruse 2014), Autodesk Thermal CFD (Autodesk 2016a), Grasshopper plug-ins Honeybee and Ladybug (Roudsari et al. 2013; Roudsari 2017b). The paper findings are based on the creation of a Rhino geometrical model of the Rolex Learning Center at the EPFL Campus in Lausanne (Switzerland), which features a series of geometrically complex outdoor spaces that are intertwined within the building.

OUTDOOR COMFORT SIMULATION

In the last decade, the scientific community has become increasingly interested in outdoor human comfort analysis. A few modelling tools exist to quantify outdoor human comfort as well as the microclimatic conditions of the built environment. Among them, the most commonly used in the research domain are ENVI-met (Bruse 2014), SOLWEIG (Solar and Long-Wave Environmental Irradiance Geometry (Lindberg 2015), the RayMan model (Matzarakis 2015) and the UTCI calculator (Wojtach 2016). All of them can quantify outdoor environmental conditions as well as outdoor human comfort, by way of the Physiological Equivalent Temperature (PET), Universal Thermal Climate Index (UTCI) and Mean Radiant Temperature (MRT). They have been applied to compute climatic conditions that range from urban canyons to city scale (Elnabawi et al. 2013, Lindberg et al. 2016, Taleghani et al. 2015). Among these tools, just one, ENVI-met, can represent more complex 3D geometry.

In the last three years, several practice-oriented tools have also been developed and refined to include outdoor comfort modelling. These are based on 3D models: CitySim Pro, Ladybug/Honeybee and Autodesk CFD. The tools vary in their simulation engine nature as later described. Although a variety of Comfort Indexes defines outdoor Comfort, it has been decided to analyse the MRT as the output of the analysis, as it describes the environmental exchanges due to radiation of the built environment (Matzarakis 2014). The Mean Radiant Temperature (°C) is defined as the "the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space"(ASHRAE 2010). Finally, since this study is not related to schematic design tools, but to more advanced detail development, a further criterion for tool selection is the possibility of modelling 3D complex shapes. SOLWEIG, RayMan models and UTCI calculator are thus not an object of the study.

CitySim Pro (Kaemco 2016) aims to simulate and optimise the sustainability of urban settlements by predicting energy fluxes at various scales, from a small neighbourhood to an entire city. Its microclimatic modelling is on-going research, with the objective to quantify the MRT (Coccolo et al. 2016b), ITS (Coccolo et al. 2014) and COMFA*(Coccolo et al. 2015). ENVI-met (Bruse 2014) is a three-dimensional microclimate model designed to simulate the surface-plant-air interactions in an urban environment by defining the microclimatic conditions of the selected sites. Ladybug and Honeybee (Roudsari 2017a and 2017b) are two open source environmental plugins for Grasshopper built on top of several validated simulation engines. Autodesk CFD (Autodesk 2016b) provides computational fluid dynamics and thermal simulation; it allows to calculate outdoor comfort indexes based on finite element methods (FEM), including MRT (Autodesk 2016a).

DATA ENTRY, GEOMETRY MODELLING AND MODELLING ECOSYSTEMS

This paper discusses the creation of geometrically complex outdoor comfort models from the user of the performance simulation. It defines criticalities from that point of view and discusses some of the options the users have today, with the hope that the discussion will lead to fewer struggles in simulating the outdoor comfort of complex forms. The paper does not attempt to deal with software capabilities and limitations that were addressed in previous publications (Naboni et al. 2017a; Naboni et al. 2017b; Mackey et al. 2017).

The study focuses on the steps that are necessary to prepare a sound model that allows for an outdoor comfort simulation. This consists in the creation of a model, the attribution of materials, the definition of building operations, the definition of boundary climatic conditions and the assignment of a weather file. A further focus of the paper is on how tools cooperate with their modelling and digital design ecosystems.

The paper does not focus on the time of computation (CPU time), nor on simulation results accuracy. However, models are prepared for the least time of computation that provides a reasonable quality of MRT results.

To scrutinise tools “in action”, a case study involving a multifaceted curvy geometry was chosen. This is in opposition to the simple urban canyon geometry used in several studies. The design of contemporary buildings and spaces should not always be reduced to linear urban boxes, and simulating complex form is oftentimes a need of the practice. To evaluate the selected tools, the EPFL campus of Lausanne (Switzerland) is chosen as a case study, where the outdoor environment around and under the Rolex Learning Center is analysed (Figure 1). Its waved geometry occupies an area of 166 by 120 meters that organically welcomes the public to the courtyards. The building generates different outdoor comfort conditions. The undulating floor affects the air flows underneath the building, and the fourteen voids create a complex set of zones (e.g. sun-lighted/shaded, the wind exposed/protected) and ground materials (hardscape and vegetation).

A base architectural 3D architectural model was created with Rhinoceros (Figure 2), one of the most popular modelling tools among international design practices (Naboni 2014b). The model, made with the use of closed poly surfaces, is set up to reflect the details that potential designers would create with no simulation tools in mind at this first stage. Its extension, which includes all the surrounding buildings and surfaces that may affect radiation and convection exchanges, is of 600 by 600 meters. The 3D was imported into CitySim Pro, Autodesk Thermal CFD, and Ladybug / Honeybee. The model needed to be rebuilt within the ENVI-met interface.

Figure 1. View of the space complex underneath the Rolex Center. (Credits: Sanaa).

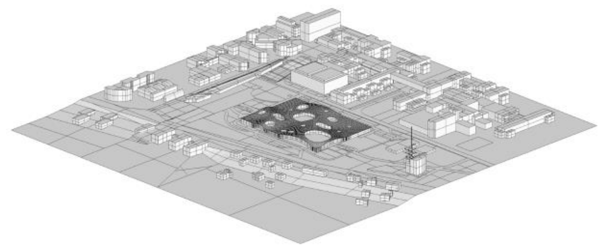

Figure 2. View of the full rhino Model of the Rolex Center and the surrounding campus.

A typical meteorological year (TMY) profile of the city of Lausanne was generated with Meteonorm (Remund et al. 2015). Simulations were performed with an i5 dual core Personal Computer with a processor clocked at 1.70 GHz. As a supplement to the test, and with the aim to present comprehensive information, all the software manuals and online information were scrutinised (Autodesk 2016a; ENVI-met 2015; Roudsari 2017a and 2017b). Moreover, there were interviews and email exchanges with the software developers of each of the presented tools, to acquire all the information that is necessary for the most efficient geometry transformation and the data inputting.

THE PATH TO A FIRST SUCCESSFUL RUN

It is here described for each of the tools the procedures that lead to a successful run. CitySim Pro has, at the time of writing, no guide to the modelling. It was key to establish a dialogue with the developers to understand how to create a model. The software has straightforward rules for the creation of thermal zones, geometry and materials with the aid of Rhino. The adaptation of the Architectural Rhino model is based on the creation of Rhino surfaces for ground and shading surfaces, and the creation of closed polylines for buildings (Figure 3). With CitySim it is necessary to build a new model in Rhino that is functional to the simulation, and it is necessary to re-assign materials.

The model must then be exported as meshes to have it ready to be opened by CitySim Pro (Figure 4). It is necessary to operate within the script of CitySim Pro to create materials. Each of the surfaces of the model has to have normal vectors directed toward the outside. Each element type (building, ground, shading surface) needs a proper layer and a correct name in the transformation of the architectural model into a Citysim, base model. The thermal reflectivity of each mesh in shading surfaces needs then to be assigned for each surface, which can take longer.

CitySim Pro calculates an MRT based on the Integral Radiation Measurement (Coccolo et al. 2016b; Miller et al. 2015) and the time of computation of MRT is relatively short. In two hours of simulation, a full year of outdoor MRT data can be computed for a given point. An essential element to improve the time for simulations is to reduce the number of surfaces, this also to facilitate the manual inputting of each surface thermal reflectivity. CitySim computes buildings surface temperature also on the bases of building operations sound insulation level (Walter et al. 2015).

ENVI-met requires a specific work in preparation of the geometrical model (Figure 5) which is time-consuming for a complicated building as the Rolex Center. The geometry needs to be built within the ENVI-met modelling tool. Assigning all the materials is part of the preparation of the model. In comparison to other tools, ENVI-met has a complete library of materials, which facilitates the process of data research. The ConfigWizard tool helps to create and edit ENVI-met simulation file (.SIM), putting the weather data manually to start the simulation. All the model geometrical modifications are operated within the software.

Time of computation depends on the dimension of the voxel, which for the experiment is set to $2m^3$. It is key that the user defines the best compromise between the resolution and the time of computation. For this specific experiment, the time of computation of MRT in a given hour required two hours of computation. This is because, within a three-dimensional model, both vegetation and buildings modify all of the radiative and convective fluxes. Depict the long time required for simulations, the output provided by ENVI-met is complete as it is a native software conceptualised for outdoor studies and allows for the full microclimatic description of the site.

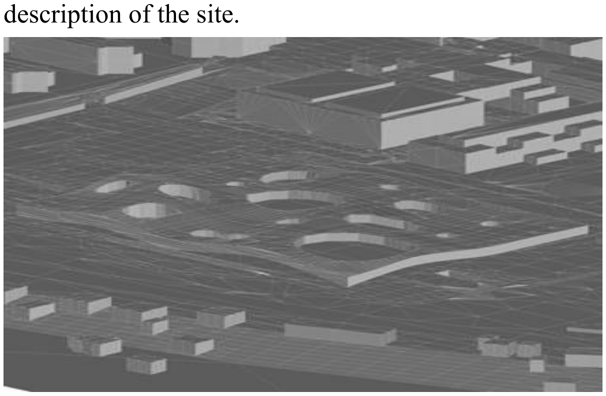

Figure 3. Rhinoceros. Meshed model ready to be imported into CitySim Pro.

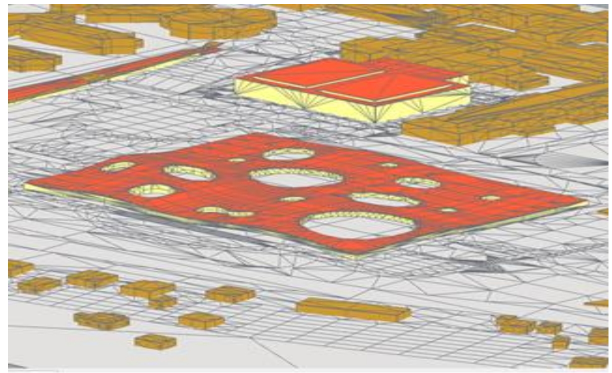

Figure 4. CitySim-Pro. The model includes an explicit subdivision of layers (Buildings, Shadings, Grounds).

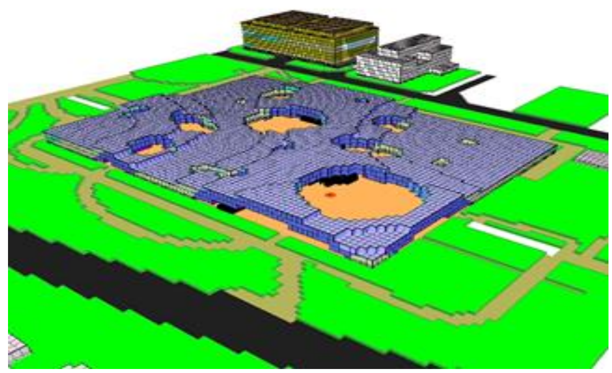

Figure 5. ENVI-met. The model was manually created based on a jpg map.

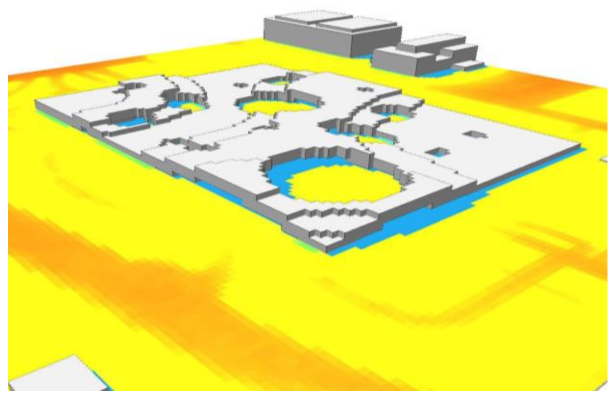

Figure 6. ENVI-met. MRT Output.

The Ladybug and Honeybee calculation of MRT is based on a specific component defined by Mackey in 2017 as “hybrid” as it “separates the factors that contribute to outdoor thermal comfort and simulating each individually with an engine that is validated to model each of this factor”. A further Computational Fluid Dynamics (CFD) tool, Butterfly, could be coupled with the radiative transfer calculations in order to calculate outdoor comfort maps.

It is possible to use the geometry from a Rhino (Figure 7), and creating simplified closed poly surfaces in order ro reduce the computation time (Figure 8. Thermal zones and materials need to be inserted according to the EnergyPlus format in order to calculate surface temperatures. The ground was also subdivided according to a grid. The resolution of the grid has an impact on the calculation times as well as on the accuracy of localized results. The Rolex surfaces are thus broken up into a minimum number to reduce the time of computation.

Time of computation is comparable to the one of ENVI-met and results can be customized in several formats and representations. The advantage of the Ladybug Tools is that it is open to use input and outputs from different calculation engines. For instance, it can derive building temperatures from CitySim, rather than with EnergyPlus, thus reducing the time of computation by a significant factor (Peronato et Al.).

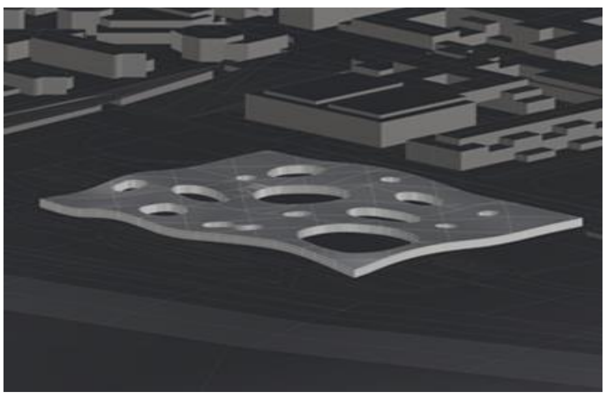

Figure 7. Ladybug. Any native Rhinoceros model can be used.

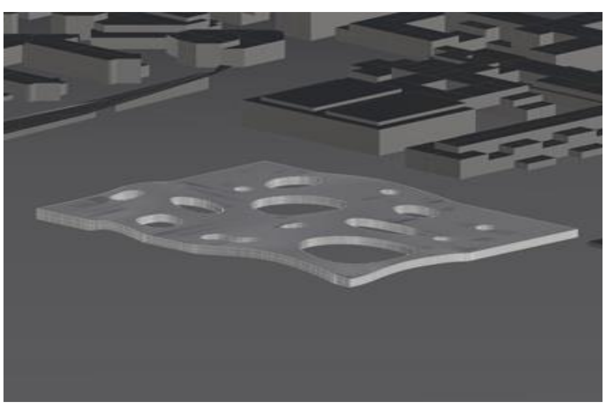

Figure 8. Rhinoceros. Optimised 3D model for Ladybug with a limited number of surfaces.

Autodesk CFD requires the geometrical transformation of the architectural model into one that is importable. The Rhino model needs to be optimised (Figure 9). The entry geometry necessities to be composed of solid volumes (closed extrusion or closed poly surface), avoiding gaps to prevent voids filling with air (watertight). Before running a CFD analysis, the geometry is automatically meshed by the CFD tools into small pieces called elements (Figure 10).

Meshing is an important feature that is facilitating the adoption of CFD in architectural design. It simplifies the set-up of analysis models, resulting in less time spent assigning mesh sizes. The quality and number of elements have a direct impact on the computation time and soundness of the analysis results', and this setting can be optimised within the tool. There is no preferable setting of layers in Rhino, as the materials need to be re-assigned. Each of the materials has to manually given to every surface within the tool.

Autodesk CFD activates both flow calculations and heat transfer calculation based on solar radiation to account for MRT (Autodesk 2016a). The interaction of natural ventilation flow with thermal heat transfer properties of solid materials is computationally very intensive. To reduce the computational time a forced convection analysis is set up. The flow and heat transfer can be solved separately because the flow does not depend on the temperature distribution. An often-used technique is to compute the flow solution before calculating the thermal distribution: the flow and heat transfer solutions are decoupled. With this method, the CFD can reach convergence and provide Steady State results in a reasonable time.

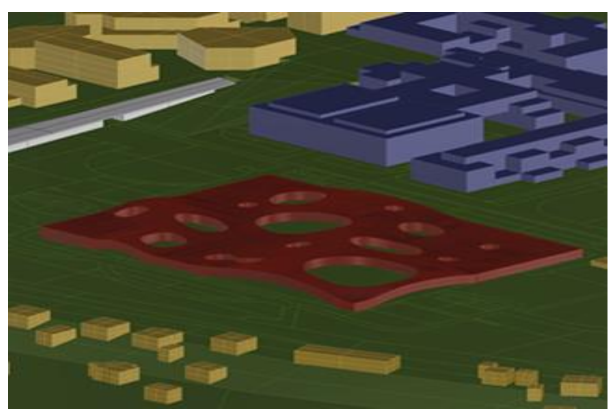

Figure 9. Rhinoceros. Closed model ready to be imported on Autodesk CFD.

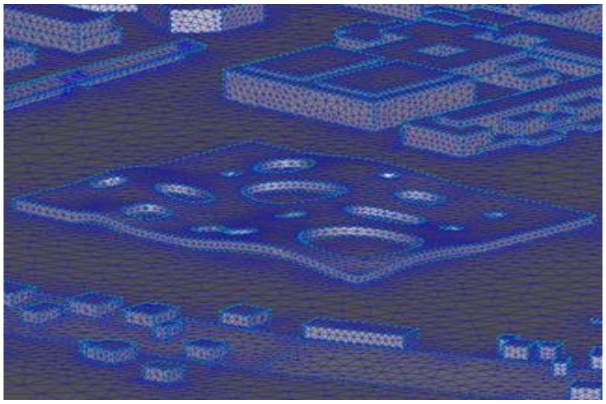

Figure 10. Autodesk CFD. Meshed model made by the Meshes sizing command.

DISCUSSION

The challenge of modelling a non-orthogonal space as the one underneath the Rolex building allows the appraising of modelling capabilities. In all of the tools, it is recorded, via the conducted experiments, that the effort in the preparation of simulation input is in getting the first successful run. The process that comprises input definition debugging, computer runs and analysis of results are repetitive and based on feedback. It takes many iterations before the result is satisfactory. Subsequent additions and modifications to simulation input that might be needed for other runs require, in general, comparatively little effort.

It is known that the "outdoor simulation view" of a model is different from the architects' and engineers' view. To achieve a proper model, it is necessary to understand the engine logic behind the calculation of MRT. To get accurate MRT results in a reasonable time, the geometry of analysis models needs to be simplified. Some details should be wholly omitted; for example, architectural details that do not significantly affect radiation and convective exchange with the human body should be neglected in order to reduce the time of computation. The preparation of outdoor comfort simulation models involved for each of the tools thus requires knowledge of thermodynamics principles to simplify the model intelligently. Although the outdoor thermal simulation view should contain much less information, it may demand peculiar details to be added. For instance, in CitySim, Ladybug Tools and in Autodesk CFD, the ground should be subdivided into multiple surfaces for accurate results.

To a designer that is preparing the Rhino geometry, converting a building and space geometry which contain several geometrical entities such as surfaces, open poly surfaces, closed poly surface, meshes, etc. into the specific geometry entities that are required by any specific outdoor comfort simulation tool is a challenge, as, not surprisingly, each simulation tool can receive just one specific geometrical entity.

CitySim fully import complex geometries in .dxf, .gml and .stl formats. CitySim does not allow to modify the model geometry once imported. Using ENVI-met means that the model needs to be re-drawn according to an orthogonal Arakawa C-grid. Using such grid means that certain objects and details are difficult to be modelled and needs to be approximated. Ladybug and Honeybee allow for Rhino's real-time geometrical modifications, and details can be included. Accordingly, there is no need of importing models. Autodesk CFD imports complex geometries in several file format as .3dm, .stp and .unv. It requires the entry geometry to be composed of closed extrusion or poly surface.

As the complexity of the buildings/spaces increase, input preparation could become more and more the primary catalyst for abandoning (or not even starting) the simulation project. Moreover, some repetitive manual operation that in essence amounts to a duplication of already existing data contained in the architectural model is needed. This process could be error-prone, and the resulting simulation input code could be difficult to debug.

When budgeting for outdoor comfort performance simulation, the time of input preparation and the time of simulation runs (i.e., computer run management and computer time) vary depending on the tool. CitySim Pro (which does not account for airflows computation) is rather fast and suitable for yearly simulations. The MRT calculations in ENVI-met and Ladybug takes a similar amount of time, and they are suitable for calculation specific to chosen hours of the year. Ladybug Tools can provide a more competitive time of computation when CFD calculation via the Butterfly tool is not included, which is a legitimate approach for specific sites. Using Autodesk CFD for MRT studies of complex geometry is less efficient as the computation times is quite extended.

Finally, it is critical to understand how they participate in a digital design ecosystem. The advantages of operating within the BIM or Parametric tools kits (Mackey & Roudsari 2017) should be factored when selecting a tool. While ENVI-met is independent and with no connection to CAD software tools but the output is exportable in excel formats. Autodesk CFD belongs primarily to the BIM ecosystem. However, the final outputs are simple images that cannot be used. Citysim relates to Rhino, and numerical results can be easily used and imported in other tools such as Grasshopper. Ladybug and Honeybee tools link to Rhino/Grasshopper, and input and output are easily transferable and usable in customized workflows.

CONCLUSION

This paper examines from the users' point of view the modelling of outdoor comfort calculation of complex architecture models, with the use of four simulation tools that are potentially usable by architects and urban designers: CitySim-Pro, ENVI-met, Ladybug/Honeybee, Autodesk CFD. The paper qualitatively discussed the options of moving from a Rhino architectural model to the tools. In all cases, building geometry is revised because one cannot import the needed definitions directly from Rhino files that contain the original information.

It is clear that the idea of "seamless" acquisition of building geometry for outdoor comfort performance simulation is not at hand. Experienced human intervention is unavoidable to define the geometry and the materials of the simulation in all tools. Ladybug and Honeybee are the tools closest to the seamless and real-time use of Rhino with no modifications. CitySim and Autodesk CFD tools can automate parts of the process that establishes the definition and import of building geometry. These tools can expedite the process, avoid most errors. ENVI-met on the other hands does not import geometry, but once the model is built, it is very interactive and modifiable.

In summary, a performance analyst with modelling capability could today perform outdoor comfort analysis, and they could coordinate with designers to require specific characteristic models. Furthermore, the integration of outdoor comfort simulation in an architectural and urban planning and typical design process may not be as fluent as one would think. This paper does not come close to covering it with the depth required, but it provides the reader with an overview of the possibility to prepare an optimised model for outdoor comfort simulations.

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