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Integrating urban energy simulation in a parametric environment: a Grasshopper interface for CitySim

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Abstract: The increasing popularity of parametric design tools goes hand in hand with the use of building performance simulation (BPS) tools from the early design phase. However, current methods require a significant computational time and a high number of parameters as input, as they are based on traditional BPS tools conceived for detailed building design phase. Their application to the urban scale is hence difficult.

As an alternative to the existing approaches, we developed an interface to CitySim, a validated building simulation tool adapted to urban scale assessments, bundled as a plug-in for Grasshopper, a popular parametric design platform. On the one hand, CitySim allows faster simulations and requires fewer parameters than traditional BPS tools, as it is based on algorithms providing a good trade-off between the simulations requirements and their accuracy at the urban scale; on the other hand, Grasshopper allows the easy manipulation of building masses and energy simulation parameters through semi-automated parametric workflows.

In this paper, we present a preliminary version of the developed plug-in and a typical design workflow for the simulation and visualization of building performance at the neighbourhood scale. We conclude by discussing its scalability to larger urban areas using 3D geodata as input and the coupling with Computational Fluid Dynamics (CFD) simulations and optimization algorithms.

Keywords: building performance simulation, parametric design, solar potential, early-design phase

Introduction

Although it can be argued that design has always been parametric, today it is empowered by the use of digital models and, during the last decade, parametric tools have become part of the standard design workflow in architectural practice (Davis, 2013). In parallel, the advances in computational models enacted the use of building performance simulation (BPS) tools as part of the design process, even if their application at the early design stage is still not widespread. For this reason, Attia et al. (2009) stressed the importance of graphical representation of building simulation results and comparative evaluation of design alternatives at the early design phase, when architects are usually involved. In this sense, BPS tools coupled with parametric design techniques can give a visual feedback on different form variants so as to support a performance-oriented design process.

The use of parametric design coupled with BPS tools is already well established (Lagios, Niemasz, & Reinhart, 2010; Jakubiec & Reinhart, 2011; Roudsari & Pak, 2013) for sustainable building design. Honeybee (Roudsari & Pak, 2013) and DIVA 4.0 (Solemma, 2016) are two of the most known BPS interfaces for parametric design. However, they are intended for detailed design phases focusing on the building envelope, since they are based on advanced simulation engines like EnergyPlus and Radiance/Daysim.

Conversely, applications of BPS and parametric urban design are not common, although previous studies have shown their potential (Peronato, 2014; Peronato, Nault, Cappelletti, Peron, & Andersen, 2015; Nault, Moonen, Rey, & Andersen, 2017). They present in fact some limitations. For instance, Ladybug (Roudsari & Pak, 2013), a Grasshopper plug-in which is specifically conceived to support early-design decisions through solar and climate analysis, lacks capabilities for hourly solar and thermal simulations. Moreover, when applied for parametric analysis or optimization of a large number of design variants, simulations with traditional BPS are time-consuming. For this reason previous applications were limited to small samples of neighbourhood designs (Peronato, 2014), even if a meta-model of building energy performance can provide a valid faster solution (Nault et al., 2017). Finally, a large number of parameters is typically required by traditional BPS tools, and the lack of information at the planning and early-design phase is hence a major problem.

In order to overcome some of the above-mentioned limitations, this paper presents a new tool built upon existing software intended for neighbourhood-scale assessments of building energy performance, integrating a scale-appropriate simulation software within a parametric design workflow. We also present some possible applications, including assessment of solar irradiation and energy need, in the framework of a parametric analysis at the early-design phase.

Proposed method

The proposed tool consists in a new interface to CitySim (Kämpf, 2009; Robinson et al., 2009; Robinson, 2012), a simulation software that is faster and requires less parameters than conventional tools, as it includes models and algorithms that are intended for urban-scale applications. CitySim is usable as a command-line solver, just like EnergyPlus or ESP-r. It takes as input an XML file that describes the scene and saves as text files the hourly simulation results.

The tool is developed as sets of components for Grasshopper, a popular parametric design platform, and relies on the Grasshopper plug-in Honeybee (Roudsari & Pak, 2013). Therefore, it inherits all parametric features from the Grasshopper platform, easing parametric design explorations on building masses and other physical parameters, and it can be easily integrated into existing workflows based on Honeybee.

Description of the tool

The developed tool provides access to most of the CitySim features related to energy and solar irradiation simulation directly from the Grasshopper canvas. As Honeybee and Ladybug, the Grasshopper components are written in Python, which has become a popular language among computational designers because of its integration in many 3D-modeling software (such as Rhinoceros and Blender) and its relatively simple syntax. The plug-in source code is freely accessible and distributed with an open licence, easing the tool’s scalability and integration with other simulation software.

The tool uses the Honeybee thermal zones (*HBzones*) as the main simulation object. This allows an easy integration into existing workflows based on Honeybee, as well as the access to its construction library and import-export features.

The main simulation parameters are defined through Grasshopper components, which write the XML code that can be subsequently parsed by the CitySim solver. The output files produced by the solver can also be parsed by a Grasshopper component included in the tool so as to import the simulation results as a Grasshopper data-tree, for post-processing and visualization.

Definition of simulation input data and parameters

Below are presented the main simulation parameters and input data that can be defined through the components composing the interface of the tool (Figure 1).

Building geometry

The developed tool imports the building geometry through the Honeybee thermal zones. Each building must be hence geometrically modelled as a closed Boundary Representation (BRep) so that it can be transformed into a Honeybee thermal zone. In a typical case, each building surface (e.g. façade, roof face) is defined by a single BRep face. However, for detailed solar radiation studies, each surface can be subdivided into multiple co-planar sub-surfaces, for each of whom the incident solar radiation will be simulated. To reduce the memory and CPU expense of this task, an alternative workflow, based on simple 3D polygons with associated reflectance values and on CitySim's Simplified Radiosity Algorithm (Robinson & Stone, 2004b), has been developed in parallel to this work and proposed for urban-scale BIPV potential assessment (Peronato, Rey, & Andersen, 2017b).

Building constructions (composed of multiple material layers) are imported as part of the Honeybee thermal zones and defined by five physical parameters (solar reflectance, conductivity, thermal capacity, density and thickness). The solar reflectance of each building surface is set in CitySim as the one of the outermost layer.

The boundary conditions are also imported as part of the Honeybee thermal zones. By default, all surfaces are considered as outdoor exposed, except floor surfaces with boundary condition set to ground and other surfaces with alternate boundary conditions which are considered as adiabatic. The latter case is typical in building surfaces that are adjacent to those of other buildings and can be easily handled by using the Honeybee *IntersectMasses* and *SolveAdjc* components.

Building obstructions

Geometric obstructions can be included through the *Horizon* and *ShadingSrf* components. The former is conceived for far-field obstructions, while the latter is intended for close obstructions and terrain.

Far-field obstructions are defined as horizontal (azimuth) and vertical view angles. The far-field obstructions cannot be defined in traditional BPS tools such as Radiance/Daysim and EnergyPlus, unless they are geometrically modelled as a solar mask or already included in the climatic input (e.g. by adjusting the solar radiation for the time-steps in which the sun cannot be seen from the project location). However, far-field obstructions are particularly important for urban scale simulations for which the focus is usually on the relation between buildings and surrounding context rather than on the building itself.

Through the ShadingSrf component, complex 3D geometries can be also included in the simulation, accounting for their shading and reflective properties. This typically includes the terrain, vegetation and other surrounding constructions which can be imported as mesh geometries and assigned one or multiple solar reflectance coefficients.

Internal loads

Internal loads in CitySim can be defined as an activity associated to a device and as occupants. At the moment, the presented tool only supports internal loads related to occupants. Through the occupancy component it is possible to create different daily occupancy profiles (expressed as hourly ratio of total occupants) and yearly schedules (expressed as daily occupancy profile IDs).

Windows

Unlike the standard Honeybee workflow, in which windows are geometrically modelled as required by EnergyPlus, in the proposed tool windows are defined only by the Window-to-Wall ratio, as well as by three physical parameters (U-Value, g-value, openable ratio). This type of input-setting is particularly adapted to urban-scale simulations, in which the actual position of windows on façades is usually not known, while their influence on the energy balance is still very relevant. In the current release, the windows settings can be applied separately per each building (wall surfaces) or to all of them.

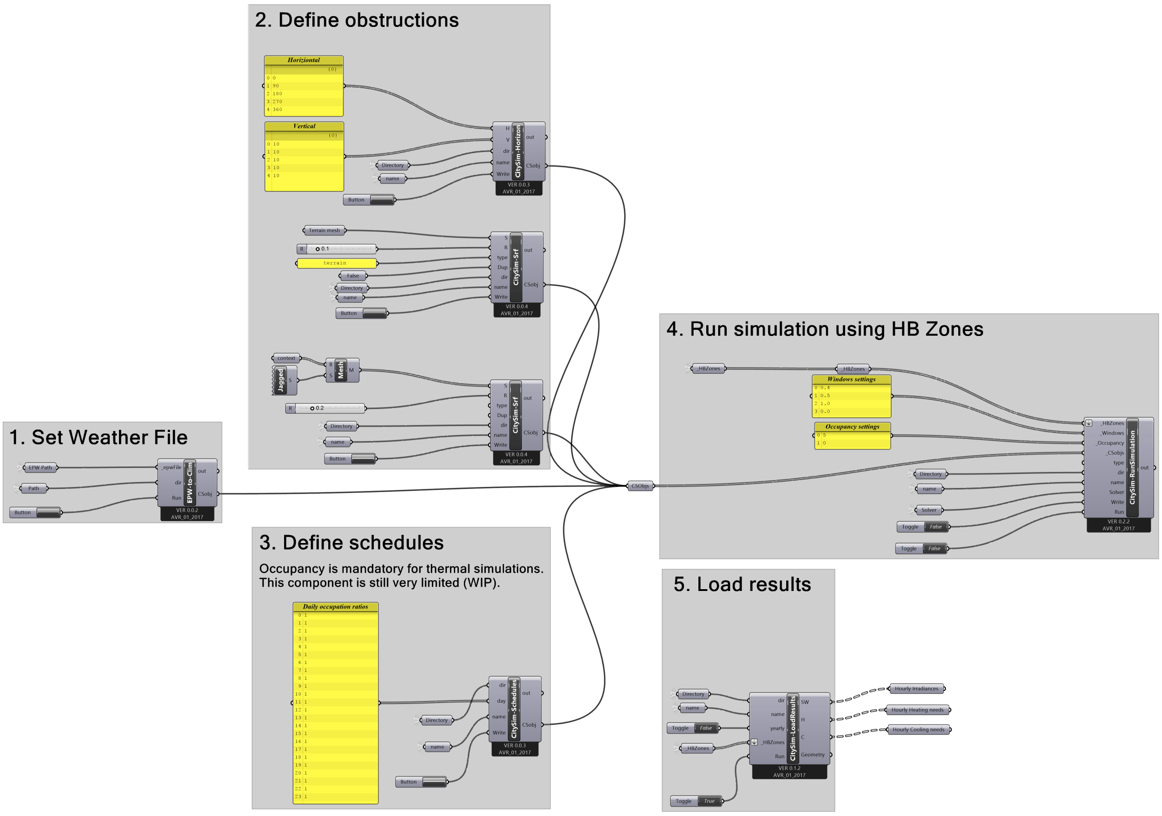

Figure 1. The interface of the tool on the Grasshopper canvas.

Sample applications

From an experimental point of view, the tool can be used for parametric studies, for example in the context of a sensitivity analysis or optimization process. As in other simulation interfaces based on Grasshopper, the simulation engine can be triggered whenever there is a change in the parameters and/or in the geometry. By using the “animate” function included in Grasshopper slider components, the simulation process can be thus easily automated. For instance, it is possible to run a simple parametric analysis or a fully combinatorial experiment by “animating” a single slider looping over a list of parameters.

From an analysis target point of view, the proposed tool can be applied to many fields requiring an assessment of solar irradiation and building energy needs since the planning or early-design phase. Unlike the GenCumulativeSky algorithm (Robinson & Stone, 2004a), included in Ladybug and DIVA providing time-cumulated energy simulations, CitySim calculates hourly values of energy demand and available solar irradiation. The hourly analysis allows a better understanding of energy flows than typical annual or monthly values and can therefore be included in energy network analyses, as well in neighbourhood-scale self-sufficiency/consumption estimations.

To test some of these capabilities, we here propose sample applications, which have been tested on a case-study derived from a student project (Peronato, Rastogi & Andersen, 2017; Rey, 2017).

Detailed solar irradiation study

The analysis of short-wave solar irradiation is useful for assessments of potential for solar energy systems. Typical applications include estimation of passive solar gains and energy production from solar thermal and photovoltaic systems (Compagnon, 2004). For this kind of applications, a detailed surface analysis is typically required so as to account for the complex urban shading and reflecting effect (Peronato, Rey, & Andersen, 2017a). Even if CitySim is conceived for thermal simulations in which a single value of solar irradiance for each façade is generally sufficient, higher resolution assessments are also possible. We can for example create building surfaces from detailed meshes with a target edge length and the solar radiation algorithm will then be computed for each mesh face, as can be seen in Figure 2 (left).

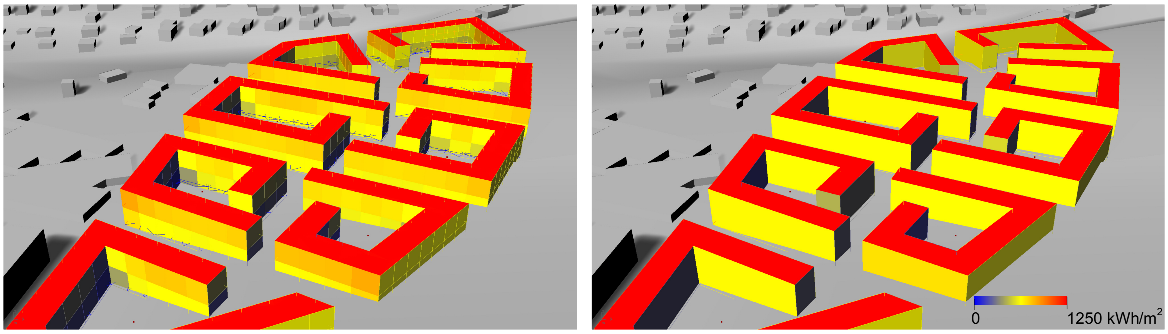

Figure 2. Annual solar irradiation study on meshed at 10-m resolution (left), simple surfaces (right).

Analysis of buildings energy needs

The analysis of the energy demand is particularly useful for estimating the passive behaviour of buildings. As shown by Nault et al. (2015), simplified geometric metrics and rules of thumb such as the shape factor (Surface/Volume) cannot fully capture the actual energy performance of a neighbourhood design, which depends on complex interactions between buildings, occupants and the natural environment. For this reason, it is interesting to use BPS tools to assess the actual energy demand for space cooling and space heating as an indicator of the buildings passive behaviour. To this end, the proposed tool allows a quick evaluation of the sensitivity of building energy needs to typical urban design parameters, such as the Floor Area Ratio (FAR), as shown in Figure 3.

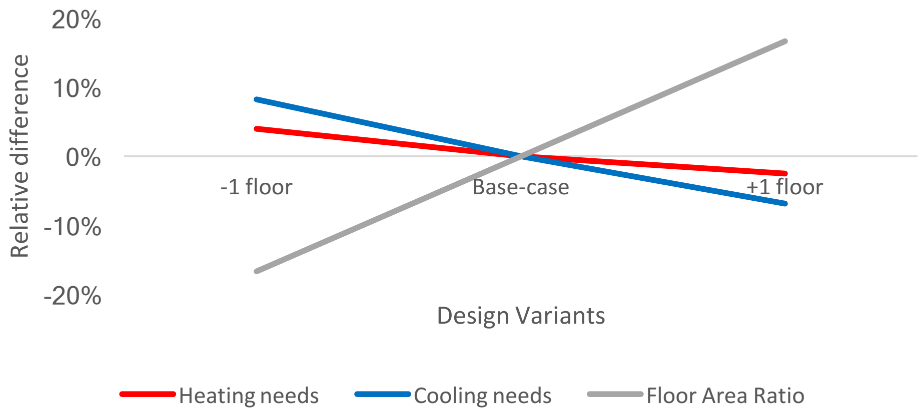

Figure 3. Parametric analysis comparing different building heights.

Limitations and outlook

Although the tool relies on the CitySim solver, at the current development stage it only supports a small part of its features. In particular, the tool is limited to thermal loads and solar radiation assessments, while support to HVAC modelling and district energy networks features are not included. However, the human-readable syntax of CitySim XML input files makes the future addition of these features relatively easy.

The analysis can be extended with details from 3D geo-information of existing urban areas. Typical data that can be imported and included in simulations are derived from LiDAR surveys and can be used to model terrain, vegetation (Peronato, Rey, & Andersen, 2016) and far-field obstructions. In terms of scale limitation, it is difficult to estimate the maximum size of analysis that can be conducted using this tool, as this is mainly dependent on the number of surfaces (and mesh faces) that can be handled in the memory of Rhino-Grasshopper. However, for large-scale analysis the area can be subdivided in smaller tiles, a common approach in GIS-based workflows.

Allegrini et al. (2013) showed how coupling CitySim with the CFD simulation engine OpenFoam can improve the accuracy of the simulated building energy demand, for instance using convective heat transfer coefficients derived from the CFD simulation taking into account the actual air flows in the urban environment. Since the Butterfly plugin-in recently introduced OpenFoam simulations for Grasshopper, in the future it should be possible to couple the two simulation engines directly in a parametric workflow, using some of the output data of OpenFoam as input for CitySim's thermal model.

Conclusion

This paper presented a preliminary version of a tool for urban energy assessments, based on the validated simulation engine CitySim, the popular parametric design platform Grasshopper, and built upon its plugin Honeybee. We described the tool's main components and listed possible applications with different experimental techniques and analysis targets. We also showed its advantages compared to existing tools in terms of number and type of input parameter, which are more suited for urban-scale analyses. We finally discussed future extensions including the use of 3D geodata and CFD simulations.

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Online repository

The Grasshopper components and the source code can be downloaded from an online repository accessible through the following link: http://lipid.epfl.ch/GH-CitySim.

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