An overview of urban building energy modelling (UBEM) tools

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Abstract

The construction of energy-efficient buildings and the planning of suitable energy supply systems are fundamental undertakings to reach a more sustainable future. Decision-makers need evaluation criteria and possible scenarios to establish the best options to decrease cities' energy consumption. Thus, in the last decade, several tools for Urban Building Energy Modelling (UBEM) have been developed to achieve this result. The aim of this paper is to give a practical overview of the different methods and approaches used by UBEM. The work compares the available and most relevant UBEM tools, to assess their potential and limits. The characteristics of the main UBEM tools are compared with the intent to create a brief selection guide for new users.

Introduction

The department of economics and social affair of the United Nations states that around 55 % of the world population currently lives in urban areas and this percentage is foreseen to rise further (United Nations, 2018). The construction of energy-efficient buildings and the planning of suitable energy supply systems are therefore fundamental undertakings to reach a more sustainable future, maintaining high-quality life standards in cities (Sokol et al., 2017). This is true for both the already developed urban areas and for the new ones. The former should be better managed in order to decrease their energy and carbon footprint, whereas the latter should be designed to assure the highest performances (Causone et al., 2018). To accomplish these tasks, decision-makers should be provided with evaluation criteria and scenarios to establish the best options to decrease cities' overall energy consumption. Urban Building Energy Modelling (UBEM) may provide an answer to this request.

Several tools and models available nowadays are focused on the single building scale. The UBEM tools analysed in this paper, are focused on buildings as well, but they are able to aggregate the results on the urban scale and to integrate also other detailed analyses that are peculiar of urban environments. Only this type of tools can be employed to identify the strategic mix of policies and renovation measures for large building stocks (Nagpal and Reinhart, 2018).

The existing literature is rich in reviews on the topic of urban building energy modelling (Frayssinet et al., 2018; Li et al., 2017; Sokol et al., 2017; Swan and Ugursal, 2009), but a user-oriented overview is missing. The goal of the present work is, therefore, to compare the capabilities of the different tools, as already done for building energy modelling (BEM) programs (Crawley et al., 2008).

UBEM tools show great heterogeneity, both for their aims and in terms of simulation approach (from dynamic complex engines as EnergyPlus to quasi-static approaches). The intrinsic differences among tools are exacerbated for large-scale analysis (from district- to city-scale), when different methods are used for the buildings modelling (and simplification) and their characterization through archetypes. The present paper aims to underline these differences creating a practical guide for final users to select the most appropriate UBEM tool for a specific analysis. Further one-to-one comparative analyses will be performed in future on specific topics, tools and outputs, since such a kind of analysis is not adequate to provide an overall overview of the characteristics of such a heterogeneous group of tools.

Urban modelling approaches

Urban modelling is a vast subject that can be addressed at different levels of detail, its nature is inherently dynamic since it concerns flows of goods, energy, waste and people. The possible analyses are numerous, they include buildings, traffic, renewable energy sources (RES), energy network, etc. However, in the field of urban modelling, it is possible to identify three main areas of interest, as follows. Land-use and transportation models are one of the first dynamic models applied to the urban environment; reference tools are UrbanSim (Waddell, 2000), OPUS (Waddell et al., 2005), ILUTE (Salvini and Miller, 2005) and ALBATROSS (Arentze and Timmermans, 2004). A second area is Urban Energy System Modelling (UESM), already reviewed in the literature (Allegrini et al., 2015; Keirstead et al., 2012). This type of energy modelling focuses on simulating and optimizing cities' energy systems, considering the distribution and transmission networks. Reference tools are EnerGIS (Girardin et al., 2010), Syncity (Keirstead et al., 2009), iTEAM (Salvini and Miller, 2005). A sub-group of UESM is represented by tools and methods aimed at modelling solar and photovoltaic (PV) potential of cities and districts (JRC, 2012; Kanters et al., 2014). The third and last area is the one concerning UBEM,

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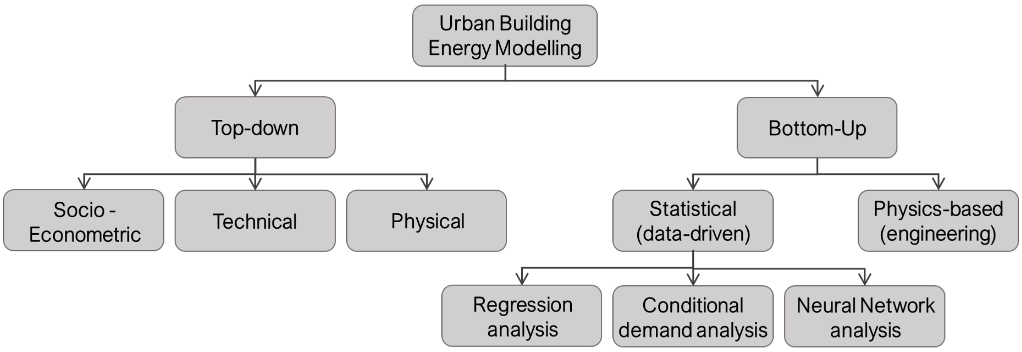

Figure 1: Schematic of the UBEM approaches.

focused on buildings modelling at urban-scale. This category includes different types of tools and methodologies with different scopes. Some tools deal with single and specific aspects, such as modelling the urban environment to assess and optimise daylight in buildings (Dogan et al., 2012), or the assessment of the effect of new green areas in cities (Castaldo et al., 2018). Other tools are focused on Life Cycle Assessment at urban scale (Davila and Reinhart, 2013) or include simplified but effective methods that are specifically focused on energy savings derived by building renovations (Dall'O' et al., 2012).

More complex tools and methodologies are needed when the purpose is to consider different aspects together. Among the modelling approaches two main categories can be identified: top-down and bottom-up (Kavgic et al., 2010; Li et al., 2017; Swan and Ugursal, 2009). In Figure 1 a schematic of the UBEM approaches is presented.

Top-down modelling methods

Top-down models estimate the energy consumption of buildings from agglomerated data on large scales. They estimate long-term relationships between the energy use of an urban area and some drivers. The typology of these drivers brings to a further differentiation: socio-econometric, technical and physical models. The first group is the most numerous and includes models that refer to social, economic and market-derived drivers (Bentzen and Engsted, 2001). The technical models provide a more detailed analysis of buildings, using buildings' technical features as drivers (such as systems, envelope, etc.) (Huo et al., 2019). The third group identifies environmental characteristics (e.g., the weather) as main drivers (Kavgic et al., 2010). These models need a few input data to describe buildings that usually consist of easily available aggregated data. In addition, long-term socio-economic aspects can be included in the model. However, this determines a limitation too, since they try to predict the future energy consumption on past interconnections between the energy and the economic sectors. A second drawback is the lack of technical detail.

Bottom-up modelling methods

Bottom-up models calculate the energy consumption at a single building scale and then aggregate the results at different levels, considering an integrated framework. To perform properly, they need a large quantity of data whose availability may be hindered by privacy and other issues. Among this typology of models, further differentiation is possible, between statistical and physics-based models. This differentiation is here proposed on the basis of the energy demand calculation method.

The statistical (or data-driven) models use data mining and machine learning techniques to assess the energy demand of buildings. The most used techniques include regression analysis, conditional demand analysis and neural network analysis. Regression methods are based on the regression analysis that links the energy demand of the building to combinations of several parameters (which are expected to directly affect the energy demand) (Capozzoli et al., 2015; Geyer et al., 2017; Mastrucci et al., 2014; Mostafavi et al., 2017). Conditional demand analysis methods estimate energy uses combining data derived from surveys, consumption registrations and weather data (Parti and Parti, 2016). The last methods implement neural networks techniques to assess the energy demand

Table 1: Summary of the analysed UBEM tools.

Tool	Website	Developer	Typology	Energy simulation	Presented in
CitySim	https://citysim.epfl.ch/	EPFL	Software in Java and C++	Equivalent electrical circuit	(Robinson et al., 2009)
SimStadt	http://www.simstadt.eu/de/index.jsp	University of Stuttgart	Software	ISO 13790	(Nouvel et al., 2015)
Umi – Urban modelling interface	http://urbanmodellinginterface.ning.com/	Sustainable Design Lab, MIT	Plug-in for Rhinoceros 5	EnergyPlus	(Reinhart et al., 2013)
CityBES – City Building Energy Saver	https://citybes.lbl.gov/	LBNL	Online Platform	EnergyPlus	(Hong et al., 2016)
CEA – City Energy Analyst	https://cityenergyanalyst.com/	ETH Zürich and Singapore	Plug-in for ArcGIS	(Fonseca and Schlueter, 2015)	(Fonseca et al., 2016)
TEASER - Tool for Energy Analysis and Simulation for Efficient Retrofit	https://github.com/RWTH-EBC/TEASER	RWTH Aachen University	Open source on Phyton	Design-driven reduce order model	(Remmen et al., 2018)

of buildings (Nutkiewicz et al., 2017; Talebi et al., 2017). A well-developed tool, that uses a combination of these three methods, is given by Environmental Insights Explorer (Google, 2018), that through advanced data analytics give support to policymakers to understand the carbon emission, solar potential and in general the feasible green future of cities.

The physics-based (or engineering) models deal with detailed modelling and simulation techniques derived by BEM. This last group is the one that this paper intends to study with major detail, since it includes the tools that may better evaluate scenarios for current and future urban environments management and design. In the last years, physics-based models experienced a rapid evolution, nevertheless they are usually time-consuming (detail description of the buildings is needed) and they require substantial computing powers.

Bottom-up physics-based UBEM tools

The earliest physics-based UBEM models implement tools directly from BEM, and they perform co-simulation with other detailed software for specific topics. An example is SOLENE-microclimate (Morille et al., 2015). However, at large-scale, the characterization of buildings is not easy and manually feasible, as for single buildings. Numerous researches deal with this problem and they propose methodologies to simplify the model enough to reach reasonable time and computing efforts. A method is presented to run successfully reduce-order urban scale simulations with EnergyPlus (Heidarinejad et al., 2017) and an algorithm is proposed that rapidly and automatically creates multi-zone urban models for the simulation with the same software (Dogan and Reinhart, 2017). Other methods are proposed to use the software IDA ICE (Nageler et al., 2017) and Dymola (Kim et al., 2013). The characterisation of the buildings in such approaches remains a challenge, and thus, other tools intended specifically for urban-scale simulations have been created. They are usually based on simulation engines used for BEM, but they optimised the processes to be scalable for large building stocks. They mainly use different strategies to create clusters of similar buildings (called archetypes) to assign characteristics to the 3D representation of the building stock that is usually based on Geographic Information System (GIS). The two main parameters used to create archetypes in the building stock are the layout of the buildings (geometry and typology (Bonhomme et al., 2012; Sokol et al., 2017)) and their year of construction (Caputo et al., 2013). In other cases, specific technical features of the building regarding the envelope or the systems (Monteiro et al., 2017), or the occupancy profiles (Buttitta et al., 2017) are used. In the following section, the main bottom-up physics-based UBEM tools are analysed, as summarized in Table 1. They are all characterized by different but simplified Graphical User Interfaces (GUIs). The order used in the tables refers to the first publication in which they were presented to the scientific public. Some advanced tools, as URBANopt (Macumber et al., 2016), are not included because they are not publicly released yet. This overview is intended as a developing study that will increase in detail and in the number of included tools with the advancement of the studies related to UBEM.

Comparison and discussion

The aim of this section is to answer some questions regarding the tools, such as:

- Which are the input data needed to run a simulation?
- Which are the outputs of the tool and how can they be used in a post-processing phase?
- What is the scope of each simulation tool and who can be interested in it?
- Who is the main potential user of a tool and which are the basic knowledge needed for its use?

This comparison will be performed considering the inputs, the outputs, the scale of analysis and the GUIs. From these comparisons, a comprehensive overview of the differences between the tools will be provided, to guide the user in the selection of the best option.

Input

All the tools require as input data the description of the geometry under analysis, the thermo-physical characterization of the buildings and the weather dataset. Table 2 summarises the different inputs necessary to run simulations with each of the considered tools.

The basic method to set the geometry of the building stock is by uploading a manually created 3D model. Since, on large-scale, it can be difficult to create a detailed 3D model of the built environment, tools as SimStadt, CityBES, CEA and TEASER are directly integrated with a GIS. CEA, being a plug-in for ArcGIS, is able to directly analyse the data from GIS databases, when available. In particular, SimStadt, CityBES and TEASER allow the users to upload XLM-based format files from CityGML (Open Geospatial Consortium, 2018), that is used to store and exchange virtual 3D city models. However, XLM-format files and GIS repositories are not always available for all cities and regions, especially for developing countries, and thus, these methods could be not easily applicable in all contexts. Therefore, all the tools allow the user to import a geometric model of the area of interest from manually created 3D files.

A fundamental phase of the settings is the characterization of the 3D geometry. Building fabric, technical systems, and schedules of buildings' uses must be assigned to each 3D geometry to be treated as a building during the simulation. Some tools use a simplification method that, based on just a few input data, can assign the characteristics to the buildings via archetypes. Archetypes are a powerful tool, however, they need a large quantity of data from which these "typical buildings" can be derived; thus, almost all the tools propose to the user already developed archetypes. CitySim and CityBES for example, allow integrating a default dataset based on general characteristics of the buildings with their intended use and year of construction and other data provided by the user to adjust the characterization of the buildings. TEASER allows, with the *data enrichment function,* to assign default characteristics based on three usually available data: the intended use, the year of construction and the volume of the buildings. SimStadt and CityBES, being well integrated with CityGML, allow the use of Energy ADE (Agugiaro et al., 2018). It is an extension of CityGML that helps running an urban scale simulation, since it includes further details of the buildings in addition to the ones available in standard geometry CityGML files, such as the thermal zones that compose a building, the building fabric, the occupancy conditions and the technical systems. These advanced datasets are useful to easily run simulations on large-scale.

All tools allow the user to upload a weather dataset in lots of readable formats (e.g., epw, txt, ddy, etc.). CitySim is able to extract it automatically for the set location. In building simulations, the effect of using not-reliable weather dataset is widely demonstrated (Erba et al., 2017). For example, dealing with cities' simulation, the urban effect on climate (e.g. heat island effect) should be considered, thus, urban weather dataset should be created. For this purpose, Umi is integrated with the *Urban Weather Generator* tool. It exploits a variety of characteristics of the urban area to convert a weather dataset of the rural station into a usable urban weather dataset accounting for hourly urban heat island effects. Other boundary conditions are the energy conservation measures to be tested and the energy targets to be achieved. CityBES and CEA have an easy interface to work with them and it is possible to directly understand the effects of changes on the building stock.

Output

Table 3 summaries the different outputs resulting from the simulations run with the considered tools. All tools calculate the energy needs of buildings and the efficiency of their systems. For almost all of them (except for CitySim and TEASER) the domestic hot water and electricity use are addressed directly as outputs. CitySim and Umi perform also daylight analyses inside buildings. Regarding the resource potential, CEA has the most advanced model that considers the ambient heat potential (e.g. geothermic, lake water and source of waste heat) and solar potential. Umi and CityBES directly perform the analysis to calculate the solar potential for the installation of PV panels, and SimStadt does the same using other databases (e.g. PVGIS (JRC, 2012)). Few tools are able to integrate urban energy systems in the simulation of the urban areas. TEASER allows the modelling of district heating and cooling, performing analysis on energy network efficiency and management. Regarding other large-scale evaluations, SimStadt, CityBES and CEA compare different scenarios of energy efficiency strategies, allowing also the evaluation of Green House Gas (GHG) emissions. In particular, CityBES is provided with 75 different strategies to be compared and evaluated including buildings envelope, HVAC and lighting. CEA is provided with a tool to perform a cost-benefit analysis of the applied strategies to provide an economic point of view in the evaluation of scenarios. The last possible outputs concern transport and mobility. CitySim is integrated with Multi-Agent Transport Simulation toolkit (MATSim-T (Community, 2019)) to perform transport analysis, whereas Umi is able to run simulations evaluating the efficiency of a district considering its walkability. All the tools provide outputs in the form of spreadsheet files (usually in CSV-format), allowing the easy post-processing of the results. All the tools, except TEASER, are equipped with automatic interfaces for the visualization of the results on the 3D geometry. With this type of visualization, the results are easily understandable and communicable.

Scale and simulation features

A fundamental aspect that has to be considered, when running a simulation, is the scale of the building stock that the tool can manage. With scale, it is intended the dimension of the area or the number of buildings that a tool is able to analyse. There is, nevertheless, a difference between the intrinsic limitation of the tool and the practical one. A simple example is given by the difference between CityBES and Umi. Even if they are based on the same simulation engine (EnergyPlus), the first one is an online platform that runs the simulation without the limitation of a personal computer, contrary to the second. Moreover, to evaluate different scenarios, CityBES includes a specific module, whereas to evaluate scenarios with Umi, at the current release, the input data should be changed. This example does not mean that Umi is a less powerful instrument, but that differences exist between the tools, although they use the same calculation engine.

Another issue concerning the scale is about the terminology. The term "city" includes, indeed, a wide variety of scales: from Shanghai (its area is about 6300 km^2) to Milan (its area is about 182 km^2). Unfortunately, the literature does not provide a common terminology or guides about the different tools. In order to perform a comparison among them, we do propose the following terminology. The basic case is the one of a *single building*, this case is easily modelled with traditional BEM tools,

Table 2: Summary of the possible inputs of the considered UBEM tools, in bold the mandatory input data.

Tool	Geometry		Building characteristics							Boundary Conditions		
			From single data									
	Manual 3D	GIS	Intended Use	Year of Constr	Volume	Others	Archetypes	Energy ADE	Manual	Weather data or location	Energy Conservation Measures	Targets
CitySim	x		x	x		x			x	x		
SimStadt	x	x						x	x	x		
UMI	x						x		x	x		
CityBES	x	x	x	x		x	x	x	x	x	x	x
CEA	x	x				x	x		x	x		x
TEASER	x	x	x	x	x	x	x		x	x		

also subdividing it into thermal zones. When multiple buildings are aggregated together and divided from other buildings by streets, they can be defined as a *block*. More blocks together can form a *neighbourhood*, that can be aggregated composing a *district*. The sum of all the districts creates a *city*.

The six UBEM tools in Table 1 can perform simulations at the scale of the block, of the neighbourhood, of the district and of the city. However, depending on the features of the tool (e.g., typology of simulation, inputs needed, etc.) one tool could facilitate large-scale analysis respect to another. SimStadt is well integrated with CityGML and Energy ADE, thus, it is easily exploitable for simulation from the neighbourhood-scale to the city-scale. Umi, for example, running very detailed analysis through EnergyPlus (differently from SimStadt or CEA that, at the current release, use simplified methods, as reported in Table 1) could be limited by the computer used to run the analysis. CEA seems to be the most versatile tool, easily allowing simulations from the block-scale to the city-scale. CityBES is optimized to run simulations on a large scale, from district to city-scale. Lastly, TEASER allows simulation on different scales, however, to consider urban energy systems the tool should be used at least at the neighbourhood scale. As highlighted in Table 1, the tools have different calculation engines. CityBES and Umi run dynamic energy simulations via EnergyPlus, whereas CitySim, SimStadt, CEA and TEASER adopt simplified calculation approaches. It means that, given the same scale of simulation, the first two require a much higher calculation power, although their results are more accurate (since based on dynamic simulation) and thus adapt to advanced analysis. CitySim, SimStadt and CEA may run faster simulations for large scale geometries, thus are very good for early design stage analysis when several options must be investigated in a short time. In general, there is not a specific computational requirement, and the time to run a simulation depends on the computational capacity of the CPU and of the complexity of the analysis. The time can increase exponentially if the analysis includes drop shadows, thermal networks simulation and/or optimization or renovation scenarios. CityBES based on an on-cloud platform overcomes this limitation running the analysis on a server.

Potential users

Different decision makers (e.g., politicians, distribution and transmission operators, district heating and cooling managers, designers, modellers and researchers) could be interested in implementing UBEM tools, for their different needs. For example, a politician that wants to optimize the public transportation in an area could use the results from CitySim, integrated with MATSim-T that was specifically developed to run such analysis. Policy makers, designers, modellers and researchers interested in the comparison of different energy conservation measures, could use the results of CityBES, CEA and SimStadt. Especially the first two, already integrate numerous energy conservation measures in the form of databases and allows automatic comparisons between scenarios. On the other hand, TEASER that is well integrated with the design of urban energy systems could be used by designers and managers of systems and by distribution and transmission operators. Umi is well developed to analyse relatively small areas such as neighbourhoods, in fact, it allows a detailed overview of the energy needs of buildings, daylight analysis, solar potential and walkability. Its results could be used by municipalities to optimize new and existing urban areas. In the perspective of a low-carbon future, the results of SimStadt, CityBES and CEA can be used to assess the GHG emissions of urban areas. This could be a fundamental step for policymakers that want to design new policies or measure the effects of existing ones.

All the tools require a sound experience in energy modelling to provide meaningful output (as any BEM tool). Depending on the complexity of the engine used to run the energy simulation, some specific technical knowledge could be required. Moreover, each tool is characterised by a GUI that can facilitate the modelling for users not highly skilled in urban energy simulations. Among the analysed tools, CityBES is the one, so far, with the friendliest GUI. The sub-tools succeed one another in the right order, to allow easy implementation of all the potential of the tool. CityBES is very well developed for the nine cities available on the website, and the developing team supports users with new case studies, allowing also to people with little knowledge of the tool to analyse their cases. CEA is characterised by a simple GUI too, however, the user is freer to start new case studies and to create advanced analysis, and thus, energy

Table 3: Summary of the possible outputs of the considered UBEM tools.

Tool	Building use related					Resource Potential		Urban energy systems		Large-scale general evaluations				Typology of output	
	Daylighting	Energy use for heating/cooling	Systems	Energy use for domestic hot water	Electric energy use	Solar Potential	Environmental energy potential	District Heating/ Cooling	Energy Network	Evaluation Scenarios	GHG Emissions	Cost-Benefit Analysis	Transport/ Mobility	3D Mapping	Spreadsheet/ Graph
CitySim	x	x	x										x	x	x
SimStadt		x	x	x	x	x				x	x			x	x
UMI	x	x	x	x	x	x							x	x	x
CityBES		x	x	x	x	x		x		x	x			x	x
CEA		x	x	x	x	x	x		x	x	x	x		x	x
TEASER		x	x					x	x						x

modelling knowledge is necessarily needed. Umi does not have a dedicated GUI, but it is accessible via Rhinoceros and Grasshopper interfaces, thus knowledge of these tools is required. CitySim and SimStadt are characterised by a GUI based on BES software, thus, is oriented to users with general knowledge of simulations. TEASER is the most demanding one, even if it allows a simple characterisation of buildings through the *data enrichment function*. Good knowledge of urban energy systems is required to exploit the tool at its full potential.

Conclusion and future outlooks

In this paper, an overview of different UBEM tools is reported. Firstly, a clarification of the two main urban modelling approaches is given and secondly, a focus on bottom-up physics-based UBEM tools is provided. The most developed tools, currently available, are considered and described in detail. The analysis is concluded with the description of the inputs needed and the outputs provided by each tool, the scale at which the tools can run simulations, and, finally, the potential user of each tool in relation also to the available GUI. Increasing the knowledge of what is available and what is possible to achieve with the different tools, may allow the users to choose the best tool for their aims. The overview confirms that each tool allows to deepen some topics and overlooks others. Some tools are focused on the evaluation of different scenarios for energy efficiency strategies, such as SimStadt, CityBES and CEA. In particular, CityBES is provided with the easier interface to achieve this goal and with the larger catalogue of strategies. TEASER allows the integration of UBEM with UESM, permitting the optimization of energy networks and systems (both on large-scale and for single end-users). Whereas, CitySim, integrated with MATSim-T, allows the analysis of transport and mobility in an urban area. Finally, Umi is suitable for neighbourhood and district simulations also for new settlements, including analyses on walkability.

Two major obstacles have been met while performing the analysis. Firstly, in the description of the tools, different nomenclatures are used, regarding the scale, as already discussed in section 3.3, but also, and mostly, regarding the outputs. The tools do not use a standardized terminology, and this can hinder the interpretation and comparison of results. Following a common standard, such as the ISO 52000-1, could be a solution, since it provides terms and definitions regarding energy and buildings. The second obstacle was the limited access to some tools. To this purpose, a further collaboration with tools' developers will provide a more comprehensive comparison. This work cannot, nevertheless, be accomplished without the active collaboration of the whole urban simulation community. As a further step, cross-comparisons between similar tools, based on a common case study, could be performed.

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