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Modeling the heating and cooling energy demand of urban buildings at city scale

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Abstract

Many computational approaches exist to estimate heating and cooling energy demand of buildings at city scale, but few existing models can explicitly consider every buildings of an urban area, and even less can address hourly -or less- energy demand. However, both aspects are critical for urban energy supply designers. Therefore, this paper gives an overview of city energy simulation models from the point of view of short energy dynamics, and reviews the related modeling techniques, which generally involve detailed approaches. Analysis highlights computational costs of such simulations as key issue to overcome towards reliable microsimulation of the power demand of urban areas. Relevant physical and mathematical simplifications as well as efficient numerical and computational techniques based on uncertainties analysis and error quantification should thus be implemented.

Keywords: Heating and cooling in buildings, Power demand prediction,

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District, City.

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1. Introduction

1.1. General context

The study of urban energy consumption is becoming more and more important because of three main facts:

- (1) Urban population is increasing: in 1950, 30% of the world population lived in cities, and 54% in 2014, and this ratio will reach 66% in 2050, that being around 6.5 billion of persons, i.e. 2.6 billion persons more than nowadays [1]. Therefore, urban development is a crucial issue, in particular from an energy point of view as urban energy consumption per capita is also increasing (+32% in the last 40 years [2]).
- (2) The energy paradigm changes: the need of dramatically reducing greenhouse gas emissions as well as fossil energy issues favor the use of renewable energies, which are often decentralized and intermittent. Related

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polices currently ongoing in many countries worldwide [3] change the previous centralized energy management scheme, which requires a better understanding and forecasting of power demand and power production, in particular in cities, where the network is dense.

- (3) Urban heat stress during hot seasons due to the urban heat island (UHI) effect may further intensify effects of probable more frequent heat waves in the context of climate change [4]. This can lead to dramatic public health problems as well as energy issues due to the multiplication of active cooling devices, which would also contribute to increase urban air temperatures [5].

Therefore, urban energy consumption has been a critical research problem for the last 30 years (Keirstead et al. [6] referenced 219 papers concerning only urban energy models), and will certainly still remain a major issue for the following years.

1.2. Scope

This paper focuses on the building sector, which is responsible for the main part of the global energy consumption (40% of total final energy in the European Union [7]), and in particular on space conditioning (heating and cooling), which currently represents about 75% of the energy consumed by European residential buildings in 2014 [8]. The building sector is identified to have a “great potential” to improve energy efficiency [7] and to reduce greenhouse gas emissions, thanks to refurbishment, including insulation and replacement of low-efficient energy technologies.

Moreover, renewable energy may relevantly be produced and used in buildings (e.g. solar panel and combined heat and power). But such a change

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9 implies to focus on power demand because of district network balance man-
10 agement problems (storage, sharing, etc.), and no more only on long term
11 consumption.
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14 Hence, this paper addresses building energy modeling at city scale, as
15 integrated tools are needed for urban energy suppliers to manage energy
16 networks and for city decision-makers to plan strategies in a context of urban
17 growth and energy transition (point (2) of Sec. 1.1).
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23 *1.3. Modeling issues*

24 The energy *demand* represents the energy used by energy systems, con-
25 sidering their efficiency and their behavior, to provide the energy *needs*. The
26 *energy consumption* refers to the assessment (the sum) of the energy demand
27 over a period, assuming that the energy demanded was supplied, whereas the
28 *power demand* represents the instantaneous energy demand. Hourly energy
29 demand is commonly used in building energy simulations (BESs) as the min-
30 imal temporal resolution required to estimate the power demand.
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39 Simulating urban building power demand is more complex at the city
40 scale than at building scale, mainly because of three reasons:
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- 43 • A huge amount of information about built structures (geometry, phys-
44 ical properties of components, etc.) is needed because of the large size
45 of the domain studied, whereas they are often unknown and difficult
46 to obtain accurately [6, 9]. Their determination needs expensive and
47 time-consuming surveys and measurements;
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- 53 • The behavior of the occupants (direct actions and use of systems) has
54 a major impact on building energy demand [10–13] while at the distrit
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9 scale or larger, the temporal variability of occupants' behaviors makes
10 the maximal total power demand different from the sum of the individ-
11 ual maximal power demands. This *diversity* requires specific models
12 themselves based on extensive surveys [14];
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17 • Because of the urban environment, buildings cannot be assumed standing-
18 alone as it is usually supposed in building energy models (BEMs). Ef-
19 fects of the urban environment on building energy needs have to be ac-
20 counted for [15–22], while external loads, such as meteorological loads,
21 cannot be estimated generically as they are particular for each building.
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28 More precisely regarding this last point, meteorological loads of urban
29 buildings and subsequently their energy behavior depend on (see Figure 1):
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33 • Obstructions caused by surrounding constructions, which decrease the
34 sky view factor, and consequently reduce solar gains (increase of the
35 heating needs in winter and decrease of the cooling needs in summer)
36 and the radiative cooling to the sky (reverse effect on the space condi-
37 tioning needs) [15–19, 21, 23];
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43 • Surrounding surfaces, which reflect solar radiations and emit and reflect
44 longwave radiations, impact on the surface energy balance of urban
45 buildings (e.g. a north-oriented surface may receive solar radiations
46 from a south-facing opposite surface, therefore its thermal losses may
47 be reduced) [17, 19];
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53 • Urban morphology, which modifies airflows around buildings, and, con-
54 sequently, impacts convective heat exchanges [18, 20, 21] and the po-
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tential of natural ventilation of urban buildings, including infiltration [24];

- The general UHI effect, which means that air temperature within a city is often higher than in rural areas (decrease of the heating needs but increase of the cooling one [15, 20, 25–28]). According to Oke [29], the UHI results from the combination of the above mentioned phenomena, which generally increase urban surfaces temperatures, in addition to the high thermal absorbance of urban materials, the lack of vegetation (evaporative cooling), and the anthropogenic heat sources.

1.4. Objective

The aim of this paper is not to give an exhaustive review of studies addressing the simulation of building energy demand at the urban scale, but *to identify the approaches and the models developed in the literature in order to simulate building heating and cooling power demand, from the building scale to the urban scale, taking into account the urban environment and possible changes in building characteristics*. For this purpose, the paper is structured as follows: a first part (Sec. 2) presents the main approaches and methodologies used to estimate urban building energy consumption and particularly power demand at district or city scale; then a second part (Sec. 3) details the specific models used in these approaches in order to tackle modeling issues in the urban context; finally, the last part (Sec. 4) closes the paper and specifies outlooks.

2. Overview of urban energy models

At the city scale, numerous phenomena of various scales interact, urban geometry is very complex and heterogeneous, and materials are diverse. Therefore, explicit simulation of urban energy demand requires huge amount of data, which are difficult to gather, and high computational capacities, which are currently not available for usual use [6, 9]. Consequently, simplified approaches have been mostly developed.

2.1. Top-down and bottom-up approaches

Two approaches addressing urban energy issues were commonly defined: *top-down* and *bottom-up*. According to the review of Swan and Ugursal [30] about modeling techniques of energy consumption in the residential sector:

“Top-down models utilize the estimate of total residential sector energy consumption and other pertinent variables to *attribute* the energy consumption to characteristics of the entire housing sector. In contrast, bottom-up models *calculate* the energy consumption of individual or groups of houses and then extrapolate these results to represent the region or nation.”

In other words, top-down models study city as an entity, according to its general characteristics. As the components of the city are not considered explicitly, top-down approaches are not able to consider explicitly the energy demand of each individual urban building. The total urban energy consumption is related to macroeconomic parameters, such as energy price and income, and to other parameters related to the city, such as population

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density and urban morphology. They are generally designed to give information for policy-makers, for whom monthly or annual energy consumption and aggregate information are sufficient. On the other hand, bottom-up models reconstitute the behavior of a city from the behaviors of its components, i.e. the buildings. Therefore, the urban energy demand is calculated as the sum of the energy demand of each building.

Bottom-up approaches enable each end-use consumption and the consumption of each building to be distinguished using *statistical* and *engineering* methods [30]. Statistical methods rely on huge amounts of various data originating from field measurements, energy supplier recordings, government publications or surveys, for instance. These historical data are used in regression analysis to establish relations between energy consumption and other parameters related to the building considered. In contrast, engineering methods calculate the energy demand of each energy system of buildings, using engineering-based models. These methods require an important collection of data about the physical properties of buildings components and characteristics of systems.

Hence, only engineering methods are able to simulate the consequences of important changes, as technology break, massive refurbishment or change of occupant behaviors, thanks to their high level of detail and their physical models, on the contrary to statistical approach based on historical data [14, 30, 31]. However, deterministic approaches used in engineering models are not able to properly consider diversity [14, 30, 32] and statistical models are necessary to relevantly include occupants' behaviors. Statistical tools can also simplify the determination of the huge amount of inputs of engineering

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9 models [31] (as for buildings stock dataset [32]).

10 11 12 *2.2. Toward micro-simulation*

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14 In contrast to top-down and large scale bottom-up models, which consider
15 aggregated and averaged quantities due to their large spatial and temporal
16 resolutions, it is necessary to explicitly simulate each building of a city in
17 order to accurately account for the distribution of the power demand at
18 urban scale. This category of simulation (and, by extension the tool and the
19 model associated) is called *micro-simulation* [9]. The *micro* scale refers to
20 the building scale, and by extension, the meso scale to the district scale and
21 the macro scale to the city scale. According to the classification of Swan and
22 Ugursal [30], this type of model belongs to “sample engineering bottom-up
23 models”, but with the sample size equal to the domain size of the study (also
24 called “urban building energy models” by Reinhart et al. [33]). Therefore,
25 such models could be called *full detailed* sample engineering models, because
26 each building belonging to the domain is explicitly considered. As the micro-
27 simulation exhaustively considers each building of the city, it is the strictest
28 bottom-up approach.

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9 meteorological phenomena and specific building characteristics, specific val-
10 idation should be performed albeit it is made difficult by privacy issues and
11 the lack of suited validation data.
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15 Hence, to identify modeling approaches suited for urban power micro-
16 simulation, this part reviews existing approaches used to explicitly simulate
17 urban building energy demand.
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20 21 *2.2.1. Building energy simulation* 22

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24 BES estimates heat transfers in the different building's elements and predict
25 the behavior of energy systems, in order to provide detailed building en-
26 ergy assessment. The scales of the BESs are the followings: the micro-scale
27 refers to components of the buildings (systems, elements of facade, etc.) and
28 the macro-scale to the building (see Figure 2). BEMs can be also used to
29 characterize archetype buildings of engineering-based bottom-up approaches
30 [31, 34, 35]. In these cases, BEMs are solely used because it is unnecessary
31 to precisely consider the local urban effects.
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35 Towards urban micro-climate, the use of BES programs may be extended
36 to evaluate effects of urban environments on building energy behavior. In
37 particular, [25–27, 36, 37] performed BESs parameterized with local mea-
38 sured or generated weather data (see Sec. 3.2.3) for a generic building. The
39 aim was to convert an increase of temperature due to an UHI into a varia-
40 tion of space conditioning energy consumption, considering building thermal
41 behavior, rather than considering real urban building with its specific urban
42 environment. Extending this approach, BEMs were coupled with an urban
43 canopy model (see Sec. 3.2.1) in order to study the interactions between
44 urban building energy demand and the urban climate [28, 38–40]. In this ap-
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proach, BESs are neither run for a specific building, but for a representative one, in order to determine its general impacts on the urban climate and the feedback on its energy needs.

More specific studies were also recently carried out. Especially, Ref. [17, 19] respectively used EnergyPlus [41] and ApacheCalc coupled with Daysim in order to determine the lighting electrical and space conditioning demands of a test room depending on the shading and reflection of solar radiation induced by different surrounding built structures (building heights, street widths, orientation, etc.).

Accounting for more physical phenomena and using the BES tool EnergyPlus, Yang et al. [21] evaluated the effects of urban environments on building energy needs by modifying the BEM boundary conditions and modeling of external solicitations based on microclimatic simulations performed using ENVI-met [42]. With this coupling, effects of urban environments in terms of short and long wave radiative heat transfers and local air temperature on building energy behavior were estimated. Also, Allegrini et al. [20, 43] used the BES tool TRNSYS [44] to simulate a street canyon in order to analyze the impact of its aspect ratio and its orientation on building energy needs considering both radiative and airflow-induced effects. More precisely, the street canyon was modeled as a large open atrium so that the indoor radiation model using Gebhart factors can apply to evaluate outdoor reflections of short and long wave radiations effects, and CFD-based specific external convective heat transfer coefficients were used to evaluate convective heat losses.

Hence, although BEMs are able to model the behavior of building com-

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ponents and are thus the bases of explicit urban power modeling, usual BES
are not suited to perform district or urban scale simulations. As BEMs are
originally designed for stand-alone buildings, they need improvements or cou-
plings to integrate urban effects on urban building energy demand. According
to the above-mentioned examples, BES were mainly used to simulate the en-
ergy demand of one, often theoretical, building in an urban context in order
to identify general trends, not to study a real case. Surrounding buildings
are often only assumed as obstructions, without explicit modeling of their
thermal behaviors. As BESs tools are not designed to simulate numerous
buildings while considering accurately the interactions between each others,
performing BES at urban scale would require an important computational
effort because of the consecutive calculations and the coupling processes [45].
This is all the more true if building interactions through microclimate is ex-
plicitly simulated using computational fluid dynamics (CFD) simulations.

37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 *2.2.2. Urban building energy simulation*

Noticing that BES are originally designed for a stand-alone building,
some tools were developed in order to model the interactions between urban
structures and urban climatic conditions as well as building energy behavior.
These tools are often thermo-radiative tools initially designed for urban light-
ing or pedestrian comfort studies, which were improved in order to evaluate
building energy needs. They sometimes also include microclimate models. In
the present paper, this category of combined models is called urban building
energy model (UBEM) and the simulation associated urban building energy
simulation (UBES).

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For example, He et al. [16] designed a “simulation tool for predicting the effect of outdoor thermal environment on building thermal performance in an urban block”. They modeled geometrically the urban block and defined a uniform Cartesian mesh grid with a spatial resolution of 0.2 m for exterior surfaces, and split indoor volumes into thermal zones (one per story). Thermo-physical properties were attributed to each cell of the grid. Then the program solved heat balance equations for each cell every 15 minutes, giving the surface temperature of each cell, the indoor temperature and the power demand of the zones of a specific building. This simulation was based on a tool initially designed to predict outdoor thermal comfort [46] and improved to predict building energy needs.

Similarly, Bouyer et al. [18] added a building energy model to the thermo-radiative model SOLENE and coupled it with the CFD program Fluent [47], in order to simulate the hourly energy needs of a building located in an urban block. SOLENE was first designed to model precisely solar luminance distribution within an urban area, and was then improved to compute thermo-radiative transfers and radiation-energy budgets [48], based on surface finite-elements of around 1 meter square. SOLENE was further coupled with Code_Saturne [49] to form the software suite SOLENE-microclimat [50, 51].

To recapitulate, UBEMs are improved urban thermo-radiative models able to predict building energy needs. They can be coupled with a CFD program in order to account for local wind and air temperature. They rely on a relatively fine temporal and spatial resolution for the accuracy of the thermo-radiative model. This particularity makes the simulation computa-

tionally expensive. as the duration of the calculation substantially increases with the number of cells [46, 52]. Therefore, their adaptation to simulate the energy behavior of numerous buildings would require substantial computational capacities (or time) or simplifications, especially when a CFD coupling is implemented (the simulation lasts 164 hours in Ref. [18] for two weeks).

2.2.3. *City energy simulation*

In order to overcome inherent limitations of BEM and UBEM for the calculation of the energy demand of numerous urban buildings, specific city energy models (CEMs) were developed. For instance, the platform called CitySim [53], the successor of SUNtool [54], was specifically designed for urban problems, to help urban decisions in a perspective of sustainable development, focusing on urban energy uses and various resource flows: energy, waste, water, etc. Compared to UBEMs, CitySim relies on a specific simplified radiation model [55, 56] and involves lower spatial resolution. It is therefore possible to explicitly simulate whole neighborhoods or districts to predict individually the energy demand of buildings over a year, as done in Ref. [57], where a neighborhood of 100 buildings is simulated. With this approach, urban surface temperatures are thus not finely determined, but the model mainly focuses on energy demand.

Other CES recently developed, or under development, are briefly recap in the Table 1. All of them can be used for city energy micro-simulation, but focus on different aspects (grid management, energy production, urban environment assessment, etc.).

Some adapted UBES performed on large urban areas and providing information about the energy demand of several buildings may be also included

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9 into CESs. In particular, Kawai et al. [22] used the same UBEM as He et
10 al. [16] (see Sec. 2.2.1) for simulating the energy demand of a neighborhood
11 but only for some days. Also, Gros et al. [58, 59] coupled SOLENE with a
12 zonal-empirical microclimate model based on QUIC-URB [60], for airflows,
13 coupled with zonal energy balance model [61], for external air thermal behav-
14 ior. The resulting CES tool called EnviBatE, aims thus to assess the energy
15 demand of neighborhoods taking into account microclimatic conditions while
16 substantially reducing computational costs compared to e.g. SOLENE mi-
17 croclimat. In Ref. [58], a six months calculation of a neighborhood lasts 48
18 hours. Hence, the extension of UBES to CES is made possible using simpli-
19 fications of the building energy and/or environmental model, by reducing
20 the simulated period or model resolution or by increasing computational ca-
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34 Alternatively, several tools and platforms have been developed in order
35 to calculate the energy demand of each building of a city directly from Geo-
36 graphical Information System (GIS), as in the Energy Atlas Berlin initiative
37 [62], in EIFER works [63], with the SimStadt platform [64, 65], in the En-
38 erCity project [66] and in the Li et al.’s methodology [67].¹ These approaches,
39 called GIS-based simulations in Figure 3, can be considered as the successors
40 of the Ratti et al.’s approach which estimated the building energy demand by
41 analyzing digital elevation models [69]. Energy demand is roughly estimated
42 based on geometrical data extracted from the GIS and building characteris-
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52 ¹The majority of the models use the CityGML format (<http://www.citygml.org/>) for
53 more interoperability and standardization. Furthermore, an application domain extension
54 have been specifically developed to store and exchange energy simulation results [68].
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9 tics defined by typologies or by the users, using monthly quasi-steady-state
10 simple energy models. Some GIS-based simulations include electrical de-
11 vices and domestic hot water energy calculations but effects of the urban
12 environment and the occupant behaviors are generally neglected or coarsely
13 considered. Results are sometimes validated with measured annual aggre-
14 gated energy consumption. Hence, these models represent an alternative to
15 classical bottom-up approaches in order to calculate the annual energy de-
16 mand, with the advantage of considering explicitly, but roughly, each urban
17 building. Nonetheless, they are not able to consider accurately the dynamics
18 of the building energy demand. To overcome this limitation and calculate
19 hourly energy demand for each building rather than only monthly demand,
20 Tian et al. [70] applied an EnergyPlus model to each building extracted from
21 GIS. Using a computing cluster to parallelize the different simulations, only
22 4 hours of simulation were necessary to simulate about 10,000 buildings over
23 a year. Nonetheless, given that each model is independent from the others,
24 no interaction is considered. A similar method was used by Reinhart et al.
25 [71] on a lower scale.

26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 *2.3. Summary and discussion*

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45 Simulating the energy demand of each building of an urban area at a
46 district or city scale requires to explicitly model each building; this is micro-
47 simulation. In such an approach, it is essential to consider the impact of
48 the urban environment on the energy needs of the simulated buildings. As
49 shown in Figure 2, different types of models referring to different scales may
50 be used to estimate building energy demand in an urban context.

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56 More precisely, Figure 3 positions the different urban energy models with

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respect to their domain size and temporal resolution, i.e. the shortest time step which could be considered. Some of the above-mentioned studies are also plotted on the graph with respect to their spatial resolution, i.e. the level of detail for the calculation of the incident radiations modified by the urban environment, and simulated period. As Figure 3 shows:

- UBEMs are designed to account in detail for the effects of urban surroundings on building energy needs. They also calculate surface temperature field. UBESs are mainly performed on restricted domains because the objective is to determine precisely the thermal behavior (high resolution) of a building in its urban environment (small domain). Furthermore, the simulation is generally too computationally expensive to simulate numerous buildings;
- Top-down and “implicit” bottom-up approaches are efficient for determining annual or, at least, monthly total building energy demand (or consumption) of a city (large domain), but it is impossible to access to the power demand of a particular building in the city (low resolution) as all buildings are not explicitly modeled on contrary to micro-simulations (UBES and CES);
- CEMs aim simulating the energy demand (notably GIS-based models), and sometimes the power demand, of numerous buildings while relatively simply considering effects of the urban context. Due to simplifications and lower resolution the computational cost of CESs are reduced compared to UBESs. But validity of simulation results at short time step is expected to be further analysed and confirmed.

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Hence, because of computational limitations, detailed models are used for small domain sizes and short periods, i.e. at building scale during a few days or weeks. Larger domains need simpler models, which generally imply lower spatial and / or temporal resolution in order to neglect some transient phenomena. As can be seen in Figure 3, developing simulations able to calculate the power demand (at least, hourly energy demand) at the district of city scale is complex as this requires using high resolution models on large domains. This objective may be achieved by:

- (1) increasing computational capacities and / or use efficient numerical techniques and computational strategies (in particular optimized algorithms or parallelization);
- (2) implementing computationally efficient modeling techniques and simplifications, which minimally impact on the accuracy of the urban energy model. This implies handling the induced uncertainties by performing sensitivity analyses.

In order to identify the main modeling techniques which are, or could be, used for city energy micro-simulation, and which ones appear the most suited for this purpose, next section gives an overview of the main models used in BES, UBES and CES potentially usable in micro-simulation.

3. Overview of sub-models used in building and urban energy simulations

As introduced in Sec. 1.3, urban environment affects the energy needs of urban buildings by conditioning their boundary conditions in terms of short-wave and longwave radiations, airflows and local air temperature. There-

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fore, estimating external loads of urban buildings requires specific models (currently referred as sub-models) and couplings to assess microclimatic conditions as well as their effects on the building energy behavior especially through the envelope. In addition, towards detailed and integrated micro-simulation of urban energy, diversity in behavior of occupants and equipments use at city scale should also be modeled using stochastic models and agents-based models [12, 53, 63, 72–74], Nonetheless, as BESs generally involve deterministic scenarios and this review focuses on physical models, these models are not further detailed.

Hence, the following gives an overview of the different existing methods used to estimate radiative exchanges and microclimatic conditions in urban areas as well as heat transfers through building envelopes.

3.1. Radiations models

3.1.1. Solar radiations

Alterations (shadowing and reflections) of solar (shortwave) radiations are identified as one of the loads which affect the most needs of urban buildings compared to stand-alone ones, in particular for low-energy building designed to maximize solar gains in winter [75].

Solar radiations are generally split into two categories: direct and diffuse radiations. Direct radiation comes directly from the sun, following its direction. It is generally provided in meteorological weather input data of BES. In urban environment, an important part of solar rays may be obstructed. This part can be estimated thanks to ray-tracing [17, 19, 46] or to projections methods [48, 56, 76] at each simulation time-step, or can be calculated for some days and regressed for the others to save computational time. Diffuse

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9 radiation corresponds to solar radiation diffused by the atmosphere. Dif-
10 fuse flux can be provided by weather data or estimated using isotropic or
11 anisotropic sky models [77]. Although BESs often assume diffuse radiation
12 as isotropic and directly derive it from weather input data, this simplifica-
13 tion lead to substantial deviation in the estimated annual solar irradiance
14 compared to more detailed anisotropic sky models [55], which, on the other
15 hand, need more detailed parameterization. In addition, in urban areas, dif-
16 fuse radiation is also often obstructed by surrounding constructions. The
17 effective diffuse flux received by urban surfaces (assumed isotropic) is thus
18 generally estimated based on the sky view factor of surfaces. This factor can
19 be estimated by ray-tracing or projection methods as for direct radiation,
20 but it is time-invariant on contrary to the shading factor of direct radiations.
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23 In addition to shadowing, urban environments reflect solar radiations.
24 It is generally accepted that urban environment reflects solar radiations
25 isotropically following the Lambertian law. This assumption is acceptable
26 for opaque materials and enables the radiosity method or simplified asso-
27 ciated methods to be used [56, 61]. The radiosity method is based on an
28 analytic formulation of the problem on a finite number of surfaces, which
29 leads to a matrix problem whose size depends on the model spatial resolu-
30 tion. In theory, infinite reflections should be considered when resolving this
31 matrix problem by inversion, but in practice, the matrix problem is often
32 solved iteratively, i.e. considering only a finite number of reflections.
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35 *3.1.2. Longwave radiations*

36 Longwave radiations impacts on building energy needs are smaller than
37 solar radiations effects [21], but urban infrared exchanges may still have
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9 substantial effects [18, 50].

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11 Calculations of longwave radiations exchanges are similar to procedures
12 used for diffuse solar radiations (radiosity and ray-tracing methods), excepted
13 that transfers occur between both urban surfaces and with the sky. Nonethe-
14 less, it is often considered that urban materials are black-bodies [46, 58], be-
15 cause their emissivity is generally close to 1, so that reflections are not con-
16 sidered. Moreover, longwave radiations emitted by urban surfaces depend on
17 their respective temperatures. This coupling implies to iterate the thermal
18 model and the radiative model until convergence, which can be very time
19 consuming. Therefore, surrounding surface temperatures are often roughly
20 estimated as equal to the air temperature [41], to the temperatures given by
21 the radiative model without any converging iteration [21], or to the temper-
22 ature estimated the previous time-step [53].
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34 35 *3.1.3. Summary and discussion*

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37 Radiosity and ray tracing methods are generally used to compute ra-
38 diative transfers in urban areas. Simulation are computationally expensive
39 because of the numerous calculations needed to estimate the incoming radi-
40 ations for each surface considering the interactions with all the others. Com-
41 putational time can be saved by reducing the number of surfaces considered
42 (approximated formulation or decrease of the resolution) or to a reduction
43 of the number of reflections considered.² As simplifications can substantially
44 alter the accuracy of predictions, sensitivity studies should be performed to
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53 ²It is also possible to accelerate ray tracing computations by using parallelization on
54 graphics processing units (GPU).
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9 determine the best compromise between results accuracy and computational
10 time and so the best level of modeling.
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13 14 *3.2. Urban climate models*

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16 It was observed for a long time that cities alter local climate. Indeed,
17 temperature, wind features and species concentrations (such as humidity)
18 are modified compared to rural areas, which impacts on the building energy
19 needs (see Section 1.3). However, the modeling of urban microclimates is very
20 complex because of cities' geometric complexity and heterogeneity as well as
21 the wide range of spatial and temporal scales characterizing atmospheric
22 phenomena [78]. In addition, governing equation of fluid dynamics are non-
23 linear and strong interactions between buildings and microclimate require
24 the use of coupled approaches. Therefore, different modeling strategies were
25 developed in UBES or CES to model urban microclimatic conditions and the
26 induced boundary conditions. They are reviewed hereafter.
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38 *3.2.1. Urban canopy models*

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40 During the last decades, meteorologists developed models of urban ar-
41 eas to determine their impacts on mesoscale processes (see Ref. [79] for
42 more information about urban boundary layer modeling and Ref. [80] for
43 a complete review of such models). Such models are called *urban canopy*
44 *model* (UCM). While first models simply parameterized urban surfaces using
45 equivalent albedo, roughness, and others surface parameters [81], more re-
46 cent models consider homogeneous cities with simple geometry. These simple
47 geometries are generally 1D [82] or 2D [83] array of parallelepiped buildings,
48 or street canyons [84]). Rasheed et al. [85] proposed a method to find an
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9 equivalent geometry of UCM, which fits as best as possible for real geometry
10 of the city.

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13 Urban canopy models estimate energy exchanges between horizontal and
14 vertical surfaces of the representative urban element and the atmosphere, and
15 representative values of air temperature and wind speed within the urban
16 canopy are deduced. The thermal behavior of buildings is generally modeled
17 with basic BEM.
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22 23 *3.2.2. Microclimatic models*

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25 To estimate temperature and wind distribution within the urban canopy
26 layer in detail, CFD should generally be used, as done in Ref. [86] for CES
27 and in Ref. [18, 21] for (U)BES. However, these studies stressed the high
28 computational cost of CFD, while the microclimatic model has theoretically
29 to be coupled with BEM using an iterative process to determine accurately
30 surface temperatures.
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37 Otherwise, to enlarge the domain and energy demand simulation from
38 a single urban building during some days to a neighborhood during several
39 months, fluid dynamic modeling can be simplified by applying energy balance
40 to large control volumes, which corresponds to a zonal approach [15, 61]. This
41 method, coupled with the empirical-based wind field model QUIC-URB [60],
42 is used by Gros et al. [58, 59] to simulate the microclimate in EnviBatE
43 (Figure 3). Although the generalization of such models is not assured because
44 of the empirical law describing some phenomena, such an approach requires
45 less input parameters than CFD, and involves significantly less computational
46 cost.
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56 Another promising alternative to usual CFD simulations based on the
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9 Navier-Stokes equations as it does not alter model accuracy is to use the
10 lattice Boltzmann method (LBM) for urban aerodynamic simulation [87]. Due
11 to its local and explicit formulation, this method is inherently parallel and
12 allows a very cost effective implementation on GPUs [88] thus substantially
13 reducing computational time compared to usual CFD methods.
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19 *3.2.3. Measured and generated weather data*

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21 Local measured data can also be specified as inputs for the urban building
22 energy model [25, 27]. However, collecting suited measurements necessitate
23 expensive and extensive experimental field campaigns, which are necessarily
24 spatially and temporally limited, and which could only be set to existing
25 place. To overcome this limitation, it is possible to extend measured weather
26 data from one place (e.g. synoptic meteorological station usually located in
27 airports) to another places thanks to extrapolation techniques or to weather
28 generators [36, 37]. These approaches do not necessitate additional calcu-
29 lations (only pre-process) and provide similar forms of input data as usual
30 BES input data. However, they are not able to predict the effects of UHI-
31 countermeasures on urban microclimate, except if the weather generation is
32 launched again, with modified properties.
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46 *3.2.4. Summary and discussion*

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48 Ideally, CEMs have to be coupled with microclimate models, themselves
49 coupled with a mesoclimate model, as suggested in Ref. [89]. But, to the
50 best knowledge of the authors, this has still not been achieved because of
51 computational and methodological limitations.
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55 Nowadays, climatologists couple mesoscale models with urban canopy
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models, which replace in a simple way microclimate and city energy models. By contrast, urban energy engineers couple their micro-simulations of city with urban climate models, but generally with many simplifications. Nevertheless, because of the complexity and computational costs of such coupled approaches compared to the expected accuracy improvement, CES often neglect microclimate (the white crosses in Figure 3 indicate the references that model microclimate). Indeed, SUNtool developers evaluated the determination of velocity, temperature and pressure fields via CFD as “not computationally tractable”, and explained that error induced by simplified models are “similar or larger than errors due to ignoring urban-rural temperature differences” [54]. However, since then and as shown in Table 2, semi-empirical models have been improved and CFD have become more accessible for urban simulation thanks to increase in computational capacities and the development of efficient computational approaches such as the LBM, which makes microclimatic models more suitable for use in CES.

To conclude, on both sides (urban climatology and urban energy engineering), models become more and more sophisticated thanks to the continual improvements of computer capacities, and it is probable that, in the future, urban canopy models would be urban energy micro-simulation with real explicit representation of the city. But, for the moment, detailed simulation tools were mostly used for simple geometrical cases or relatively small urban areas. Reciprocally, simplified models were applied on more complex configurations and large urban areas.

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3.3. Envelope models

Being the interface between indoors and outdoors, which mainly conditions heating and cooling energy needs, the envelop modeling is critical for micro-simulation. This part presents the main envelope models used in (U)BES and CES. Soil models are not developed in this paper, but the models used are quite similar to envelope models.

3.3.1. Resistance-Capacitance analogy method

The most common envelope model is based on electrical analogy obtained by discretization of the wall in layers (usually one, two or three) characterized by specific thermal resistance and capacitance (R-C) [18, 53, 72, 74, 90, 91]. The determination of the R-C values can be law-driven (white-box), or data-driven (grey-box).³ In the first case, value are deduced from a discrete form of the heat equation, according to material properties. In the second case, training stages are necessary in order to determine optimal values. This method is easy to implement, and to adapt to any type of wall, but the choice of the width of the layer—and so the thermal capacitance—is not generic as it depends on the thermal depth penetration, which itself depends on the solicitation frequency [93]. Indeed, Berthou [94] showed that the optimal R-C values which match measurements have to be modified every month for a better accuracy.

Usual R-C methods are well suited for calculation of energy demand over a long period because rapid thermal dynamics become negligible. However, these models become too inaccurate when considering short dynamics, as

³It also exists black-box models [92] using regressions not based on physical model

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9 required to assess power demand. To increase the accuracy, it is possible to
10 increase the number of layers (i.e. finite difference method, as in [16]), but
11 this also increases the computational cost.
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15 *3.3.2. Spatially-analytical method*

16 Because the accuracy of discrete numerical methods (as finite difference)
17 is limited by the number of layers considered, especially at the boundaries,
18 Wang et al. [95] proposed a spatially-analytical scheme for building envelope
19 in urban canopy model. This approach accurately reproduced the thermal
20 behavior of the walls (without discontinuity, allowing considering thin lay-
21 ers), was unconditionally stable and computationally efficient. Nonetheless,
22 applying analytic methods to heterogeneous (multilayered) envelopes adds
23 continuity equations and thus increases computational cost. Furthermore,
24 the analytic formulation is composed of an infinite series of terms, and even
25 if these terms tend to zero, their truncation order depends on the fabric con-
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42 *3.3.3. Response factors method*

43 In Gros et al.'s building model [58] the conductive heat transfer is com-
44 puted using the response factor method, an external representation method
45 similar to the coefficient transfer function method used in EnergyPlus default
46 method [41] and TRNSYS [44]. These external representation methods di-
47 rectly express the conductive heat fluxes at the inside and outside wall faces
48 as a linear function of the historical values of surfaces temperatures. Their
49 time series values are obtained by discrete convolution of the external loads
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9 (heat flux or temperature) and the pre-calculated *weighted factors*. These
10 factors, pre-calculated with usual analytical or numerical methods, corre-
11 spond to the time series values of the wall surface temperatures exposed to
12 unitary external loads. Thus, on contrary to implicit finite discretisation
13 methods, the response factors method, after pre-calculation, avoids consid-
14 ering all internal nodes temperature and to inverse a matrix problem. This
15 is particularly interesting when considering high discretization of the wall to
16 improve the model accuracy (especially when numerous internal nodes are
17 considered). Nonetheless, the shorter the time step is, the higher the number
18 of factors is.
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29 *3.3.4. Reduction methods*

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31 The objective of the reduction methods is to characterize as accurately
32 as possible a detailed model with a minimal number of parameters. These
33 parameters are determined with mathematical methods by diagonalizing the
34 matrix problem in a specific base.
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39 For example, a second order reduction model called *Grey-box* [96] was
40 used in SUNtool [54]. This model estimated energy need of a building with
41 two parameters (one for the static and the second for the transient behavior)
42 via transfer functions. These parameters are defined according to the typol-
43 ogy of the building. However, this method is only valid for the cases from
44 which the transfer functions have been beforehand defined, and the physical
45 meaning of these parameters is lost.
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52 Alternatively, Kim et al. [97] proposed a reduced model for an urban
53 building envelope. In this case, a reduction technique was applied to the
54 thermal model of the building envelope. With this technique, only 7 equa-
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tions were required to characterize accurately the thermal dynamics of the buildings, instead of the 194 initial equations. Compared to the detailed model, the computational cost of the reduced model was strongly decreased without compromising accuracy. Hence, reduction method allows to consider high level of wall discretization and hence to estimate accurately the conductive heat flux while using low computational resources.

3.3.5. Summary and discussion

Simple R-C models are often used to simulate the thermal behavior of envelopes, mainly because they are relatively cost effective compared to detailed models. However, such approaches only give rough estimations of the dynamics of building energy demand. On the other hand, other approaches as weighted factor or reduction methods enable building envelope to be considered with a high level of detail without leading to prohibitive calculation time. Therefore, these methods appear promising for urban energy simulations.

The drawback of these last methods is that the model parameterization is assumed constant during the whole simulated period. This assumption can be strong, in particular for natural ventilation which is very variable and can strongly affects the building energy need. In order to consider these changes, it is necessary to compute again the external representation or reduced models. These additional steps increase computational cost and reduce the interest of such approaches. Alternatives may be found in non-linear systems methods.

4. Conclusions and outlooks

Many approaches to simulate city energy demand exist, but only micro-simulation is adapted to calculate individually the power demand of all buildings within an urban area. To the best knowledge of the authors, there is still no entirely validated tool able to simulate accurately and explicitly the power demand of urban buildings at the city scale, which can be explained, at least partly, by the substantial computational cost required.

Indeed, urban energy micro-simulations rely on a high level of detail for large domains. As a consequence, simulations are computationally expensive, especially when they include microclimatic modeling. In order to reduce computational costs, physical and model simplifications and computationally efficient urban environmental and climatic approaches are needed. With respect to simplification, some models were developed, but studies are still to be carried out to assess the level of simplification suited for use in urban energy micro-simulation and to validate them, especially at short time-step. With respect to computationally efficient approaches, problem formulation and numerical technics suited for massive parallelization will certainly play an important role in the decrease of the computational costs.

Nonetheless, although simplifications required by urban scale energy micro-simulation may increase results uncertainties to some extent, it is worth mentioning that the uncertainty of input parameters may induce larger uncertainties than uncertainties involved by model simplifications. Therefore, their determination is also a crucial issue for urban energy micro-simulation, and their uncertainties have to be integrated during the modeling process.

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Name & Reference	Short presentation
Smart-E [72]	Simulation environment for study on the potentiality of flexibility in the building thermal and electrical demand, focusing on power demand.
DIMOSIM [73]	Simulation platform for optimization of the global district energy system included energy system, thermal network, energy production and storage; implemented in Matlab
Virtual PULSE [86]	Web-based urban scale modeling platform for quantitative assessments of the influence of urban neighborhoods on building energy consumption (building energy and air flow).
AMBASSADOR Project [92]	Simulation platform for grid management optimization for energy at building and city scale, based on Matlab Simulink environment.
OpenIDEAS [74]	Open framework for integrated district energy simulations including simultaneous transient simulation of thermal, control and electric systems at building and neighborhood level, building models and stochastic model of occupant behaviors; based on Modelica libraries and Python scripts.
[91]'s tool chain	Tool chain for complex city district modeling and simulation from GIS and database, developed with Modelica and Python interfaces

Table 1: Brief presentation of some CES

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Method	Results	Main application	Maximum domain size	Spatial resolution	Temporal resolution	Computational cost
Urban canopy models*	Global and averaged temperature and wind at city scale	Urban climate	City	1-10 m	Hour	Medium
Microclimate (Micro-scale CFD* + thermo-radiative model)	High resolution fields of temperatures and wind velocity	Urban microclimate, pedestrian comfort	District	0.1-10 m	Second	Very high for LES (lower with LBM-LES), high for RANS
Zonal and empirical models	Low resolution fields of temperatures and wind velocity	Urban microclimate, building energy simulation	City	1-10 m	Hour	Medium
Weather generator	Global or local information	Urban (micro)-climate, building energy simulation	City	0.1 m-1 km	Hour	<i>Preprocessed (Very high if climate model; Low if regression)</i>
Full-scale measurements	Local information	Local climate, building energy simulation	City	1 m-1 km	Second	-

* See Table 1 in [98] for more details

Table 2: General characteristics of urban climate models.

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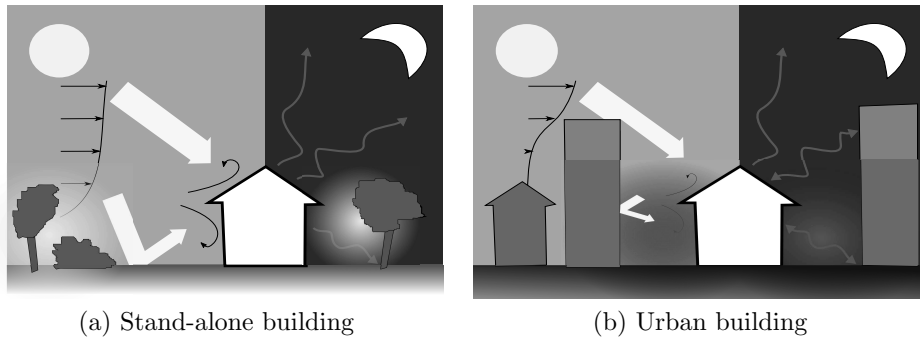


Figure 1: Modification of the energy balance of an urban building compared to a stand-alone one

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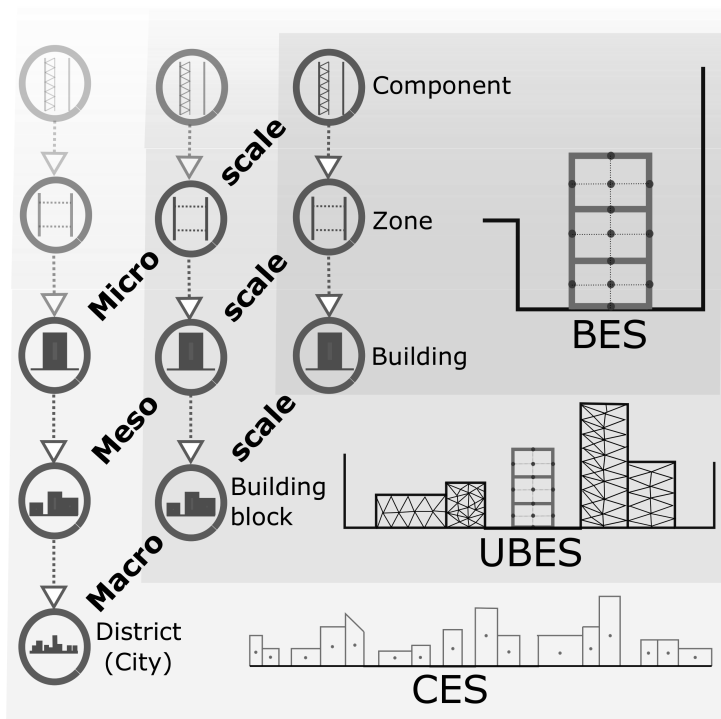


Figure 2: Scales of the different categories of simulation.

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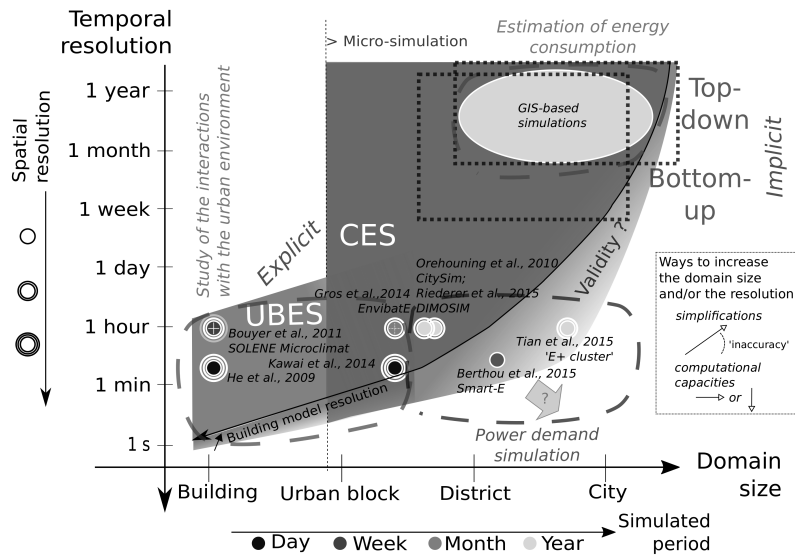


Figure 3: Comparison of the domains of availability of the different categories of energy simulation of urban buildings.

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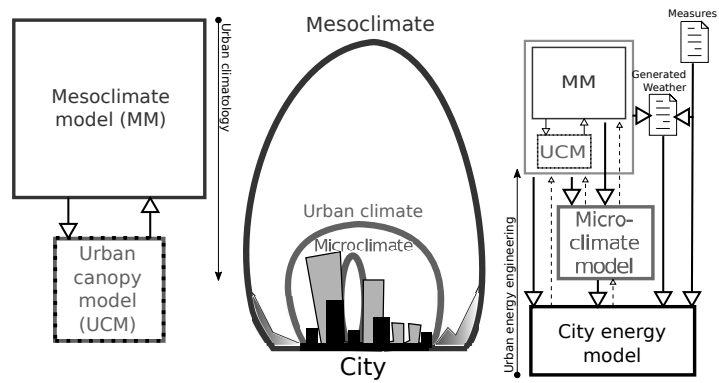


Figure 4: Nesting of the urban climate scales and related modeling approaches.