



# How building energy models take the local climate into account in an urban context – A review

Nicolas Lauzet, Auline Rodler, Marjorie Musy, Marie-Hélène Azam, Sihem Guernouti, Dasaraden Mauree, Thibaut Colinart

## ► To cite this version:

Nicolas Lauzet, Auline Rodler, Marjorie Musy, Marie-Hélène Azam, Sihem Guernouti, et al.. How building energy models take the local climate into account in an urban context – A review. *Renewable and Sustainable Energy Reviews*, 2019, 116, pp.109390 -. 10.1016/j.rser.2019.109390 . hal-03489027

**HAL Id: hal-03489027**

**<https://hal.science/hal-03489027>**

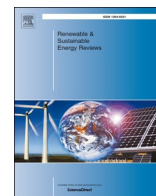
Submitted on 20 Jul 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License



## How building energy models take the local climate into account in an urban context – A review



Nicolas Lauzet<sup>a,b,\*</sup>, Auline Rodler<sup>c,d</sup>, Marjorie Musy<sup>d,e</sup>, Marie-Hélène Azam<sup>d,e</sup>,  
Sihem Guernouti<sup>d,e</sup>, Dasaraden Mauree<sup>f</sup>, Thibaut Colinart<sup>b</sup>

<sup>a</sup> TRIBU, Environmental and Sustainable Development Consulting Agency, 69003 Lyon, France

<sup>b</sup> Univ. Bretagne Sud, UMR CNRS 6027, IRDL, F-56100, Lorient, France

<sup>c</sup> Ensa Nantes, CRENAU UMR CNRS/ECN/MCC 1563, F-44200, Nantes, France

<sup>d</sup> Cerema, Equipe-Projet BPE, F-44000, Nantes, France

<sup>e</sup> Univ. Nantes, CNRS UMR 6183, GeM, F-44000, Nantes, France

<sup>f</sup> Solar Energy and Building Physics Laboratory, Ecole Polytechnique Fédérale de Lausanne, Lausanne, CH-1015, Switzerland

### ARTICLE INFO

#### Keywords:

Urban climate modeling

Building energy model

Coupling/chaining simulation tools

### ABSTRACT

The urban context is often simplified or neglected in Building Energy Models (BEMs) due to the difficulties of taking accurately into account all the heat fluxes emanating from the environment. Oversimplifying the urban context can impact the accuracy of the BEM predictions. Nevertheless, several approaches can be used to allow for the impact of the urban environment on the dynamic behavior of a building, its heating and cooling demands, and thermal comfort. This state of the art review provides a critical overview of the different methods currently used to take into account the urban microclimate in building design simulations. First, both the microclimate and building models are presented, focusing on their assumptions and capabilities. Second, a few examples of coupling, performed between both modeling scales are analyzed. Last, the discussion highlights the differences obtained between simulations that take the urban context into consideration and those that simplify or neglect urban heat fluxes. The remaining scientific obstacles to a more effective consideration of the urban context impacting the BEMs are indicated.

## 1. Introduction

### 1.1. Context

In Europe, buildings are responsible of about 40% of final energy consumption [1]. In the framework developed with new energy policies, the building sector is urged to improve energy performance: new construction should move towards Nearly Zero Energy Buildings (NZEB), while efficient retrofit should be done on the existing building stock. To meet these objectives, Building Energy Models (BEM) are powerful tools to evaluate various technical solutions and opportunities.

In their review, Fouquier et al. [2] listed three approaches for predicting building energy performance: “white box”, “black box”, and “grey box”. The first is based on physical models for evaluating thermal dynamics and energy behavior on components or whole buildings. This approach is currently the most widespread as highlighted by the hundreds of software tools available [3]. The second uses statistical

techniques to estimate heating or cooling needs of buildings. The third approach, called hybrid method, uses both physical and statistical techniques.

BEM require inputs like geometrical and construction data, usage schedule and occupancy or meteorological data in order to calculate heat and mass flows in and around buildings. Particularly, six heat fluxes may be considered on buildings' external surface:

- The convective heat flux at the external surface: it depends on both the near-wall air velocity and local variations in outside air temperature [4].
- The solar radiation exchange: it depends on the shading, the optical characteristics of the building's surfaces and of the surrounding ones [5].
- The Long-Wave (LW) radiation exchange with the sky and surrounding surfaces: it depends on form factors, temperature and emissivity of the building's surfaces and of the surrounding ones [6].
- Heat losses due to ventilation and air infiltration: they depend on

\* Corresponding author. TRIBU, 103 avenue de Saxe, 69003, Lyon, France.

E-mail address: [lyon@tribu-concevoirdurable.fr](mailto:lyon@tribu-concevoirdurable.fr) (N. Lauzet).

<https://doi.org/10.1016/j.rser.2019.109390>

Received 4 February 2019; Received in revised form 9 August 2019; Accepted 11 September 2019

1364-0321/© 2019 Published by Elsevier Ltd.

the flow rate driven by the gradient of pressure on the building's facades as a result of wind velocity and local variations in outside temperature [7]. Inlet air humidity brought by ventilation can also have an impact on air conditioning latent heat load [8].

- Thermal conduction through walls: internal or external insulation lead to different internal and external surface temperatures, thus also influencing the exchanges between the indoor and outdoor environments.
- Latent heat fluxes due to hygrothermal transfers: similar to heat transfer, moisture transfer may occur through the wall and depends on internal and external relative humidity.

These fluxes are usually evaluated for stand-alone buildings by using weather datasets including air temperature and relative humidity, wind velocity and direction and solar radiation at least. Nowadays, numerous datasets are available for multiple regions worldwide in viable format (TRY, TMY, etc.), even if they are provided for reference weather stations, that are located outside the cities.

In urban context, the local microclimate and the heat fluxes exchanged between a building and its environment are different [9]. For instance, the geometrical environment is more complex: on the one hand, surrounding buildings cause shadowing effects which reduce solar gains during the daytime; on the other hand, the sky view factor is decreased which limits the radiative cooling to the sky. In addition, solar and infrared interreflections are increasing with neighboring buildings' surfaces. Because of urban morphology, local wind speeds are lower and airflows around buildings are modified. Last, Urban Heat Island (UHI) effect results in higher air temperatures.

All the above-mentioned phenomena influence the prediction of buildings energy performance [10–17] and may be one of the causes explaining the gap between targeted and measured buildings performances [18–21]. Therefore, it is relevant to explore methods that account for the local microclimate and the effect of neighboring buildings when conducting energy simulations.

## 1.2. Previous reviews and overview of this paper

To date, numerous reviews have been conducted at the building or urban scale.

BEM are usually classified into top-down and bottom-up approaches [22]. The second approach being more widespread in the building community, other reviews classified them according the methodology: engineering methods, statistical methods, artificial intelligence models, machine learning and hybrid methods [23–25].

In recent years, the scientific knowledge on urban climates has improved at all scales of interest: from the street (micro) scale through the neighborhood (local) to the city and regional (meso) scale [26–29]. Therefore, previous reviews have covered recently aspects of the field of Urban Climate Modeling (UCM) [30–32]. In 2007, Kanda [30] presented a short overview of simulation techniques and distinguished “simple” urban canopy models from CFD models. Later, Lun et al. [31] classified various tools into mesoscale meteorological models, microclimate models, building models and human thermal models, for urban climate studies. In the framework of an international project, Grimmond et al. [32] compared 33 urban land-surface models in terms of accuracy and complexity. Since microclimate models are composed of CFD, radiation transfer and heat conduction models, some state-of-the-art focus rather on one of these three subcategories [6,33,34].

In the last 5 years, previous reviews have covered also hybrid modeling approaches between the building scale and the city scale; the most relevant are summarized below.

Allegrini et al. [35] reviewed modeling approaches that address district-level energy systems, namely district energy systems, renewable energy generation and urban microclimate as it relates to energy demands. The authors highlighted the possibilities of twenty tools in a simple comprehensive matrix.

Anderson et al. [36] proposed a broad overview of main research area at building and urban scale. They argued that the interaction between both scales should be considered in particularly to account for induced impacts in life cycle assessment studies.

Reinhart and Cerezo Davila [37] reviewed bottom-up urban building energy models (UBEM). Their review focuses on the energy performance of neighborhoods (several dozens to thousands of buildings). After discussing the validity of UBEM, the authors underlined that uncertainty and the definition of level of investigation remain the main challenges.

Li et al. [38,38] listed top-down and, more in detail, bottom-up approaches for implementing urban-scale building energy models (UBEM). In addition, they discussed the recent advances in the integration of geospatial techniques in UBEM. They noted that there are still challenging issues associated with model preparation and calibration.

Frayssinet et al. [39] reviewed existing computational approaches to estimate heating and cooling energy demand of buildings from individual building in urban environment to city scale. The authors suggested that finding relevant physical and mathematical simplifications and implementing efficient numerical and computational techniques are crucial issues for urban energy micro-simulation.

Sola et al. [40] limited their review only on Urban-Scale Energy Modeling (USEM) (at the district or city level). They focused their work not only on building energy demand modeling, but also building energy supply modeling and energy transportation models (even if the methods on how to couple these models are not discussed).

Castaldo and Pisello [41] proposed an extensive overview of BEM possibilities and questioned on how to simulate buildings in realistic dense urban environments. In their conclusions, the authors call for extending multiscale simulation approaches between BEM and UCM.

These previous reviews focused mainly on modeling of energy demand of several buildings in urban level. The general consensus is that physically-based bottom-up methods seem to be the most interesting for catching the physical phenomenon in spite of computational cost and uncertainties. These methods rely on the modeling of stand-alone buildings in built environment. Unfortunately, only a general overview of the last point is given in the previous reviews. Our review aims to address this topic through a more focused and detailed examination. Particularly, we detail the heat fluxes exchanged between a building and its environment, how they are taken into account at both modeling scales, and how the coupling attempts have managed to represent these fluxes.

The aim of this paper is twofold. First, Section 2 and Section 3 give an overview of the kind of local data provided by UCMs (variables, spatial and temporal discretization) and of the different ways BEMs take fluxes into account at the building's external surface, respectively. Second, through the analysis of eight examples of coupling or chaining attempted in research works in Section 4, we show what kind of strategies has already been carried out, analyze the encountered difficulties, the capacities of the resulting tools and how these attempts enhanced our understanding of the physical phenomena occurring between these scales. In the discussion (Section 5), we analyze the issues that must be addressed, especially in terms of the spatial and temporal description of the local climate and buildings, but also arising from the assumptions that are made in the physical modeling of the microclimate or of the building. This could bring to new developments for the use of BEM directly coupled with UCM.

## 2. Urban Climate Modeling

UCM is usually performed at different scales related to the land surface represented and the resolution at which balance equations are written [26]. At the mesoscale, a whole city and its surroundings (suburban and rural areas) can be examined over a zone of several kilometers. At the local scale, a district is extracted from its urban

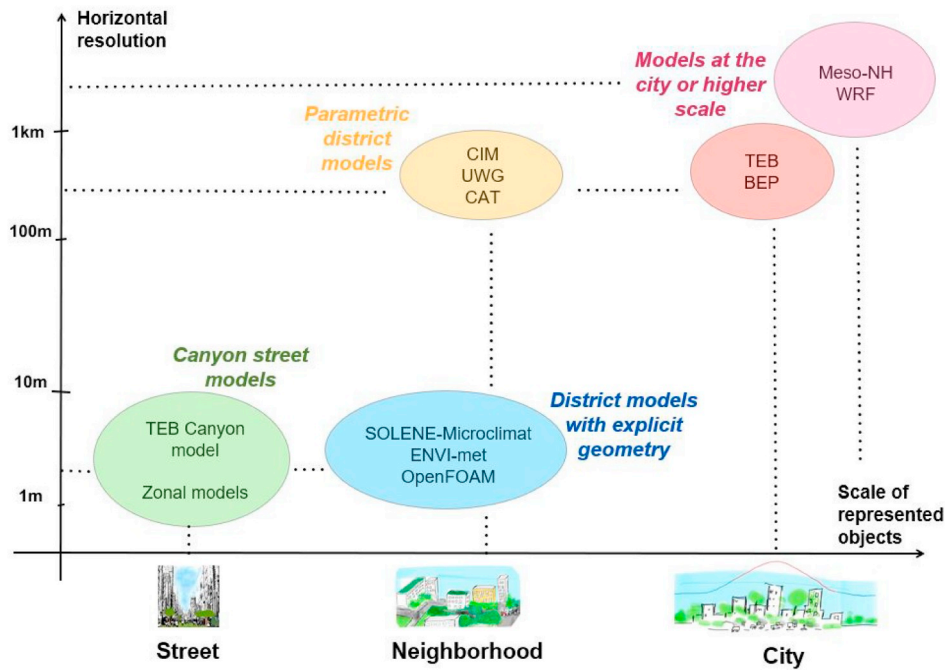


Fig. 1. Classification of UCMs in terms of their spatial study scales and resolution.

context, and climate solicitations are specified for an area whose dimensions range from hundred meters to a few kilometers. This scale allows for the representation of the meteorological phenomena in the urban canopy layer (UCL). Building forms, materials, natural surfaces, etc. can be considered explicitly or through mean parameters (rugosity, albedo, etc.). At the microscale, an urban zone of a few meters or a hundred meters is examined, and physical processes can be computed in more detail ( $\sim 1$  m). In Fig. 1, we classify the models detailed in the paper, using two criteria: spatial scale of the represented areas (in terms of urban scale) and the horizontal resolution (the horizontal size of the mesh elements used in the model). These spatial scales are also closely linked to the temporal scale.

## 2.1. City-scale models

The impact of urban areas can be examined at the city scale to estimate meteorological patterns. The domain for such models usually extends both horizontally (beyond the urban areas) and vertically (above the urban boundary layer) [42]. The local characteristics are hence parameterized, as the low horizontal resolution of the horizontal grid cells does not allow for an explicit representation of the urban areas. The results are obtained for homogeneous cells, the dimension of which is generally more than 200 m. At this scale, it is, for example, worth analyzing the interactions between the urban surface and the urban boundary layer in the development of the UHI over a city [43].

### 2.1.1. MESO-NH & TEB

The MESO-NH model [44] is a non-hydrostatic mesoscale model that has been applied in many studies of climate change impacts at city scale [45–47]. A comprehensive surface model, SURFEX [48], is integrated and includes the Town Energy Balance (TEB) model. TEB is a single layer urban canopy model [49] that incorporates multiple urban parameterizations. In MESO-NH, a city is discretized, and at each grid point, TEB shows the average characteristics of the local environment as a single urban canyon composed of a ground-based surface bordered by two flat-roof buildings of same height. The urban environment is thus described based on four distinct elements that compose the urban canyons: *roof*, *wall*, and for the ground-based surfaces, a combination of impervious and natural covers referred to as *road* and *garden*,

respectively. It can be highlighted that recent development of the models included the integration of trees [50]. For each urban facet, the model computes a radiation budget and a surface energy balance. It also resolves an equation of the temperature evolution with a single surface temperature associated with each facet. For natural soils and vegetation, the radiative and energy exchanges with the atmosphere, and the hydrological and thermal processes in the ground are parameterized with the interaction soil–biosphere–atmosphere model (ISBA) [51]. Such a representation, based on the canyon analogy, has the advantage of taking into account the urban context and the location of the site in the city. It provides mean microclimatic values (temperature in the canopy, wall roof and soil surface temperatures, net radiative fluxes, wind velocity) for the cell, but not the accurate value for a building depending of the other surfaces arrangement. TEB can also be run alone with 1D meteorological forcing [52] (see section 2.3).

### 2.1.2. Weather research and forecast model & BEP

The Weather Research and Forecast (WRF) model [53,54] integrates three urban schemes [55]. The first one is the SLAB model that does not include the canopy parameters [56]. The second one is the Urban Canopy Model (UCM) [57,58] with properties similar to the TEB model. The last one, the Building Effect Parameterization (BEP) [59], is integrated into WRF. The BEP is a multi-layered canopy model that provides direct interactions with the planetary boundary layer (PBL). It includes the vertical and horizontal surface impacts on the momentum, temperature, and turbulent kinetic energy (TKE). A turbulent scheme based on [60] is also integrated into WRF to include a source TKE term that also uses modified turbulent length scales. A BEM has also been introduced to improve the representation of the buildings and to include anthropogenic heat fluxes [61,62]. Additionally, CIM has also been recently integrated in WRF to improve the computation of high resolution vertical profiles within the urban grid cells.

## 2.2. District scale models

At the district scale, we distinguish two families of models. The first one brings together models that do not represent the urban shapes explicitly but use parameters that translate their impact. They produce homogeneous data for the district examined. The second one includes

models that use the geometrical representation of the district and mesh it so that they explicitly resolve the governing equation for the inter-exchanges.

### 2.2.1. Parametric models

For parametric models, the climate characteristics are assumed to be constant in the UCL, in terms of the urban shapes, surfaces, materials and vegetation, etc.

- UWG and CAT

The Urban Weather Generator (UWG) [63], and the Canyon Air Temperature (CAT) models [64], start from one point of measurement outside of the city exposed to the same mesoscale climatic conditions, such as an operational measure station at an airport or standardized weather files [65].

The UWG is based on energy conservation principles and is a bottom-up building stock model. It uses input parameters that describe urban morphology, geometry, and surface materials. The UWG has four coupled modules: the rural station model (the forcing temperature), the vertical diffusion model, the urban boundary layer model, and the urban canopy and BEM. This chain of models makes possible translating rural temperatures into urbanized ones for a specific site in the city. It can be extended for simulations at the city scale. From the UWG [66], have developed the spatial urban weather generator (SUWG), which computes (horizontally) a 2D field for the temperature above the UCL and takes into account wind advection and height of the boundary layer depending on the weather type.

The CAT model can be used to simulate the air temperature in a specific site of a city. However, due to the lack of advection processes, it cannot be used to simulate regional/city-scale UHI.

- CIM

The Canopy Interface Model (CIM) is a 1D meteorological model [67] that can be either coupled with a 3D meteorological model (such as the WRF [54,68]) or used in an offline mode as a stand-alone module [11,69]. In such a case, the meteorological variables used as boundary conditions for the top cell of the column are usually taken from a climatic dataset. The district or block geometrical characteristics (building characteristics, street widths, and number of cells where buildings are present) are also given as input to the model. The CIM stands out from other canopy models by its ability to show different building sizes in the *x* or *y*-direction, and it can also calculate an adaptive mixing length along the *z*-axis based on the density in each cell. The CIM solves a diffusion equation derived from the Navier-Stokes equation reduced to one-dimension and calculates high-resolution vertical profiles of meteorological variables (wind speed, wind direction, and air temperature). It includes a 1.5-order turbulent closure scheme and resolves locally the turbulent kinetic energy by considering the obstacles present in the canopy, which is usually not the case in other canopy models [67].

### 2.2.2. Explicit models

An explicit 3D shape of the area of interest is modeled in these UCMs. The urban surfaces and the surrounding air volumes are meshed, which provides a detailed representation of the microclimatic variables around the buildings.

- ENVI-met

ENVI-met [70,71] is a widely used tool that includes air flow, heat and moisture exchanges, and vegetation. The scene representation is pixelated with a typical horizontal resolution ranging from 0.5 to 5 m. The aerologic flow is resolved using a computational fluid dynamics (CFD) simulation. Only the absorbed and reflected shortwave (SW)

radiative flux densities are calculated (inter-reflections are not included). Longwave (LW) radiation and conduction in walls has recently been added using a simplified scheme (including the mean temperature of walls and soil and fixed view factors) [72]. The surface-plant-air interactions model is very detailed and documented to assess the effects of green architecture visions on local comfort conditions. The typical simulation period is 24–48 h with a time step of 1–5 s.

- SOLENE-Microclimat

SOLENE-Microclimat is the result of the coupling of two tools, Code-Saturne [73] (a CFD open source code developed by EDF) and SOLENE (a radiative tool [74]), to which different modules have been added to represent conventional built elements (conduction in paved soil, building thermal models) as well as natural elements and climate adaptation solutions (trees, natural soil, green roofs and walls, water ponds, pavement watering). Because of a flexible geometry representation, all kinds of geometry aspects can be handled. The canopy is meshed to run CFD simulation and the lower boundary of this mesh corresponds to the surface mesh used by SOLENE and the building model. At each time step, the absorbed solar radiation of each facet is computed as the result of the direct and diffuse solar radiation received by the facet directly from both the sun and the sky, plus reflections from all other facets in view, minus the reflected flux away from the surface. To link the different fluxes, a thermal model incorporates LW radiation, conduction and storage in built surfaces. The LW radiation is calculated from surface temperatures using the radiosity method [75,76]. For one building, energy balance can be applied; it is partitioned according to its floors, and the choice is given to assess the energy needed to maintain comfort conditions or to evaluate comfort using the adaptive comfort model. Conduction is represented by a 1D detailed finite difference model [77]. For the other buildings (in which balance is not calculated), the indoor temperature is imposed, and the conduction model is a lumped-capacitance R2C one [78]. As a result, outdoor air temperature and humidity, wind velocity, and surface temperatures can be calculated in the mesh so that the impact on the local climate characteristics of the planning can be evaluated, together with more integrated indexes such as comfort indexes (MRT, PET, UTCI). Indoor comfort conditions or building energy demands can be assessed for the building for which energy balance is calculated.

### 2.3. Street models

The street scale is the lowest scale at which the local climate is examined. The street defines a confined air volume bordered by walls, in which the solar trapping effect and airflow regimes can easily be defined. As seen in section 2.1.1, the canyon model on which TEB is based can be used alone to study a particular street [50].

Bozonnet [79] proposes a zonal model of a canyon street including airflow and heat transfer (radiation, convection, conduction). Solar radiation is the only driving force in the street air movement. The value of such an approach is to show the interaction between the street and the buildings and to take into account the impact of cooling loads on the air temperature within the canyon [79]. This kind of model has also recently been developed by Liang et al. [80] with the aim of assembling several canyons and linking the local climate with the energy balance of buildings.

### 2.4. Discussions

The list of tools presented in this section is not meant to be exhaustive; other tools can be used to calculate fluxes above a district, such as Lazer-F [81], or energy needs at the district scale, such as EnviBatE [82].

Table 1 summarizes the different physical processes taken into account in the models presented for each scale.



**Table 1**  
Summarizing of climatic tools features.

Scale	Tools	Air temperature	Wind velocity	LW Radiation	SW Radiation
City	MESO-NH + TEB	mean in a 200*200 m array	mean in a 200*200 m array	mean per surface type in a 200*200 m array, considering all surfaces temperatures + Sky radiation	mean per surface type in a 200*200 m array, considering inter-reflections
Neighborhood	WRF + BEP	value at the center of the grid cell	value at the center of the grid cell	BEP- values for each facade orientation	BEP- values for each facade orientation
	ENV1-met	Locally around the building	Locally around the building	On all building facets, calculating incoming sky radiation and using mean temperature of wall, ground and vegetation	On all building facets, but only incident radiation minus reflected one.
Street	SOLENE-Microclimat	Locally around the building	Locally around the building	On all building facets, considering all surfaces temperatures + Sky radiation	On all building facets, considering inter-reflections
	UWG/CAT	mean for a location in the city	mean for a location in the city	same as TEB	same as TEB
	CIM	mean for a location in the city	mean for a location in the city	same as BEP	same as BEP
	TEB (canyon)	Vertically in the street	Vertically in the street	Mean per surface (each side of the street is a facet), taking into account all surface temperatures + Sky radiation	Mean per facet (each side of the street is a facet) considering inter-reflections
	Zonal models	Calculated in each cell of the zonal partition of the canyon	A velocity vector at each interface between zones	Bozonnet [79]: a simplified SW radiation model considering inter-reflections	Bozonnet [79]: a simplified LW radiation model considering inter-reflections

### 3. Building energy modeling

The first building energy simulation programs appeared in the 1960s (DOE-2 or BLAST in the U.S.). As they were designed in the days of mainframe computers, expanding their capabilities further became difficult, time-consuming, and prohibitively expensive. Next, significant advances in analysis and computational methods and power occurred, providing an opportunity for significant improvement of these tools. Then, in the 1990s, models such as EnergyPlus (U.S.) [83] or Comfie (France) [84] appeared, and some of them were sold to software companies in the 2000s. Since the 2010s, these numerical tools have often been used to help decision makers for building design projects.

BEMs are still improving, taking more phenomena into account, to propose a better representation of the complex reality. In this paper, the potential, the assumptions, and the accuracy level are detailed for the following widespread models: TRNSYS [85], Design Builder, Pleiades [84], EnergyPlus [83], BuildSysPro [86], CitySim [87], and Virtual Environment. Since Design Builder uses EnergyPlus as a calculation model and facilitates simulation with its user-friendly interface, the capabilities of EnergyPlus and Design Builder are deemed to be the same; hence, they are examined as one software (the last version of Design Builder V5 allows people to load their own EnergyPlus model). Although CitySim [87] is not primarily used at the building scale, we included it in our analysis as there are not many BEMs working at the district scale. Before exploring the BEMs, we can already differentiate BuildSysPro and EnergyPlus from the others as they are mostly used in research. Even if the others are also used in research projects, they are first adapted to be convenient and user friendly for engineers working in a consulting agency. Tittlein [88] classifies the dynamic BEMs into two categories: the “monolithic” software tools and the modular ones. Pleiades, in the first category, does a good job for building envelope design. In the second category, BuildSysPro, TRNSYS, and EnergyPlus, with all their modules, can offer coupled studies as for example between a building and a specific Heating Ventilation and Air-Conditioning (HVAC) system. As specified in the introduction section, we only focus on the way BEMs take into account local climate conditions.

The following subsections show the comparisons of BEMs regarding the different fluxes, summarized in tables: conductive heat transfer, solar radiations, infrared radiations, flux linked to aerualic systems, and hygrometry.

#### 3.1. Heat transfer by conduction in the building envelope

In the BEMs, the 1D transient heat conduction through walls, floors and roofs are modeled using computational transfer function (CTF), finite difference (FD), finite element (FE) methods or model order reduction techniques. For the CTF case, the Direct Root-Finding (DRF), State-Space (SS) and Frequency-Domain Regression (FDR) approaches are used to determine the CTF coefficients. In TRNSYS, the DRF approach is found, whereas EnergyPlus uses the SS one. Both can cause errors that increase depending on the reciprocal of the product of the Fourier number and the thermo-structural characteristics of the building. In other words, for small time steps (inferior to 15 min), the more the building is insulated and inertial, the bigger are the errors. With the FDR approach, the simulation error is always inferior to 1% (Delcroix et al. [89]). However, compared to DRF and SS approaches, the FDR one is time consuming. Additionally, when considering the computational resources, the CTF solving method is faster than the FD one, but the finite difference gives better accuracy results for short time steps simulation [90]. Pleiades, Virtual Environment, and EnergyPlus use one dimensional FD method [84,91,92]. In Pleiades, the model is reduced by modal analysis in order to improve calculation times [84]. CitySim uses a simplified method by making an analogy with an electrical circuit with resistance and capacitance, which offers a good compromise between simplicity, data requirements, and computational time [93].

**Table 2**  
Methods used to solve conductive heat transfer through the walls.

BEM	Transfer function	Finite Difference	Finite Element	Model Order Reduction	Simplified models
TRNSYS PLEIADES	Heat transfer: Z- transfer function [89]			Heat transfer: Finite Difference model reduced by modal analysis [84] Can be used	
BuildSysPro EnergyPlus	Can be used Heat transfer: CFT response factor.	ThermalHeat Transfer (modelica library) For phase change material or variable thermal conductivity: Crank-Nicholson semi-implicit or Euler implicit scheme [92]. Euler implicit scheme [91]	Can be used Heat and Moisture Transfer (HAMT) model [83]		
DesignBuilder	Moisture transfer: Effective Moisture Penetration Depth (EMPD) model				
Virtual Environment CitySim					Resistance-Capacitance model

An interesting option for coupling 1D thermal and moisture transfer is available in EnergyPlus: the Heat and Moisture Transfer (HAMT) Model [83]. It uses the FE method. However, the HAMT option is about 100 times more time consuming for simulation than the standard one, the CTF [16] (Table 2).

### 3.2. Solar radiation

Solar radiations plays a major role in the building energy balance and indoor comfort. In temperate climates, maximizing the solar gains in winter and minimizing them in summer is the biggest challenge for all building design projects. Therefore, it is important to know how the BEMs take this phenomenon into account. Solar radiation is divided into three components: direct, diffuse, and inter-reflection.

#### 3.2.1. Direct, diffuse SW incoming radiation

All BEMs take the direct and diffuse part of solar radiation into consideration, and most of them take into account the shading of neighboring buildings. A sky-view factor can be calculated to obtain a more precise computation of the incoming solar radiation. Other far masking effects from distant obstruction, such as topography, can sometimes be included.

The direct and diffuse SW incident flux on a component (e.g. wall, window) is either partly absorbed and/or partly transmitted, depending on the type of surface. The transmitted part is then distributed over the interior building surfaces either by solar tracking [88,94] or through a weighted method. Different weighted methods can then be used: it can be affected directly to the floor, or spread by geometrical parameter of the surface (i.e. the surface area ratio).

#### 3.2.2. SW radiation: inter-reflection

Calculating solar inter-reflection between building surfaces and the surrounding ones requires geometrical simulation and the knowledge of surfaces albedo. It is the reason why the BEMs commonly take into account only the reflection from the soil in a unidirectional way (i.e. a part of the solar flux received by the soil, which is reflected towards the building wall). The ground plane is considered to be unobstructed, the shadowing of the ground by the building itself or by other obstructions is ignored. Design Builder provides a “reflection option”. In this case, building surfaces reflect solar radiation onto another section (and vice-versa). The building surfaces are assumed to be reflecting diffusely if they are opaque and specularly if they are windows or glass doors. The shadowing of the ground is taken into account if the reflection option is used. CitySim takes a slightly different approach. A surface energy balance is conducted for each of the surfaces in the model, thereby accounting for both the inter-reflection and the shadowing between the buildings (Table 3).

### 3.3. Infrared radiation

Two bodies at different temperatures and in co-visibility with each other tend to exchange energy by LW radiation (infrared) in order to reach an equilibrium. These exchanges occur inside and outside the building. When studying them, the difficulty is that all surrounding surfaces must be taken into account, including the sky. The exchanges will be calculated between each surface of the building and all the others, the temperature and emissivity of which must be known. Moreover, in these calculations, the surface temperature appears with an exponent 4, which complexifies calculations. Infrared calculations thus require the thermal calculation of a larger system to be performed and introduce non-linear terms, so that simplifications have been proposed. First, exchanges between urban surfaces are commonly neglected, external building surfaces are assumed to be at the same temperature, and so at the thermal equilibrium. Then, only exchanges with the sky are taken into account.

**Table 3**

Ways BEMs take solar radiation into account.

BEM	Direct	Diffuse	Inter-reflection	Inside: Solar radiation incidence
TRNSYS	x	x	Only with the soil	Weighted method
PLEIADES	x	x	Only with the soil	Surface area ratio
BuildSysPro	x	x	With the soil in base, but can include the others urban surfaces by external calculation (not available in the opensource model)	Any weighted method can be parameterized
DesignBuilder/EnergyPlus	x	x	In base: With the soil Option: with building surfaces	Weighted method
Virtual Environment [91]	x	x	Only with the soil	Solar tracking
CitySim [91]	x	x	With the soil and with external building surfaces	Weighted method

- Infrared exchanges with the sky included in convection

The simplest way to consider this infrared exchange is to linearize it, to estimate sky temperature as a function of air temperature depending on sky type (clear or covered), thus making it possible to aggregate this transfer with the external convective one by increasing the convective heat transfer coefficient (CHTC) by a constant value. This is what is done in the Pleiades and Virtual Environment software.

- Infrared exchanges with the sky

In EnergyPlus, building facades are assumed to be at the same temperature; hence, there is no LW radiation between them. The exchanges occur with the sky and the ground using the view factors calculated between surfaces and the sky (SVF).

- Infrared exchanges with the sky and between built surfaces

BuildSysPro and CitySim are the only programs capable of simulating the infrared radiations between building facades [67,87,95], using view factors (Table 4).

### 3.4. Aeraulic flows

Aeraulic flows impacts several terms in the energy balance of the simulated building. Wind speed and direction as well as the local thermal gradient change the CHTC. Air pressure at the facade level causes infiltrations of fresh external air inside the building through openings (case of natural ventilation) and envelope defects (air permeability).

#### 3.4.1. Convection

CHTCs are commonly assumed to be a constant, or just depending on the facade inclination, horizontal or vertical [96]. They can also be calculated using wind speed (forced convection), and/or from surface-air temperature (natural convection). However, in these two cases, as BEMs cannot calculate near wall values of wind speed or air temperature, these values are taken from weather data and do not take local features into account. Regarding wind speed, the weather station velocity can be resettled, considering site characteristics and wind speed calculated at any height using these adapted profiles. It is not the case for temperatures for which no method exists (Table 5).

**Table 4**

IR calculation options taken by the different BEMs.

BEM	Included in the convective coefficient	Only with sky	Whole infrared calculation
TRNSYS		x	TRNSYS is a program with large modularity so this calculation might be implemented
PLEIADES	x		
BuildSysPro	Can be included		A module has been developed (not available in the opensource model)
DesignBuilder/EnergyPlus	Can be included	x	EnergyPlus is open source model; hence this calculation may be implemented
Virtual Environment		x	The LW radiation received from the ground is estimated
CitySim			x

#### 3.4.2. Infiltration and ventilation

To assess wind pressure and then infiltration flows, BEMs use pressure coefficients that vary depending on the exposure of the surface to the wind (upwind or downwind). These coefficients are taken from tables of the Air Infiltration and Ventilation Center [97], and wind speed can be adjusted to take into account the height of the surface and site rugosity [98]. Ventilation flows are calculated in the same way in the case of natural ventilation and resulting heat fluxes calculation uses outdoor temperature from the weather station. It is the same for the calculation of flows driven by buoyancy forces (Table 6).

### 3.5. Hygrometry

In a comfort study, the advantages of using hygroscopic materials has been experienced on site. It is through the numerical calculation at the design stage that such materials could be highlighted and then appear in the building project. In most of the BEMs, hygrometry is not very well integrated in the calculations. Often, the relative humidity of the air from the weather file is considered in post processing for thermal comfort studies (Givoni [99] diagram, ISO 7730 norm). Nevertheless, some tools such as EnergyPlus give a choice of many solving options and one of them allows for moisture transfer through a wall: the Heat And Moisture Transfer (HAMT) finite solution. This calculation combining both heat and moisture transfers could give evidence of the utility of specific materials able to regulate hygrometry inside a building.

### 3.6. Vegetation

Vegetated walls can be represented in building thermal simulation. The process can be very simple (i.e. changing the albedo of the surface), or the representation can be more complete and involve the evapotranspiration of the vegetation. These phenomena impact the surface temperature due to the solar absorption level for the first case or due to the latent energy consumed for evapotranspiration for the second. However, the vegetation representation rarely influences the level of the relative humidity of the air in the BEMs, although it has been shown it can have an impact on latent cooling loads [8]. An evapotranspiration model has also been recently included in CitySim to represent natural surfaces and trees [100,101].

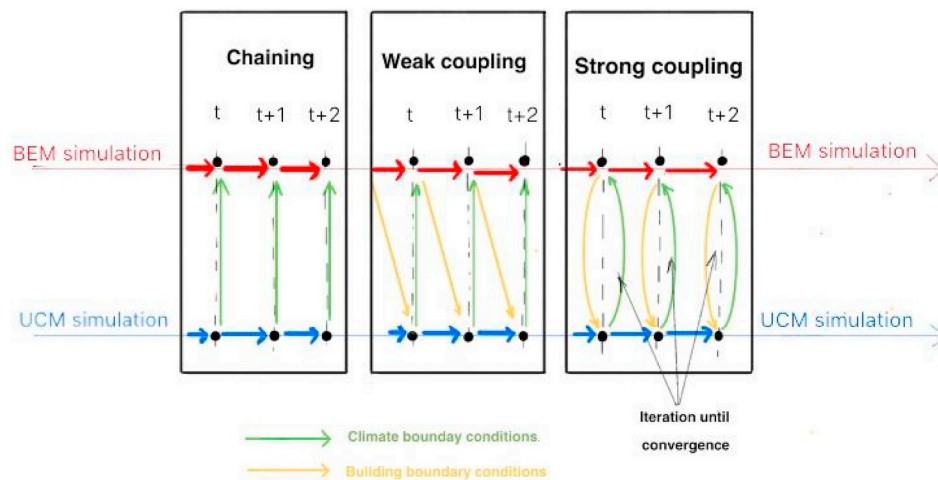


**Table 5**  
Calculation of the external heat convection coefficient.

BEM	Constant	Natural convection (function of the temperature gradient)	Forced convection (function of the wind speed)	LW radiation exchanges taken into account
TRNSYS	x	Can be implemented	Can be implemented	Can be implemented
PLEIADES	x			x
BuildSysPro	x	x	x	Can be included
DesignBuilder/EnergyPlus	With “CIBSE”	With “Adaptive Convection Algorithm” or “Simple Combined”	With “Adaptive Convection Algorithm”	Can be included with “Simple Combined”
Virtual Environment	x		x	
CitySim		x	x	

**Table 6**  
Calculation of infiltration and natural ventilation.

BEM	Constant (Simple method)	Flows rate equations	Computational Fluid Dynamics CFD
TRNSYS	x	TRNFLOW model	
PLEIADES	x	x (based on CONTAM model)	
BuildSysPro	x	Can be included	Can be included
DesignBuilder/EnergyPlus	x	x	x (SIMPLER algorithm)
Virtual Environment	x	MacroFlo model	MicroFlo model
CitySim	x		



**Fig. 2.** Sketch to introduce coupling and chaining methods.

### 3.7. Discussion

This section comparing BEMs shows how, with more or less accuracy, every flux is taken into consideration in the tools. These BEMs have been developed mostly about one decade before UCMs; hence, they are adapted to integrate external climatic solicitations with the available data at that time, i. e. weather data at mesoscale. Nowadays, the development of UCMs gives new perspectives to introduce the urban climate or even urban microclimate in BEMs. Temperature, humidity, and air speed are taken as one homogeneous value for the whole building envelope; hence the output data from the UCMs can be easily transferred to BEMs through a “new local climatic file”. On the other hand, for the radiation solicitations such as solar rays or infrared exchanges, the link between UCMs and BEMs is complicated. In BEMs, global radiation data are taken from the weather file, and then a radiation calculation is performed to attribute those fluxes to the different external building surfaces such as walls or windows. Even for modular BEMs with good flexibility (TRNSYS, EnergyPlus, BuilSysPro), it can be difficult to match the geometries of both the UCM and BEM tools to give the possibility of integrating the radiation flux for each building envelope part.

### 4. Coupling or chaining UCMs and BEMs

After searching for published papers describing the chaining or coupling of UCMs and BEMs, we selected a set of eight projects ([11,102–108]). The selection was made so as to represent a range of UCMs and BEMs as large as possible, using the information we could extract from the publications in order to have an accurate understanding of the interaction between the UCMs and the BEMs. All the information was obtained from the cited publications, cross-checked with the information provided on the UCM and BEM tools, and sometimes checked by contacting the authors.

This section presents a non-exhaustive set of UCM and BEM coupling or chaining published attempts. Our aim is to highlight the particularities of each one as well as their main limitations. Then, we give a global overview of these chaining or coupling attempts in terms of impacts on the BEM results, simulation time period capabilities, and the main locks that have appeared.

To consider the local climate in a building energy simulation, chaining or coupling strategies are adopted to link UCM and BEM software. Coupling strategies show strong coupling or weak coupling. For strong coupling, both UCM and BEM solvers are running at the same time to converge to a consistent result and go through the next

time step simulation (Fig. 2). For weak coupling, solvers of the UCM and BEM tools are running but in an iterative way to go ahead to the next time step simulation (Fig. 2). Coupling strategies allow feedback regarding building use on the local climate, in particular the anthropogenic emissions released outside due to air-conditioning or heating systems (such as heat pumps). In strong and weak coupling methods, UCM and BEM simulations have an impact on each other. Finally, the chaining method involve making a whole UCM simulation for the study period and providing the results into the weather files used in a BEM tool (Fig. 2); it thus involves one-way communication from the UCM to the BEM, without feedback.

All the weather data used by the BEMs are found in mesoclimatic files. Theoretically, they could be modified, using information resulting from the UCMs, to obtain a better representation of the surrounding climatic conditions for a study case. Depending on the kind of UCM used, the local climate information is more or less aggregated to specify the temperature and humidity of the outside air and the wind velocity without changing the climatic file format. Concerning radiation exchanges (SW and LW), explicit geometry tools are needed to determine the data all around the building, that can be used in a BEM if it can integrate such heterogeneity.

In the following section, we present and analyze practical examples of these strategies, as well as attempts that include the simplified representation of the direct surroundings through canyon models. The chaining or coupling strategies are summarized in Fig. 3 and detailed in the following sections.

**Table 7**  
UWG + TRNSYS.

Phenomenon	Treatment
Long wave	TRNSYS configuration
Short wave	TRNSYS configuration
Convection	TRNSYS configuration with local air temperature and relative humidity
Ventilation and infiltrations	TRNSYS configuration with local air temperature, fixed air flow rate

#### 4.1. Chaining strategies

##### 4.1.1. UWG and TRNSYS

**Aim and method:** Palme et al. [102] present a methodology for considering the urban heat island (UHI) to enhance a building performance simulation. The method is applied to four different residential building types (two-story family housing, semi-detached house of two floors, block of apartments of five floors and tall building of twenty floors). The urban weather files are generated by using the UWG software for numerous urban tissue categories (UTCs). In this case, UTCs are classified according to their morphological characteristics, i.e. the built-up area, the green area, and the facade to site area ratio. Then, a building performance simulation is performed for each building type with TRNSYS using the generated weather files. In this work, the UCM is a global parametric model and the used BEM is a detailed multizone model.

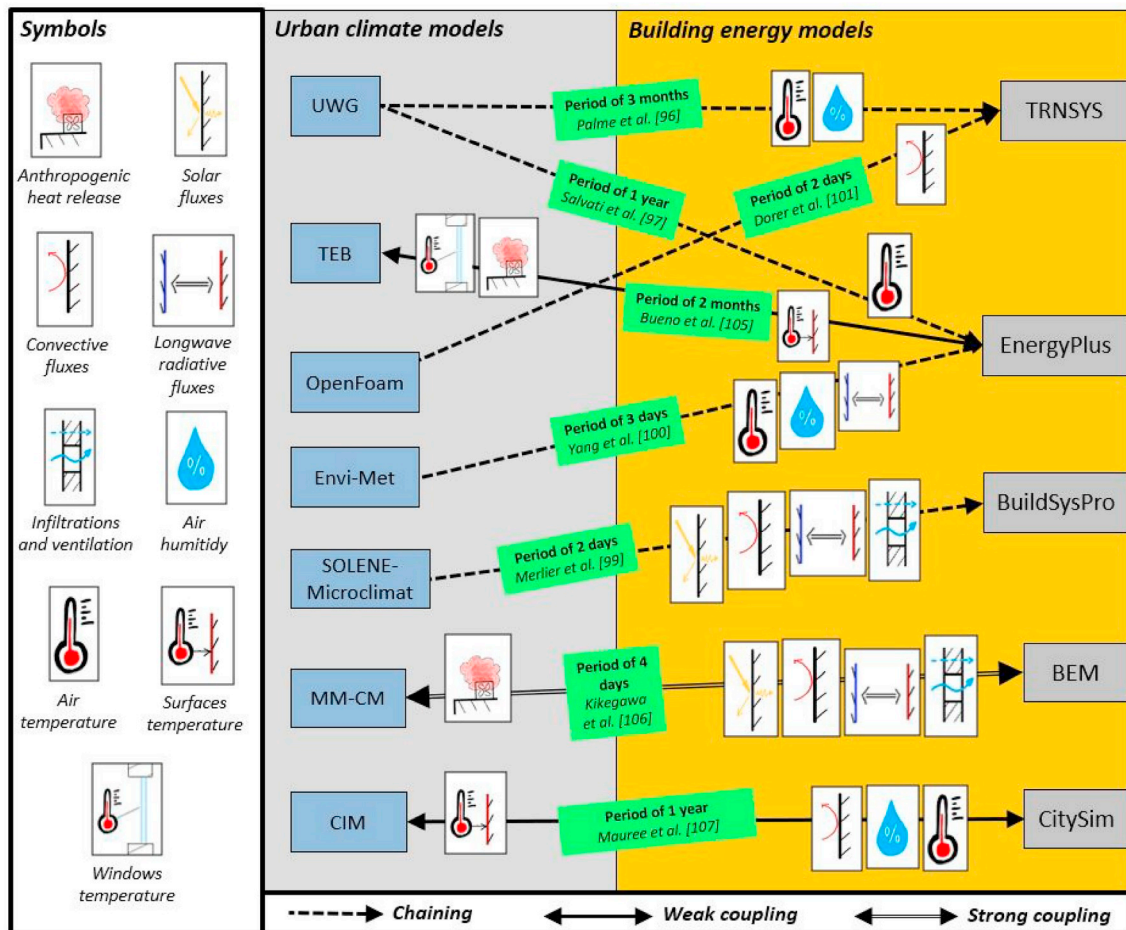


Fig. 3. Different coupling and chaining projects.

**Analysis of the coupling:** In this case, the chaining is quite simple as it involves modifying only part of the input weather files for the BEM without changing specific parameters of the model such as CHTC. (Table 7). Even if the building model is quite detailed only a unique outdoor air temperature can be used for the whole building. This is independent of the coupling method used as it is proper to the BEM (here Trnsys).

**Capabilities and limits:** As a parametric model, the UWG can rebuild hourly weather data with homogeneous values over the study zone. Long simulation periods are possible; the study presents 3 months of simulation.

As the UWG has an implicit representation of the study case, radiation solicitations are not calculated which is a drawback. So, this coupling allows to consider air temperature due to UHI but not the complete impact of urban forms and materials. Thus, the obtained results, particularly the impact of the size and orientation of buildings, should be put into perspective as the environment is only represented through the air temperature. Taking into account the solar radiation reduction due to urban form would decrease this effect as shown in the next coupling strategy (Salvati et al. [103]). To that end, it would have been possible to consider the advanced capabilities of TRNSYS such as the calculation of local short wave radiation to better represent the surrounding environment and urban surfaces, still with the limits related to TRNSYS and described above. However, this would require to explicit the building environment, what is, in the case of the study conducted by Palme et al. [102], somewhat contradictory to the generalization toward which the authors tend.

One can also note that there is no feedback from the BEM to the UCM to take into account the thermal loads due to cooling systems.

However, bearing in mind the above-mentioned limitations as well as those mentioned by the authors, this chaining method could be extended to study the impact of adaptation strategies on buildings' energy consumption at the urban scale.

#### 4.1.2. UWG and EnergyPlus

**Aim and method:** Salvati et al. [103] seek to investigate the direct and indirect effect of urban morphology on buildings energy performance in the Mediterranean climate, by means of the use of the global parametric UCM UWG and the detailed multizone BEM EnergyPlus. The improvements include local outdoor air temperature and radiation. A sensitivity analysis was carried out on typical realistic urban forms and buildings within these urban forms in order to quantify how these two changes modify the building energy demand.

**Analysis of the coupling:** UWG calculates hourly values of urban air temperature from the data measured at an operational weather station located outside the city. This calculated temperature is then used at the whole building scale. In addition, the SW received by walls and road is calculated by assuming an average urban canyon orientation. The LW radiation between walls, road and the sky is computed by linearization of the Stefan–Boltzmann equation. To conclude, the chaining consists in modifying the input weather files (outdoor temperature and radiation) for the BEM without changing specific parameters of the model Table 8. Here again, there is no feedback from the BEM to the UCM to take into account the thermal loads due to cooling systems.

**Capabilities and limits:** As for the first example, the UWG uses a

long time simulation period; in this case, one year is studied. This is valuable in terms of next estimating the heating needs, which are usually expressed over a whole year. Concerning thermal comfort, the number of uncomfortable hours is often provided from early May to late September, namely over a five 5 months period.

As stated previously, without an explicit 3D geometry of the zone examined, the UWG cannot simulate radiations; in this case, an alternative methodology is proposed by estimating a ratio of incoming shortwaves from an averaged urban canyon orientation. The paper demonstrates that this is crucial when willing to assess the impact of urban environment on buildings' energy consumption.

It remains that the urban environment effect is averaged on the building which does not allow detailing spatially the impacts within the building, which is a limit for the use of the coupling for comfort assessment purposes.

With the previous limitations, this chaining method could be used to improve the consideration of the built environment in buildings' design process but it will not allow an accurate assessment of the impact of a specific climate adaptation strategy at the neighborhood scale.

#### 4.1.3. SOLENE-microclimat and BuildSysPro

**Aim and method:** Merlier et al. [104] develop a methodology aiming at modeling the local thermo-aeraulic environment of buildings and studying the relative effects of radiative, convective, thermal and pressure conditions on their thermal behavior. The microclimate tool used is the explicit 3D model SOLENE-Microclimat and is then linked to the BEM BuildSysPro. In order to show the uncertainties related to the use of default boundary conditions in usual dynamic building energy studies different simulations have been launched:

- a default simulation taking the Meteonorm weather file but with no surrounding environment;
- a simulation considering the boundary conditions given by SOLENE-Microclimat for a single isolated building;
- a simulation where SOLENE-Microclimat is applied to buildings arranged in plots and provides the fluxes obtained for the central building that are used in BuildSysPro.

**Analysis of the coupling:** This chaining method uses the output of SOLENE-Microclimat directly as input to BuildSysPro, but there is no feedback to the SOLENE-Microclimat model. The different heat fluxes calculated by SOLENE-Microclimat and used by BuildSysPro are described in Table 9. As SOLENE-Microclimat uses a detailed triangular meshing for solar radiative exchanges, a mean solar radiation is calculated for each wall element in BuildSysPro. Mean heat flows are taken by each wall and depend on the convective heat transfer coefficient. This latter is calculated by using the wind speed calculated by SOLENE-Microclimat with Equation (1):

$$CHTC = 4 \cdot v_{air} + 4 \quad (1)$$

with  $v_{air}$  the wind speed.

As in the previous examples, there is no feedback from the BEM to the UCM to take into account the thermal loads due to cooling systems.

**Capabilities and limits:** The high meshing level of SOLENE-Microclimat (characteristic length of 2 m) is time consuming for the calculation, which leads to short study periods (2 days are simulated in this example, using an hourly time step).

**Table 8**  
UWG + EnergyPlus.

Phenomenon	Treatment
Long wave	EnergyPlus configuration
Short wave	EnergyPlus configuration with ratio applied to incoming solar flux
Convection	EnergyPlus configuration with local temperature from UWG
Ventilation and infiltrations	EnergyPlus configuration with a fixed rate of 2 vol/h

**Table 9**  
SOLENE-Microclimat + BuildSysPro.

SOLENE-Microclimat + BuildSysPro	
Long wave	All LW exchanges (with the sky and urban scene) are calculated by SOLENE as input to BuildSysPro.
Short wave	SW provided from SOLENE-Microclimat: incident solar radiation on building facades and the shadowing effects of adjacent obstructions are calculated
Convection	CHTCs are calculated using the wind speed from SOLENE-Microclimat and Equation (1) from the French Regulation
Infiltrations and ventilation	Infiltrations are modeled assuming a homogeneous wall permeability (K) and a power law for infiltrated air flow rates: $Q_P = K \Delta P^n$ . The external pressure is computed using default pressure coefficient values and the building height. For the ventilation, the air temperature of the weather file is considered.

In this case, all fluxes are modified so as to take the local context into account. However, the main limitation is the need to average local data because BuildSysPro can include only one value per facet so that the spatial detail capacity of the UCM is not completely used. This is limiting to carry out detailed inside thermal comfort assessments.

With the previously underlined limitations, this chaining method could be used to improve the consideration of the built environment in buildings' design process, including the impact of specific climate adaptation strategies at the neighborhood scale. However, due to the calculation time, a focus on specific conditions such as heat waves is required.

#### 4.1.4. ENVI-met and EnergyPlus

**Aim and method:** Yang et al. [105] present a method for the quantitative analysis of building energy performance under any given urban contexts. The authors linked EnergyPlus with the explicit 3D micro-climate simulation tool ENVI-met. A case study is presented to show the impact of microclimatic boundary conditions on an individual building performance.

**Analysis of the coupling:** An initial simulation was performed in ENVI-met to obtain microclimatic parameters, which were averaged and used in a modified weather file for an EnergyPlus simulation. One of the assumptions in EnergyPlus is that the surface temperatures of ground and obstructions are the same as the outdoor air temperature: therefore, the authors had to replace the original ground/obstruction surface temperature (equal to the outdoor air temperature) in EnergyPlus with the mean temperature of all neighboring surfaces calculated by ENVI-met. The incident solar radiation is directly calculated by EnergyPlus taking the masks into consideration. There are therefore no inter-reflections. Finally, the convective flow, infiltration, and humidity were calculated by ENVI-met and modified in EnergyPlus. The different heat fluxes calculated and used as input to EnergyPlus are summarized in Table 10.

**Capabilities and limits:** As in the previous case, the high precision of ENVI-met describing explicitly the study area leads to short study periods; in this case, 3 days are simulated.

One of the major limits is that inter-reflections are not taken into account in the SW radiations calculated thanks to EnergyPlus. However, it would have been the same using the output from ENVI-met.

**Table 10**  
ENVI-met + EnergyPlus.

ENVI-met + EnergyPlus	
Long wave	LW exchanges between the surfaces of the urban scene and those of the building are calculated by replacing the outdoor neighboring surface temperature in EnergyPlus with the mean of surface temperatures calculated in ENVI-met. As there is no actuator in EnergyPlus to override the thermal radiative heat flux, the authors combine the actual LW radiative flux at the building external surfaces into the component of convection heat transfer using the same procedure as considering the actual outside air temperature.
Short wave	The incident solar radiation on building facades and the shadowing effects of adjacent obstructions are calculated by EnergyPlus, but the average ground reflectance and tree transmittance determined by ENVI-met are used for the EnergyPlus simulation.
Convection	Since the outside air temperature can not be changed in the current version of EnergyPlus (only if modifying the EnergyPlus source code), a workaround is implemented by modifying the CHTC in order to integrate the simulated air temperature by ENVI-met.
Infiltrations and ventilation	The specific humidity and air temperature along the whole building simulated by ENVI-met are averaged. The average specific humidity is converted to dew point temperature and relative humidity. The original air temperature, dew point temperature, and relative humidity of the EnergyPlus weather file are replaced by the calculated mean values.

Moreover, as for the previous case, the averaging of the heat fluxes transferred to the BEM limits the assessment of the impact of a local adaptation solutions. On the other hand, in ENVI-met an averaging of surface temperatures is already performed when calculating the infrared exchanges. Hence, this kind of study is already of limited accuracy when using ENVI-met. To conclude, concerning the air temperature and the relative humidity, ENVI-met often gives too precise results to be directly used in EnergyPlus, which is why an average is calculated. Concerning radiations, the solution adopted by the authors could be discussed if the output proposed by EnergyPlus would have been more accurate, but as previously explained, here it certainly does not add to the degradation of the results accuracy. Nevertheless, the method could be used to improve the consideration of the built environment in buildings' design process. It is less adapted to assess the impact of a climate adaption solution that would be placed especially to optimize its effect (for example a specifically treated surface just in front of a building). In addition, due to the calculation time, a focus on specific conditions such as heat waves is required.

#### 4.1.5. OpenFoam (CFD) + TRNSYS

**Aim and method:** Dorer et al. [106] analyze the impact of the urban microclimate and in particular the UHI on the space heating and cooling energy demand for typical office buildings in street canyon configurations. Therefore, the open source CFD software package Openfoam which is a district model with explicit geometry (OpenFoam, 2012 [109]) is chained to TRNSYS 17.0.

**Analysis of the coupling:** The convective heat fluxes and data are transferred to the BEM, either through CHTC or by directly coupling CFD and BEM for street canyon case modeling [106]. CFD simulations are performed using the RANS models of the open source CFD software package OpenFoam (OpenFoam, 2012 [109]). The UHI intensity is approximated by using results of the BUBBLE project [110]. A diurnal rural-urban temperature is generated for each month. For this study, TRNSYS 17.0 (TRNSYS 17.0, 2010) [111] is employed. For the external radiation fluxes, the authors use the TRNSYS 3D radiation model that has been developed to assess reflections within interior cells. To this end, they view the building surrounding spaces as an atrium with an open ceiling, so that finally, the shadowing by the neighboring buildings and the SW and LW radiation exchanges between the different



**Table 11**  
OpenFoam (CFD) + TRNSYS.

OpenFoam (CFD) + TRNSYS	
Long wave	LW radiation between the building and its surroundings is dealt with through the use of the TRNSYS 3D radiation model using a fictive atrium representing the street.
Short wave	Same as LW.
Convection	Convection aspects of the urban microclimate are modeled using the results of OpenFoam (CFD), and the data are transferred to BEM. The air temperature used can take the UHI intensity into account if a previous model from the BUBBLE project is used.
Infiltrations and ventilation	Not detailed in the paper.

buildings are taken into consideration. The SW diffuse and LW radiations are determined using Gebhart factors (view factors, corrected to include the effect of multiple reflections). The different heat fluxes calculated and used as input to TRNSYS are summarized in Table 11.

Besides this paper that mainly demonstrates the above-mentioned coupling for canyon streets, another chaining project is proposed, using OpenFoam for convection fluxes and CitySim for radiation exchanges to produce boundary conditions for TRNSYS. The first solution implies the use of several tools to prepare input data for BEM. OpenFoam estimates the CHTC, the UHI model from the BUBBLE project is used for the temperature calculations, and radiation fluxes are simulated from the TRNSYS 3D radiation model. The second solution replaces the model for radiation estimations by using CitySim.

**Capabilities and limits:** Whatever the solution adopted, because CFD calculations are time consuming, these chaining processes have been set for a short period of 2 days.

Both solutions seem to offer relatively complicated processes where different climatic solicitations provided by different tools lead to no interactions between the phenomena investigated, which could give inconsistent results.

One of the major limitations of these chaining solutions is that UHI intensities are approximated based on measured data. These data are valid for the city of Basel but if wanting to replicate this method on another city, the UHI intensity would not be correct anymore. A second one is that the method is restricted to buildings located in street canyon.

To conclude, when disposing of UHI data, the method could be used to improve the consideration of the built environment in the case of buildings inserted in canyon streets, as well as to assess the impact of a climate adaption solution applied to the street.

## 4.2. Coupling strategies

### 4.2.1. TEB and EnergyPlus

**Aim and method:** The aim of the study of Bueno et al. [107] has been to analyze how the outdoor air temperature is impacted by waste heat emissions with a realistic definition of HVAC systems which allows a broader analysis of the two-way interactions between the energy performance of buildings and the urban climate around the buildings. Therefore EnergyPlus (with a monozonal representation of the building) and the district model with explicit geometry TEB are used.

**Analysis of the coupling:** The coupled scheme EnergyPlus – TEB proposed here is a weak coupling. The iterative coupling process starts from a preliminary average-oriented canyon using TEB simulation and

off-line meteorological forcing information [49]. The wall and roof temperatures and the urban canyon climate conditions calculated by TEB are supplied as boundary conditions to the EnergyPlus simulation; external convection and radiation exchanges are thus by-passed. One of the reason for this choice is that EnergyPlus simplifies the calculation of LW radiation between building surfaces and the surrounding ones, assuming that the latter are at the outdoor air temperature, which is a strong assumption. Similarly, the calculation of convective heat flux and SW radiation differs in the two tools, so that transferring surface temperature avoids inconsistencies that would have appeared because of different flux calculation in the tools. EnergyPlus then proceeds to the building energy balance, taking into account HVAC and windows temperature and return it to TEB. TEB does not deal with transmission through windows, internal heat gains, air infiltration, and the calculation of cooling loads. The latter are used in a new iteration of TEB, which uses the window temperatures calculated by EnergyPlus in its outdoor energy balance according to the glazing ratio of building facades. This process is repeated until a convergence criterion is satisfied, reached when the average canyon temperature difference between iterations is below 0.05°C. Surrounding buildings are represented by shadowing surfaces within the average-oriented canyon in TEB. In order to match with the representation of a canyon street, which does not mesh facades vertically and uses an average oriented street, the building in EnergyPlus is monozonal and rotated by 45°C with respect to the north–south axis. This example illustrates the complete coupling regarding the main phenomenon (Table 12). However, it is worth noting that it is simplified as TEB and EnergyPlus rely on homogeneous conditions per floor.

**Capabilities and limits:** It is worth noting that the results of this coupling strategy have been confronted to experimental measurements, which showed that both TEB and EnergyPlus consistently overpredict exterior wall temperatures in winter but the general simulation results are satisfactory: a root mean square error (RMSE) between 0.3 and 1.3 K for facade temperatures and a RMSE smaller than 1 K for air temperatures.

Simulation are run over a long simulation period (2 months are coupled), allowing to carry out seasonal studies. Indeed, the coupling gives more interaction between the physical phenomena than the chaining method, but leads to more time-consuming computation.

The study focuses mainly upon the impact of the building onto the urban microclimate. Thus, the building model is really simple with only one thermal zone. Moreover, the district being represented through the canyon street analogy in TEB, radiation fluxes estimations transferred

**Table 12**  
TEB + EnergyPlus.

Phenomenon	Treatment
Long wave	LW exchanges are calculated in TEB and the external surface temperatures are used in EnergyPlus as boundary conditions.
Short wave	The solar radiation received by the four vertical surfaces are calculated from the one received by the average-oriented canyon in TEB. The paper does not explain whether and how the solar flux is transmitted through windows to the indoor surfaces.
Convection	The convection heat flux is calculated in TEB using Wall CHTC (Masson 2000 [49]) and transferred to EnergyPlus through the external surface temperature
Ventilation and infiltrations	The paper estimates the impact of the building HVAC system on the canyon energy balance, but does not explain whether the canyon air temperature is taken into account as an inlet temperature for this flux (air flow rates are fixed so that we know that air velocity is not used).



to the BEM are approximated. For these reasons, to carry out analyses focused on buildings' energy consumption with this coupling strategy, it would be necessary to assess these strong assumptions. It also limits the ability to perform studies related to people vulnerability within buildings, as comfort conditions can vary strongly depending on the considered storey. However, with further developments, the building representation could be multizonal in EnergyPlus so that to represent a typical building of the district.

It would certainly be too complicated to extrapolate the coupling of TEB and EnergyPlus performed at the street scale as presented in the analyzed paper, to developments at the city scale. A simplified monozonal BEM has been integrated to TEB so that to improve the consideration of buildings operation in urban climate simulations. TEB can now also be used to assess the impact of global urban adaptation strategies on buildings energy consumption at the city scale [112], still with the limitation that have been above-mentioned.

However, the coupling, as presented can be used at the street/district scale to assess the impact of building operation on local climate.

#### 4.2.2. Urban canopy parametrization and BEM

**Aim and method:** This paper studies the increase of energy consumption due to the artificial air-conditioning of buildings in summer. Kikegawa et al. [108] developed a numerical simulation system that can express the city-block-scale interaction between summertime outdoor thermal conditions and cooling energy demands in the urban canopies. Therefore, a new one-dimensional urban canopy meteorological model coupled with a simple sub-model for the building energy analysis is developed. The BEM is a box-type heat budget model in which the building is treated with a monozonal approach. The urban canopy model comes from a meso-scale meteorological model.

**Analysis of the coupling:** Kikegawa et al. [108] coupled a BEM to a UCM, which is itself chained with a mesoscale atmospheric model (MM). The UCM and BEM are bi-directionally exchanging, and it seems to be a strong coupling, as both tools solve the physical problem at the same time. In this approach the feedback between the urban local climate and the building energy balance can be taken into account. The interaction between summertime outdoor thermal conditions and cooling energy demands in the urban canopy is calculated for the district scale. The UCM is a vertical one-dimensional model. It can compute the temporal variations of air temperature, humidity and wind velocity in the UCL. The UCM includes the effects of SW and LW radiations (whereas LW radiation is neglected in the mesoscale meteorological model) and the effects of building drag and anthropogenic heat release. In the BEM, the two components of the cooling loads (sensible and latent) are calculated separately. The energy released in the atmosphere is calculated in terms of the heat pump coefficient of performance. All heat fluxes are summarized in Table 13.

**Capabilities and limits:** In this paper, the method has been run on a short period (4 days) but the simplicity of the UCM (compared to models using explicit geometries as (SOLENE-Microclimat or ENVI-met) that offer more precise spatial results) suggests that it could be applied to longer periods. However, the large link scales, as three models communicate (mesoscale, microscale, and building scale) could also lead in intensive computations. Then, the method results were compared to data acquired within the Ootemachi area, a central business district in Tokyo, which leads the author to consider that it reasonably

reproduces the temporal variations of the outdoor air temperature and the indoor thermal environment under summer-day conditions.

However, according to the authors, the simulation system needs to be tested to urban districts with different conditions such as a residential area. There is also a need to expand its applicability to winter urban canopies.

This coupling is focused on urban microclimate estimation taking into account the buildings' operation and particularly its consequences in terms of heat released outside by the air conditioning system in summer. As in the previous example, the building model is quite simple as it considers a monozone approach which prevents its use for application aiming at studying the impact of local strategies on a specific building. On the contrary, an up-scaling could be performed so that to integrate the anthropogenic fluxes in the UCM.

#### 4.2.3. Canopy Interface Model and CitySim

**Aim and method:** The goal of this coupling was to compute enhanced boundary conditions for both the parametric district model (Canopy Interface Model (CIM)) and the building model (CitySim), so that to provide an annual estimation of the energy demand at the district scale taking into account local climate phenomenon.

**Analysis of the coupling:** Mauree et al. [11] coupled the Canopy Interface Model (CIM) and CitySim (see Table 14). The simulation takes place in three steps. First, a simulation with CitySim is performed with the standard typical meteorological year data file to obtain the surface temperatures. Using the surface temperatures from CitySim. The density and height of the obstacles in the canopy being estimated using a methodology proposed by Mauree et al. [67], the CIM is then used to simulate the flow in the column module and to recalculate high resolution vertical profiles of meteorological variables, such as the air temperature and the wind speed. Finally, CitySim is provided with localized meteorological data to simulate the energy demand. The modification of the variables influences the computation of the CHTC and the calculation of the LW radiation.

**Capabilities and limits:** This example focuses on the energy needs of several buildings through CitySim tool which has an explicit geometry of the study area allowing for radiation exchanges. It estimates flux exchanges at the external envelop surfaces of buildings and at the ground surface. Combined with the CIM that calculated air temperature and wind speed at local scale, this coupling seems interesting to generate hourly microclimate data (air temperature and wind speed from CIM, SW and LW radiations from CitySim) and this for one year.

A comparison of the outside air temperature and the wind speed was performed over the year 2015 and gave good agreement with measurements.

The limit of this coupling strategy is that it is not a two-way coupling between CitySim and CIM. Thermal loads due to systems operation are not taken into account in CIM. This coupling project is more adapted to the calculation of energy consumption in an urban district than to design of a specific building taking into account its environment. To illustrate the first kind of applications, it has been used to downscale climate data [113] and to design urban energy systems [114]. For the second kind of applications, CitySim has been coupled with EnergyPlus recently [13]. Moreover, as CIM is a large scale model its meshing is not adapted to consider the impact of local adaptation strategies, the radiative impacts of which would be considered in CitySim.

**Table 13**  
Urban canopy parametrization + BEM.

Phenomenon	Treatment
Long wave	The re-emission of LW from the building and ground surfaces is allowed for.
Short wave	The shading effect and reflection of SW radiation are incorporated.
Convection	Convection exchanges are viewed on either windows or walls.
Ventilation and infiltrations	The heat flux from ventilation is taken into account in the BEM and the heat released by the HVAC system is returned to the canopy model taking into account the COP of the HVAC.

**Table 14**  
Canopy Interface Model + CitySim.

Phenomenon	Treatment
Long wave	The re-emission of LW from the building and ground surfaces is taken into consideration. It is influenced by the local computation of the air temperature.
Short wave	The shading effect and the reflection of SW radiation are taken into consideration.
Convection	Convective exchanges are considered on either windows or walls. The modification of the wind speed, air temperature and surface temperatures significantly influences these exchanges.
Ventilation and infiltrations	No information.

#### 4.3. Discussion

In this part, we first give as synthesis of the capabilities and limitations of the methods presented above. Second, we discuss the impact of coupling UCMs to BEMs as our interest relies in knowing whether the chaining and coupling strategies can improve forecasting building thermal behavior. The benefits of this coupling can be monitored in terms of cooling and heating energy demands differences, but also in terms of indoor air temperature and comfort. Then, we examine the simulated period during which these chaining or coupling strategies have been performed. Finally, we discuss how BEMs are adapted or not to the integration of local climate heat fluxes and we compare these strategies with integrated ones that involve either expanding the BEMs to the outdoor calculation or modeling building energy balance within UCMs.

##### 4.3.1. Synthesis of the capabilities and limitations of the studied methods with regards to potential applications

As developed above, the chaining and coupling strategies have been developed to address different issues. They are also limited due to the options retained by the developers related to the UCM, BEM and the way they proceed to articulate the tools. In Table 15, an overview of these capabilities and limitations, in terms of applications is given. Here we detail what we mean for those different applications:

- Impact of buildings' operation on UC: the heat fluxes transferred from the BEM to the UCM includes the heat released by cooling systems so that urban climate calculations take into account these anthropogenic fluxes;
- Impact of UHI and adaptation strategies on buildings' energy demand at a large scale: the chaining or coupling allows assessing the impact of UHI (air temperature) on the estimation of the building energy demand of a building stock (at the block, district or city scale);
- Impact of UHI on a building energy demand: the chaining or coupling allows assessing accurately the impact of UHI (local air temperature) on the estimation of the energy demand of a specific building;
- Impact of local thermal phenomenon on a building energy demand: the chaining or coupling allows assessing accurately the impact of strategies such as adjacent green or cool surfaces on the estimation of the energy demand (or indoor comfort conditions) of a specific building.

##### 4.3.2. Impact of coupling or chaining on the building thermal behavior

For all types of chaining or coupling projects, the urban climate impact on the building energy behavior has been assessed. We find that the urban climate has an impact on several outputs of the BEMs. The main findings are detailed below.

Using parametric models to produce local climate data [103], confirm the effect of urban morphology on the UHI intensity and then on the building energy balance. Warmer outdoor temperatures lead to an average increase of total energy demand from 10% to 35%, depending on different urban densities. At the same time, the incident radiation reduction due to urban obstruction is desirable in Mediterranean climate;

it induces a reduction of the annual energy demand up to the 19% compared to an unobstructed environment. Therefore, relevant errors may occur if the contribution of urban morphology to energy demand is neglected, approximately 89% for space heating and 131% for space cooling calculations. With another parametric model [102], results indicate that when the UHI effect is incorporated, an increase in heating or cooling energy demand between 15% and 200% can be expected.

Using district explicit models, Merlier et al. [104] show that even for an isolated building case, taking into account the surrounding environment instead of only considering outdoor conditions derived from typical weather files may modify results by 1.3°C for the indoor temperature, mainly because of LW radiative exchanges with soil. These account for an increase of the mean indoor air mean temperature by 2.05°C, while aeratic effects (ventilation and infiltration) decrease the mean indoor air temperature by 0.12°C and convection increases it by 0.07°C.

As in the previous study, Evins et al. [115] combine the effect of adding a new ground model and surrounding building model on the LW exchanges in EnergyPlus. The authors observe an increase in surface temperatures by an average of 1.9°C, with a maximum change of 6.1°C. The annual heating load decreases by 18%, and the cooling load increases by 19% due to the introduction of local LW exchanges.

Also working with an explicit district model, Yang et al. [105] show that the sensible cooling load is very sensitive to the different options that can be taken to represent or not the built environment. First, taking into account solar masks (but no UCM chaining) has a major effect, decreasing cooling loads considerably (−18.6%) and increasing heating ones slightly (+0.8%). Second, when considering local climate simulation (with trees), cooling loads increase (+10.2%) while heating ones decrease (−0.5%) due to the UHI effect. Taking into account the effect of greenery is noticeable, but not as important as in the previous options. Infiltrations are shown to be the major phenomena in summer and infrared exchanges in winter. The local microclimate is also shown to influence the mean indoor air temperature in free running conditions, with a difference that reaches 2.1°C when neglecting the microclimate boundary conditions.

Chaining a parametric model and a district explicit model to a BEM, Yi and Peng [116] show the importance of outdoor and indoor coupled assessment at microclimate level to deploy passive design features adapted to climate change. The aim of this study was twofold: first, to take into account the outdoor microclimate, and second, to take climate change projections into account (but no change in urban context) on indoor environmental performance simulations. Therefore, different tools were used: CCWorldWeatherGen to generate recent (2012) or future microclimate change (2050), ENVI-met to produce the local boundary conditions for the building, and DesignBuilder to simulate the building thermal behavior. Results show that for a meteorological air temperature in 2050 that is increased by about 1.7°C compared to 2012, the indoor thermal conditions increase by about 1.8°C. The authors show that the proposed simulation framework can be used to assess the ability of a passive building adaptive device to reduce the indoor air temperature in both 2012 and 2050 cases, by about 1.2°C, and 1.4°C respectively.

Working on a canyon street model, Dorer et al. [106] show that the space cooling demand for the stand-alone buildings is much lower than

**Table 15**  
Synthesis of the capabilities and limitations of the studied methods with regards to potential applications.

Chaining/Coupling method	Impact of buildings' operation on UC	Impact of UHI and adaptation strategies on buildings' energy demand at a large scale	Impact of UHI on a building energy demand	Impact of local thermal phenomenon on a building energy demand
UWG + TRNSYS	No BEM to UCM feedback	Developed for that purpose but only integrates the impact of air temperature changes	Limited due to the building monozonal approach	Not appropriate
UWG + EnergyPlus	Not the scope	Not the scope	Developed for that purpose	Limited due to the average of fluxes on the building's envelop
Solene-Microclimat + BuildSysPro	Not the scope	Not the scope	Included	Developed for that purpose but limited due to the average of fluxes on the building's envelop
Envi-met + EnergyPlus	Not the scope	Not the scope	Developed for that purpose	Limited due to the absence of inter-reflections and the average of fluxes on the building's envelop
OpenFoam + TRNSYS	Not the scope	Not the scope	At the street canyon scale	Limited to buildings inserted in a street canyon
TEB + EnergyPlus	Developed for that purpose	Not the scope	Limited due to the building monozonal approach	Limited due to the building monozonal approach
UCP + BEM	Developed for that purpose	Not the scope	Limited due to the building monozonal approach	Limited due to the building monozonal approach
CIM + CitySim	No BEM to UCM feedback	Developed for that purpose and includes radiative phenomenon	Possible by chaining EnergyPlus	Possible by chaining EnergyPlus

that for the buildings situated in the street canyons. For wider street canyons, the cooling demand is higher, because more solar and thermal radiation is entrapped, mainly due to multiple reflections. In narrow street canyons, the cooling demand is lower because less solar radiation enters the street canyon.

At the city scale, Bueno et al. [117] show the impact of a realistic definition of HVAC systems on waste heat emissions and outdoor air temperatures. The study shows that waste heat emissions can raise outdoor air temperature between 0.8 K for residential neighborhoods and 2.8 K for commercial neighborhoods in summer, under possible future scenarios in which air conditioning is widely used.

These results show that it is important to take into account the local configuration of all the fluxes, including LW radiation which is the most poorly treated in both BEMs and UCMs.

#### 4.3.3. Simulation period

Building energy simulation is usually performed by using as entry the weather conditions of an entire year. The long period needed for this kind of calculation is the main obstacle when aiming to account for outdoor impacts more successfully.

Very few chaining projects simulate a period of a few months or one year. Salvati et al. [103] simulate a one year sensitivity analysis of the building energy demand to the air temperature increase. Mauree et al. [11,113] Perera et al. [114] also conduct a yearly analysis of the impact of urban climate on both energy demand and energy systems. Bueno et al. [117] simulate a period of two months, based on a monthly-average diurnal cycle of urban canyon air temperature. Palme et al. [102] simulate a three month period.

Most of the coupling or chaining projects presented above are based on a simulation period of a few days or a week. For example, Kikegawa et al. [108] simulate four days, and similarly Yang et al. [105] simulate three days. Finally, Merlier et al. [104], Dorer et al. [106] simulate two days (Fig. 3).

All those chaining projects have been undertaken with an hourly time step and inputs varying at the same frequency. Very few pull down the time step although Evins et al. [115] simulate only one day with 6 min time step.

To synthesize, the chaining or coupling projects involving CFD are realized only for two or three days (Fig. 3), because these CFD projects are computationally time consuming. There is still a technological hurdle on how to reduce computation while increasing the simulation period. The only tools used for annual simulations are the parametric tools (section 2.2.1 UWG and CAT and 2.2.1 CIM).

#### 4.3.4. Are BEMs adapted to the integration of local climate heat fluxes? The remaining technological locks

In this section, we discuss the three main locks related to the construction of BEMs:

- the physical modeling and assumptions on which BEMs are built does not allow all the fluxes to be dealt with similarly, which leads developers to adopt complicated alternative solutions;
- building scale description is not the same in BEMs and UCMs, so that the detailed information from the UCMs is often lost, or it can be lacking for some building elements such as windows;
- the retro-action of buildings on the local climate is rarely taken into account.

Most of the authors do not consider all urban local fluxes simultaneously, and the heat fluxes are only partially corrected. For example, some authors do not alter the configuration of LW exchanges of their BEM [102,103]; instead, they alter the convective exchanges and the ventilation by introducing local air temperature. For the same authors [103], however, the wind velocity is not locally calculated, and therefore the convective heat flux is only partially corrected owing to the local air temperature. It is worth noting that the local relative humidity

is usually not introduced. Few authors take it into account [102]. Other authors focus on the importance of local LW exchanges with the ground and the surrounding buildings, but introduce neither local SW and convective exchanges nor local infiltration [115].

Some authors need to introduce patches or a workaround in the BEM to enable these tools to allow for local urban heat fluxes or parameters. For example, Yang et al. [105] introduce a modification of the equation of the CHTC so as to include the local outside air temperature variations, which cannot be modified directly in the used version of EnergyPlus.

The level of detail of the BEMs and the UCMs is not the same. For example, Palme et al. [102], Salvati et al. [103] modify the input weather file so as to account for the local climate. This same file, however, is used as a boundary condition for all the walls and roofs of the building, regardless of their elevation or orientation, which may be a strong simplification. Other chaining methods that involve a detailed UCM need to process the outputs of the UCM first. For example, for Yang et al. [105], the microclimate data of the grid cells within a linking unit are averaged, and then the average value is passed to the corresponding surfaces of the EnergyPlus model. Other authors adopt a similar strategy [104]: as the SOLENE-Microclimat tool uses a detailed triangular meshing for solar radiation exchanges, a mean solar radiation needs to be calculated for each wall element in BuildSysPro. The interface between UCM and BEM models, namely the building envelope, can be very differently represented in each model, thus creating inconsistencies between tools: the ENVI-met model and the EnergyPlus model use a different method to mesh the geometries, especially for the sloped roofs and the facades. The ENVI-met model uses a Cartesian mesh that is not adapted to tilted surfaces; the TEB model does not have transparent surfaces within its canyon but has to provide transmitted solar fluxes to EnergyPlus.

Some authors do take all the local urban heat fluxes as input in the BEM, but they do not introduce feedback from the BEM to the UCM [104,105], which can introduce an error due to the difference in assumed and actual temperatures [115]. This error can be pulled down for shorter time steps, as temperatures will not change dramatically. However, hourly time steps are often adopted, as seen in the above section.

#### 4.3.5. Other strategies

The above-mentioned reasons certainly explain why some authors aiming to take the local urban context into account do not propose complex chaining or coupling processes. Two other ways are explored: developing external functions in BEMs or developing BEMs in UCMs.

Introducing some patches or modifying some equations in the BEM is the strategy chosen by Vallati et al. [15] who model a street canyon in TRNSYS as an internal zone with an open air ceiling that is an atrium. Djedjig et al. [118] also develop a new module in TRNSYS so as to include the canyon street confinement effect.

Several modifications to EnergyPlus are proposed by Evins et al. [115]) because EnergyPlus posits that the ground and the obstructions to the building (i.e. the urban scene) are at the same temperature as the air. View factors and linearized radiation heat transfer coefficients are calculated for the ground, the exterior building surfaces and the sky. The incident total LW radiation can finally account for the exchanges with the ground, the sky and the obstructions (i.e. the urban scene considered at a single surface temperature). The modifications proposed in the paper improve the exterior LW radiation, including a ground temperature and other urban surfaces at a different temperature.

The option taken in TRNSYS is the development of a new module based on TEB called TEB-Type 201. Ali-Toudert and Böttcher [119] describe the module and show its user-friendliness. A sensitivity study reports the climatic conditions of a canyon (study area) regarding several parameters related to the urban context (i.e. plan density, roof surfaces/total), human activity (anthropogenic heat), building

construction (thermal insulation of walls and roofs, thermal inertia) and surface properties (albedo). A total of 729 simulations over a period of one year have been conducted for this study; they demonstrate the potential of extensive calculations of TEB-Type 201. An outlook is given to work on the feedback of TRNSYS which could be integrated in TEB-Type 201.

Some UCMs include BEMs directly. The building energy balance is integrated into the equation set, so that the coupling can be stronger, and there is no inconsistency regarding meshing or time step. However, in these cases the building energy balance is often rougher and provides fewer options for different kinds of building simulations compared to the BEM offer. Such a coupling was provided for example by Krpo et al. [61], and Salamanca et al. [62] with the integration of a Building Energy Model in the WRF-BEP model. The BEM included in TEB is monozonal [117], and those included in SOLENE-Microclimat [77] or LASER/F [81] can have only one air node per floor.

## 5. Conclusion and outlooks

This paper has presented and analyzed different proposals for chaining a UCM and a BEM, following a description of the main BEMs and UCMs. This study thus provides a baseline knowledge for researchers who aim to develop a coupling or chaining, starting from a BEM or UCM point of view. Although the issue was not the focus of this study, the analyses can also be useful for UCM developers who intend to take into account the effects of buildings.

The first conclusion from the analysis of eight coupling or chaining attempts is that all chaining or coupling projects have shown that BEMs are very sensitive to the climate, whether to estimate heating, cooling demand, or indoor comfort conditions. Previous studies have shown that 15%–89% of energy for heating is neglected if the urban context and climate are not considered, 131%–200% for space cooling and several degrees for indoor air temperature for non air-conditioned spaces in summer. Thus, performing more accurate coupling is a crucial issue in building energy modeling. However, this kind of chaining or coupling between UCMs and BEMs is only attempted in research projects, certainly because to date, UCMs are not commonly used in consulting agencies.

Most of the presented works use the uni-directional chaining method: outputs from UCMs are used as inputs to the BEMs but no feedback from the BEMs to the UCMs is provided, and no iterative process is proposed to enhance the chaining. Hence, the local climate cannot take into account the impact of buildings retro-action. This is a minor issue in low density districts but not in very dense areas [79]. Some recent studies have, however, tried to provide new methods to integrate these feedbacks [113,114].

This state of the art review has shown that three major issues need to be addressed:

a) Most chaining strategies presented in this paper are partial as most of the BEMs have not been designed to include all heat fluxes stemming from the urban context. The most difficult to integrate is the LW radiation heat flux which is often merged with the convection heat flux. Moreover, LW fluxes can be produced only by UCMs that run at the neighborhood or street scale and use an explicit geometrical model, which implies a very computer intensive process.

b) BEMs have not been developed to take spatially variable boundary conditions on the facades into account. Therefore, a workaround is often adopted to include some local mean climatic parameters. In so doing, the advantage of having performed an urban climate simulation is not fully used, which can increase numerical and modeling errors.

c) As for the spatial scale, the time scales considered are often barely compatible. In particular, explicit district UCMs, which would produce detailed inputs for the BEMs, cannot be run over a year. This kind of coupling can be run only over a several day period to verify the building thermal behavior for extreme conditions.



In the future, the chaining between BEMs and UCMs needs to be generalized to increase BEM accuracy. To improve this chaining, the present analysis shows that BEM developers should add to their models the possibility of considering all external fluxes separately and in particular LW radiation. They should also attempt to force external surface temperatures or fluxes directly. They should split the external faces of the building into several surfaces, with a minimum of one per internal zone and per floor, to which different boundary conditions can be attributed (including different air temperatures, humidity, CHTC, etc.). From the UCM point of view, intermediate solutions must be found so as to produce all the local data for external flux calculations over a year. Current, parametric models can cover the period of one year, but they do not provide all fluxes. In contrast, explicit models provide all fluxes but cannot be run over such a period. Moreover, better integration of buildings is also needed in UCMs, so as to take into account their action on the climate. More effective representation of buildings will modify the UHI intensity assessment [112]. However, as the goals are not the same, and as the data will not be available to describe all the buildings in the areas under investigation, specific consideration needs to be given to determine the best adapted description depending on the UCM spatial scale.

Collaboration between urban climatologists and building physics scientists is thus to be encouraged with a view converging towards better integration of simplified BEMs within UCMs and better coupling of UCMs and BEMs in order to use realistic urban conditions for bioclimatic efficient building design [120].

In this review, except for TRNSYS, no commercial BEM tool (PLEIADES, DesignBuilder, Virtual Environment) used by the engineering consultants was included in the chaining or coupling projects analyzed. Buildings are still designed and verified as if they were in rural areas. As cities are densifying, it is necessary to bring these advances to the market and to develop these kinds of couplings (even if imperfect) for commercial tools.

## Acknowledgements

The authors are very grateful for the strong support for the research carried out at the TRIBU consulting agency, the CEREMA, and the laboratories IRDL and LESO-PB. This research has been partly financed by the French association ANRT and of the Swiss Competence Center for Energy Research SCCER FEEB&D of the Swiss Innovation Agency Innosuisse.

## Abbreviations

*The following abbreviations are used in this manuscript*

BEM	Building Energy Model
LW	Long Wave radiation
CFD	Computational Fluid Dynamics
RMSE	Root Mean Square Error
CHTC	Convective Heat Transfer Coefficients
SVF	Sky View Factor
CTF	Computational Transfer Function
SS	State-Space
DRF	Direct Root-Finding
SW	Short Wave radiation
FD	Finite Difference
TKE	Turbulent Kinetic Energy
FDR	Frequency-Domain Regression
UCL	Urban Canopy Layer
FE	Finite Element
UCM	Urban Climate Model
HAMT	Heat and Moisture Transfer
UCP	Urban Canopy Parametrization
HVAC	Heating, Ventilation and Air-Conditioning

## References

- [1] Recast E. Directive 2010/31/eu of the european parliament and of the council of 19 may 2010 on the energy performance of buildings (recast). Official Journal of the European Union 2010;18:2010.
- [2] Foucquier A, Robert S, Suard F, Stéphan L, Jay A. State of the art in building modelling and energy performances prediction: a review. *Renew Sustain Energy Rev* 2013;23:272–88.
- [3] Crawley DB, Hand JW, Kummert M, Griffith BT. Contrasting the capabilities of building energy performance simulation programs. *Build Environ* 2008;43:661–73.
- [4] Allegrini J, Dorer V, Carmeliet J. Influence of the urban microclimate in street canyons on the energy demand for space cooling and heating of buildings. *Energy Build* 2012;55:823–32.
- [5] Wan KK, Cheung K, Liu D, Lam JC. Impact of modelled global solar radiation on simulated building heating and cooling loads. *Energy Convers Manag* 2009;50:662–7.
- [6] Gros A, Bozonnet E, Inard C. Modelling the radiative exchanges in urban areas: a review. *Adv Build Energy Res* 2011;5:163–206.
- [7] Nabinger S, Persily A. Impacts of airtightening retrofits on ventilation rates and energy consumption in a manufactured home. *Energy Build* 2011;43:3059–67.
- [8] Bouyer J, Inard C, Musy M. Microclimatic coupling as a solution to improve building energy simulation in an urban context. *Energy Build* 2011;43:1549–59.
- [9] Santamouris M. *Energy and climate in the urban built environment*. Routledge; 2013.
- [10] Mavrogianni A, Davies M, Batty M, Belcher S, Bohnenstengel S, Carruthers D, Chalabi Z, Croxford B, Demanuele C, Evans S, et al. The comfort, energy and health implications of london's urban heat island. *Build Serv Eng Technol* 2011;32:35–52.
- [11] Mauree D, Cocco S, Kaempf J, Scartezzini J-L. Multi-scale modelling to evaluate building energy consumption at the neighbourhood scale. *PLoS One* 2017;12:e0183437.
- [12] Mirzaei PA, Haghighat F. Approaches to study urban heat island—abilities and limitations. *Build Environ* 2010;45:2192–201.
- [13] Miller C, Thomas D, Kämpf J, Schlueter A. Urban and building multiscale co-simulation: case study implementations on two university campuses. *J Build Perform Simul* 2018;11:309–21.
- [14] Lauzet N, Morille B, Leduc T, Musy M. What is the required level of details to represent the impact of the built environment on energy demand? *Procedia Environ Sci* 2017;38:611–8.
- [15] Vallati A, Mauri L, Colucci C. Impact of shortwave multiple reflections in an urban street canyon on building thermal energy demands. *Energy Build* 2018;174:77–84.
- [16] Goffart J, Rabouille M, Mendes N. Uncertainty and sensitivity analysis applied to hygrothermal simulation of a brick building in a hot and humid climate. *J Build Perform Simul* 2017;10:37–57.
- [17] Santamouris M. On the energy impact of urban heat island and global warming on buildings. *Energy Build* 2014;82:100–13.
- [18] ADEME. Performances réelles des bâtiments - retours d'expériences - enseignements des campagnes de suivi et d'évaluation de 14 opérations instrumentées par l'ADEME en Rhône-Alpes, Technical Report. VILLE ET AMÉNAGEMENT DURABLE; 2016.
- [19] Spitz C, Mora L, Wurtz E, Jay A. Practical application of uncertainty analysis and sensitivity analysis on an experimental house. *Energy and Buildings*; 2012.
- [20] Cesaratto PG, De Carli M. A measuring campaign of thermal conductance in situ and possible impacts on net energy demand in buildings. *Energy and Buildings*; 2013.
- [21] Johnston D, Miles-Shenton D, Farmer D. Quantifying the domestic building fabric 'performance gap'. *Build Serv Eng Technol* 2015;36:614–27.
- [22] Zhao H-x, Magoulès F. A review on the prediction of building energy consumption. *Renew Sustain Energy Rev* 2012;16:3586–92.
- [23] Kavgi M, Mavrogianni A, Mumovic D, Summerfield A, Stevanovic Z, Djurovic-Petrovic M. A review of bottom-up building stock models for energy consumption in the residential sector. *Build Environ* 2010;45:1683–97.
- [24] Swan LG, Ugursal VI. Modeling of end-use energy consumption in the residential sector: a review of modeling techniques. *Renew Sustain Energy Rev* 2009;13:1819–35.
- [25] Fumo N. A review on the basics of building energy estimation. *Renew Sustain Energy Rev* 2014;31:53–60.
- [26] Oke T. Boundary layer climates. 2nd Methuen; 1987. p. 289p. 548.
- [27] Grimmond C, Roth M, Oke T, Au Y, Best M, Betts R, Carmichael G, Cleugh H, Dabberdt W, Emmanuel R, Freitas E, Fortuniak K, Hanna S, Klein P, Kalkstein L, Liu C, Nickson A, Pearlmuter D, Sailor D, Voogt J. Climate and more sustainable cities: climate information for improved planning and management of cities (Producers/Capabilities perspective). *Procedia Environ Sci* 2010;1:247–74.
- [28] Stewart ID, Oke TR. Local climate zones for urban temperature studies. *American Meteorological Society*; 2012.
- [29] Arnfield AJ. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *Int J Climatol* 2003;23:1–26.
- [30] Kanda M. Progress in urban meteorology: a review. *J Meteorol Soc Japan Ser II* 2007;85:363–83.
- [31] Lun I, Mochida A, Ooka R. Progress in numerical modelling for urban thermal environment studies. *Adv Build Energy Res* 2009;3:147–88.
- [32] Grimmond CSB, Blackett M, Best M, Barlow J, Baik J, Belcher S, Bohnenstengel S, Calmet I, Chen F, Dandou A, et al. The international urban energy balance models comparison project: first results from phase 1. *J app meteorol climatol* 2010;49:1268–92.



- [33] Toparlak Y, Blocken B, Maiheu B, Van Heijst G. A review on the CFD analysis of urban microclimate. *Renew Sustain Energy Rev* 2017;80:1613–40.
- [34] Garuma GF. Review of urban surface parameterizations for numerical climate models. *Urban Clim* 2018;24:830–51.
- [35] Allegrini J, Orehouin K, Mavromatidis G, Ruesch F, Dorer V, Evins R. A review of modelling approaches and tools for the simulation of district-scale energy systems. *Renew Sustain Energy Rev* 2015;52:1391–404.
- [36] Anderson JE, Wulforst G, Lang W. Energy analysis of the built environment—a review and outlook. *Renew Sustain Energy Rev* 2015;44:149–58.
- [37] Reinhart CF, Cerezo Davila C. Urban building energy modeling – a review of a nascent field. *Build Environ* 2016;97:196–202.
- [38] Li W, Zhou Y, Cetin K, Eom J, Wang Y, Chen G, Zhang X. Modeling urban building energy use: a review of modeling approaches and procedures. *Energy* 2017;141:2445–57.
- [39] Frayssinet L, Merlier L, Kuznik F, Hubert JL, Milliez M, Roux JJ. Modeling the heating and cooling energy demand of urban buildings at city scale. *Renewable and Sustainable Energy Reviews*; 2018.
- [40] Sola A, Corchero C, Salom J, Sanmarti M. Simulation tools to build urban-scale energy models: a review. *Energies* 2018;11:3269.
- [41] Castaldo VL, Pisello AL. Uses of dynamic simulation to predict thermal-energy performance of buildings and districts: a review. *Wiley Interdisciplinary Reviews: Energy Environ* 2018;7:e269.
- [42] Oke TR, Mills G, Christen A, Voogt JA. *Urban climates*. Cambridge University Press; 2017.
- [43] Lemonsu A, Masson V. Simulation of a summer urban breeze over Paris. *Boundary-Layer Meteorol* 2002;104:463–90.
- [44] Lac C, Chaboureau P, Masson V, Pinty P, Tulet P, Escobar J, Leriche M, Barthe C, Aouizerats B, Augros C, et al. Overview of the meso-nh model version 5.4 and its applications. *Geoscientific Model Development Discussions*; 2017. p. 1929–69.
- [45] Broadbent AM, Coutts AM, Tapper NJ, Demuzere M. The cooling effect of irrigation on urban microclimate during heatwave conditions. *Urban Clim* 2018;23:309–29.
- [46] Daniel M, Lemonsu A, Viguié V. Role of watering practices in large-scale urban planning strategies to face the heat-wave risk in future climate. *Urban Climate*; 2016.
- [47] Pigeon G, Zibouche K, Bueno B, Le Bras J, Masson V. Improving the capabilities of the town energy balance model with up-to-date building energy simulation algorithms: an application to a set of representative buildings in Paris. *Energy Build* 2014;76:1–14.
- [48] Le Moigne P, Boone A, Calvet J, Decharme B, Faroux S, Gibelin A, Lebeaupin C, Mahfouf J, Martin E, Masson V, et al. *Surfex scientific documentation*. Toulouse, France: Note de centre (CNRM/GMME), Météo-France; 2009.
- [49] Masson V. A physically-based scheme for the urban energy budget in atmospheric models. *Boundary-Layer Meteorol* 2000;94:357–97.
- [50] Redon EC, Lemonsu A, Masson V, Morille B, Musy M. Implementation of street trees within the solar radiative exchange parameterization of Teb in Surfex v8.0. *Geosci Model Dev (GMD)* 2017;10:385–411.
- [51] Noilhan J, Planton S. A simple parameterization of land surface processes for meteorological models. *Mon Weather Rev* 1989;117:536–49.
- [52] de Munck C, Lemonsu A, Masson V, Le Bras J, Bonhomme M. Evaluating the impacts of greening scenarios on thermal comfort and energy and water consumptions for adapting Paris city to climate change. *Urban Clim* 2018;23:260–86.
- [53] Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Wang W, Powers JG. A description of the advanced research WRF version 2. Technical Report. National Center For Atmospheric Research Boulder Co Mesoscale and Microscale Meteorology Div; 2005.
- [54] Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Wang W, Powers JG. A description of the advanced research WRF version 2. NCAR tech. Note. 2005. [Citeseer].
- [55] Chen F, Kusaka H, Bornstein R, Ching J, Grimmond C, Grossman-Clarke S, Loridan T, Manning KW, Martilli A, Miao S, et al. The integrated WRF/urban modelling system: development, evaluation, and applications to urban environmental problems. *Int J Climatol* 2011;31:273–88.
- [56] Z. Liu, D. Barker, Radiance assimilation in WRF-Var: implementation and initial results, in: 7th WRF users workshop, Citeseer, pp. 19–22.
- [57] Kusaka H, Kondo H, Kikigawa Y, Kimura F. A simple single-layer urban canopy model for atmospheric models: comparison with multi-layer and slab models. *Boundary-Layer Meteorol* 2001;101:329–58.
- [58] Kusaka H, Kimura F. Coupling a single-layer urban canopy model with a simple atmospheric model: impact on urban heat island simulation for an idealized case. *J Meteorol Soc Japan Ser II* 2004;82:67–80.
- [59] Martilli A, Clappier A, Rotach MW. An urban surface exchange parameterisation for mesoscale models. *Boundary-Layer Meteorol* 2002;104:261–304.
- [60] Bougeault P, Lacarrere P. Parameterization of orography-induced turbulence in a mesobeta-scale model. *Mon Weather Rev* 1989;117:1872–90.
- [61] Krpo A, Salamanca F, Martilli A, Clappier A. On the impact of anthropogenic heat fluxes on the urban boundary layer: a two-dimensional numerical study. *Boundary-Layer Meteorol* 2010;136:105–27.
- [62] Salamanca F, Krpo A, Martilli A, Clappier A. A new building energy model coupled with an urban canopy parameterization for urban climate simulations—part I. formulation, verification, and sensitivity analysis of the model. *Theor Appl Climatol* 2010;99:331.
- [63] Bueno B, Norford L, Hidalgo J, Pigeon G. The urban weather generator. *J Build Perform Simul* 2013;6:269–81.
- [64] Erell E, Williamson T. Simulating air temperature in an urban street canyon in all weather conditions using measured data at a reference meteorological station. *Int J Climatol* 2006;26:1671–94.
- [65] Remund J. Quality of meteoronorm version 6.0. Europe 2008;6:389.
- [66] Le Bras J, Masson V. A fast and spatialized urban weather generator for long-term urban studies at the city-scale. *Front Earth Sci* 2015;3:27.
- [67] Mauree D, Blond N, Kohler M, Clappier A. On the coherence in the boundary layer: development of a canopy interface model. *Front Earth Sci* 2017;4:109.
- [68] Mauree D, Blond N, Clappier A. Multi-scale modeling of the urban meteorology: integration of a new canopy model in the WRF model. *Urban Clim* 2018;26:60–75.
- [69] N. Lauzet, D. Mauree, T. Colinart, M. Musy, Construction d'un fichier micro-climatique urbain utilisable en STD, p. 8. IBPSA Conference, Bordeaux (France).
- [70] Huttner S. Further development and application of the 3d microclimate simulation envi-met. Germany: Mainz University; 2012.
- [71] Bruse M, Fleer H. Simulating surface-plant-air interactions inside urban environments with a three dimensional numerical model. *Environ Model Softw* 1998;13:373–84.
- [72] S. Huttner, M. Bruse, Numerical modeling of the urban climate—a preview on envi-met 4.0, in: 7th international conference on urban climate ICUC-7, Yokohama, Japan, vol. 29.
- [73] EDF. Code\_saturne web site. 2018 <https://www.code-saturne.org/cms/documentation>.
- [74] Miguet F, Groleau D. A daylight simulation tool for urban and architectural spaces—application to transmitted direct and diffuse light through glazing. *Build Environ* 2002;37:833–43.
- [75] Hénon A, Mestayer PG, Groleau D, Voogt J. High resolution thermo-radiative modeling of an urban fragment in marseilles city center during the ubl-escompte campaign. *Build Environ* 2011;46:1747–64.
- [76] Hénon A, Mestayer PG, Lagouarde J-P, Voogt JA. An urban neighborhood temperature and energy study from the capitol experiment with the solene model. *Theor Appl Climatol* 2012;110:177–96.
- [77] Rodler A, Guernouti S, Musy M, Bouyer J. Thermal behaviour of a building in its environment: modelling, experimentation, and comparison. *Energy Build* 2018;168:19–34.
- [78] Musy M, Malys L, Morille B, Inard C. The use of solene-microclimat model to assess adaptation strategies at the district scale. *Urban Clim* 2015;14:213–23. Cooling Heat Islands.
- [79] Bozonnet E. Urban microclimates impact on the building energy demand - street canyon case, Theses. Université de la Rochelle; 2005.
- [80] Liang W, Huang J, Jones P, Wang Q, Hang J. A zonal model for assessing street canyon air temperature of high-density cities. *Build Environ* 2018;132:160–9.
- [81] Kastendeuch PP, Najjar G, Colin J. Thermo-radiative simulation of an urban district with laser/f. *Urban Clim* 2017;21:43–65.
- [82] Gros A, Bozonnet E, Inard C, Musy M. Simulation tools to assess microclimate and building energy – a case study on the design of a new district, *Energy and Buildings* 114. 2016. p. 112–22. [SI: Countermeasures to Urban Heat Island].
- [83] Crawley DB, Lawrie LK, Winkelmann FC, Buhl WF, Huang YJ, Pedersen CO, Strand RK, Liesen RJ, Fisher DE, Witte MJ, et al. Energyplus: creating a new-generation building energy simulation program. *Energy Build* 2001;33:319–31.
- [84] Peuportier B, Sommeux IB. Simulation tool with its expert interface for the thermal design of multizone buildings. *Int J Sol Energy* 1990;8:109–20.
- [85] Klein SA. Trnsys-a transient simulation program. *Ashrae Trans* 1976;82:623.
- [86] G. Plessis, A. Kaemmerlen, A. Lindsay, Buildsyspro: a modelica library for modelling buildings and energy systems, in: Proceedings of the 10th international modelica conference; march 10–12; 2014; Lund; Sweden, vol. 96, Linköping University Electronic Press, pp. 1161–1169.
- [87] D. Robinson, F. Haldi, J. Kämpf, P. Leroux, D. Perez, A. Rasheed, U. Wilke, Citysim: comprehensive micro-simulation of resource flows for sustainable urban planning, in: Proc. Building simulation, pp. 1614–1627.
- [88] Tittlein P. Simulation environments adapted to the study of energy behaviour of low-consumption buildings. Theses, Université de Savoie; 2008.
- [89] Delcroix B, Kummert M, Daoud A, Hiller M. Improved conduction transfer function coefficients generation in trnsys multizone building model. Proceedings of 13th conference of international building performance simulation association. Chambéry, France; 2013. August 26e28.
- [90] Mazzarella L, Pasini M. CTF vs FD based numerical methods: accuracy, stability and computational time's comparison. *Energy Procedia* 2015;78:2620–5.
- [91] Solutions IE. Apachesim calculation methods. *IES Virtual Environ* 2018;6:75.
- [92] Pedersen CO. Advanced zone simulation in energyplus: incorporation of variable properties and phase change material (pcm) capability. in: Building simulation 1341–1345..
- [93] Kämpf JH. On the modelling and optimisation of urban energy fluxes. 2009.
- [94] Rodler A, Virgone J, Roux J-J, Hubert J. Development and validation of a three dimensional thermal transient numerical model with sun patch: application to a low energy cell. *Energy and Buildings*; 2015.
- [95] Ribault C, Bouquerel M, Brun A, Schumann M, Rusaouën G, Wurtz E. Assessing tools relevance for energy simulation at the urban scale: towards decision-support tools for urban design and densification. *Energy Procedia* 2017;122:871–6. CISBAT 2017 International Conference Future Buildings and Districts – Energy Efficiency from Nano to Urban Scale.
- [96] Mirsadeghi M, Costola D, Blocken B, Hensen JL. Review of external convective heat transfer coefficient models in building energy simulation programs: implementation and uncertainty. *Appl Therm Eng* 2013;56:134–51.
- [97] Liddament MW. Air infiltration calculation techniques: an applications guide. UK: Air infiltration and ventilation centre Berkshire; 1986.
- [98] Trocmé M. Assisting low energy consumption building design Phd thesis École Nationale Supérieure des Mines de Paris; 2009.
- [99] Givoni B. Comfort, climate analysis and building design guidelines. *Energy Build*

- 1992;18:11–23.
- [100] Upadhyay G, Mauree D, Kämpf JH, Scartezzini J-L. Evapotranspiration model to evaluate the cooling potential in urban areas-a case study in Switzerland. 14th international conference of the international building performance simulation association. EPFL-CONF; 2015. 214838.
- [101] Coccolo S, Kämpf J, Mauree D, Scartezzini J-L. Cooling potential of greening in the urban environment, a step further towards practice. *Sustain Cities Soc* 2018;38:543–59.
- [102] Palme M, Inostroza L, Villacreses G, Lobato A, Carrasco C. Urban weather data and building models for the inclusion of the urban heat island effect in building performance simulation. *Data in Brief* 2017;14:671–5.
- [103] A. Salvati, H. Coch Roura, C. Cecere, Urban morphology and energy performance: the direct and indirect contribution in mediterranean climate, in: PLEA 2015 architecture in (R) evolution–31st international PLEA conference–bologna 9-11 september, building green futures, pp. 1–8.
- [104] L. Merlier, L. Frayssinet, F. Kuznik, G. Rusaouën, K. Johannes, J.-L. Hubert, M. Milliez, Analysis of the (urban) microclimate effects on the building energy behaviour, in: Presented at the proceedings of the 15th IBPSA conference [San Francisco].
- [105] Yang X, Zhao L, Bruse M, Meng Q. An integrated simulation method for building energy performance assessment in urban environments. *Energy Build* 2012;54:243–251..
- [106] Dorer V, Allegrini J, Orehoung K, Moonen P, Upadhyay G, Kämpf J, Carmeliet J. Modelling the urban microclimate and its impact on the energy demand of buildings and building clusters. *Proceedings of BS* 2013;2013:3483–9.
- [107] Bueno B, Norford L, Pigeon G, Britter R. Combining a detailed building energy model with a physically-based urban canopy model. *Boundary-Layer Meteorol* 2011;140:471–89.
- [108] Kikegawa Y, Genchi Y, Yoshikado H, Kondo H. Development of a numerical simulation system toward comprehensive assessments of urban warming counter-measures including their impacts upon the urban buildings' energy-demands. *Appl Energy* 2003;76:449–66.
- [109] Openfoam. Openfoam web. 2018.
- [110] Rotach MW, Vogt R, Bernhofer C, Batchvarova E, Christen A, Clappier A, Feddersen B, Gryning S-E, Martucci G, Mayer H, Mitev V, Oke TR, Parlow E, Richner H, Roth M, Roulet Y-A, Ruffieux D, Salmond JA, Schatzmann M, Voogt JA. Bubble – an urban boundary layer meteorology project. *Theor Appl Climatol* 2005;81:231–61.
- [111] TRNSYS. Trnsys 2018;18 web.
- [112] De Munck C, Pigeon G, Masson V, Meunier F, Bousquet P, Tréméac B, Merchat M, Poeuf P, Marchadier C. How much can air conditioning increase air temperatures for a city like paris, France? *Int J Climatol* 2013;33:210–27.
- [113] Mauree D, Coccolo S, Perera ATD, Nik V, Scartezzini J-L, Naboni E. A new framework to evaluate urban design using urban microclimatic modeling in future climatic conditions. *Sustainability* 2018;10:1134.
- [114] Perera A, Coccolo S, Scartezzini J-L, Mauree D. Quantifying the impact of urban climate by extending the boundaries of urban energy system modeling. *Appl Energy* 2018;222:847–60.
- [115] Evins R, Dorer V, Carmeliet J. Simulating external longwave radiation exchange for buildings. *Energy Build* 2014;75(06):472–82.
- [116] Yi CY, Peng C. Microclimate change outdoor and indoor coupled simulation for passive building adaptation design. *Procedia Comput Sci* 2014;32:691–8.
- [117] Bueno B, Pigeon G, Norford LK, Zibouche K, Marchadier C. Development and evaluation of a building energy model integrated in the TEB scheme. *Geosci Model Dev (GMD)* 2012;5:433–48.
- [118] Djedjig R, Bozonnet E, Belarbi R. Modeling green wall interactions with street canyons for building energy simulation in urban context. *Urban Clim* 2016;16:75–85.
- [119] Ali-Toudert F, Böttcher S. Urban microclimate prediction prior to dynamic building energy modelling using the teb model as embedded component in trnsys. *Theor Appl Climatol* 2018;134:1413–28.
- [120] Mauree D, Naboni E, Coccolo S, Perera A, Scartezzini J-L. A review of assessment methods for the urban environment and its energy sustainability to guarantee climate adaptation of future cities. *Renew Sustain Energy Rev* 2019;12:733–46.