Towards the development of a coupled model for district simulation: buildings, energy systems and microclimate co-simulation

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Towards the development of a coupled model for district simulation: buildings, energy systems and microclimate co-simulation

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RESUME. Cet article introduit une méthodologie de couplage basée sur un modèle énergétique de quartier détaillé allant du microclimat urbain au réseau énergétique. Le modèle microclimat/bâtiment vise à prédire les bilans thermo-radiatifs et massiques. La plateforme de simulation du système énergétique prend en compte les réseaux thermiques et/ou électriques ainsi que le stockage et la production d'énergie centralisée ou locale. Les deux outils intègrent les modèles thermiques de bâtiments. Ainsi, en considérant le bâtiment comme la frontière entre les deux outils, ce dernier apparaît comme le paramètre clé pour le couplage des deux approches. Les complexités spatiales et temporelles et leur impact sur les résultats de la simulation sont analysés dans une première étape afin de valider la méthodologie de couplage. En parallèle, les données météorologiques modifiées par l'environnement et la morphologie urbaine seront obtenues par un couplage hors ligne. Enfin nous illustrons cette approche à partir de résultats de simulations obtenus pour l'étude du quartier « La Cité des Géraniums » à La Rochelle (France), quartier entièrement rénové récemment.

MOTS-CLÉS : insérer 3 mots-clés décrivant au mieux votre article.

ABSTRACT. This paper introduces a methodology of a coupling procedure based on a detailed district energy model from urban microclimate and a second one with a detailed description of the entire energy system of the district. The microclimatic model is able to represent the thermo-radiative and mass flow balances. The transient energy system simulation platform is capable to consider the entire energy system of the district (including thermal and/or electrical grids and their respective energy storage/production on a central or local level). In parallel, both tools allow to compute the thermal processes of the buildings concurrently. Thus, considering the building as the boundary between both tools, we examine it as the key coupling parameter. The spatial and temporal complexities and their impact on the simulation results are analyzed in a first step in order to validate the coupling methodology. In parallel, modified meteorological data that account for the urban form were obtained in offline coupling. Finally, we demonstrate some of the possible outcomes through a real study of a newly refurbished district in La Rochelle, France «La Cite des Geraniums».

KEYWORDS: Urban Heat Island, district energy systems & networks, urban microclimate.

1. Introduction

The built environment constitutes the largest artificial key contributor, modifying the thermal balance of the urban microclimate and constituting the dominant energy consumer of France (48%) ('Observation et Statistiques' 2016) and Europe (40%) ('Eurostat' 2017). At the same time, the Urban Heat Island (UHI) effect, combined with the global warming, causes various deterioration factors: aggravating the outdoor thermal comfort conditions, intensifying the energy consumption and peaks for cooling (Santamouris et al. 2015), placing under stress users and energy providers, especially for cities within moderate climate zones (30-60º latitude).

Taking the dependency and the interconnection of urban climate and building energy demand as a starting point (E. Bozonnet, Belarbi, and Allard 2007), various efforts have been carried out to identify and represent the dominant processes both in temporal and spatial scales. To this end, the last decades several models and methods have been developed in order to better understand and simulate the actual conditions in these various scales, starting from the two limit points (E. Bozonnet et al. 2015).

On the one hand, building energy simulation (BES) is developing with the aim to depict the thermal processes at building scale and serve the NZEB design. These models used in building regulations, target to evaluate/predict the energy use and buildings' environmental footprint. Moreover, they are independent from the urban context and use reference weather data (rural) far from bias due to anthropogenic sources and heterogeneous urban morphology. In addition, the thermal fluxes of the energy systems in which they operate are not taken into account, as their spatial limitation cannot assess this feedback. Consequently, they are missing the local but significant interactions between them and the urban environment (J. Allegrini et al. 2015).

On the other hand, the mesoscale atmospheric models were designed with the objective to serve both atmospheric research and operational forecasting needs. Therefore, they operate in a huge range of spatial scale (25km to 1km). This variety of spatial resolution and the application of the downscaling method, enabled them to integrate the urban parametrizations (1km to 100m) and launch city-urban scale simulations with the aim of firstly assess the air pollution and after the UHI effect (de Munck et al. 2013). The last years, also building energy consumption is studied with such type of models (Martilli 2007; Masson 2000; Kusaka et al. 2001; Grimmond et al. 2010). Nevertheless, their approach to represent the built environment as cells of coverage ratios (of buildings, vegetation, open spaces and built infrastructures) prevent them from addressing the detailed urban morphology (surfaces & obstacles) and their respective thermal fluxes properly.

Furthermore, a robust effort of representing the actual conditions in the district scale is performed with the evolution of microclimatic models, based in CFD approaches, such as ENVIMET (M. Bruse and Fleer 1998). The limitations of these efforts correspond to high simulation time and simplified building parameterizations. Some efforts execute BES offline-coupled with CFD models (K. Gobakis and Kolokotsa 2017; M. Martin et al. 2017), but they are restrained in terms of temporal scale; from hours to day(s).

A possible way to tackle these problems is to couple different models, each targeting different scales (D. Mauree et al. 2017). Here we describe one such approach. Considering the building (or building envelope) as the boundary condition between the local microclimate and the indoor building environment but also the similar between the thermal/electrical network and the operating energy system, we propose the development of a coupling strategy for district energy network and microclimate simulation using the scaling up building approach.

The microclimatic model is able to represent the thermo-radiative and mass flow balances. The transient energy system simulation platform is capable to consider the thermal and/or electrical grids and their respective energy storage/production on a central or local level. In parallel, both tools allow to compute the thermal processes of the buildings concurrently. The spatial and temporal complexities and their impact on the simulation results are analyzed in a first step in order to validate the coupling methodology and we present some of the possible outcomes through a real study of a newly refurbished district in La Rochelle, France «La Cite des Geraniums».

2. TOOLS AND METHODS

In this section, we provide a concise overview of the ongoing-coupled platforms, pointing emphasis to the building models. We can assume buildings as the common "variable" between both models and especially the buildings envelopes.

2.1. MICROCLIMATIC MODEL (ENVIBATE)

EnviBATE (Gros 2013) has been developed to assess the energy demand of neighborhoods taking into account microclimatic. We can classify it into three main sub-models (Figure 1), the urban canopy, the thermal surface and the building energy one. The urban canopy model is based on the zonal model approach using the thermal balance equation for each cell volume. It is coupled with the convective heat exchanges of the urban surfaces and the outside building temperatures T_{se}.

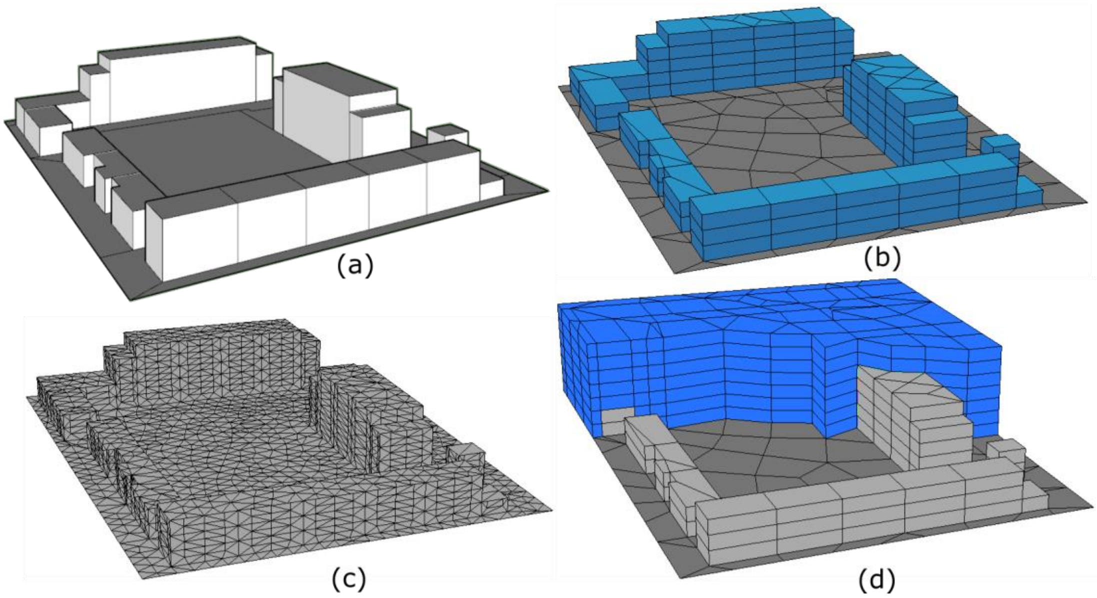

Figure 1: The original geometry (a). Produced surface (b), triangulate (c) geometry and the respective zonal mesh (d).

The developed BES is using a reduced order model (for fast computing) based on the Weighting Factors method (Rousseau 1978). The model takes into account the thermal solicitations for each studied building zone and calculates the thermal responses given either free-floating conditions or indoor set point temperature. Then, it calculates the outdoor derivative flux from the given solicitations (solar irradiance E_{SW}, outdoor surface temperatures T_{se} and indoor set point T_a) and the corresponding weighting factors FP_i. Equation **(1)** gives the outside heat flux φ_{pe} transmitted by the building wall (where Y, Z are the outgoing and incoming response factors). The urban surfaces, acting as the interfaces between the urban canopy and the buildings, constitute the thermal surface model, which also serves the thermal balance equation. The solar radiation model is based on the radiosity method using SOLENE tool (D. Groleau, Fragnaud, and Rosant 2003). The airflow model correspond to QUIC-URB (Pardyjak and Brown 2003) dispersion model taking into account forced convection phenomena. Concerning the resolution grid, an unstructured grid (Figure 1d) was preferred as its potential to mesh complex geometric forms permits variations in spatial resolution.

$$\varphi_{pe,i}(t) = \sum_{m=0}^{\infty} Y_i\,(m\Delta t)\left[\sum_{n=0}^{\infty} FP_{Esw}^{i}(n\Delta t)E_{clo}(t-(n+m)\Delta t) + \sum_{j=1}^{N_p}\sum_{n=0}^{\infty} FP_{Tse,j}^{i}\,(n\Delta t)T_{se,j}(t-(n+m)\Delta t) + \sum_{n=0}^{\infty} FP_{Ta}^{i}\,(n\Delta t)T_a(t-(n+m)\Delta t)\right] - \sum_{m=0}^{\infty} Z_i\,(m\Delta t)T_{se,i}(t-m\Delta t) \quad (1)$$

2.2. DISTRICT ENERGY SIMULATOR MODEL (DIMOSIM)

DIMOSIM (P. Riederer et al. 2015) is an integrated simulation tool for the analysis of feasibility, conception and operation of district energy systems. It consists of (a) building and thermal zone models, (b) thermal and electric network model and (c) a variety of energy system components for the various scale (sensor, emitters, hydronic distribution, production, storage and control).

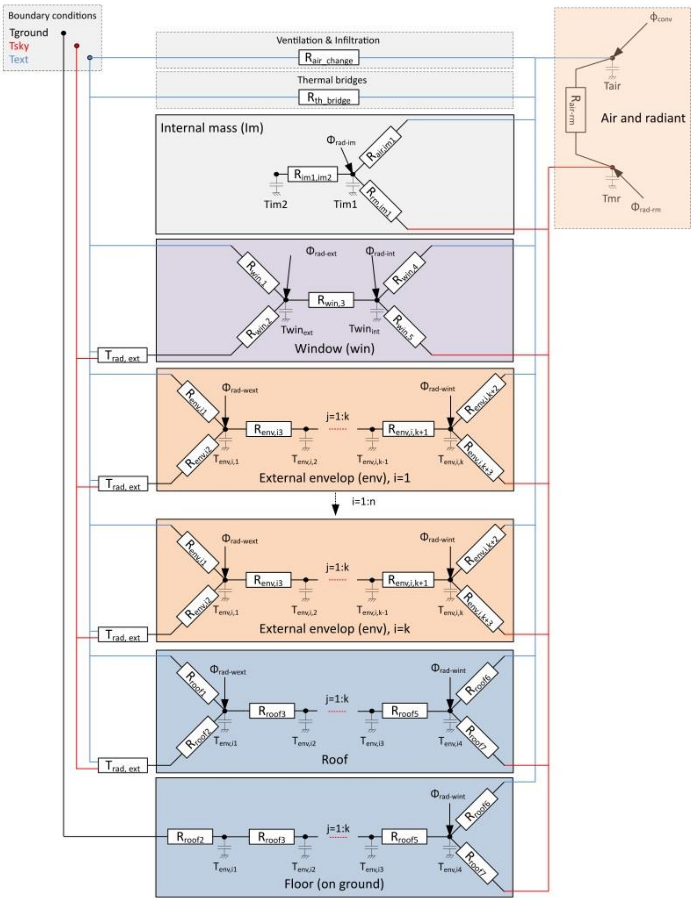

Figure 2: Layout of the thermal zone model.

More in detail, the main elements considered in the thermal zone model are: (a) windows, which are represented as a two-node model with two thermal capacitors on the external and internal surface, (b) wall envelope model which can either be applied to each individual façade or to all facades aggregated. The number of nodes for the discretization of the wall layers is between a minimum of four capacitors representing external surface, first mass layer, second mass layer and internal surface (Figure 2). Absorbed solar SW radiation is calculated in a specific radiation module for each façade and considering solar close and far masks and is injected to the outer surface of the wall. On the internal surface, radiative gains from occupants, equipment and solar radiation are injected proportionally to the area of the wall. The roof external envelope model (c) is identical to the one of the walls except that the inclination is horizontal. The ventilation module (d) calculates heat flux to the zone from ventilation and/or infiltration. The flux can be positive or negative and the system can be dealt as a simple mechanical ventilation system or a ventilation system with heat recovery. Thermal bridges (e) are estimated from the number of floors, the position of the insulation and the perimeter of the zone footprint considering a global thermal bridge coefficient and finally (f) the internal mass module, in which all adjacent and internal walls or floors are represented and allows considering the thermal inertia.

2.3. COUPLING METHODOLOGY

Given the different common physical variables concerning the buildings, the coupling procedure focuses on building envelopes. At the actual stage, an offline coupling between the two tools is ongoing (Table 1). This procedure is elementary and representative in order to define the complexities for further online set-up. At a first stage, EnviBATE performs an annual simulation. The outdoor air temperature of the zones is used to create a new meteorological file, composing the import data of DIMOSIM, which then calculates the annual loads. As the thermal behavior of the zones is changing, a step further is to continue with the radiative coupling. At this stage, the impact of a detailed radiation model will be studied for different climatic zones and geometries. While the inconsistencies between two tools are existing, the previous stages are going to guide us to solve them and set the tolerance limits. Each coupling stage separates to various sub-stages depending on the studied level of detail.

Scenarios	Methods
Coupling Stage 1	Offline Coupling of EnviBATE & DIMOSIM
Coupling Stage 2	Radiative Coupling of EnviBATE & DIMOSIM
Coupling Stage 3	Fully Coupling of EnviBATE & DIMOSIM

Table 1: Framework of the coupling strategies.

At the final stage, a cosimulation process adjusts at our ultimate objective. The selected "exchangeable" variables are the outside heat flux of the energy system (DIMOSIM) and the outdoor surface temperature (EnviBATE). The formula will be the following: due to the ability of discretized time steps (10min) DIMOSIM calculates at the t_D^5 time step the outside heat flux of the energy system and the set-point of the respective zone, dispatch and impose them to the microclimatic model at t_E^1 time step (Figure 3). At the same time, EnviBATE calculates the outdoor surface temperature and the shortwave radiation flux transmitted through the windows and impose them to DIMOSIMs t_D^6 time step.

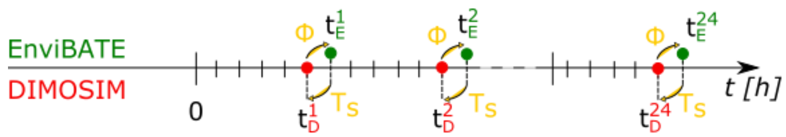

Figure 3: Temporal description of Coupling stage 3.

2.4. ON-GOING COMPLEXITIES

Online coupling of models targeting different objectives is a strenuous procedure in which a common formula has to be set. Differences on spatial characteristics remain to be addressed, as they represent a significant factor in this complex undertaking. Although common building footprints are settled, the construction of the various meshes must also follow this common formula. As an example, EnviBATE is using a triangulated mesh to serve the thermal transfers of the zones, giving spatial fluctuations on the studied parameter compared to one node representation of DIMOSIM. Another significant aspect to handle is the zonal cells in which the system fluxes are going to be imposed in order to avoid overheating phenomena, especially during low wind speed time steps. Given the fact that EnviBATEs outdoor and indoor environments are coupled in the building surface, overheating of zonal cells will automatically lead to overestimation of surface temperatures placing ostensible discrepancies to coupling stage 3. The differences on temporal characteristics were denoted in 2.3.

3. "LA CITE DES GERANIUMS" A CASE STUDY

3.1. AUDIT OF THE AREA

The referenced area is an ongoing rehabilitated district of the Municipality of La Rochelle, situated 2km in the north-western suburbs of the city center. It is oriented along the axis of a NE'N-SW'S direction (10^o from real North counter-anticlockwise). The district is characterized as residential. The building stock corresponds to single-floor residence and social housing of semi-detached, 5-storey apartment buildings. During the rehabilitation project, also 3-storey newly built apartment buildings were constructed.

3.2. INITIAL SIMULATION RESULTS

In the framework of this study we target to expose few of the capabilities of each tool. The climatic data correspond to La Rochelle standard climatic file, interpolated to 2030 according to the A1B future scenario given in the IPCC Special Report. Two annual simulations were launched within hourly time step, while the initialization temperature is set equal at 16oC. In terms of computational time, DIMOSIM is capable to execute the simulation very fast (in the order of seconds), while EnviBATE needs 9.5h depending on the complexity of treated surfaces. In a second step, we followed the procedure described in 2.3.

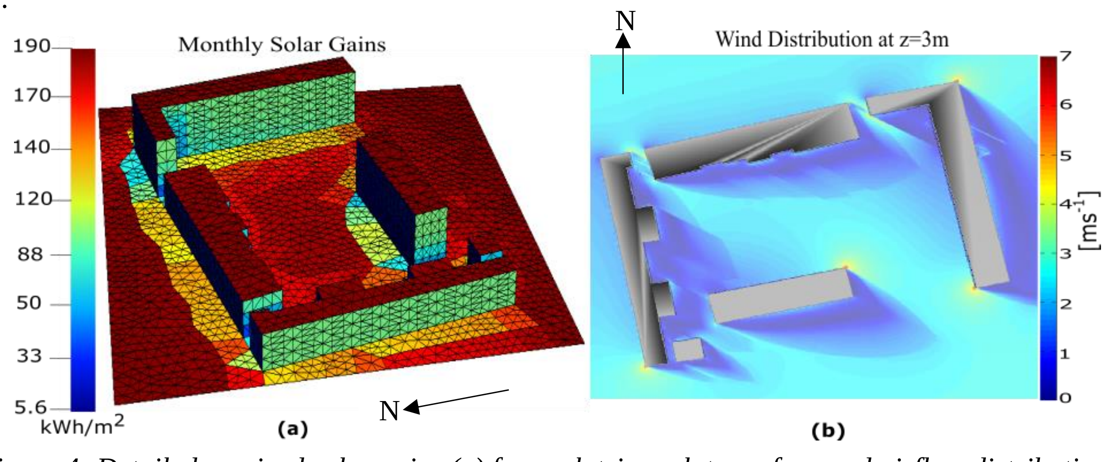

Figure 4: Detailed received solar gains (a) for each triangulate surface and airflow distribution of the examined area.

Figure *4* (a) and (b) represent the monthly received solar gains per surface on July and the distribution of the airflow (at z=3m) respectively. More in detail, roofs receive the maximum solar radiation reaching 190 kWh/m^2, while the S-SW'n facades are following with values ranging from 140-170 kWh/m^2.

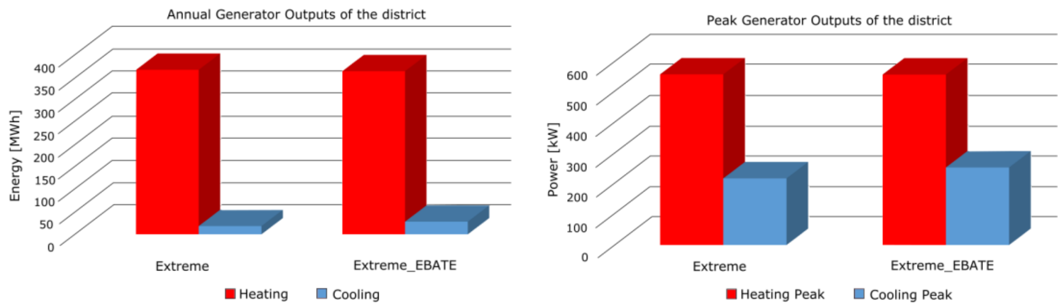

Figure 5: Annual Generator outputs of the entire district (left) and the respective peaks (right).

Concerning the energy loads, Table 2 and Figure 5 present the differences of the annual energy and peak loads of the local generator between standalone and enhanced meteorological file. The emitter type corresponds to ideal. The total energy difference between the two scenarios is reaching 2%, while the cooling energy present a significant increase (35%); taking into account the almost zero actual cooling needs of the area. Regarding the peak loads, a similar trend is observed. The cooling peak load increases by 14% and 13%, considering a local or central generator respectively. Obviously, this amount depends on the proportion of heating/cooling loads and we estimate to change for districts of different climatic zones.

Scenarios	Heating [MWh]	Cooling [MWh]	Total [MWh]
Extreme 2030	368.72	18.48	387.20
Extreme 2030 & EBATE	365.67	28.40	394.07
Differences	1%	35%	2%
Scenarios	Heating Peak [kW]	Cooling Peak [kW]	Total [kW]
Extreme 2030	561.47	219.23	780.70
Extreme 2030 & EBATE	560.90	255.12	816.02
Differences	0%	14%	5%

Table 2: Generator outputs of the district using standard and enhanced meteorological file.

Although many studies of mitigating UHI have been performed (Kyriakodis and Santamouris 2017), none of them can still capture the interconnection of buildings and energy systems and networks to the microclimate concurrently, in terms of detailed representations (of urban structures, systems and networks) and efficient computing time and this is what we scope to examine through this methodology.

4. CONCLUSIONS AND PERSPECTIVES

The aim of this study is to introduce a methodology of coupling procedure based on a detailed district energy model from urban microclimate to district network. The used tools and the complexities of this effort are analyzed in a first step. Some of the possible capabilities of the coupled tool were shown based on a case study. The initial results show the deviation of cooling loads when an enhanced meteorological file is used independently the generator type. We expect to fulfill the coupling stages in order to respond to the opposite inquiry taking into account the type of the network and the system components.

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