Simulating the energy loads at the district scale: Introduction to a dedicated platform

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Abstract

Explicit simulations of the building heating and cooling loads at the district scale is hard to achieve because of their huge computational cost and the lack of relevant data at such an urban scale. A common solution to answer both problems is to simplify the model, usually resulting in a lower accuracy. This issue rises the following question: *how to design a district energy model given computational limitations ?* A specific modelling and simulation platform, called MoDEM (Modular District Energy Model), was developed to answer this question. The level of details of the model is modular in order to fit the available data or the available computational resources. For both cases, the impact of the assumptions can be evaluated as well as the loss of accuracy. To illustrate the possibilities offered by the platform, a district is taken as a use case. The results are discussed regarding the effects of various model adaptations on simulation outputs. The introduced methodology evidences the steps making it possible to reach explicit simulations of the energy load of a district and demonstrates the ability, and the limitations, of current tools.

Introduction

The building sector plays a major role in current environmental, energy and urban growth challenges. Therefore, modeling tools are needed to guide the choices and practices of city decision makers, urban planners and building designers. Regarding more particularly the prediction of the heating and cooling energy demand of urban buildings, different approaches were developed (see Figure 1):

- Adjusted building energy models, which consider some adjusted inputs in usual programs to integrate some effects of the urban environment on the building simulation results, although this was not the original purpose of the BEMs.
- Urban Building Energy Models (UBEMs), which integrate the interactions between a building and its environment with details. UBEMs sometimes use a microclimatic coupling, which limits the simulated period because of the induced computational costs.
- District energy models (DEMs), which simulta-

neously compute the energy loads of the different buildings of a district, but often simplifying the interactions between them and with their environment.

- City Energy Consumption Models (ECMs), which can be either top-down (regression based on historic aggregated energy values) or bottom-up (extrapolation based on the consumption of representative sets of buildings). These models cannot assess the heating and cooling loads.

From these different approaches and with respect to the current challenges linked with the design of energy efficient buildings and districts - including the integration of renewables, energy sharing, smart grids and effective systems - the availability of reliable dynamic DEMs such as microsimulation appears especially essential. Indeed, as they can explicitly model the different buildings of a district, such approaches enable different scenarios to be tested spatial analyses of results to be performed. Nevertheless, the development and use of such DEMs have to face two main problems: (1) the computational costs of such detailed district energy simulations (DESSs) and (2) the lack of available relevant data/parameters. Consequently, simplifications are generally mandatory, especially with respect to the modeling of radiation, microclimate and building envelope (Frayssinet et al., 2018b). Indeed, solving conductive heat transfers in building envelopes and the directly related physical phenomena represent the most expensive part of building energy simulations (BESs), while these transfers are critical in determining the heating and cooling loads. Therefore, the present paper introduces a new simulation platform - MoDEM - standing for Modular District Energy Model, which is able to evaluate the suitability of usual DEM simplifications and to discuss the reachable objective of a DEM given its technical constraints.

The MoDEM approach is techno-explicit, physically-based and capable of studying different scenarios (Frayssinet, 2018). The tool automatically handles the generation of the model geometries based on geographical information systems (GIS), integrates up-to-date and growing standards of the new generation of building energy models (BEMs) and uses simulation parallelizing to reduce the computational time.

Figure 1: Main numerical approaches used to compute the energy consumption of urban buildings and districts.

In addition, the platform is able to automatically process geometric and building input data to generate the BEMs, with different levels of details - BEM adaptations - as well as to build the DEM including, or not, interactions between buildings - DEM adaptations.

To introduce the platform, the **Method** section presents the developed toolchain, in terms of computational implementation and embedded physics. The application case is presented in the **Case study** section. Simulation results are analyzed to discuss the suitability of current DEM simplifications depending on the simulation objective, and thus highlight the possibilities offered by the MoDEM platform. The strengths and expected improvements of the platform are further considered in the **Discussion** section. Finally, the **Conclusion** section synthesizes the main results of the study towards the definition of guidelines related to the design of DEMs depending on technical limitations and simulation objectives.

Method

Toolchain implementation

The automatic generation of the model geometry based on GIS is performed using the MERRUBI tool (Lauzet et al., 2016; Ribault et al., 2017), via sketchup. A detailed .xml (.bsp) file of the geometry is then created, and a form factor table is generated using the ray tracing method. To build the BEMs, the building properties are selected from the TABULA database (Rochard et al., 2015), which gives typical compositions of building envelopes and U-value for French residential buildings depending on the construction period and the retrofitting stage. This database has been enriched with values of thermo-physical parameters such as surface emissivity and albedo, or wall layer thickness and thermal conductivity to reach the indicated U-value. Scenarios of occupant behaviors are generated using SMACH, an EDF R&D's agent-based model (Huraux et al., 2015;

Reynaud et al., 2017) able to generate activity scenarios for each individual at short time steps, depending on parameter such as sociology, location...

Based on these data and a weather data file, BEMs are generated for each building using the BuildSysPro Modelica library (Plessis et al., 2014, 2016). BuildSysPro is developed by EDF R&D and has been validated with respect to experimental data, especially regarding highly energy efficient buildings (Bontemps et al., 2013, 2016). BuildSysPro is based on a 0D/1D approach, and a finite volume method for conduction. Each created BEM is basically an assembly of submodels, automatically generated and connected to allow the modeling of different levels of details (BEM adaptations), each geometric element being extracted from the .xml file and parameterized with data sources or default values. BESs are then run using the Dymola environment. The 'Dassl' time step adaptation solver is used to solve the Modelica equations. The basic observational time step is fixed to 1 hour because of the common time step of weather files.

The DEM is then generated as an assembly of BEMs. Then, the problem is converted using Dymola into functional mockup units (FMUs), which encompasses both a BEM and a numerical solver according to functional mockup interfaces (FMIs). This technique allows performing distributed computations, currently managed by Dacosim (Galtier et al., 2015), and makes possible the automatic integration of different levels of building interactions (DEM adaptations). For this purpose, data exchanges can be performed between FMUs by Dacosim every 900 seconds.

All the different parts of the platform are linked thanks to specific Python scripts. Figure 2 synthesizes the general structure of the MoDEM toolchain. In terms of computational performance, a typical BES lasts for 2 minutes on a 8 cores computer with

Figure 2: The MoDEM toolchain.

2.5 GHz and 8Gb of RAM, and a DES including 23 embedded BEMs lasts for 30 minutes on the same computer. Cluster computations are also possible.

Possible model adaptations

Focusing on the heating and cooling needs, which are mostly determined by the properties of the building envelope (building scale) and local micrometeorological conditions (district scale) as well as modeling assumptions, the modular MoDEM platform can automatically manage numerous BEMs and DEMs adaptations. In particular, the tool includes the different options listed below.

- In the BEMs, the following features are modular:
 - the wall discretization for conductive heat transfers: coarse resolution, e.g. a single node per wall [$Cond - \tau_{large}$], or a finer spatial resolution [τ_{small}], where τ is the characteristic time in s;
 - the building zoning: monozone [$Zoning - 0$], multizone by floor [$-lvl$], by outer wall orientation [$-ori$] or both [$-comb$];
 - the controlled physical quantity: the indoor air temperature [$Control - 0$] or the operative temperature [-1];
 - the distribution of the transmitted solar flux: on the floor [$trSol - 0$] or proportionally distributed on walls depending on their area [-1];
 - the modeling of internal long wave radiative exchanges: linearized exchanges based on the indoor air temperature [$intLW - 0$] or the operative temperature [-1];
 - the integration of the internal thermal mass:

modeling of internal walls [$inertia - 0$] or not [-1];

- the modeling of external convective heat transfers: constant convective heat transfer coefficient (CHTC) [$CHTC - 0$] or wind-dependent formulation ($CHTC = 4 + 4v$), where v is the normal projected wind velocity [-1];
- the modeling of external long wave heat transfers: linearized formulation [$extLW - 0$] or complete formulation derived from the Stefan Boltzmann law [-1];
- the general representation of the envelope: differentiation of walls depending on their properties [$EqEnv - 0$] or one equivalent thermal wall [-1].
- In the DEM, the following aspects are modular:
 - the integration of solar masks and multi reflexions: received solar flux directly derived from the weather file [$Solar - 0$] or estimated using ray tracing [-1];
 - the estimation of long wave radiative heat transfers: ground and building surface temperatures approximated by the outdoor air temperature [$LWRad - 0$] or estimated by energy simulation and the complete long-wave radiative exchange formulation derived from the Stefan Boltzmann law [-1];
 - the consideration of adjoin buildings: adiabatic half party walls [$ajoin - 0$] or coupled interface [-1].

Table 2 summarizes and illustrates most of these different model options.

Figure 3: Geometry of the use case. Dotted and parallel lines highlight the considered adjoin walls.

Case study

Modeling

To illustrate the ability of the MoDEM platform to handle DESs and analyze the effect of different BEM and DEM adaptations, a district of Paris is taken as the use case. This use case comes from a collaboration with the CES MINES Paritech laboratory and was used for model comparison in Frayssinet et al. (2018a). Figure 3 shows the selected district, which is composed of apartment buildings having the same typology. About 900 flat units compose this district built in the 1930's. Table 1 gives the main building thermal properties derived from the TABULA database.

Table 1: Building thermal properties.

Building component	U - value [$W \cdot m^{-2} \cdot K^{-1}$]
Wall	1.7
Roof	3.2
Windows	2.8
Ventilation	[vol^{-1}]
Natural	0.5

Geometric data were taken from the IGN database BD TOPO. 23 buildings are assumed connected to each others with adjoin walls (parallel lines in Figure 3). The selected weather file is that of Paris Montsouris. Because of the building typology and the regional climate, the study focuses on heating needs, with a set point fixed to 19°C.

To evaluate the effects of model adaptations, a reference model was defined. Its characteristic time τ is 900s for conduction, its basic BEM options are detailed in bold in Table 2 and are [-0]. Similarly, the reference DEM options are in bold in Table 2, they are [-1]. The different options synthesized in Table 2 were then simulated. Note that [Zoning - 1] corresponds to a division of the biggest buildings with respect to the main orientation, and not floor by floor.

Table 2: Tested model adaptations. The options of the reference model are indicated in bold.

Model option	Meaning
Wall model	
Wall discretization [Cond-] $\tau_1 / \tau_2 < 1$ $\tau = 900s / \tau = 59s$ or $15s$	
BEM - Building model	
Thermal zones [Zoning-] 0 / 1 One / One by orientation	
Controlled temperature [Control-] 0 / 1 Air temp. / Operative temp.	
Allocation of solar flux [trSol-] 0 / 1 On the floor / Distributed	
Internal long wave [intLW-] 0 / 1 Air temp. / Operative temp.	
Internal walls [Inertia-] 0 / 1 Included / Neglected	
External CHTC [extConv-] 0 / 1 Fixed / Wind-dependant	
External long wave [extLW-] 0 / 1 Linearized / Complete	
Envelope representation [EqEnv-] 0 / 1 Explicit / Equivalent wall	
DEM - Interactions between buildings	
Solar masks and reflection [Solar-] 0 / 1 Neglected / Accounted for	
External long wave [LWRad] 0 / 1 Ground and sky / + Buildings	
Adjoin buildings [Adjoin-] 0 / 1 Adiabatic / Balance	

This zoning generated 33 zones with 12 adjoin walls, represented with dotted and parallel lines in Figure 3. This configuration is considered to study the effect of adjoin walls.

Results analysis

Simulation results in terms of year-round power loads for the reference model are shown in Figure 4. Results show daily, monthly and seasonal variations of the heating needs curve. The heating period goes from mid-September to mid-June. Maximum heating loads occur during January and February.

To evaluate model adaptation effects, Table 3 gives three indicators informing on the relative effect of the different BEM and DEM adaptations in terms of power difference between the reference model and the selected adapted models. More precisely, considering the time series differences:

$$D = \{p_i^{(a)} - p_i^{(ref)}, i \in [1, N]\} = \{d_i, i \in [1, N]\} \quad (1)$$

where p is the power load, the superscripts *ref* and *a* refer to the reference and adapted models and d is the power difference, the indicators are:

the mean value ($m(\cdot)$)

$$m(D) = \sum_{i=1}^N \frac{d_i}{N}, \quad (2)$$

the standard deviation ($\sigma(\cdot)$)

$$\sigma(D) = \sqrt{\sum_{i=1}^N \frac{(d_i - m(D))^2}{N}}, \quad (3)$$

and the maximal value ($M(\cdot)$)

$$M(D) = i \in [1, N] \max(|d_i|). \quad (4)$$

The mean value ($m(\cdot)$) quantifies discrepancies in terms of annual energy predictions. The standard deviation ($\sigma(\cdot)$) quantifies discrepancies in terms of power fluctuation amplitudes and phase shifts. The maximal value ($M(\cdot)$) quantifies discrepancies in terms of ability to handle particular events.

Results show that lower wall discretization has few effect on the mean and standard deviation but deviation can locally be more important. Indeed, low wall discretization delays the building response to dynamic solicitations, especially linked with rapid solar loads. Regarding other BEM adaptations, results highlight that modeling multizone buildings does not significantly alter the prediction of heating needs. Controlling the operative temperature instead of the air temperature generally increases the simulated heating needs. This trend is explained by the fact

Table 3: Relative effects [%] of the model adaptations on heating on the mean ($m(\cdot)$) standard ($\sigma(\cdot)$) and maximal ($M(\cdot)$) deviations.

Option	$m(\cdot)$	$\sigma(\cdot)$	$M(\cdot)$
Wall - Reference [$\cdot$ -] : 900s			
[Cond-] 59	-0	0	1
[Cond-] 1296000	0	5	24
BEM - Reference [$\cdot$ -] : 0			
[Zoning-] 1	1	1	8
[Control-] 1	4	6	26
[trSol-] 1	0	1	5
[intLW-] 1	-13	16	64
[Inertia-] 1	3	6	72
[extConv-] 1	-10	10	74
[extLW-] 1	-1	1	7
[EqEnv-] 1	7	7	40
DEM - Reference [$\cdot$ -] : 1			
[Solar-] 0	-4	5	37
[LWRad-] 0	1	0	5
[Adjoin-] 0	0	0	0

that the wall temperature is lower than the air temperature. Uniformly distributing the solar flux over the different walls has few effects on simulation results. This conclusion may be explained by the higher availability of solar heating but a lower heat storage which balances each others. For the same reason as the control temperature, using the operative temperature instead of the air temperature to estimate long wave heat transfers decreases the prediction of heat losses with a typical daily pattern. Deviation is lower around midday because the operative temperature is closer to the air temperature due to the sun heating. Note that the mean and standard deviation of this adaptation are the highest of the tested adaptations. Maximum deviation is also substantial. Neglecting internal walls tends to decrease the simulated floating temperature periods and increase heating needs, also with a dynamic temporal pattern. Heating is more necessary after sunny periods, because of the absence of buffer effect. Considering the wind-dependency of the external CHTC tends to decrease the predicted heating needs as the estimated CHTC is generally lower than the constant default value. This effect is significant, both in terms of mean and standard deviation. It is also the most influential model adaptation with respect to the maximum deviation. This effect has no specific temporal pattern as wind does not depend on solar loads in the model. Not considering the linearized formulation of the long wave external exchanges also induces lower heat losses and thus estimates of heating needs. This effect is however less important than the effect of the CHTC. Finally, considering an equivalent envelope does not much change the general trends, but causes significant local deviation.

Figure 4: Simulated power load curve (1 hour time step) for the reference district model and a typical year.

tion as the dynamic behavior of the envelope is altered by the equivalence assumption.

Regarding DEM adaptations, almost only the adaptation of the short wave heat flux is highlighted as influential on simulations results. Indeed, accounting for solar masks increases the estimates of heating needs because of less solar heating, leading to substantial local deviations. The effect of estimating long wave radiative heat exchanges using BEMs results and taking the thermal balance of adjoin walls into account appear negligible. These results have nonetheless to be modulated by the facts that the present study focuses on the heating needs and that the adjoin wall surfaces is very small compared to the total building envelope area. Present results may thus be very case specific.

Hence, this case study suggests that if the output of interest is the annual heating energy demand of an old residential district, usual BEMs and DEMs adaptations are acceptable, with the exception of assimilating the indoor surface temperature to the indoor air temperature to compute long wave radiative heat exchanges, and neglecting the wind-dependency of the external CHTC. Conversely, when aiming to study the load curve, considering that the operative temperature is controlled and a fine discretization of walls, even more if considering an equivalent envelope, as well as the modeling of internal walls and of the solar shading appear mandatory, as maximum deviation criteria is also restrictive. A control model would also be required.

Discussion

According to the developed methodology and case study, the MoDEM platform is able to quantitatively evaluate the effects of different model adaptations/simplifications with respect to a given quantity of interest - presently the heating load curve. Note that only a first order analysis (no coupling between adaptations) was carried out in this study as it focused on adaptation effects. Interactions are thus not crucial. Despite focusing on a specific use case, results show

that the developed platform is able to highlight deviations, which, when further relevantly quantified and compared to a defined tolerance, can state on the suitability of a given model adaptation depending on the simulation objective. Reciprocally, the developed approach can also inform on a model uncertainty given a lack of relevant input data or technical/numerical possibilities.

Nonetheless, it is worth mentioning that the analysis presented in this paper only focuses on usual indicators to quantify the effects of the different model adaptations. When analyzing the time-dependent load curve, many other methods could alternatively be used. Indeed, as there is no consensual specific and relevant indicator, methodologies derived from the uncertainty quantification analysis such as local sensitivity analysis, Morris methods or Sobol indexes can also be considered. As present model adaptations do not correspond to parametric uncertainties but to model uncertainties, modeling options can be considered as functional parametric uncertainties. Possible indicators of suitability are thus various and more or less adapted to a given objective. Therefore, a combination of some of the previously-mentioned indicators with some graphical representations could be advantageously used to relevantly inform on the suitability of modeling adaptations.

In addition, to better address energy loads issues in urban areas, the platform could still be improved. Expected model developments are notably:

- the consideration of non residential buildings, which are now often mixed with housing to reduce commutation,
- and the integration of the complementary part of the envelope modeling, i.e. the modeling of systems, a better integration of occupants and a more complete modeling of local microclimatic conditions.

Although the present study focused on the relative effects of different model adaptations, a validation study appears also essential, but this aspect high-

lights one of the main difficulties of addressing district scale high resolution energy problems: the access to detailed and accurate input data (geometry, system efficiency, materials etc.), and to the quantity of interest (currently the load curve), as well as the diversity and complexity of the aspects that the model have to handle to reproduce as close as possible realistic conditions (envelope, systems, local climate, occupants, etc.).

Conclusions

The present paper introduces a new techno-explicit DEM platform - MoDEM- able to automatically handle DESs from GIS data, with different levels of details regarding BEMs and their interactions. This platform was developed with up-to-date and growing standards of the new generation of BEMs (python, Modelica, FMU) and uses simulation parallelism to reduce the computational cost. Its main application is to predict the energy load of a district taking into account interactions between buildings. In this paper, the platform is used to evaluate the suitability of different BEM and DEM adaptations, which are often made necessary because of the lack of available and relevant data or computational resources. Indeed, such adaptations, which generally correspond to simplifications of the description of buildings or physical phenomena, could lead to substantial uncertainties and errors on simulation results. Such inaccuracies become more and more critical with respect to the contemporary issues related to the dynamic energy management at the urban scale. The MoDEM platform can thus discuss the relevancy of a DEM to deal with a given problem. Further, reduction techniques of state models can be used (Kim et al., 2014). Doing so, the computational cost of city scale energy demand computations can be substantially reduced (up to 2000 times (Garcia-Perez et al., 2018)).

To illustrate possibilities offered by the MoDEM platform, a case study was developed, considering a district of old residential buildings located in Paris. The effects of various BEM and DEM adaptations were analyzed. Results especially showed that usual BEMs and DEMs adaptations are relevant when addressing the annual energy demand of buildings. However, substantial local deviations were highlighted, when analyzing the time-dependent heating load curve, i.e. when considering short time periods. These effects may be counterbalanced over a day and are thus not critical for general energy problems, but can become critical for the management of electric grids and/or smart grids. Such conclusions may be even more stringent if considering the cooling needs of new energy efficient buildings including passive strategies.

Hence, this study highlights that further detailing the physical model allows to better capture the fast dynamic behavior of a district. Such improvements appear critical in a context of climate change and en-

ergy conservation challenges. Nevertheless, increasing the level of details generally has a substantial computational cost. For example, considering a simple BEM, estimating and considering internal wall temperatures to control the operative temperature or better estimate the long wave radiative heat exchanges doubles the computational time. Considering the actual building envelope and not an equivalent envelope is also two times more costly. Even more costly would be the consideration of a full microclimatic coupling including computational fluid dynamics to estimate more accurately the external CHTC of buildings and natural ventilation potential/infiltration (Merlier et al., 2019a,b). Such a simulation would in addition require a supplementary expertise of the modeler. Increasing the level of details of a DEM has thus also to face other issues than the computational time and the physical description of the intrinsic building heat transfers, as identified at the beginning of this study. These issues especially concern the access to relevant and detailed input data, such as the internal composition of buildings to estimate internal long wave exchanges or the behavior of occupants, or the access to the very local microclimatic conditions to better estimate building boundary conditions. Therefore, the development of pluridisciplinary collaborations (e.g. with computer, data, environmental and social sciences and geomatics) appears as very beneficial to better address the complexity of the problem.

Nomenclature

BEM: Building energy model
BES: Building energy simulation
DEM: District energy model
DES: District energy simulation
FMI: Functional mockup interface
FMU: Functional mockup unit
GIS: Geographical information system
 τ : Characteristic time

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