REDUCTION OF BUILDING MODELS FOR USE IN URBAN ENERGY ANALYSIS

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ABSTRACT

This papers describes a building model designed for city simulation tools. In this context, the simplicity and accuracy trade-off is particularly important. The computing time is also a strong constraint. The methodology involves physical simplifications and model order reduction. The physical simplications ensure to keep most relevant physical phenomena and sollicitations whereas the order reduction eliminates the non-significant state variables. Both steps are justified and compared to a reference model described in a one-dimensional detailed thermal model. The final model is reduced, linear and time-invariant and described in a state-space form. The results show the accuracy of the heating and cooling load estimation (less than 2% in error) and a computing time decrease.

INTRODUCTION

Design of sustainable cities through simulation tools has become a hot-topic during the last decade (Robinson, 2011). It is regarded as one of the solutions to reduce the greenhouse effect and handle resources scarcity in complex ecosystem such as urban areas. This paper is focused on building envelopes, one of the key points in city model. Some existing building models are usually too complex and computationally expensive, and others are too simple and consequently inadequate for a precise load prevision.

With developments in commercial tools such as Trnsys (Klein et al., 2010), Energy+ (EnergyPlus, 2013), building simulation models have been directly used for urban energy simulation (Courchesne-Tardif et al., 2011. Huber et al., 2011). Since the simulation of such models are time-consuming, the authors simulated all buildings *a priori* to get ideal energy load profile before the system simulation. Another way is to decrease the number of buildings in simultaneous simulations.

Other than these existing building models, some city-oriented simulation tools have been developed with different simplified building models.

The Solene, originally an architectural and urban radiance tool, integrates a building thermal model as a Solene sub-model. The model is derived from a nodal network model representing a multizone building (Roux, 1984). The physical formulation is based on an analogical method using electrical network representation of building elements (windows, walls, roof, floor, etc.). Therefore, a building is composed of thermal zones, and each zone is described by thermal resistances and capacitances (RC model).

More recently, the urban simulation tool CITYSIM (Robinson et al., 2009) adopted the similar RC model. In this case, a zone is represented by 2 capacitances describing the indoor air node and the building enveloppe node. A comparison (Kämpf et al., 2007) with a reference model in ESP-r (Clarke, 2001) showed that the model error in the annual energy is of the order of 10% and deviations of indoor temperatures and hourly loads are significant (e.g. 5°C for some wall types).

Another urban simulation tool SUNtool (Robinson et al. 2003) integrates building models of grey-boxes defined for a specific building typology. The grey-box model is based on the model reduction technique that reduces the model order of a full-knowledge physical model (Déqué et al., 2000). Although this kind of model is capable of reproducing thermal dynamics of building, the procedure to generate the grey-box models includes a number of simulations, and therefore the model pertinence is highly sensitive to the number of test simulations (Plessis et al., 2011).

The work presented in this paper aims at developping efficient and accurate building models suitable for city simulation tools. The methodology is based consecutively on a physical simplification and a model order reduction. A Detailed Model (DM) is used to deduce a Simplified Model (SM) once for all by using physical knowledge and sensitivity analysis. A Reduced Model (RM) is then derived from the SM model. The methodology ensure to be independent from a specific typology, to keep the building dynamic behaviour and to be efficient from a computing time point of view.

The proposed model takes into account the most significant sollicitations and physical phenomena: outdoor temperature, solar fluxes, long wave radiations to the surrounding, thermal inertia and heat transfer throught the building enveloppe. Computation of those boundary conditions is not discussed in this paper, so they are regarded as known. In the following sections, we will present the three models and methodologies used for the model simplification and reduction.

DETAILED MODEL (DM)

In this part, the DM model is presented from which the SM and RM models are developed. It will be used as a reference model for comparison. The models used to define the DM model in this work are composed from sub-models of the simulation tool CLIM2000 (EDF/DER 1998). They have been validated by the BESTEST inter-model comparisons (Judkoff, R., Neymark, J. 1995). The current DM model presented hereafter is defined with typical hypotheses used for the well-known simulation tools. Further investigation on the DM itself is reserved for a future work as the process from the DM to the RM is almost the same for different levels of detail of the DM model.

MODELICA-based model

Modelica, an acausal modelling language, is used in this work using Dymola (Dymola, 2013). The building components of the DM model are modelled using the EDF's library of Modelica models. One of the benefits of this acausal modelling tool is that we can easily modify the pre-defined component models for our own purpose as the resolution algorithm is separated from the modelling part. By including or excluding certain physical phenomena in the component models, it helps to evaluate their impact on target variables. This sensitivity analysis has been done in a previous work to define the SM model presented in the next section. In addition, whole-building matrices necessary for the RM model can be easily obtained using a Modelica function that can export symbolic state-space representation.

Description of the DM model

The DM model uses one-dimensional component models of walls and windows. In this DM model, wall layers, correspondent meshes, and the insulation position (inside or outside) are fully specified. They account for the conductive heat transfer between inner computation nodes, the convective heat exchange with the ambient air and the short- or long-wave radiation heat exchanges. As commonly used, the conductive and convective heat transfer coefficients are assumed constant, but the radiative coefficient is variable in function of temperatures of concerned bodies. The window model includes the solar transmission process using variable transmittance rates (τ) that is a function of the solar incident angle. The solar flux transmitted through windows is assumed entirely absorbed on the floor. In addition, the DM model considers heat loss through ventilation using a constant air change rate.

The DM model is composed of several components of walls or windows depending on the building morphology. For a building of n wall-orientations, $3n$ solar irradiation information (Φ_{dir} – direct, Φ_{dif} – diffuse, cos$i$ – incident angle) should be given to the model as seen in Figure 1. For example, if a simulated building is a form of parallelepiped with a southern window and 6 walls, 7 component models are required, and the building model uses at least 3×5 inputs for the 5 orientations: horizontal, southern, northern, eastern, western. A complex configuration of building envelope increases that number of inputs. Together with these inputs, the outdoor and sky temperatures are required as input variables. The overall thermal input (P) provided from internal gains and air-conditioning systems is the last input to the DM model. As a result, 18 inputs and 7 components are required in this single zone case.

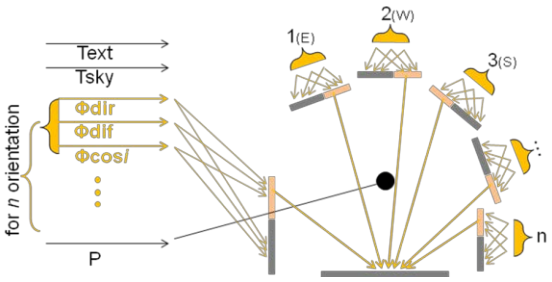

Figure 1. Inputs to the DM model (n-orientation single zone case)

SIMPLIFIED MODEL (SM)

Above all, simplifications to the SM model are considered when being helpful to define generic building models. This may allow fewer parameters and consequently less labour to define all urban building models.

Another reason to develop the SM model is to create a linear and time invariant model. It is important to use the state reduction technique that is applicable only for such a system.

Solar transmittance through windows

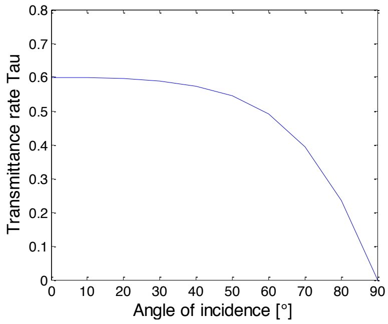

Figure 2. Example of the variable solar transmittance rates

Treatment of the solar transmittance process through windows is one of the main issues to establish a generic and linear building model. The solar transmittance rate (τ) is strongly variable in the function of the solar incident angle to the normal vector of the window as seen in Figure 2. From sensitivity tests carried out ahead of this work, a constant τ assumed for simplicity resulted in significant errors particularly for glass dominant buildings. As a result, it is indispensable to take into account the variable characteristic.

To get the linear building model, the solar transmittance process is taken out from the DM model and then placed upstream of the model. It means that the solar flux transmitted through all windows is separately calculated in advance using the variable rates, and the obtained flux becomes one of the input variables to the model. In this work, a mean input value is used, and it can be calculated as:

$$\overline{\Phi}_{trans}(t)=\frac{\sum_i S_{win\_i}\times(\Phi_{dir}\times\tau_i(t)+\Phi_{dif}\times\tau_0)}{\sum_i S_{win\_i}} \quad (3)$$

Where, $\overline{\Phi}_{trans}(t)$ is the mean value (W/m²) of total solar transmitted flux through all windows, $\tau_i(t)$ the variable transmittance rate, and τ_0 the constant diffuse transmittance rate of windows. S_{win_i} means the window area (m²) for each orientation i. Φ_{dir} and Φ_{dif} indicate the direct and diffuse solar irradiation (W/m²) on the windows, respectively.

This amount of flux is multiplied in the model by the total window surface, and then it is directly absorbed on the floor.

Orientation-independent model

Each solar absorbed irradiation on opaque walls and windows is averaged for the SM model as the mean transmitted flux is calculated. Accordingly, those values ($\overline{\Phi}_{abs\_win}$ and $\overline{\Phi}_{abs\_wall}$) are given as:

$$\overline{\Phi}_{abs\_win}=\frac{\sum_i S_{win\_i}\times\alpha_{win\_i}\times(\Phi_{dir}+\Phi_{dif})}{\sum_i S_{win\_i}} \quad (4)$$

$$\overline{\Phi}_{abs\_wall}=\frac{\sum_i S_{wall\_i}\times\alpha_{wall\_i}\times(\Phi_{dir}+\Phi_{dif})}{\sum_i S_{wall\_i}} \quad (5)$$

Where, α is the thermal absorptivity for windows and walls (indices *win* and *wall*, respectively).

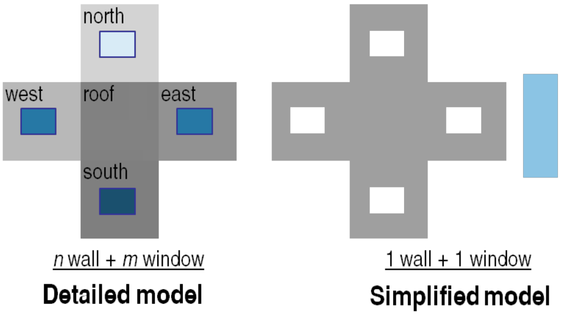

Figure 3.Treatement of absorbed solar fluxes on walls and windows

Use of mean values for the absorbed flux modifies boundary conditions of the SM model as seen in Figure 3. Other than the DM model where distinct surface temperatures are observed (see the left of the figure), the SM model has the same outside surface temperature of walls and windows as they are exposed to the same boundary condition of the average solar irradiation. Since the target variable of the building model is the indoor temperature relatively apart from the outside of walls, this simplification would not much affect the results.

All three mean values allow the SM model to use an equivalent single component for walls and another component for windows.

Linearization of coefficients

As mentioned earlier, in the DM model, the convective and conductive heat transfer coefficients are assumed constant, and the radiative heat transfer rate (Φ_{rad}) is variable according to the non-linear function of relative temperatures:

$$\Phi_{rad}=\varepsilon\times\sigma\times(T_{sky}^{4}-T_s^{4}) \qquad (6)$$

Where, σ is Stefan-Boltzmann constant ($=5.7x10^{-8}$ W/m^2K^4), ε the body emissivity, T_{sky} the sky temperature, and T_s means the external wall surface temperature.

It gives:

$$\Phi_{rad}=\varepsilon\times\underbrace{\sigma\times(T_{sky}^{2}+T_s^{2})(T_{sky}+T_s)}_{\gamma}(T_{sky}-T_s) \quad (7)$$

For linearity, the part γ in Equation (7) can be assumed constant using annual-constant temperatures for T_{sky} and T_s. This value γ is normally set between 4 and 6 depending on the weather. The temperatures T_{sky} and T_s of the portion γ are approximated in this work as 263.15K and 283.15K respectively (γ≈4.5).

Final simplified model

From previous sensitivity tests carried out for this work, three mean inputs of solar radiation (W/m²) described in the above are required to accurately simulate the building thermal behaviour: mean transmitted radiation, mean absorbed radiation on windows, mean absorbed radiation on opaque walls. In the SM model, the mean transmitted radiation is multiplied by the total window area ($\Phi_{trans}\times\sum S_{win}$) and then absorbed on the floor as treated in the DM model. The two mean absorbed values (Φ_{abs_win} ,Φ_{abs_wall}) are also multiplied by each area and absorbed on their respective surface with a given absorptivity coefficient (α).

As a result, 3 one-dimensional envelope components are only used in the SM model for a single-zone case: an opaque wall, a window, and a floor as shown in Figure 4. In the case of a multi-storey building that is yet treated as a single-zone, an additional fictive floor component can be added to this SM model to take into account the capacitance of floors between storeys. This fictive component has the total area of the inter-floors of the building, and it shares proportionally the transmitted solar flux with the real floor component.

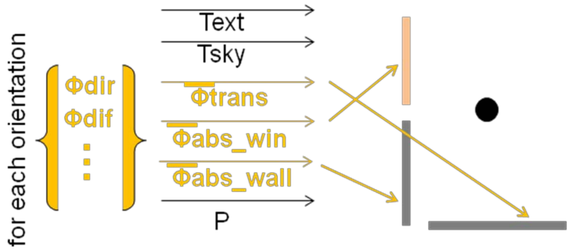

Figure 4. Inputs to SM model

The SM model is orientation-independent so that it could use less inputs and states compared to the DM model. After all simplifications, the SM model becomes a linear system, and finally it can be expressed by a state-space representation:

$$\begin{cases} C\dot{T} = AT + BU \\ Y = JT + DU \end{cases} \qquad (8)$$

Where, *T* indicates an assembly of thermal nodes of walls, windows and indoor air. *U* represents inputs to the SM model. In this single zone case, six inputs are used (see also Figure 4). *Y* is the observation variable and it is the indoor zone temperature in this model. All terms of the state model matrices *C, A, B, J, D* are constant.

This SM model is the initial model from which users will specify all parameters relative to the building envelope. Then, all processes from the SM model to the RM model are automatically performed.

REDUCED MODEL (RM)

From the SM model defined above, a reduction model is deduced using one of the existing reduction techniques. The main objective of the reduction method is to reduce the state model size from n to r ($n>>r$). It is hardly said that one technique is better than the others existing reduction techniques. However, some previous studies (Palamo et al., 1997) showed that the following balanced realization method can give relevant results for the building simulation application.

Balanced realization method

The truncation methods have been largely used in the building simulation: Marshall's method, aggregation methods, Moore's method, etc. Among them, Moore's method (Moore, 1998) is called the balanced realization method since the method is based on balanced concept between the controllability and observability. Simply speaking, the controllability can be defined as the possibility to acquire and vary the model states by means of the system inputs while the observability as the possibility to establish the model states using the outputs.

The reduction can be achieved by eliminating the state variables of lower degrees of controllability and observability defined by their controllability gramian W_C and observability gramian W_O. These gramian matrices (W_C and W_O) are also solutions of the following Lyapunov equations:

$$\begin{cases} (C^{-1}A)W_C + W_C(C^{-1}A)^T = -(C^{-1}B)(C^{-1}B)^T \\ (C^{-1}A)W_O + W_O(C^{-1}A)^T = -J^T J \end{cases} \qquad (9)$$

Since each state variable has not necessarily the same degree of controllability and observability, the initial system (Equation 1) is transformed in basis ($T \rightarrow X$) to balance the degrees. The system after state coordinate transformation becomes:

$$\begin{cases} \dot{X} = \Omega X + \Pi U \\ Y = HX + DU \end{cases} \qquad (10)$$

$T = MX$, $\Omega = M^{-1}C^{-1}AM$, $\Pi = M^{-1}B$, $H = CM$.

Where, M is a state-transforming matrix.

Finally, the same degree of observability and controllability gramians is established for new state variables X. According to a user-defined reduction order r, the reduced model (RM) can be defined by selecting the r-state variables that have more controllable and observable features. Equation 10 can be subdivided into two groups: the selected reduced part X_1 and the eliminated part X_2:

$$\begin{Bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{Bmatrix} = \begin{bmatrix} \Omega_{11} & \Omega_{12} \\ \Omega_{21} & \Omega_{22} \end{bmatrix} \begin{Bmatrix} X_1 \\ X_2 \end{Bmatrix} + \begin{Bmatrix} \Pi_1 \\ \Pi_2 \end{Bmatrix} U \qquad (11a)$$

$$Y = \begin{bmatrix} H_1 & H_2 \end{bmatrix} \begin{Bmatrix} X_1 \\ X_2 \end{Bmatrix} + DU \qquad (11b)$$

As a result, the RM model can be expressed as:

$$\begin{cases} \dot{X}_r = \Omega_r X_r + \Pi_r U \\ Y = H_r X_r + D_r U \end{cases} \qquad (12)$$

$X_r = X_1$,
$\Omega_r = \Omega_{11} - \Omega_{12}\,\Omega_{22}^{-1}\,\Omega_{21}$, $\Pi_r = \Pi_1 - \Omega_{12}\,\Omega_{22}^{-1}\Pi_2$,
$H_r = H_1 - H_2\,\Omega_{22}^{-1}\,\Omega_{21}$, $D_r = D - H_2\,\Omega_{22}^{-1}\Pi_2$

It is hard to select *a priori* an optimal reduction order r for all cases since it is a function of the solicitation frequency and building types. For the Moore's method, it is however said that the RM model in the order of more than 5 ($r>5$) can give satisfied results for typical building cases in hourly building simulations (Palamo et al., 1997).

FINAL MODEL

As the final RM model is obtained using Moore's method from the SM model. The final order *r* was set at 6 in this work. To the authors' knowledge and from some sensitivity tests previously carried out, the selected order is sufficient to reproduce fast dynamics of building.

The procedure to get this RM model from the SM model is as follows:

- All thermal properties and dimensions of wall layers, windows and thermal zone are set in the SM model
- the *Modelica* function *linearize* is used to export the state-space matrices ABCD ($C^{-1}A$, $C^{-1}B$, J, D respectively in Equation 8)
- the RM model (Ω_r, Π_r, H_r, D_r) of Equation 12 is obtained using our own Matlab code that includes functions relative to Moore's method

While yet all these procedures have not been treated in an automatic way, it is surely one of our future subjects.

RESULTS

Description of the test model

A parallelepiped building of two storeys is used as a test model. The floor area is 100 m² in each storey and the total is 200 m². The ceiling height is 2.4 m, and thus the total building volume is 480 m^3. All vertical walls are equipped with windows with different window ratios. The walls are composed of concrete, insulation, and plaster. The total mesh number for each wall is 8. The parameters used in the model test are summarized in Table 1.

Table 1. Parameters

PARAMETER	VALUE	UNIT
$U_{envelope}$	0.2	W/m²K
Total floor area	200	m²
Volume	480	m^3
Air change rate	0.35	1/h
Window surfaces	20/10/10/10 (S/N/E/W)	m²
U_g	1.0	W/m²K
Tau	0.544	
Absorptivity of windows	0.1	
Absorptivity of walls	0.6	

The hourly weather data of the northern-French region Trappes are used, and the indoor air temperatures without internal gains and the hourly loads are compared between models: DM, SM and RM.

Model comparisons

Each building model is defined by a set of equations that are relative partly to states (capacitances) or to variables. As seen in Table 2, the model simplification is effective to decrease the number of equations. The SM model that is orientation-independent uses a single external wall while the DM model has 5 external walls. As the RM model has 6 states (X_r) and 1 output (Y), only 7 equations are used for the model.

Table 2. Number of equations in models

	DM	SM	RM
N of equations	698	194	7

For tests, the indoor air temperatures are firstly compared. Figure 5 shows those temperatures of the three models obtained from an annual hourly simulation. The lower portion of the figure is allocated to show the errors (°C) of the test models (SM and RM) compared to the DM model. The three models show similar indoor temperatures, and the maximum error compared to the DM model is under 0.5°C for the SM and RM models. For detail, the SM model has a very similar evolution during winter, but the errors increase as time progresses toward summer. This is to be expected as the SM model uses constant sky and wall surface temperatures for a constant long wave heat exchange coefficient, and these selected temperatures in this test are closer to the winter conditions. It means that the SM model can be enhanced by varying the constant values, but it is not treated in this test. The RM model that is lower order than the SM model shows systematic errors of about 0.1°C to the model over the year.

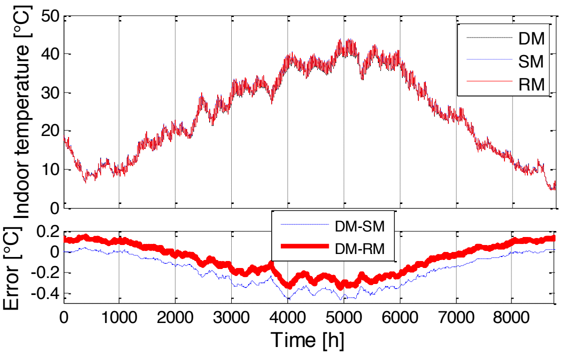

Figure 5. Indoor air temperatures

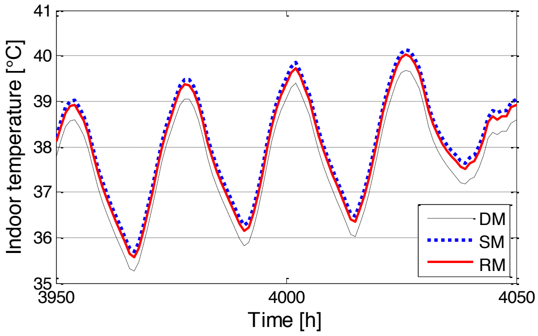

Figure 6. Zoom of Figure 5

Figure 6 is a zoom of Figure 5 for the period of 3950-4051 hour where the errors are more important. From this figure, it is assured that the reduction technique is pertinent to reproduce thermal behaviors of its precedent model (SM) from which the RM model is deduced.

Then, the hourly loads over the year are also compared. For load calculation, the comfort zone is fixed between 20°C and 26°C. Thus, for hours where the indoor temperatures are beyond the comfort zone, heating or cooling power required to reach the zone is fed to models via the input variable *P*. These *P* values called hourly loads are measured for the models.

Figure 7 and 8 show hourly loads differences between models: SM vs. DM and RM vs. DM, respectively. The plus sign (+) denotes the heating loads (red-coloured crosses) while the minus (-) the cooling loads (blue-coloured dots).

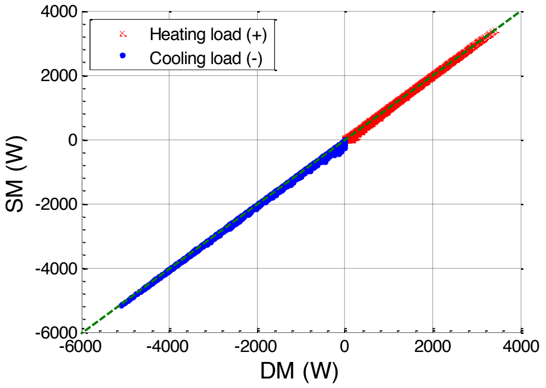

Figure 7. Loads comparison (SM vs DM)

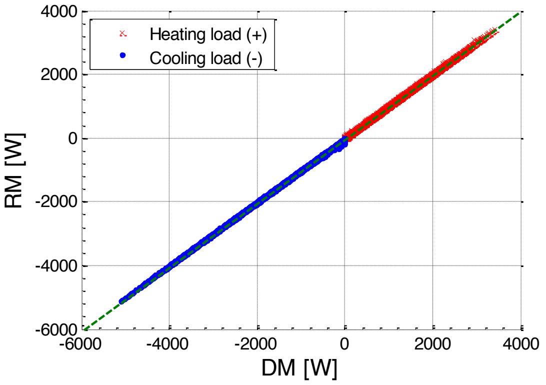

Figure 8. Loads comparison (RM vs DM)

Table 3. Annual energy and load errors of test models compared to DM

	Error in annual energy [%]		Maximum error in load [W]	
	heating	cooling	heating	cooling
SM	0.4%	3.7%	160W	290W
RM	0.3%	1.7%	120W	170W

The loads of the reference DM model are plotted for the abscissa, and the test models SM or RM are given for the ordinates. Thus, the more the loads points approach to the diagonal, the smaller errors are found between models. Results show that both test models (SM and RM) are nearly the same as the reference model DM. Table 3 details errors in load and annual energy. The final RM model shows very relevant results (less than 2%) in spite of reduction in order.

Load curves of the models are also compared, and Figure 9 traces the load curves for the time where the temperature errors were important (see Figure 5). Other than the temperature curves, almost no difference is detected. It is worth noting that load or energy consumption estimation is one of the main purposes of the urban energy simulation.

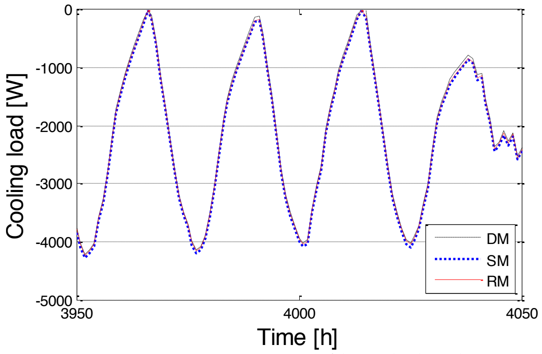

Figure 9. Comparison of hourly loads

Sensitivity analyses

Sensitivity to the mesh number is above all tested using a coarse mesh for the DM model. For this test, DM model uses half of meshes of the reference DM model. Thus, it has 4 meshes for each one-dimensional wall while the reference DM has 8.

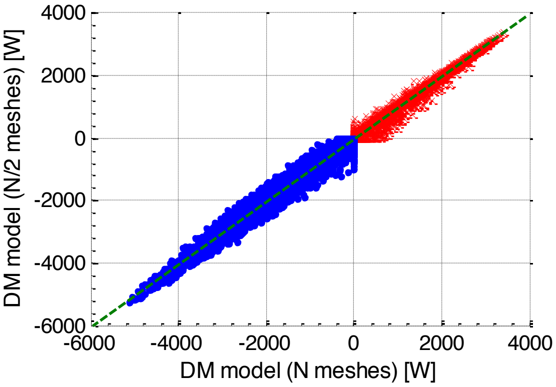

Figure 10. Test of DM model of N/2 mesh

As shown in Figure 10, the hourly loads of the test model are dispersed compared to the reference, but the annual energy estimations are almost the same. It means that a detailed model is required to accurately estimate hourly energy consumption. The proposed RM model has an advantage for urban modeling as it always uses the same order (i.e. 6) even for detailed-mesh cases.

An optimal order of the RM model is strongly dependent on building types, physical hypotheses, time steps, etc. Therefore, a 2-order RM model may be optimal for some cases. In fact, the actual test building case shows no difference between 2-order and 6-order RM models. However, as it is earlier recommended to use more than 5-order for a generic RM model, some sensitivity tests previously carried out showed discrepancy between 2- and 6-order RM models. Figure 11 is one of results of the tests, and it shows clearly the sensitivity of the RM order. It justifies the selection of 6-order.

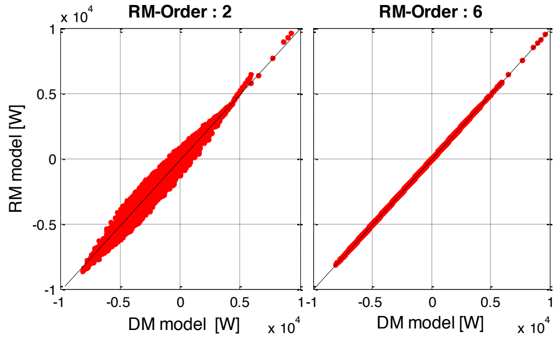

Figure 11. Example of sensitivity tests on RM order

Computing time benchmark

One of the key objectives was to ensure a reasonable computing time for city simulation tools. Therefore, a benchmark was performed between the three models presented previously, DM, SM and RM. Since the RM is derived from the SM, its total time takes into account both reduction and simulation steps. The benchmark was performed on a common computer equipped with an Intel Core i5-2520M 2.5 GHz and 4 GB RAM. The computations were performed for the DM using Dymola 2013 with the DASSL solver and for the SM and RM with Matlab and an implicit ODE solver. Therefore a straight comparison between on one hand the DM and on the other hand the SM and RM cannot be done.

The CPU times presented in the Table 4 are obtained for an annual simulation with 600 seconds time-step. The impact of the states number was also studied thanks to 3 different configurations: coarse, intermediate, and fine mesh wall, respectively 27, 50 and 80 states. The order of reduction chosen for the RM is 6.

Table 4. Computing time benchmarking

		Reduction time [s]	Simulation time [s]	Total time [s]
27 states	RM	0.01	0.73	0.74
	SM		0.84	0.84
	DM		42.27	42.27
50 states	RM	0.01	0.73	0.74
	SM		0.98	0.98
	DM		49.50	49.50
80 states	RM	0.02	0.73	0.75
	SM		1.28	1.28
	DM		69.12	69.12

From Table 4, one can notice the computing time to perform the reduction is small, around 3% of the simulation time for the RM. Its CPU time for a building is only of order of 1/100 second. The total computing time for the RM is significantly less than the simulation for the SM, between 12% to 41% depending on the discretization scheme adopted. This ratio will be more important for multi-zones buildings since the model order for the RM remains unchanged while the SM order will be multiplied by the number of zones. Therefore, simulations with the RM model necessitates almost constantly less calculation time for any mesh schemes and thermal zoning. From a computing point of view, all these observations confirm the feasibility of the direct reduction from a number of urban building models and the interest of use of the RM models instead of the SM or the DM models. Finally, to highlight the model efficiency, the total computing time of the RM is much smaller than for the DM, between 57 and 92 times faster.

CONCLUSION

As development of urban building models is one of the key parts for urban simulations, some simplified models are proposed in this paper. The physical simplifications that use average solar fluxes and linearized heat exchange coefficients lead to an oriented-independent and linear building model, which is then reduced in order using Moore's reduction technique. Finally, a 6-order reduced model is proposed for simulations of all types of buildings.

A Dymola-based detailed model (DM) ahead of simplifications is used as a reference model to test the proposed models: simplified (SM) and reduced (RM) models. Results show that the simplifications and reduction are pertinent to reproduce the thermal behavior of the DM model. Particularly, the RM model, the final building model, has errors less than 2% for annual load estimation, and its hourly load profile is almost the same as the DM model. In addition, some results of sensitivity tests recommend to use a SM model of detailed mesh to obtain 6-order RM model from it. In terms of computation time, the RM model shows its advantage compared to the other models.

This paper focuses on building envelope part, so pre-processing required to correctly calculate average solar irradiation under urban building shading is not treated. This will be a following subject with development of simulation platform.

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