Proceedings of BS2015:
14th Conference of International Building Performance Simulation Association, Hyderabad, India, Dec. 7-9, 2015.

THERMAL BUILDING MODELLING ADAPTED TO DISTRICT ENERGY SIMULATION

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ABSTRACT

This study is based on the DIMOSIM (DIstrict MOdeller and SIMulator) simulation platform for modelling and simulation of urban energy systems. In order to allow feasibility or concept studies but also the study of detailed control strategies, several levels of detail in the modelling of all necessary components have been implemented into the tool.

This paper analyses different building modelling approaches: a mono-zone RC model and a multi-zone RC model distinguishing different zones uses as various electrical consumptions, occupancy profiles thus internal heat gains, control… The level of modelling detail in space and time resolution is determined to ensure the required accuracy for the district simulation objective.

INTRODUCTION

The overall objective of the project is to provide methods and tools for optimization of complex multi-energy systems and for evaluation of district energy performance. The DIMOSIM simulation platform (Riederer et al., 2015) developed must be a good compromise between robustness, accuracy and speed.

One of the key elements in a district simulation is the building since it is the base for any calculation of heating, cooling and electric loads that energy systems are supposed to cover. Therefore, a special attention should be devoted to its modelling so as to well represent the reality and also by considering the integration in its urban environment. The concept of modelling several buildings in an urban location for studies raises complex questions.

Properties that should be integrated in the model influence the model conception. The main input parameters that are the basis of typical models are: geometric data (length, width and height), composition of the envelope (elements types, thickness, layer position, thermal resistivity, heat capacity, density…) and properties of window (surface by orientation, heat transfer coefficient, solar transmission factor…). Additionally, Heating, Ventilation and Air-Conditioning (HVAC) systems characteristics with specific thermal control setpoints and internal heat gains due to different occupations and uses of equipment should be correctly implemented. The model designed for district level must also integrate additional boundary conditions such as the environment properties (outdoor temperature, solar flux and masks…) that strongly depend on the district location and shape. On the building level, the mixing of different profiles as residential and tertiary may involve significant influences on consumptions. The modelling has thus to be appropriated to these factors. Moreover, the effects of abundance of different profiles increase the difficulties.

The model must be scientifically validated for any type of buildings regardless of the configuration. It has to be as simple as possible for computational time, and complex enough to well transcribe physical behaviours with the known properties.

STATE OF ART

The use of classic dynamic thermal simulation programs is not appropriated to simulate a lot of buildings at the same time due to their high computational time and/or large number of required parameters. That leads to use of simpler models especially because they are only one part of the district simulation tool that also includes production systems and energy networks. Grey models as those which are simplified by resistance-capacitance technique are typically used to describe transient heat transfer in buildings. They are used to represent and simplify physical properties for simulating dynamic behaviours of buildings.

Kämpf and Robinson (Kämpf et Robinson, 2006) suggest a simplified R5C2 model with one capacitor for the wall node and the other for air node, that represents one zone. A multi-zone model is obtained combining several other zones. It is the basis of building modelling for district studies.

Lauster, Teichmann et al. (Teichmann et al. and Lauster et al., 2013) compare standards models (ISO 13790 and VDI 6007) and suggest modified low order models based on the standard ones. The final model contains three capacitors, one for each specific part of the model: envelope, air and inner mass.

Berthou et al. (Berthou et al., 2014) recently published a simplified model, R6C2, assorted with a comparison between different models and a sensitivity analysis.

Reynders et al. (Reynders et al., 2014) identify similarly suitable RC models for a study bringing together several dwellings with a sensitivity analysis on input data set. The chosen model is a R6C4.

Achterbosch et al. (Achterbosch et al., 1985) define a R15C12 model with particularities like capacitors placed into air and glazing node, or two nodes with capacitor for internal elements. Intern floors and walls are distinguished.

Wang and Xu (Wang et Xu, 2005) differentiate roof and external wall with two capacitors for each. Like others, they put one capacitor on the air node and two for the internal mass.

This brief survey of the literature shows the diversity of different approaches and models that composed the grey RC-model family. Presenting a relatively low number of capacitors, they are properly suitable for district energy simulation thanks to their good compromise between accuracy and low computational time. The model described in this paper has been developed in accordance with these requirements and the adequate range of complexity.

MODEL DEVELOPMENT

In this section are described the various phenomena that have been taken into account in the developed building model.

Mathematical definition of the system

The physical behaviour of the building is mathematically represented by a system of 1st order differential equations. It can be represented by the state space approach as:

$$\dot{X} = A \cdot X + B \cdot U \tag{1}$$

where X is the state vector and U the input vector. A and B are matrices with the coefficients related to physical phenomena. This state space equation can be solved with solvers of different order such as:

- 1st order solver (Euler 1 method)
- 2nd order solver (Euler midpoint method)
- 3rd order solver (Bogacki-Shampine method)

Weather data

The data base is constituted by a main source: EnergyPlus weather data. It contains: ambient temperature, sky temperature, humidity, irradiation... This set of parameters is reconstructed from climatological measurements data from weather stations and geostationary satellites. The result is a typical year given with an hourly time step.

Solar masks processor and radiation processor

In building simulation, the shades and more generally the horizon shading positions are required to well describe solar gains in urban areas. In order to overcome this, a solar masks processor has been developed. It provides a 360° azimuthal mask at a specified point, induced by the environment: other buildings around, vegetation and land topology.

The equations used for the calculation of solar radiation are not presented here since they are basically used in the same way in other modelling and simulation environments such as TRNSYS etc. In the DIMOSIM platform, angle of solar radiation and solar orientation are given to calculate the outputs (direct and diffuse radiations) and finally are filtered with the solar masks data to obtain radiation data for each individual building.

Building model

The building model presented in this paper has to correctly define the thermal loads of buildings in an urban context. All thermal behaviours are expressed using a formal analogy with electrical circuits in order to allow fast simulations. The representation of thermal-electrical analogy, the equivalent electrical circuit, is built with resistances and capacitors.

A R7C4 mono-zone model has been developed to consider the major phenomena and components: four resistances and three capacitors to take into account the entire opaque envelope, one resistance for windows, air change rate (ACH) and thermal bridges, two resistances and one capacitor for the inner mass. The discretization of the casing type allows the distinction of external, internal or infill insulation for a correct modelling and the capacitor position is chosen to optimize accuracy of the model (nodes 1 and 3 close to external and internal surfaces and node 2 in the main part). The indoor air temperature is represented by node 4. Nodes 5 correspond to the node at the surface of the inner mass that allows injecting heat fluxes at the surface instead of in the middle of the inner mass (node 6). This configuration of RC model signifies that all components are aggregated by types with a pre-calculation of the average physical properties, i.e. walls and roof properties are gathered in the casing part, weight by their respective area.

All thermo-physical properties are known, or guessed with the type of building, and fixed in line with the usable data. The model structure is presented on Figure 1.

Thermal bridges are identified and considered in adequacy with the French thermal regulation (Réglementation Thermique 2012) which recommends taking a default value for the linear thermal transmittance (Ψ) of 0.5 $W.m^{-1}.K^{-1}$.

Regarding ACH, no pressure calculation is performed. So its influence is integrated as a scalar input coupled to the R_7 resistance. Moreover, it is tough to obtain this data precisely.

The applied heat transfer coefficients (constants) are:

- External convective heat transfer coefficient: $h_e = 15\ W.m^{-2}.K^{-1}$

- Internal convective heat transfer coefficient: $h_i = 3$ W.m^{-2}.K^{-1}
- Internal and external radiative heat transfer coefficient: $h_r = 5$ W.m^{-2}.K^{-1}

The resistances are defined as follows:

$$R_1 = \left(\frac{1}{h_e + h_r} + \frac{e_1}{\lambda_1}\right) \cdot \frac{1}{S_m} \quad (2)$$

$$R_2 = \frac{e_2}{\lambda_2 \cdot S_m} \quad (3)$$

$$R_3 = \frac{e_3}{\lambda_3 \cdot S_m} \quad (4)$$

$$R_4 = \left(\frac{1}{h_i + h_r} + \frac{e_4}{\lambda_4}\right) \cdot \frac{1}{S_m} \quad (5)$$

$$R_5 = \frac{1}{h_i + h_r} \cdot \frac{1}{2 \times S_{floors}} \quad (6)$$

$$R_6 = \frac{e_6}{\lambda_6 \cdot 2 \times S_{floors}} \quad (7)$$

$$R_7 = \frac{1}{U_w \cdot S_w + \frac{\rho_{air} C p_{air}}{3600} \cdot V_{bat} \cdot ACH + a \cdot p \cdot \Psi} \quad (8)$$

For the air node, no capacitor has been used since the time constant can be neglected. The equivalent capacitors for each node are defined as follows:

$$C_1 = (e_1 \rho_1 C p_1 + e_1 \rho_2 C p_2) \cdot S_m \quad (9)$$

$$C_2 = \left((e_2 - e_1)\rho_2 C p_2 + (e_3 - e_4)\rho_3 C p_3\right) \cdot S_m \quad (10)$$

$$C_3 = (e_4 \rho_3 C p_3 + e_4 \rho_4 C p_4) \cdot S_m \quad (11)$$

$$C_6 = (e_6 \rho_6 C p_6) \cdot 2 \times S_{floors} \quad (12)$$

The distance between nodes (i-1) and (i) is fixed. Thermal conductivity (λ_i), density (ρ_i) and specific heat capacity (Cp_i) are calculated as the weighted averages of the characteristics of different materials on the length in question.

The area of the inner mass is an important element that needs to be defined based on the available input data of the model. Typically, it is represented by the theoretical surface of all the internal floors of the building, including the half part of the ground floor that permits to model every type of building, even if it is a single-storey house. Inner walls are unknown, but the French thermal regulation states that 5% of the floor space is occupied by the walls (30 cm of thickness and 3 m of height). So the internal mass of floors is increased by a factor 1.5 to take into account a minimum viable of internal walls. Assumptions must be made about the physical properties of this inner mass: they are taken similar as the envelope properties in terms of type of material and with a total thickness of 30 cm.

The building model allows attaching files for electrical loads and internal heat gains for the occupation, lighting and all equipment. The heat gains are injected into casing, inner mass and air nodes, depending of the convective/radiative ratio of each equipment and occupant. The same distinction is made for emitters. Solar radiation is considered separately: solar gains through windows are calculated using their transmission factor and only injected into the inner envelope surface. All fluxes from internal conditions can be summarized as follows with their associated parameters:

- Fluxes from internal heat gains (equipment and/or occupants): α_{gains} (convective part) and β_{gains} (ratio of radiative part injected in casing)
- Fluxes from HVAC systems: α_{hvac} (convective part) and β_{hvac} (ratio of radiative part injected in casing)
- Fluxes from solar radiation

This mono-zone model is then extended to an upgraded model that allows the distinction of zones

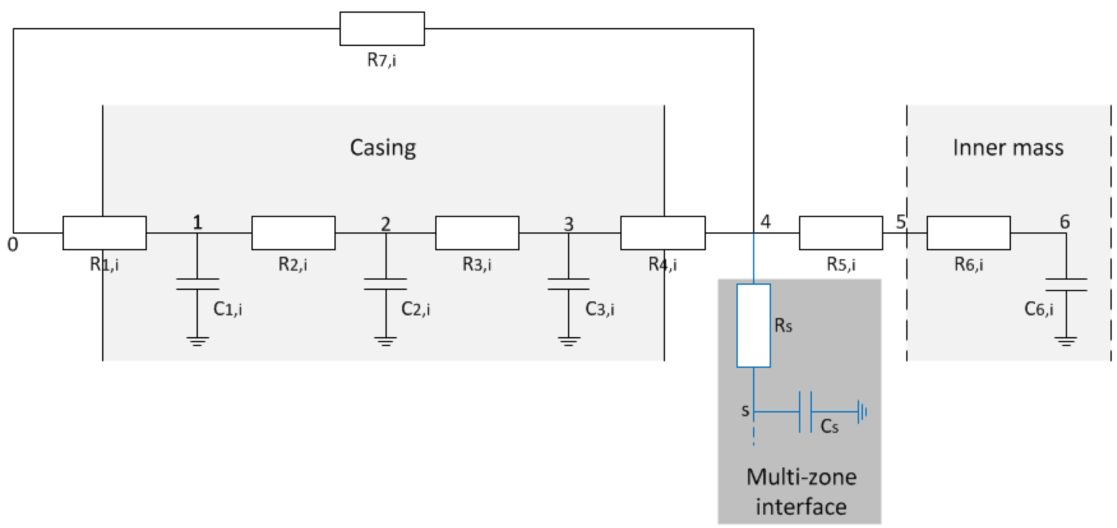

Figure 1 Thermal network of DIMOSIM mono-zone building model

$$abs\_sol \cdot S_m \cdot \Phi_{rad} + \frac{1}{R_{1,i}}\left(T_0 - T_{1,i}\right) + \frac{1}{R_{2,i}}\left(T_{2,i} - T_{1,i}\right) - C_{1,i}\frac{dT_{1,i}}{dt} = 0 \quad (13)$$

$$\frac{1}{R_{2,i}}\left(T_{1,i} - T_{2,i}\right) + \frac{1}{R_{3,i}}\left(T_{3,i} - T_{2,i}\right) - C_{2,i}\frac{dT_{2,i}}{dt} = 0 \quad (14)$$

$$\frac{1}{R_{3,i}}\left(T_{2,i} - T_{3,i}\right) + \frac{1}{R_{4,i}}\left(T_{4,i} - T_{3,i}\right) - C_{3,i}\frac{dT_{3,i}}{dt} + \beta_{gains,i}\left(1 - \alpha_{gains,i}\right) \cdot \Phi_{gains,i} + \beta_{hvac,i}\left(1 - \alpha_{hvac,i}\right) \cdot \Phi_{hvac,i} = 0 \quad (15)$$

$$\frac{1}{R_{4,i}}\left(T_{3,i} - T_{4,i}\right) + \frac{1}{R_{7,i}}\left(T_0 - T_{4,i}\right) + \frac{1}{R_s}\left(T_s - T_{4,i}\right) + \frac{1}{R_{5,i}}\left(T_{5,i} - T_{4,i}\right) + \alpha_{gains,i} \cdot \Phi_{gains,i} + \alpha_{hvac,i} \cdot \Phi_{hvac,i} = 0 \quad (16)$$

$$\frac{1}{R_{5,i}}\left(T_{4,i} - T_{5,i}\right) + \frac{1}{R_{6,i}}\left(T_{6,i} - T_{5,i}\right) + f_{trans} \cdot S_{w,i} \cdot \Phi_{rad,i} + \left(1 - \beta_{gains,i}\right)\left(1 - \alpha_{gains,i}\right) \cdot \Phi_{gains,i} + \left(1 - \beta_{hvac,i}\right)\left(1 - \alpha_{hvac,i}\right) \cdot \Phi_{hvac,i} = 0 \quad (17)$$

$$\frac{1}{R_{6,i}}\left(T_{5,i} - T_{6,i}\right) - C_{6,i}\frac{dT_{6,i}}{dt} = 0 \quad (18)$$

$$\frac{1}{R_s}\left(T_{4,i} - T_s\right) + \frac{1}{R_s}\left(T_{4,i+1} - T_s\right) - C_s\frac{dT_s}{dt} = 0 \quad (19)$$

in a building. This might be pertinent for buildings with completely different uses (residential, office, commercial etc.). In this case, a single zone is not suited enough to take into account these discrepancies.

To properly aggregate several models together, the part of the common internal mass must be separated from the inner mass system and calculation for heat transfer between the zones is added. As a result, two resistances Rs (defined in the same way as R_6) symmetrically arranged on each side of one capacitor Cs (defined in the same way as C_6) are introduced to represent this R2C1 interface, as it is represented on Figure 1. Obviously, there are modifications of the parameters but their expressions are still the same.

The main result of this modification is the modelling of the dynamic behaviour of the physical interface (node s) by the Equation (19). That leads to modify the equation system. The number of zones that can be coupled is unlimited as long as the separation of interface from the internal mass is made with the addition of the associated system of equations.

In line with Kirchoff's law at each node, the complete system of balance equations for one zone of the simple multi-zone model is Equations (13-19).

Finally, the equations system can be expressed in the following way:

$$\dot{T} = A \cdot T + B \cdot U \quad (20)$$

Hereunder are listed the main assumptions:

- 1D heat transfer
- Uniform indoor air temperature
- Constant air change rate including infiltration
- Only four orientations for facades implemented to date: South, West, North and East
- Simplified ground floor boundary conditions

Building temperature control modes

The building model temperature control can be done in two ways:

- Calculation of the necessary heat/cold flux to guarantee setpoint(s): ideal calculation. The load is calculated based on air node set point temperature.
- Calculation of the temperature with a real produced heat flux and a real controller: real calculation. There is a complete control loop with HVAC systems that allowing free-floating temperature that is necessary for free-cooling.

VALIDATION TESTS AND ANALYSIS

Criteria of validation

In order to compare models, it was chosen to follow established rules by ASHRAE guideline 140 (ASHRAE Guideline 140, 2004) which is based on BESTEST, considering power in addition of energy main criteria.

The following standard criteria are used:

- Difference step by step (states and fluxes)
- Energy relative error:

$$ERE = 100 \times \frac{\int P dt - \int P_{ref} dt}{\int P_{ref} dt} \quad (21)$$

with P the power (in W) needed to maintain the temperature between setpoints. P refers to the model results and P_{ref} to the reference results.

- Normalised root-mean-square error:

$$NRMSE = 100 \times \frac{\sqrt{\frac{\int (X - X_{ref})^2 \, dt}{\int dt}}}{\max(X_{ref}) - \min(X_{ref})} \quad (22)$$

X can be temperature (in °C) or power (in W) with X the model results and X_{ref} the reference results.

The criterion limits, based on the ASHRAE guideline limits, are presented in the Table 1. The maximum computational time accepted for one building is also included.

Table 1
Criterion limits (ASHRAE Guideline 14, 2002)

Criteria	Limit
ERE	]-10%,10 %[
NRMSE	< 10 %
Computational time	< 20 s

Validation of mono-zone model

The model validation at the building scale involves the validation of its accuracy to larger ones (e.g. district). So, to validate it and to test its robustness, a batch of annual simulations is performed on the building model. Results are then compared with TRNSYS type56 outputs that are taken as reference. The time step used is one hour and the input data set is exactly the same in the two modelling systems.

For the DIMOSIM building model, each test is carried out with the default set of simulation parameters: one year simulation with a time step of one hour, solved with the Euler midpoint method. Three models are selected for the study to highlight and confirm the choice of the model. They are composed with casing resistances and capacitors (Rm, Cm) and inner mass resistances and capacitor (Ri, Ci):

- R5-Cm3 called simple (R5C3)
- R4-Cm2-R2-Ci1 called intermediate (R6C3)
- R5-Cm3-R2-Ci1 called complex (R7C4)

Case study 1

The first stage of testing program concerns the building type which is defined in the Table 2, tested in different situations. Table 3 provides information on the different maximum powers and Figure 2 shows the results, for temperatures and fluxes, of all configurations tests with the three models.

Table 2
Principal building parameters

	Building parameters
Type:	R+5 building without a basement
Dimensions:	20 m (South and North) by 15 m (East and West) with a storey height of 3 m
Wall properties:	30 cm of concrete 10 cm of mineral wool
Roof properties:	30 cm of concrete 5 cm of mineral wool
Ground properties:	30 cm of concrete 10 cm of mineral wool 1 cm of tiling
Windows properties:	U= 3 $W.m^{-2}.K^{-1}$, solar transmission factor of 77% and proportion of 33% for each façade
Air change rate:	0.4 $vol.h^{-1}$
Control:	On/Off (20-26 °C)
Other:	no internal heat gain and no shade

At the first sight, the “complex” model is the only one that fitted and gives acceptable results for all cases, except the cold fluxes for the Stockholm location. The reason for this is that cooling is needed only during a short period for this location. Other models are clearly less effective than the complex one. It shows that only two capacitors for casing are not really sufficient as well as a complete casing design without inner mass.

Case study 2

The second case study concerns an extreme configuration: a glass building based on the geometrical configuration of the previous building. The parameters of the glass building test named case study 2 are identical to those of case study 1 except for the values of U_{window} and f_{trans} which are equal to 1.45 $W.m^{-2}.K^{-1}$ and 0.45 respectively. Moreover, the proportion of window is equal to 94% for each façade.

Figure 2 gathers results of this case study, and clearly, the inner mass is fully necessary in this case

Table 3
Maximum heating and cooling power for each test

Location	Maximum heating power (kW)		Maximum cooling power (kW)	
	Interior Insulation	Exterior Insulation	Interior Insulation	Exterior Insulation
Nice (NCE)	35.9	31.7	63.8	54.4
Stockholm (STO)	86.6	84.1	72.8	57.7
Madrid (MAD)	53.2	47.7	92.4	75.2
Glass Building	39.7		139.7	

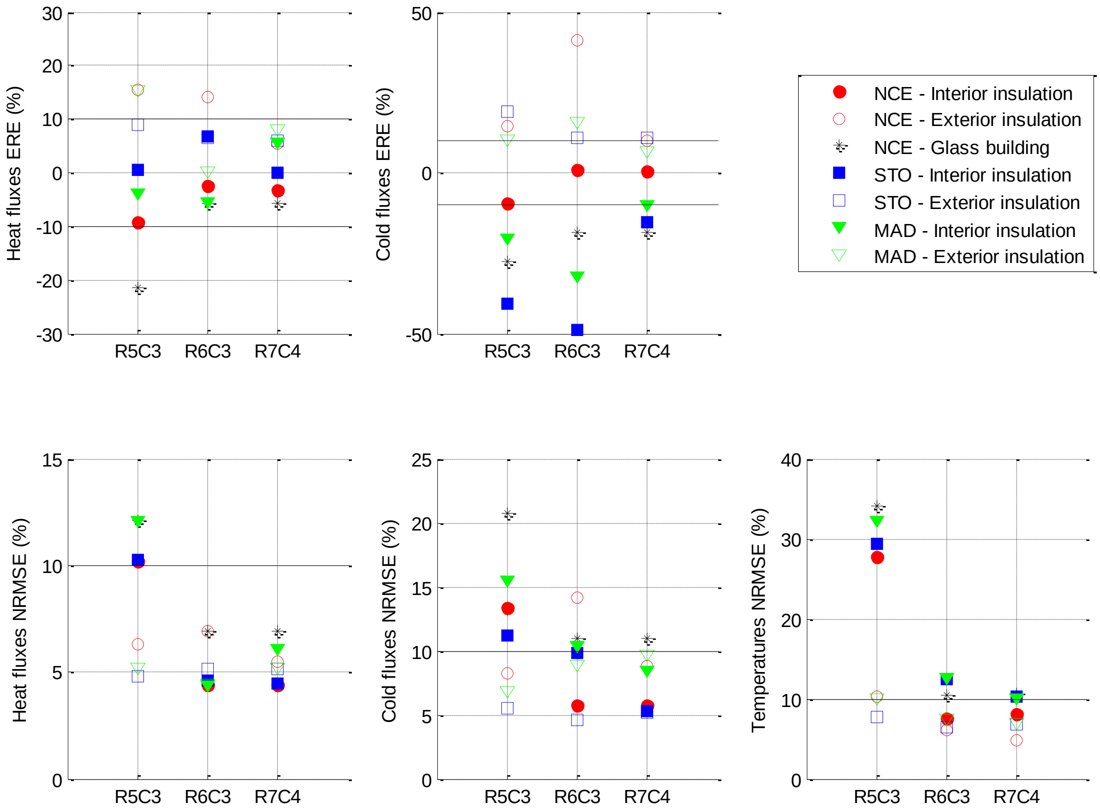

Figure 2 All results of different case studies

Solar radiations increase with the window area, the necessity to properly represent radiative heat transfer is obvious. The high amount of glazing does not allow differentiation between the two different configurations of the casing. This test configuration does not include shading, blinds in particular. However, in these extreme conditions, the results obtained are admissible even if it is advised to study separately the very particular buildings when that is possible to improve the accuracy of the obtained results.

Certainly, the complete mono-zone DIMOSIM model is validated in comparison with the well-known type56 model of TRNSYS, even with a fixed time step of one hour. Whatever the input data, it has always remained in close vicinity around the benchmark.

Validation of multi-zone model

In this part, the gain in accuracy using a multi-zone model shall be studied. Indeed, the choice of dividing building into several zones and making dynamic interfaces between them must be justified because of the loss on computational time. To understand the phenomena induced by the multiplicity of areas and their interfacing, three different approaches of multi-zone are modeled:

- Multi zones with dynamic interface
- Multi zones with adiabatic interface
- One zone with pre-processing reduction

The mono-zone pre-processing consists basically to weight all multi-zone specific characteristics by the surface of the zone envelope to obtain only one set of input data.

To carry out this part of the study, a representative example is considered, based on the case study 2, with the two first floors occupied by offices and the other four floors for residential. All physical characteristics of the building are the same than in case study 2 with interior insulation but observing fewer constraints. The studied building is located in the technology park of Sophia Antipolis, France.

Table 4
Multi-zone validation test for Nice climate

Model	Heat Flux		Cold Flux	
	ERE (%)	NRMSE (%)	ERE (%)	NRMSE (%)
Mono-zone	-18.36	4.59	-3.33	4.82
Adiabatic	-11.62	1.34	-10.76	3.06

The solar mask processor generates the horizon shading for the two affected zones induced by other buildings, vegetation and land topology.

For instance, specific internal heat gains are generated by a pre-processor and injected in each zone. The temperature setpoints are assumed to be close to reality and dependent on the type of zone.

Regarding the two zones with a dynamic interface model as reference and with all the specifications previously presented, Table 4 summarises the results of the study. Only criteria on fluxes can be given because of impossibility to compare temperature from one zone with two.

The results are inconclusive on the simplification of the full dynamic model. The adiabatic model fits well with the reference in terms of NRMSE (less than 5%) but ERE are significant (more than 10%), while the mono-zone induces, in addition, a loss of the hourly information. Finally, the choice of making a modular building model is justified. It is highly preferable to separate the building model into several zones with a dynamic interface, if they are identified, in order to reduce errors.

Time step and solver

All validation test simulations were conducted with typical time step of one hour, second order solver and take less than two seconds for a mono-zone model. Nevertheless, the two simulation options (i.e. time step and solver) influence computational time and accuracy. A linear correlation exists between computational time and time step; it is inversely proportional, see Table 5. Solver type has not a great leverage on it.

Table 5
Mono-zone DIMOSIM model computational time for case study 2

Time step (min)	Computational time (s)		
	1st order solver	2nd order solver	3rd order solver
60	1.72	1.76	1.81
30	3.46	3.54	3.59
15	6.94	7.04	7.22
5	20.86	21.14	21.68
1	103.46	105.68	107.86

It should be noted that computational time is taken for a complete building modelling. Consequently, measured simulation contains loading of weather file, radiation processor, initialisation of the model, calculation and writing of the results.

For the two-zone model, it takes 3.06 seconds to complete the simulation, always with a time step of one hour and a second order solver. It can be concluded that the part relating to the calculation of loads is about 1.3 seconds for one zone (initialisation, calculation and writing of the results).

For the accuracy, as it is expected, it increases with the lowering of the time step, see Figure 3 and 4. The solver does not make substantial difference on ERE (Outputs of the TRNSYS model reference are hardly affected by the time step) which is taken as a comparison criterion because the loads are the most important output of the building model.

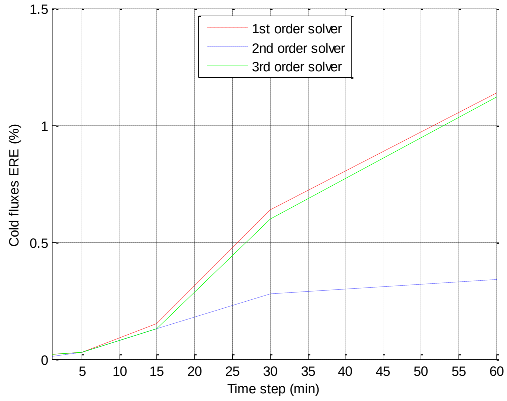

Figure 3 Mono-zone Dimosim model cold fluxes ERE for case study 2

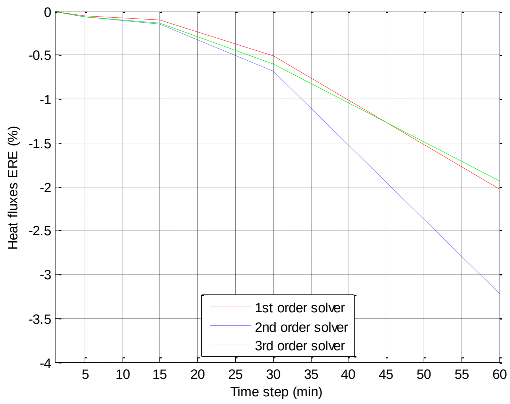

Figure 4 Mono-zone Dimosim model heat fluxes ERE for case study 2

The results converge to the reference by reducing the time step but an excellent accuracy is achieved for a 30 minutes time step with EREs lower than 1%. Therefore, time step is the major element which leads computational time and accuracy. Accordingly with the results, time step does not require to be lower than 5 minutes except for special cases as detailed energy control strategies for example.

CONCLUSION

In this paper, a new building model for the urban scale has been described and evaluated for representing accurately the building energy loads. This core technology for district energy simulation fulfils the technical specifications induced by this type of modelling approach. The suggested model has 3 capacitors for the envelope and 1 for the inner mass. It correctly describes the dynamic behaviours of major components with the generally available data at district level, but also with a complete set.

The DIMOSIM building model is appropriated for the modelling of a simple multi-zone model by coupling several mono-zones, with a dynamic interface. The multi-zone approach is a necessity to better recreate the real response of a building composed of various categories of uses.

Concerning general simulation options choices, time step affects both computational time and accuracy. The optimal range is between 5 minutes and 1 hour to satisfy them. There is no particular need for the resolution method, simple orders are sufficient.

Definitely, different strategies can give good results but this study presents a reliable and suitable model with low computational time and acceptable accuracy.

NOMENCLATURE

Latin letters

a = correction factor for thermal bridges (-)
abs_sol = solar absorption coefficient (%)
ACH = air change rate (vol.h^{-1})
C_i = equivalent capacitor of node i (J.K^{-1})
Cp_i = specific heat capacity between nodes i-1 and i (J.kg^{-1}.K^{-1})
dt = time step (s)
e_i = distance between nodes i-1 and i (m)
f_{trans} = solar transmission factor of window (%)
h_e = external convective heat transfer coefficient (W.m^{-2}.K^{-1})
h_i = internal convective heat transfer coefficient (W.m^{-2}.K^{-1})
h_r = internal and external radiative heat transfer coefficient (W.m^{-2}.K^{-1})
p = perimeter of a floor (m)
R_i = equivalent resistance between nodes i-1 and i (K.W^{-1})
S_{floors} = area of inner mass (m²)
S_m = area of the opaque envelope (without windows) (m²)
S_w = area of windows (m²)
T_i = temperature at node i (°C)
U_{window} = window heat transfer coefficient (W.m^{-2}.K^{-1})
V_{bat} = heated building volume (m^3)

Greek letters

α_{gains} = convective part of internal heat gains (%)
α_{hvac} = convective part of emitters (%)
β_{gains} = radiative part of internal heat gains injected in building envelope (%)
β_{hvac} = radiative part of emitters injected in building envelope (%)
λ_i = mean thermal conductivity between nodes i-1 and i (W.m^{-1}.K^{-1})
ρ_i = mean density of node i (kg.m^{-3})
Φ_{gains} = heat flux from internal heat gains (W.m^{-2})
Φ_{hvac} = heat flux from HVAC systems (W.m^{-2})
Φ_{rad} = heat flux from solar radiation (W.m^{-2})
Ψ = average linear thermal transmittance of thermal bridge (W.m^{-1}.K^{-1})

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