

## A MULTIZONE BUILDING MODEL FOR MATLAB/SIMULINK ENVIRONMENT

Zaki El Khoury\*, Peter Riederer\*, Nicolas Couillaud\*, Julie Simon\*\*, Marina Raguin\*\*

\*Centre Scientifique et Technique du Bâtiment, 84, Avenue Jean Jaurès, 77421 Marne la Vallée Cedex 2, France

\*\* Gaz de France - GDF, 361 Avenue Président Wilson, 93211 Saint Denis la Plaine, France

### ABSTRACT

Matlab/Simulink is known in a large number of fields as a powerful and modern simulation tool. In the field of building and HVAC simulation its use is also increasing. However, it is still believed to be a tool for small applications due to its graphical structure and not to fit well for the simulation of multizone buildings. This paper presents the development of a new multizone building model for Matlab/Simulink environment, implemented into the SIMBAD Building and HVAC Toolbox. It's general enough to model a variety of useful cases. Conforming to the Simulink philosophy, the model is modular and structured into blocks to represent the modelled phenomena. To simplify the description of the simulated building, a graphical user interface SIMBDI is developed in parallel, generating an xml building description file. This file can be read directly by the SIMBAD multizone building model. Finally, a simulation case is presented in order to compare the new model with the Trnsys multizone building model.

### INTRODUCTION

The present work is intended to complete the model library Simbad Building and HVAC toolbox (SIMBAD, 2003). This toolbox provides ready to use HVAC models and related utilities to perform dynamic simulation for buildings and HVAC plants. The development of this toolbox was motivated by the IEA annex 17 concerning virtual laboratories (Annex 17, 1993), where several research groups developed principles for the realisation virtual laboratories (Laitila, 91) and (Vaézi, 91).

To date, Simbad has several building models that are mono-zone models. When the user needs to simulate a multizone building, he had to break it down to several monozone blocks and to couple them manually, that can be a source of mistakes. Therefore, CSTB, in cooperation with GDF, started to develop a multizone building model that facilitates the modelling of multizone buildings. This new model is developed with a graphical interface 'SIMBDI' to draw the building and to enter data interactively.

Among other features, the Simbad multizone model allows the use of small timesteps (in the order of

seconds) that is crucial for control purposes, has modular structure (so it's easy to replace a block or add a new one) and is transparent to the user (an expert Simulink user can access internal variables of the model). This transparency is due to the exclusive use of Simulink blocks and Matlab language (no S-functions written with C...).

### MATLAB AND SIMULINK

#### Matlab

Matlab is a high level language dedicated to technical computing (Matlab, 2004). It is based on matrix operations: the matrix is the basic datatype for Matlab. Beside its built-in and main functionalities, Matlab has a wide variety of toolboxes developed for specialized technologies such as control systems, neural network and several other domains.

#### Simulink

Simulink is a software package for dynamic systems (Simulink, 2004), used in parallel with Matlab. It can model linear and nonlinear systems using continuous time, sampled time or a combination of both.

Simulink is very suitable for problems that have a known configuration. On the other hand, it is more difficult to deal with general purpose models, such as a complete building model. For example, it is simple to model with Simulink a time independent state space problem. It is given by:

$$\dot{X} = AX + BU \quad (1)$$

When A and B are time independent matrices, this system can be easily modeled with Simulink (cf. figure 1). The matrices A and B can either be defined directly (if known) or calculated in separate Matlab functions or scripts. Simulink will initialise those matrices before the simulation start.

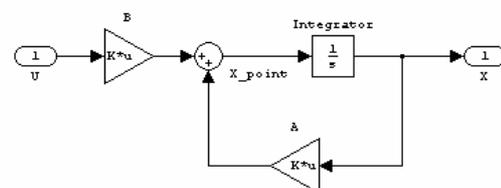


Figure 1 A state space problem with Simulink;

The problem is more complicated when these matrices are time dependent. In this case, the modeller has two possibilities:

1. Split down the problem to a set of time independent blocks;
2. Use the ‘‘S-function’’ block that allows to use other programming languages such as C and Fortran.

For this building model, we have chosen the first approach. Its implementation is described hereafter.

## MODEL COMPONENTS

A complete description of the mathematical and numerical treatments is not possible in this paper. So only a brief description of the assumptions and the mathematical formulation is given for the model components as well as a general description of the different modules of the model.

### Air zones model

Each air zone is assumed to be homogeneous in temperature. Every zone has two set points: one for cooling and one for heating. The zone air temperature can vary between these two set points.

When the air temperature is allowed to fluctuate (inbetween the two setpoints), the zone heat balance is used to predict the air temperature variation:

$$\rho_a \cdot V \cdot C p_a \cdot \dot{T}_{a,z} = P_{w,c} + P_{eq,c} + P_{g,c} + P_v + P_{cpl} \quad (2)$$

where

$$P_{w,c} = \sum_i h_{c,i} \cdot A_i \cdot (T_{s,i} - T_{a,z}) \quad (3)$$

$$P_v = \sum_i \dot{m}_{v,i} \cdot C p_a \cdot (T_{v,i} - T_{a,z}) \quad (4)$$

$$P_{cpl} = \sum_i \dot{m}_{cpl,i} \cdot C p_a \cdot (T_{a,az,i} - T_{a,z}) \quad (5)$$

In the case where the air temperature tends to be outside both set points, the heat balance is used to calculate the heating or the cooling loads related to the corresponding set point:

$$P = P_{w,c} + P_{g,c} + P_v + P_{cpl} \quad (6)$$

To be used into the multizone model, the above equations must be defined in a matricial format (for all zones of the building). For example, the final format of the equation (2), used in the model is (now equivalent to equation (1)):

$$\dot{\bar{T}}_a = A_a \bar{T}_a + B_{a,s} \bar{T}_s + B_{a,p} (\bar{P}_{eq,c} + \bar{P}_{g,c} + \bar{P}_{cpl} + \bar{P}_v) \quad (7)$$

The bar above a variable indicates a vector (not a scalar).  $A_a$ ,  $B_{a,s}$  and  $B_{a,p}$  are matrices that are defined by the building zones. This way of description is also used in the following sections.

### Walls model

Multilayer walls are modelled using constant thermo-physical properties for each layer. The heat transfer is assumed to be one-dimensional. The wall surfaces can be of two kinds: those in contact with air and those with imposed surface temperature (called ‘‘boundary’’ surfaces).

The governing equations for a wall are thus:

The heat conduction equation within each layer (j) of the wall:

$$\frac{\partial T_w}{\partial t} = \alpha_j \frac{\partial^2 T_w}{\partial x^2} \quad (8)$$

where

$$\alpha_j = \frac{k_j}{\rho_j \times C p_j} \quad (9)$$

The boundaries conditions are:

- If the first surface of the wall is on contact with air:

$$-k_1 \frac{\partial T_w}{\partial x} \Big|_{x=0} = h_{c,1} (T_{a,1} - T_w \Big|_{x=0}) + \varphi_1 \quad (10)$$

- If it has an imposed temperature:

$$T_w \Big|_{x=0} = T_{b,1}(t) \quad (11)$$

- If the second surface of the wall is on contact with air:

$$-k_n \frac{\partial T_w}{\partial x} \Big|_{x=L} = h_{c,2} (T_{a,2} - T_w \Big|_{x=L}) + \varphi_2 \quad (12)$$

- If it has an imposed temperature:

$$T_w \Big|_{x=L} = T_{b,2}(t) \quad (13)$$

For each interface between two layers (j and j+1):

$$k_j \frac{\partial T_w}{\partial x} \Big|_{x=x_j^-} = k_{j+1} \frac{\partial T_w}{\partial x} \Big|_{x=x_j^+} \quad (14)$$

This set of partial differential equations has been discretized using a combined finite difference and finite volume schemes. The discretization step for each layer is calculated by:

$$\Delta x_j^2 = \zeta \cdot \alpha_j \cdot \Delta t \quad (15)$$

The resulting final differential equation for all walls in matrix form is given by:

$$\dot{\bar{T}}_w = A_w \bar{T}_w + B_{w,a} \bar{T}_a + B_{w,\varphi} \bar{\varphi} \quad (16)$$

where  $\bar{\varphi}$  is a vector that contains absorbed incident fluxes (IR and solar radiation) on the walls surfaces:

$$\bar{\varphi} = \bar{\varphi}_{IR} + \bar{\varphi}_{solar} \quad (17)$$

### Windows model

The window model is a relatively simplified model for external windows with sun blinds. The model assumes that the window solar transmittance and absorptivity are independent from the incidence angle of the solar radiation. Hence the same solar transmittance and absorptivity are used for both beam and diffuse component of the solar radiation.

The window is divided into a clear part and a shaded part. Each part is modelled by two temperature nodes: interior node and exterior node. The window thermal inertia was neglected.

The used window parameters are:

1. Its total area;
2. Sunblind position (0 = completely open, 1 = completely closed)
3. U-values for both shaded and clear parts;
4. Solar transmittance and absorptivity for both parts.

The surface temperatures of the clear part of the window can be explicitly calculated from the air temperatures and the total radiative absorbed fluxes (IR + solar) on the two window surfaces. This can be formulated in the following matricial equation:

$$\bar{T}_{wn,cl} = B_{wn,cl,a} \bar{T}_a + B_{wn,cl,\varphi} \bar{\varphi} \quad (18)$$

A similar equation is used for the window shaded part:

$$\bar{T}_{wn,sh} = B_{wn,sh,a} \bar{T}_a + B_{wn,sh,\varphi} \bar{\varphi} \quad (19)$$

The window mean surface temperatures are calculated using the sunblind position as weighting factor. So

$$\bar{T}_{wn,s} = f \cdot \bar{T}_{wn,cl} + (1-f) \cdot \bar{T}_{wn,sh} \quad (20)$$

As before, elementary equations for individual windows are assembled into one unique matricial equation (for the following only elementary equations will be given).

### Infrared heat exchange

The infrared heat exchange model is based on the assumption that all surfaces behave as black bodies. The black body equation has been linearised. This is justified by relatively small differences between surface temperatures in buildings.

The resulting linearised radiative heat transfer coefficient is:

$$h_{rad} = 4 \times \sigma \times (T_{s,m} + 273)^3 \quad (21)$$

This coefficient was modified to include a first correction for the black surface assumption using a mean surface emissivity. The used coefficient is:

$$h_{rad} = 4 \times \varepsilon \times \sigma \times (T_{s,m} + 273)^3 \quad (22)$$

The model distinguishes between internal infrared heat exchange (internal surfaces) and the external one occurring between the external surfaces and the surrounding (composed of the sky and the surrounding objects):

The internal IR flux calculation is based on the zone mean radiant temperature concept. This is equivalent to use the following view factors:

$$f_{ij} = \frac{A_j}{A_t} \quad (23)$$

If the indexes  $i$  and  $j$  represent surfaces within the same air zone;

$$f_{ij} = 0 \text{ otherwise.} \quad (24)$$

Radiant powers from equipments and internal heat gains are treated within the internal IR exchange and are distributed to the zone surfaces according to their areas.

The external IR fluxes are calculated using the fictive sky temperature that can be estimated using correlations available in the literature (Matrin & Berdahl, 1984). The net IR flux between an external surface and the sky is:

$$\varphi = h_{rad} \times f_{sky} \times (T_{sky} - T_s) \quad (25)$$

An inclined planar surface with slope  $\theta$  beyond the horizontal plane has a sky view factor given by:

$$f_{sky} = \frac{1 + \cos(\theta)}{2} \quad (26)$$

The external IR fluxes due to surrounding objects are calculated assuming the surrounding temperature to be equal to the ambient temperature.

$$\varphi = h_{rad} \times (1 - f_{sky}) \times (T_{ext} - T_s) \quad (27)$$

## Solar radiation

The solar radiation is composed of two parts: beam and diffuse. Solar radiation measurements can have several formats. This model uses normal solar beam radiation and solar diffuse radiation.

The position of the sun in the sky is defined by the zenith  $\beta$  and the azimuth.  $\gamma$ . Both are necessary to model the beam solar radiation. It can be calculated using trigonometric formulas available in the literature for example from ASHRAE Handbook of Fundamentals (ASHRAE, 1972). From sun position, slope and azimuth of each of the building facets, the solar radiation fluxes on the building facets can be calculated.

The beam solar radiation is divided into two parts:

1. Beam solar radiation absorbed on the external surfaces of the building;
2. Beam solar radiation transmitted through windows into the building zones.

The transmitted beam radiation is distributed on the internal surfaces of the building. The building description for the model is not based on geometrical data. The user has thus to specify coefficients that determine the distribution of solar radiation to the particular internal surfaces. For example the whole beam solar radiation can be injected on the floor. The reflected part of the beam radiation is assumed to be diffuse so it is treated by the diffuse solar radiation model.

The diffuse solar radiation on an external surface of slope  $\theta$  is composed of two parts:

The first part coming from the sky:

$$\varphi_{d,sky} = \frac{1 + \cos(\theta)}{2} \times \varphi_d \quad (28)$$

The second part is the reflected solar radiation from surrounding objects:

$$\varphi_{d,gr} = \frac{1 - \cos(\theta)}{2} \times \rho \times \varphi_g \quad (29)$$

The global radiation on the horizontal plane is then calculated by:

$$\varphi_g = \varphi_d + \varphi_n \sin(\beta) \quad (30)$$

The total diffuse solar radiation (transmitted through windows to a zone + the reflect part from the beam solar radiation) is distributed to the internal surfaces using the following distribution factors (Trnsys, 2000):

$$f_{d,i} = \frac{\alpha_i A_i}{\sum_j (1 - \rho_j) A_j} \quad (31)$$

## MODEL STRUCTURE

In this section, the link between the thermal phenomena is described. The graphical and modular methodology of Simulink is used to structure the model using layers (subsystems). A full presentation of this structure will be cumbersome so we've restricted it to the most important features.

### Structure of the building model

Figure 2 shows a simplified representation to the model first layer in a top to down approach. This layer has two main blocks: Building envelope and air zones.

The block "building envelope" calculates surface temperatures for all the building surfaces (walls and windows) depending on weather data, blind positions of windows, radiant fluxes due to equipment and internal gains as well as the air temperatures for the building zones.

The block "air zones" calculates the air temperature in the zones depending on the building surface temperatures and all convective powers in each of the zones.

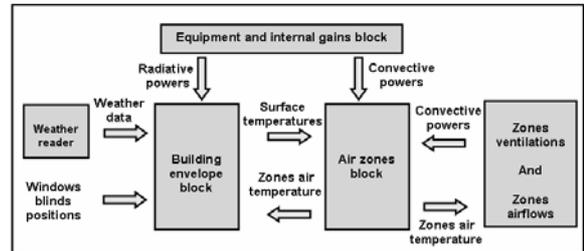


Figure 2 Simplified representation of the model structure's first layer;

Ventilations and interzone airflows are integrated in a separate block ("Zones ventilations & Zones airflows"). This allows variable values for all flow rates: a direct integration into the air zones matricial equation would make the matrices A in equation (1) time dependent which would need the calculation of A at each time step. The approach to calculate the heat fluxes due to ventilation separately allows to consider these fluxes in the matrix B for the input vector U (equation (1)).

### Structure of the block "building envelope"

The building envelope is shown in figure 3. The solar processor block calculates the absorbed solar fluxes for all surfaces (windows and walls). These fluxes are input to the windows and walls blocks. The other inputs, external and internal air temperatures and IR fluxes for all surfaces are fed back from a separate block "IR exchange" and the air zones block

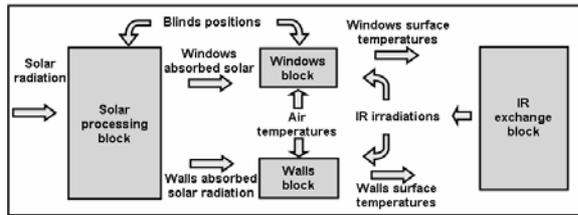


Figure 3 Simplified representation of the building envelop layer;

### Link between the different blocks

When modelling with Simulink it is convenient to avoid algebraic loops because they slow down the model and can sometimes provoke non-convergence. An algebraic loop occurs in a model when the inputs of a block depend on its own outputs through a direct feedback. The problem can thus not be solved in a straightforward way and an iteration process is needed. In the case of the windows model which is based on a steady state heat balance, an algebraic loop is created (the window surface temperatures are function of the IR fluxes on the windows surfaces which at the same depend on the windows surface temperatures). A transient model would break this loop but would lead to a model of higher order. The problem has been solved by decoupling both models by a so called “memory block” at the surface temperatures outputs for the windows model. This feeds back the value of the window surface temperature to the IR from the previous time step. Since the model is used mainly for control applications with a small time step this decoupling has a negligible impact on simulation results.

Another interesting point concerning the windows model is the way to deal with the variable geometry of the window due to the variable positions of sun blinds. As mentioned previously, variable matrices are not convenient for Simulink blocks (except for the S-function block). To avoid this difficulty the window is split into two representative parts: a clear part and a shaded part of 1m<sup>2</sup> each. The resultant surface temperature of the whole window is then determined by equation (20). In this way the variable configuration problem has been split down into two invariable configuration problems.

### BUILDING DESCRIPTION INTERFACES

The Simulink model as described in the previous sections demands two kinds of parameters:

- General building description data:  
An independent graphical user interface “Simbdi” (Simbad Building Description Interface) has been developed in Visual Basic environment. This interface allows the user to draw the building floor by floor in 2 dimensions.

The interface automatically generates adjacency between zones of successive floors. The user can define its own wall types or uses those from the interface library. The interface finally generates an xml file.

This xml building description file could also be written manually but becomes cumbersome when the building has several air zones.

This file is read in the Simulink model mask, translated to a text file by an automatic translator and finally used to define the matrix parameters necessary for the Simulink model.

- Project and system related data

Project and system related parameters are to be specified by the user in a second interface, the block mask of the Simulink building model block. The parameters to be specified are eg. The geographical location of the building, ground reflectance, choices of model calculation modes (eg. Walls models) as well as interzonal air flow parameters.

This double approach for the interface has been chosen in order to separate general building characteristics that do not depend on geographical location or other project related parameters. The building, once described, can then be transferred to other locations without the need for modification.

### MODEL VALIDATION

In a first step, the model has been confronted to a series of simple (but important) validation cases: for example, the simulated building was set in an ambiance that has a given constant external temperature without solar radiation (the sky temperature was set equal to the external one). The steady state air temperature of the building zones was found equal to the outside one.

In further steps the new model is planned to be validated on other cases such as BESTEST.

In this paper, first comparisons with TRNSYS “Type 56” multizone model (Trnsys, 2000) have been carried out. This series of tests is not completely finished yet, but there was good agreement for all tested cases. An exemplary test is shown in the following section. Validation work is still ongoing.

### **Some differences between Trnsys type 56 and Simbad**

It’s interesting to mention some main differences between Trnsys “Type 56” and the Simbad multizone model:

1. Trnsys uses transfer function to simulate walls heat conduction, while Simbad uses a combined finite difference/finite volume scheme.

2. Trnsys uses the so called “star temperature” (Seem et al., 1987) to simulate IR exchange for internal surfaces, while Simbad uses the common mean radiant temperature.
3. Trnsys uses a detailed model for windows that reads output data from the WINDOW 4.1 program (WINDOW4.1, 1994). Trnsys takes thus into account the variation of solar transmittance and absorptance with the incidence angle and uses hemispherical transmittance and absorptance for the diffuse radiation. Simbad windows model is rather simple and uses the same constant solar transmittance and absorptance for both beam and diffuse radiation.

- 4- Absolute humidity;
- 5- Wind velocity (not used);
- 6- Wind direction (not used).

Table 1 pane properties of the window;

PANE PROPERTY	VALUE
Thickness	4.0 mm
Thermal conductance	225 W/m <sup>2</sup> K
Normal solar transmittance	0.83
Normal solar absorptance	0.095
Hemispherical solar transmittance	0.749
Hemispherical solar absorptance	0.106

### The simulated case

One comparison case is presented here. This case consists of a building (cf. figure 4) composed of two zones. Ventilations, airflows between zones, equipments power, and internal gains are set to zero.

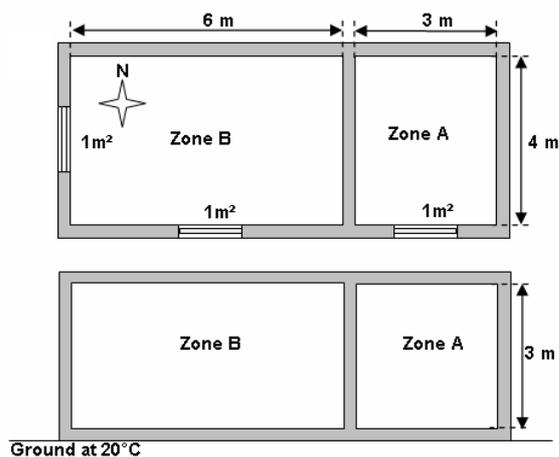


Figure 4 Simulated building - plan and section view;

The building walls are identical to those used in the BESTEST cases (Judkoff & Neymark, 1995). A heavyweight construction is used for exterior wall, floor and roof. The internal wall is taken from the case 960.

The 3 windows are similar and are composed of a single glass panel without frame and spacers. The glass pane has the properties given in table 1 below. The hemispherical values were used for the Simbad model.

A weather data file for Madison from Trnsys package was used. This file contains the following weather data:

- 1- Normal direct solar radiation;
- 2- Total solar radiation on horizontal plane;
- 3- Outside air temperature;

A slight modification was needed on the Simbad model to accept the solar radiation of the Trnsys format. The simulation was run for one summer week. Figures 5 & 6 show air temperature and solar radiation for this week.

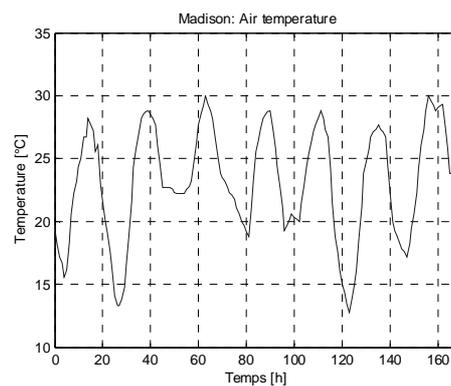


Figure 5 Air temperature during the simulated week;

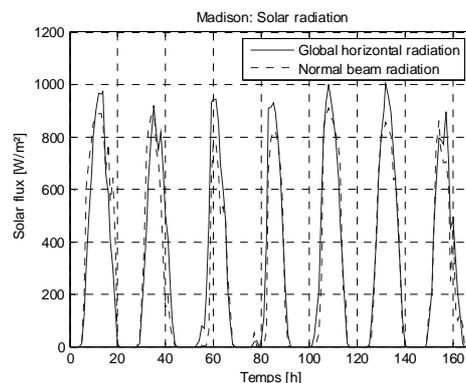


Figure 6 Solar radiation for the simulated week;

### Simulation results

The air temperature is used to compare the outputs of the two simulation tools. As the window model in

Trnsys is more detailed than the Simbad one regarding radiation phenomena, two cases are presented here:

- 1- Case with solar radiation (cf. figures 7 & 8);
- 2- Case without solar radiation (cf. figures 9 & 10).

Table 2 shows the maximum and the mean value of the absolute difference between Trnsys and Simbad results. As we can expect the difference between the two simulation tools is higher when there's solar radiation since the window model is more detailed into Trnsys but they stay close to each other.

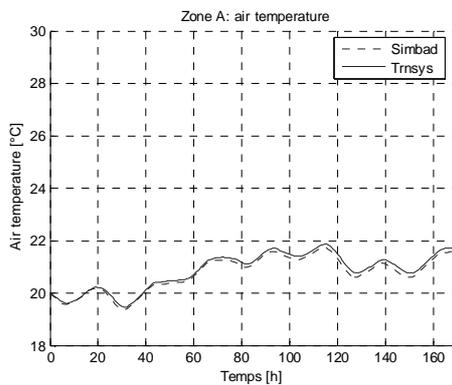


Figure 7 Simbad versus Trnsys – air temperature for Zone A (case without solar radiation);

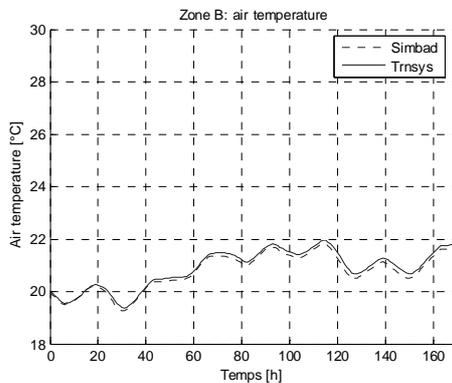


Figure 8 Simbad versus Trnsys – air temperature for Zone B (case without solar radiation);

Table 2 Mean and maximum values of the absolute difference between Trnsys and Simbad results;

ZONE	SOLAR RADIATION	MEAN VALUE	MAX. VALUE
A	off	0.1°C	0.2 °C
B	off	0.11	0.22
A	on	0.23	0.47
B	on	0.26	0.58

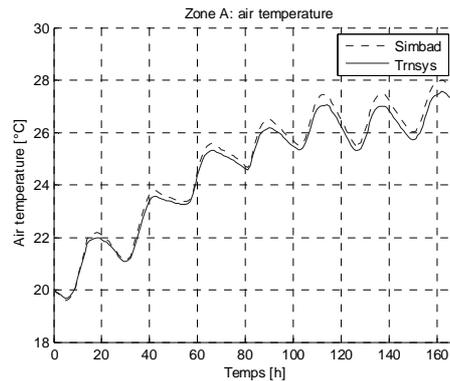


Figure 9 Simbad versus Trnsys – air temperature for Zone A (case with solar radiation);

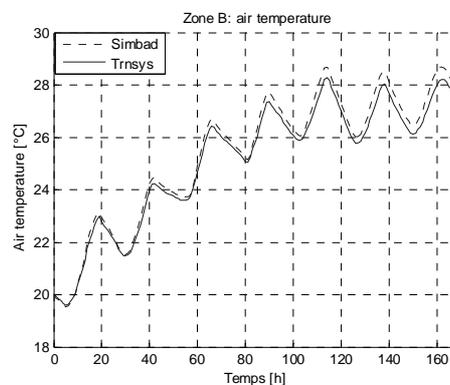


Figure 10 Simbad versus Trnsys – air temperature for Zone B (case with solar radiation);

## CONCLUSION

This paper has shown a new multizone building model for Simulink. The originality of this model, the integration of a multizone building case in the graphical Simulink environment has been explained in a first step. The main equations as well as the structure of the new model in Simulink environment have been described.

A brief presentation of the related graphical interface for the building description has been given. In a last step, the paper presents first validation results, a comparison with Trnsys simulations. The results are very promising, but further validations are in progress in order to ensure the validity of the model.

Due to the graphical Simulink environment, the model can be linked to other blocks. A large number of HVAC systems can thus be simulated (eg. Addition of air flow pressure networks for VAV or ventilation systems).

Due to the small time steps that can be used in Simulink and the developed model, the new model is very suitable for the study and development of control algorithms.

## NOMENCLATURE

### **Romaine letters**

A	area (m <sup>2</sup> ).
A	matrix coefficient of the state vector.
B	matrix coefficient of the inputs vector.
C <sub>p</sub>	heat capacity (J/kg.K).
f	matrix of blind positions.
f	view factor between surfaces.
f	beam solar radiation distribution factor (-).
h	linearized heat transfer coefficient (W/m <sup>2</sup> K).
k	thermal conductivity (W/mK).
L	total thickness of the wall (m).
$\dot{m}$	mass flow rate (kg/s).
P	cooling or heating load (W).
P	gain, power (W).
t	time (s).
T	temperature (°C).
U	inputs vector.
V	zone volume (m <sup>3</sup> ).
x	abscise belong the wall thickness (m).
X	state vector.

### **Greek letters**

$\alpha$	thermal diffusivity (m <sup>2</sup> s <sup>-1</sup> ).
$\alpha$	solar absorbtivity (-).
$\beta$	zenith angle of the sun (rad).
$\gamma$	azimuth angle of the sun (rad).
$\Delta t$	Timestep (s).
$\Delta x$	space step (m).
$\varepsilon$	mean IR emissivity for the building surfaces.
$\theta$	slope with respect to the horizontal plane (rad).
$\xi$	stability safety factor for wall discretization.
$\rho$	density (kg/m <sup>3</sup> ).
$\rho$	reflectivity (-).
$\sigma$	Stefan-Boltzman constant for black body = $5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$ .
$\varphi$	heat flux (W/m <sup>2</sup> ).

### **Indices**

a	air
az	adjacent zone
b	boundary
c	convective, convection
cl	clear part (for the window)
cpl	coupling between zones
d	diffuse horizontal solar radiation
eq	equipments
ext	exterior (air)
g	gains
g	global horizontal solar radiation
gr	ground
i	zone, surface, ventilation, coupling number
IR	infrared radiation
j	layer, surface number
m	mean
n	total number of layers in the wall
n	normal beam solar radiation

p	power
s	surface
rad	radiative
sh	shaded part (for the window)
sky	relative to the sky
solar	solar radiation
t	total
v	ventilation
w	wall
wn	window
z	zone
$\varphi$	flux
1	first face of the wall
2	second face of the wall

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