The Benchmark of a New SIMULINK Library for Thermal Dynamic Simulation of Buildings

Jean Pierre Campana – University of Bologna - jeanpierre.campana2@unibo.it
Mara Magni – University of Bologna – mara.magni2@unibo.it
Matteo Dongellini – University of Bologna – matteo.dongellini@unibo.it
Gian Luca Morini – University of Bologna – gianluca.morini3@unibo.it

Abstract

Nowadays, the complexity of the interactions between thermal plants and buildings for NZEB buildings is increasing. The decrease in primary energy consumption by NZEB is generally pursued by maximizing the use of renewable energy which gives a discontinuous contribution during the season; it becomes important to study in detail the dynamic interactions between the building and the adopted HVAC systems, by taking into account unsteady state behaviour of walls, roofs, windows, and so on. This kind of analysis can be carried out with conventional dynamic simulation software (i.e. TRNSYS, ESP-r, Energy Plus, DesignBuilder). It has been demonstrated that a detailed analysis of controlled HVAC systems can also be carried out by using SIMULINK, and in the past open block libraries made in SIMULINK were proposed for HVAC system analysis, like in the case of the CARNOT blockset. However, besides its completeness, the building modelling is still considered a weak point of CARNOT due to its limited flexibility. For this reason, a new specific library named ALMABuild based on SIMULINK blocks for the dynamic modelling of a building is presented in this paper with the aim to integrate and improve the blocks already available in CARNOT.

In ALMABuild, the modelling of a building with SIMULINK is driven by means of a series of Graphical User Interfaces (GUI). In this paper a benchmark of ALMABuild is shown by using TRNSYS as a reference. The comparison evidenced a good agreement between the two methods. However, differences were present each time that the procedure indicated by the European Standard EN ISO 13790:2008 (and integrally followed by ALMABuild) was not in agreement with the procedure followed by TRNSYS (based on American standards).

1. Introduction

During the last two decades, the awareness of the public opinion on the environmental costs of the overall energy consumption has strongly increased. Since the building sector represents one of the most important energy consumers (up to 40 % of the European Union final energy demand), the European Commission issued a series of Directives to improve building energy efficiency and the exploitation of renewable energy sources (European Commission, 2010). As a consequence, the current legislation of most Member States imposes upper limits to the annual energy consumption of HVAC systems coupled to buildings. During the design phase, the evaluation of the predicted building energy needs is carried out by means of simulation models, according to various techniques: some of them are based on the knowledge and resolution of the thermal balance equations of the building, while others are based on the monitoring of data inside the thermal zones (Foucquier et al., 2013).

SIMULINK has been demonstrated in the past decade, to be an efficient framework to develop Lumped Parameters Whole Room models (LPWR), which evaluate the behaviour of a thermal zone by lumping the whole zone, and Lumped Parameter Construction Element models (LPCE) that simulate each building high mass element (i.e. walls, roofs, and so on) by means of RC models (Oliveira Panao et al., 2016; Morini and Piva, 2007 and 2008). More specifically, Fraisse et al. (2002) and Hudson et al. (1999) developed RC models of high mass elements in SIMULINK in order to study the minimum number of capacities needed for the accurate evaluation of the surface temperature of both sides of a wall,

Part of
Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2018. Building simulation applications BSA 2017. bu,press.
https://doi.org/10.13124/9788860461360

whilst Riederer et al. (2000) and de Wit (1988) showed how a room and a multi-zone building model can be obtained in SIMULINK.

In 2000, the Solar Institute Juelich (Wemhöner et al., 2000) proposed an open library of SIMULINK blocks for the modelling of solar plants. This library is commercially available since 1999 with the name of CARNOT blockset (Conventional And Renewable eNergy Optimization Toolbox). The development of CARNOT was started with the financial support of Viessmann GmbH, a German manufacturer and market leader for house heating equipment, who needed models of conventional and renewable components of house heating systems to accelerate the design process of the control systems. However, the success of CARNOT has been scarce, as proved by the actual limited diffusion of this library (limited to German countries). Nowadays, under the impulse of Viessmann, CARNOT contains a set of blocks representative of the most important HVAC devices but only simplified blocks for the building modelling are available, this aspect is still an open problem for the diffusion of the CARNOT blockset. One of the main advantages to operate in a MATLAB/SIMULINK framework is that this platform is very well known and spread both in academic and professional environments and it becomes easy for the users to approach it in order to model new HVAC devices and building elements. In this way each user can easily add new components to the library both by designing directly new graphical Simulink models and by using C-, Fortran- or MATLAB M-scripting languages.

Since the authors are convinced of the huge potential of this approach and are aware that the improvement of the building modelling is one of the most important constraints to be removed in order to enhance the spreading of CARNOT, in this paper a SIMULINK library named ALMABuild, useful for the realization of LPCE models, is presented. ALMABuild allows to describe and to evaluate the heat transfer mechanisms in a thermal zone by coupling a 3R4C model to each massive building element.

Each elementary building element is modelled through customized SIMULINK blocks, by means of which the energy conservation equation is solved according to a lumped formulation procedure. Since this approach is the same proposed by CARNOT, the complete compatibility of the new ALMABuild library blockset with CARNOT has been guaranteed by adopting the same structure of the bus connection among blocks. In this way ALMABuild can be used as an integration of CARNOT blockset in a similar way in which TRNBuild is used in TRNSYS in order to improve the native building modelling.

2. The ALMABuild Library

ALMABuild contains all the elementary blocks needed for a complete description of the heat transfer mechanisms in a building. The ALMABuild blockset is composed by three different kinds of blocks: (i) Building Massive Element blocks (BME) that contain the physical model of each massive opaque building component (walls, floors, roofs, etc.); (ii) Building Clear Components (BCC) that contain the physical model of low mass clear components of the building envelope (windows, etc.) and (iii) Building Thermal Balance (BTB) blocks that enable to couple BME and BCC blocks in order to solve the thermal balance of the thermal zone.

The BME blocks are based on a fourth order RC model in which three thermal resistances and four capacities (3R4C) are used to calculate the dynamic trend of temperature and heat flux across the building element.

On the contrary, BCC blocks contain a 1R2C model for the dynamic analysis of light and clear building elements. BTB blocks are based on a two-star model for the calculation of the air and the radiative temperature associated to a single thermal zone defined by a series of BME and BCC blocks. One BTB block is used for each thermal zone in order to put together all the BME and BCC blocks related to the zone. Since each building element (i.e. walls, roofs, floors, ceilings, windows) differ in exposition (internal, external, or on the ground), slope (vertical, inclined, or horizontal) and optical behaviour (clear or opaque), in order to facilitate the creation of a complete model for each element, ALMABuild uses a series of Graphical User Interfaces (GUIs) by means of which all the properties of each building element and each thermal zone can be defined. In this way a

complete set of BME, BCC, and BTB are created automatically without the use of the SIMULINK graphical desktop. GUIs facilitate the use of ALMABuild also for users without experience in the use of SIMULINK.
Once all the data requested by the GUIs are set, each thermal zone will be associated to a BTB block and the connections between the different BTB blocks are automatically created in SIMULINK.
In this way, the creation of a building model in ALMABuild is faster than in CARNOT and, most importantly, the risk of making a mistake during the creation of the building model in SIMULINK is strongly reduced.

3. ALMABuild vs TRNSYS

With the aim to demonstrate the accuracy of the numerical results by using ALMABuild for the dynamic modelling of a building, a comparison between ALMABuild and TRNSYS was carried out. In order to test each single heat transfer mechanism, a series of numerical runs have been done to decouple a single mechanism from the other ones. The first test considers a single thermal zone delimited by opaque components only. In this way, it is possible to test how ALMABuild is able to reproduce the expected dynamic behaviour of the opaque walls linked to: (i) the heat transfer due to the inner and outdoor temperature difference (ii) the external radiative heat transfer with the sky, (iii) the heat transfer linked to the absorption of solar radiation on the wall external surface. The second test is related to the thermal zone behaviour in the presence of a clear component (vertical window). In this way it is possible to check if ALMABuild is capable of predicting accurately the effect on the zone's thermal balance due to the entrance of solar radiation into the room. In all the numerical runs shown in this paper, the external conditions, are evaluated using METEONORM climatic data of Bologna (Italy). No internal gains or HVAC systems are considered.

3.1 Room with Opaque Walls Only

3.1.1 Heat transfer due to inner and outlet temperature difference

In this first numerical run a thermal zone delimited by opaque walls only is considered. The internal volume of the room is 210 m^3, the room has a rectangular shape and is closed with 4 external vertical walls, two of them of 21 m^2 (East and West) and the other two of 30 m^2 (North and South), an adiabatic floor and a horizontal roof of 70 m^2. The main characteristics of the layers of the external walls and roof are described in Table 1 and Table 2.

Table 1 – Thermophysical characteristics of the main wall layers (from the internal to the external side)

Layer	s [cm]	λ [W m^{-1} K^{-1}]	ρ [kg m^{-3}]	cp [J kg^{-1} K^{-1}]
Plaster	1.5	0.9	1800	910
Bricks	25	0.287	800	840
Insulation	6	0.039	30	1200
Plaster	1.5	0.9	1800	910

Table 2 – Thermophysical characteristics of the main roof layers (from the internal to the external side)

Layer	s [cm]	λ [W m^{-1} K^{-1}]	ϱ [kg m^{-3}]	cp [J kg^{-1} K^{-1}]
Ceiling	24	0.65	800	840
Screed	4	1.35	2000	1000
Insulation	3	0.039	30	1200

Solar absorbance and infrared emissivity of all components are set to zero. In this way, the only heat flux considered across the opaque walls is due to the temperature difference between the inside and the outside. The numerical simulation period started on January 1 and lasted for the full month of January. In order to have more readable figures, only the result of the last two simulated days were plotted.
It is important to highlight that for each opaque element ALMABuild uses an RC-model (3R4C); on the contrary TRNSYS uses the Mitalas transfer function

method (Mitalas et al., 1972) for the modelling of the dynamic heat transfer across opaque walls.

Fig. 1 shows a comparison between the room air temperature calculated for the room described before by ALMABuild and TRNSYS models.

It can be noticed that both ALMABuild and TRNSYS give the same value of the room air temperature with an average difference less than 0.01°C; in addition, the phase lag between internal air temperature and the external one is the same, be it with TRNSYS or ALMABuild. However, Fig. 1 evidences a slight average time delay of the order of 20 minutes, between the two temperature trends. However, these results show that the 3R4C model and Mitalas transfer function method are in good agreement, and that the total thermal inertia of the room is correctly accounted for by ALMABuild.

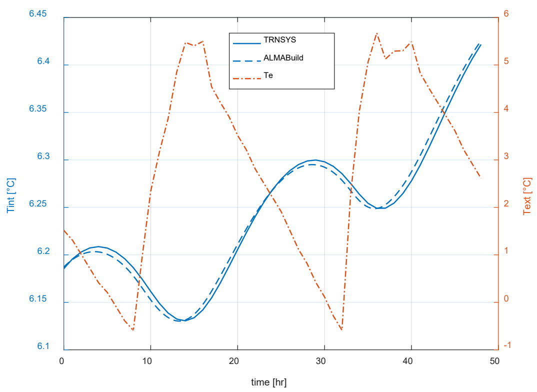

Fig. 1 – Comparison of the room air temperature (T_{int}) obtained with ALMABuild (dashed line) and TRNSYS (solid line)

3.1.2 Radiative heat exchange with the sky

The infrared emissivity coefficient of all the opaque walls was set to 0.9, in order to verify the effect of the radiative heat exchange between the external surface of the opaque walls and the sky.

ALMABuild calculates the radiative heat transfer in agreement with UNI EN 13790: 2008 and UNI TS 11300-1: 2014; the sky temperature is obtained as a function of the external vapour pressure following the method proposed by UNI TS 11300-1. On the contrary, TRNSYS uses as sky temperature with hourly values as given by the METEONORM database.

The comparison of the radiative heat transfer (Q_{sky}) calculated by ALMABuild and TRNSYS is shown in Fig. 2. It is evident that the values of Q_{sky} calculated by ALMABuild and TRNSYS are of the same order of magnitude but their trend is very different. This is mainly due to the fact that the effective sky temperature, T_{sky}, used in the two models, is not the same, as evidenced in Fig. 2.

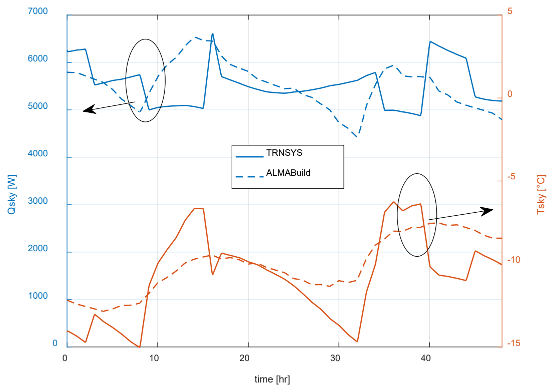

Fig. 2 – Comparison of the radiative heat exchange with the sky (left side, upper lines) and effective temperature of sky (right side, lower lines) obtained with ALMABuild (dashed line) and TRNSYS (solid line)

In order to check if the difference in terms of Q_{sky} is mainly due to the different way to calculate T_{sky}, the same evaluation has been repeated by imposing in both ALMABuild and TRNSYS, the same trend of T_{sky}. The values of Q_{sky}, obtained by assuming the same value of T_{sky} are shown in Fig. 3. It is evident that a systematic difference between the predictions of ALMABuild and TRNSYS still remains; however, the maximum deviation in the evaluation of Q_{sky} is reduced from 19 %, using different T_{sky} values, down to 5 %, using the same trend of T_{sky}.

The 5 % difference evidenced in Fig. 3 is due to the use of a different Q_{sky} formulation in TRNSYS and in ALMABuild. In fact, TRNSYS takes into account that the radiative heat transfer between the external surface of a building and the sky is in reality a three-body radiative problem in which also the presence of the ground surface must be taken into account. On the contrary, ALMABuild, according to the European Standard UNI EN 13790: 2008 ignores the presence of the ground.

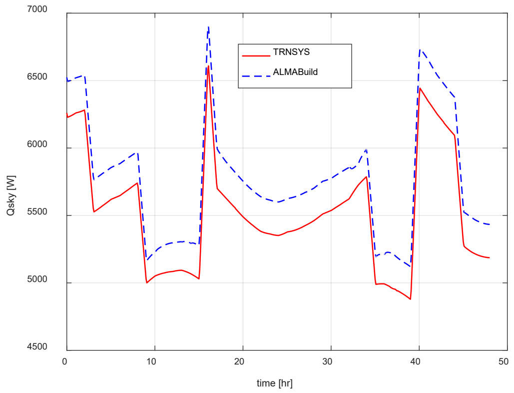

Fig. 3 – Comparison of the radiative heat exchange with the sky obtained with ALMABuild and TRNSYS, using the same T_{sky}

Fig. 4 puts in evidence the effect of the difference evidenced by Q_{sky} on the room air temperature. In this specific case, the different values of T_{sky} lead to a different evaluation of the room air temperature of 0.5 °C. This difference goes down to 0.2 °C if the value of T_{sky} is the same.

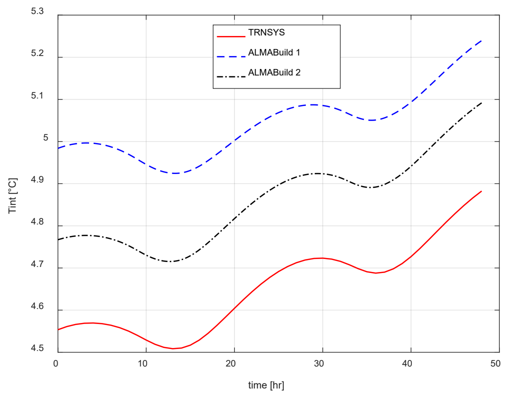

Fig. 4 – Comparison of the room air temperature considering radiative heat exchange, with the same T_{sky} used in TRNSYS, (ALMABuild 2) and with a different T_{sky}, ALMABuild 1

3.1.3 Solar heat gain

In this section, the radiative heat exchange with the sky of the external walls is once again disabled (by setting the infrared emissivity coefficient to zero), whilst solar heat gain of the opaque walls is enabled by setting thesolar absorbance coefficient to 0.3.

In this way, starting from the same climatic data, it is possible to compare the calculation of the solar radiation that strikes a surface with a defined orientation and slope made by TRNSYS and ALMABuild, and its effect on the room air temperature.

Fig. 5 shows the solar radiation that strikes a vertical surface exposed to South. From Fig. 5, it is clear that the two models give the same results since the calculation of the solar radiation is based on the same solar model due to Perez (Perez et al., 1990).

Fig. 6 shows the difference in terms of room air temperature between the values obtained with TRNSYS and ALMABuild. It is evident that the trend is similar to the trend shown in Fig. 1; this means that TRNSYS and ALMABuild count the contribution of the solar gains exactly in the same way.

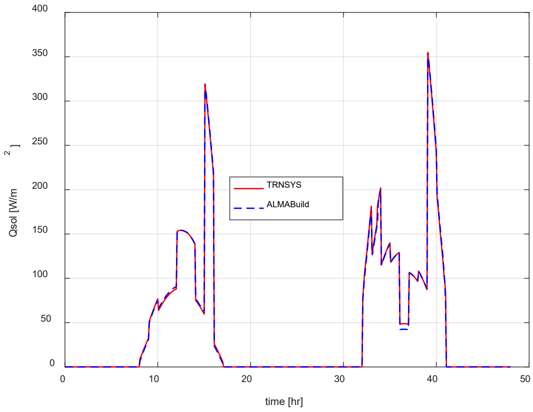

Fig. 5 – Comparison of the incident solar radiation, per surface unit, on a vertical South wall, obtained with TRNSYS and ALMABuild

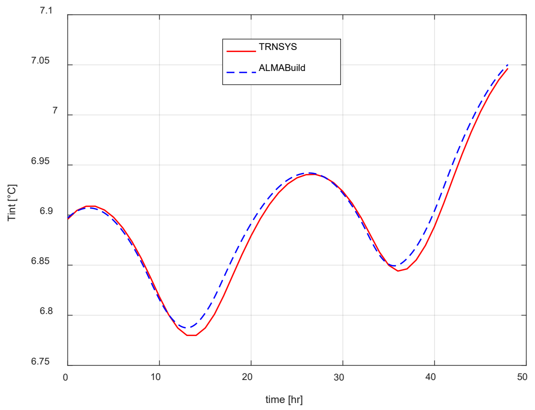

Fig. 6 – Comparison of the room air temperature, considering solar heat gains, with TRNSYS and ALMABuild

3.1.4 The overall simulation

After analysing the differences between TRNSYS and ALMABuild in terms of each single thermal flux, all the main heat transfer mechanisms are simultaneously taken into consideration. The infrared emissivity and solar absorbance coefficient of all the external opaque surfaces are set to 0.9 and 0.3 respectively.

In this way, it is possible to see if there is any interference between the different mechanisms and

which is the overall effect on the room air temperature.
Fig. 7 shows the room air temperature trend obtained by using TRNSYS and ALMABuild. In this comparison the evaluation of T_{sky} in ALMABuild is done according to UNI TS 11300-1.
It is evident from Fig. 7 that the trends of the room air temperature obtained with TRNSYS and ALMABuild have the same phase lag but a systematic shift of 0.3 °C which is less than the greatest deviation noticed when only radiative heat exchange, with a different evaluation of T_{sky}, was considered (see Fig. 4).

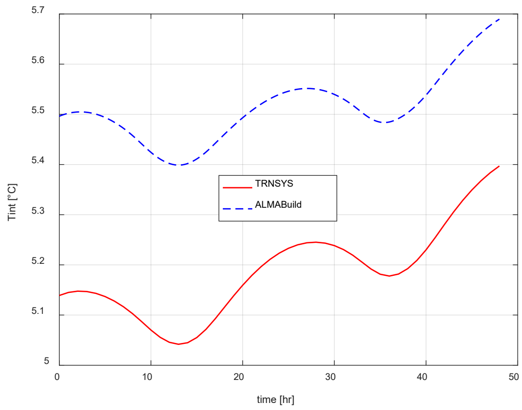

Fig. 7 – Comparison of the room air temperature, considering all the thermal fluxes on the opaque component, with TRNSYS and ALMABuild

This means that the combination of different heat fluxes across the building elements leads to a compensation of the single deviation between the two considered models.
In summary the results shown in Fig.s 1–7 can be considered a positive benchmark for ALMABuild when only opaque building elements are present in a thermal zone.

3.2 Room with a Window

In this section a clear component (windows) is added to the previous thermal zone.
The room is the same of the previous simulations but there is a window inserted in the South wall, the properties of which are shown in Table 3. The goal of the following simulation is to compare the clear building component model used by TRNSYS with the BCC block of ALMABuild. Incident solar radiation in a window surface can be absorbed or reflected by the frame or by the glass, and transmitted through the glass. In order to define a window, reflection, transmission, and absorbance coefficient have to be known, since they are functions of the angle of incidence of the solar radiation. Moreover, not only the window model is more complex than the model for an opaque component, but also the introduction of a clear component in a thermal zone makes the thermal balance model of the zone more complex. In fact the incoming solar radiation transmitted by the window, has to be distributed among the internal surfaces of the opaque components that bind the thermal zone.
The TRNSYS model calculates the global heat flux through the window glazing, evaluating the pane temperature distribution with an iterative procedure. The distribution of the incoming solar radiation is carried out evaluating the short wave radiation distribution factor (Klein et al., 2010) defined by the user.

Table 3 – Window properties

Property	Value	Unit
Surface	2	m^2
Frame Fraction	20	%
Number of glass	2	-
Thermal Transmittance	1.4	$W\ m^{-2}K^{-1}$
Solar Transmittance	0.589	-

On the contrary, in ALMABuild windows are described using a 1R2C model, so that the temperature of the internal and external side of the window is calculated, whilst the short wave radiation distribution factor is automatically evaluated as a function of the thermal zone geometry.
The external conditions considered are the same for ALMABuild and TRNSYS models, but with a different evaluation of T_{sky}.
Fig. 8 shows the global solar radiation incoming in the thermal zone, that is the solar radiation transmitted by the window, evaluated by using TRNSYS and ALMABuild. It can be noticed that the two profiles are very similar with a maximum absolute deviation of about 10 W/m^2. The room temperature

evaluated by TRNSYS and ALMABuild are compared in Fig. 9.

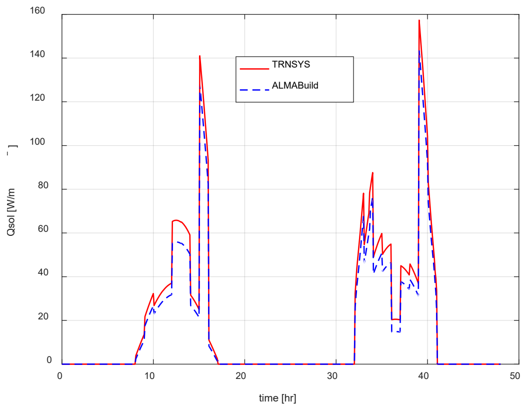

Fig.8 – Comparison of the solar radiation entering the thermal area from the window, with ALMABuild and TRNSYS

From Fig. 9, we can notice that the maximum deviation between these two profiles is around 0.3 °C, which is the same value reached by considering a room with only opaque elements.

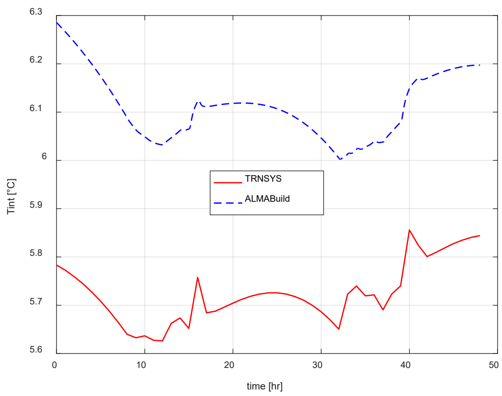

Fig.9 – Comparison of the room air temperature, considering the thermal zone with a window, obtained with TRNSYS and ALMABuild

3.3 Annual Simulations

Annual simulations by considering the room with a window have been made in order to compare TRNSYS with ALMABuild. For this comparison the BESTEST methodology was followed, even if the geometry of the room is different from the cases proposed by the BESTEST procedure (Judkoff et al., 1995). In Table 4 the maximum, minimum, and average annual hourly-integrated internal room temperature values are shown. The annual incident solar radiation is not reported because the results are identical, since the two codes use the same solar model.

Table 4 – Comparison of the annual result obtained using TRNSYS, ALMABuild 1 (considering different T_{sky}) and ALMABuild 2 (considering the same T_{sky})

Internal Temperature	TRN Build	ALMA Build 1	ALMA Build 2
Max (°C)	26.47	25.85	26.33
Min (°C)	2.81	3.01	2.86
Mean (°C)	15.66	15.63	15.71

The results reported in Table 4 show a good agreement between TRNSYS and ALMABuild in terms of internal temperature, both considering equal and different T_{sky} values. Moreover, the hours at which minimum and maximum temperature values were observed with ALMABuild are shifted by 2 and 6 hours with respect to TRNSYS, for both equal and different T_{sky} values. The results quoted in Table 1 confirm that ALMABuild is in good agreement with TRNSYS. However, the validation process of ALMABuild is at its early stage, that is why new validation cases, following the BESTEST procedure, are scheduled in the future.

4. Conclusion

In this work the benchmark of a new SIMULINK library for building modelling named ALMABuild is presented. This library is composed by Building Massive Element (BME) blocks based on 3R4C models, by Building Clear Components (BCC) blocks based on 1R2C models and by Building Thermal Balance (BTB) blocks based on a two-star thermal balance model of a thermal zone.
Comparing the main results, in terms of heat fluxes and room air temperature profiles, with the results obtained using TRNSYS, the benchmark of ALMABuild has been set. The results shown in this paper highlight that differences are present each time that the procedure indicated by the European Standard EN ISO 13790:2008 (and integrally followed by ALMABuild) is not in agreement with the procedure followed by TRNSYS (based on American standards), like in the case of the evaluation of radiative heat transfer between the building external

surface and the sky. Even if further validations are planned, it is possible to conclude that ALMABuild library can be considered a good tool for dynamic simulation; its strengths are its full coherence with European Standards and its full compatibility with the CARNOT blockset.

Nomenclature

Symbols

cp	Specific heat capacity (J/(kg K))
Q	Heat flux (W)
s	Thickness (cm)
T	Temperature (°C)
λ	Thermal conductivity (W/(m K))
ρ	Density (kg/m^3)

Subscripts/Superscripts

ext	Referred to the external air
int	Referred to internal room air
sky	Referred to the sky
sol	Referred to the solar radiation

References

de Wit, M.H. 1988. "ELAN - a multizone simplified thermal simulation model". In: *Proceedings of the sixth international PLEA Conference*. Porto, Portugal: PLEA.

European Commission. 2010. *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings*. Brussels, Belgium: European Commission.

Foucquier, A., S. Robert, F. Suard, L. Stéphan, A. Jay. 2013. "State of the art in building modeling and energy performances prediction: a review". *Renewable and Sustainable Energy Reviews* 23: 272-288. doi: 10.1016/j.rser.2013.03.004.

Fraisse, G., C. Viardot, O. Lafabrie, G. Achard. 2002. "Development of a simplified and accurate building model based on electrical analogy". *Energy and Buildings* 34: 1017–1031. doi: 10.1016/S0378-7788(02)00019-1.

Hudson, G., C. Underwood. 1999. "A simple modeling procedure for Matlab/Simulink". In: *Proceedings of the IBPSA Building Simulation 1999*. Kyoto, Japan: IBPSA.

Judkoff, R., J. Neymark. 1995. *International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method. NREL/TP-472-6231*. Golden, U.S.A.: National Renewable Energy Laboratory.

Klein, S., W. Beckman, J. Mitchell, J. Duffie, N. Duffie, T. Freeman. "TRNSYS 16 - A transient system simulation program, User manual". Madison, U.S.A.: University of Wisconsin-Madison.

Mitalas, G.P., J.G. Arseneault, 1972. *Fortran IV program to calculate Z-transfer functions for the calculation of transient heat transfer through walls and roofs*. Ottawa, Canada: National Research Council Canada, Division of Building Research.

Morini, G.L., S. Piva. 2007. "The simulation of transients in thermal plant. Part I: Mathematical model". *Applied Thermal Engineering* 27: 2138-2144. doi: 10.1016/j.applthermaleng.2006.05.030.

Morini, G.L., S. Piva. 2008. "The simulation of transients in thermal plant. Part II: Applications". *Applied Thermal Engineering* 28: 244-251. doi: 10.1016/j.applthermaleng.2006.05 .035.

Oliveira Panao, M.J.N., C.A.P. Santos, N.M. Mateus, G. Carrilho da Graça. 2016. "Validation of a lumped RC model for thermal simulation of a double skin natural and mechanical ventilated test cell", *Energy and Buildings* 121: 92-103. doi: 10.1016/j.enbuild.2016.03.054.

Perez, R., P. Ineichen, R. Seals, J. Michalsky, R. Stewart. 1990. "Modeling daylight availability and irradiance components from direct and global irradiance". *Solar energy*, 44(5): 271-289. doi: 10.1016/0038-092X(90)90055-H.

Riederer, P., D. Marchio, P. Gruber, J. C. Visier, R. Lahrech, A. Husaunndee. 2000. "Building zone modelling adapted to the study of temperature control systems". In: *Proceedings of ASHRAE/ CIBSE Conference 2000*. Dublin, Ireland.

Wemhöner, C., B. Hafner, K. Schwarzer. 2000. "Simulation of solar thermal systems with CARNOT blockset in the environment MATLAB-Simulink". In: *Proceedings of Eurosun 2000.* Copenhagen, Denmark: ISES.