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# The prediction of thermal loads in building by means of the EN ISO 13790 dynamic model: a comparison with TRNSYS

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**Abstract**

The heating and cooling requirements in buildings are primarily dependent on weather conditions and on the physical and geometrical characteristics of the envelope, and secondly on occupant behaviour. Likewise, regarding the electrical loads, in the presence of multi-generation systems that employ also renewable sources, the prediction of heating and cooling load profiles allows a better planning of the production units, with consequent economic benefits. Furthermore, in a future scenario of Smart Grids, a coordinated production of heating and cooling plants with adjacent systems could be achieved. In order to assess the best operational conditions, an estimate of heating and cooling needs is required in home automation systems to minimize or to rationalize the consumption of primary fossil sources, especially in the presence of a district thermal network. Heating and cooling demands in buildings can be determined by simplified calculation models, which must provide consistent results with those obtainable by more sophisticated commercial software, which are difficult to interface in these automation systems. Therefore, the dynamic model 5R1C described in the standard EN ISO 13790 that employs 6 parameters (5 resistances and 1 capacitor) was tested. This model is simple, requires limited computational times and can be implemented with common programming language. The 5R1C model, in function of the envelope characteristics, determines heating and cooling loads of buildings taking into account the effects linked to thermal inertia. Furthermore, if appropriately predicted climate data are provided, the expected load profiles can be obtained. In order to determine advantages, limitations and accuracy of the 5R1C model, a comparison with the TRNSYS software for three different types of buildings was conducted.

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*Keywords:* expected heating and cooling loads; simulations; simplified models; TRNSYS; Smart Grids

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## 1. Introduction

The rational use of home automation devices allows for a reduction of the energy requirements in buildings, to be applied to new and existing building-plant systems, in accordance with the targets defined in EC Directive 2002/91/EC [1]. Such devices provide an optimal management of the multi-generation systems for heating and cooling, especially if supplied by both fossil and renewable sources. The optimized management of these systems allows for a reduction of building operational costs; furthermore, the diffusion of home automation devices allows for a major spread of thermal networks in smart cities. However, a rational exploitation of fossil and renewable sources, in relation to their availability, requires advanced knowledge of the producible energy in the several heating and cooling devices, the quantity of thermal energy stored in tanks and, especially, the energy needs of building envelopes. The latter are usually determined with quasi-steady methods, referring to the daily average calculation conditions and employing utilization factors of heat gains in winter and of thermal losses in summer [2]. The calculation of heating and cooling requirements can be carried out by the standard EN ISO 13790 [3], which defines a simplified monthly or seasonal procedures that do not take into account the actual dynamic variation of thermal loads. In particular, thermal losses are determined by considering the daily average outdoor temperature, as well as energy gains that are evaluated by monthly daily average values concerning the incident solar radiation. Moreover, the standard assumes a constant indoor air temperature and a continuous operation regime of the air-conditioning plant for the whole calculation period. These calculations are clearly not accurate, but result useful for energy characterization and energy labelling of buildings. Instead, they are inaccurate for assessing the actual energy consumption in function of climatic zone, construction type and profile use. Such inconsistency is even more evident in the case of evaluations of building summer energy consumption, as the quasi-steady method specified in EN ISO 13790 is less reliable, especially for Mediterranean climatic conditions [4].

An accurate evaluation of energy requirements has to consider a transient calculation procedure considering variable weather conditions and envelope thermal capacity, in order to assess the actual response of the building-plant system to the external forces. For this purpose, several dynamic methods are available in literature, such as the TFM method (Transfer Function Method) proposed by AHSRAE and, recently, the Heat Balance method (HB method) or the simplified RTS method (Radiative Time Series) [5]. The TFM method has found commercial application in many calculation programs, such as TRNSYS [6] or Energy Plus [7]. The HB and RTS methods, instead, sometimes have been implemented in some proprietary development software, for instance the ODESSE code developed by the Italian research centre ENEA [8]. Despite the employment of suitable graphical interfaces, none of the aforementioned codes is easy to use, because they all require specific skills for the evaluation of building energy performances. Moreover, if expected weather data are available, the transient calculation also allows for a predictive calculation of the heating and cooling needs.

In order to use home automation devices in a rational way, the different information that users have to insert must be direct, clear and easy to understand. Therefore, these devices have to be equipped with simple mathematical models where non-expert users must insert few and concentrated parameters. Among these simplified dynamic models, that described in the standard EN ISO 13790:2008 and called 5R1C, is very attractive because the building envelope is described by a simple electric circuit, whose solution requires the employment of limited input data. The equivalent electric circuit consisting of five resistances and one capacitor is shown in Fig. 1. The 5R1C model considers both the thermal conductance and the thermal capacity of the envelope and, in order to obtain a significant calculation simplification and reduction of the computational efforts, the thermal capacity is modelled by a single capacitor. In order to take account of the thermal exchanges of internal and external surfaces, the model employs 5 electric conductances coupled with 3 internal nodes, representing the walls surface temperature ($\theta_s$), the temperature of the effective thermal mass ($\theta_m$) and the indoor air temperature ($\theta_{air}$), and with 2 external nodes representing the outdoor and ventilation temperature ($\theta_e$ and $\theta_{sup}$). The model can be generalized to consider different types of building affected by different climatic conditions. HRovat and Dovic, for instance, have determined hourly energy needs for typical Croatian dwellings, and they found that the comparison with the results provided by the quasi-steady procedure is not sufficiently accurate [9]. Millet compared the results of the simplified model with more sophisticated commercial codes, evaluating different levels of accuracy [10]. Regarding typical German districts and municipalities, Ramirez-Camargo has involved the 5R1C method in a GIS-based method for predicting hourly domestic energy needs for space conditioning and DHW production [11]. Finally, Narowski et al. found non accordance between the results provided by the 5R1C model and the results provided by more sophisticated software, therefore they proposed an improvement in the model by adding an additional resistance in the equivalent electric circuit [12].

In this paper, with reference to the buildings investigated in the European project TABULA [13], the results obtained with the 5R1C model are compared with those provided by the TRNSYS code by using typical climatic data of a Mediterranean city. The aim of this comparison is that of evaluating whether the results provided by the simplified model can be reliable, in order to implement it in home automation devices for the rationalization of energy consumption in buildings.

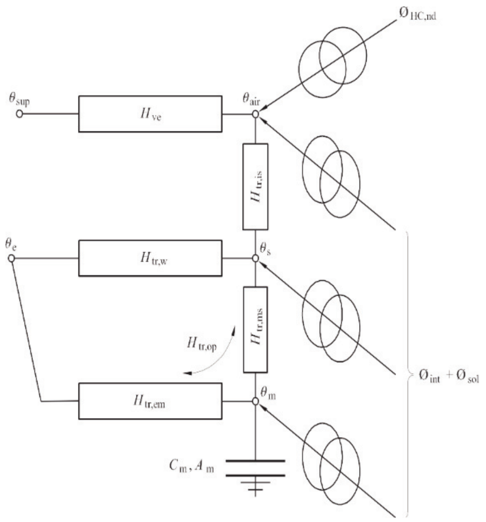


Fig.1 - Electrical scheme of the 5R1C model [3]

## 2. Description of the simplified model 5R1C

The main variables employed in the model are the thermal transmission coefficients, distinguished between window ($H_{tr,w}$) and opaque walls ($H_{tr,op}$); the latter is furthermore separated in a first term concerning the effective thermal mass that accumulates thermal energy ($H_{tr,em}$) and in a second term for the whole surface mass ($H_{tr,ms}$). The thermal losses are determined in function of the outdoor air temperature. Moreover, the thermal transmission coefficient due to ventilation ($H_{ve}$) and the thermal conductance between the surface temperature node and the indoor air temperature node ($H_{tr,is}$) have to be calculated. The parameter concerning the internal thermal capacity of the envelope ($C_m$) is required and can be determined in a simplified way by using the values listed in Tab.1. The thermal transmission coefficients of the windows and the wall is calculated starting from the correspondent values of thermal loss coefficients and surface area, while the contribution linked to the surface mass is given by the relation:

$$H_{tr,ms} = h_{ms} \cdot A_m \tag{1}$$

while:

$$H_{tr,em} = \frac{1}{\frac{1}{H_{tr,op}} + \frac{1}{H_{tr,ms}}} \tag{2}$$

The thermal exchange coefficient between the nodes *m* and *s* is set to 9.1 W/m²K [3], while $A_m$ can be taken in a simplified manner from Tab. 1 in function of the floor area $A_f$. The coefficient $H_{ve}$ can be determined in function of the ventilation air temperature by the typical procedures concerning natural or mechanical ventilation [3]. Finally, the thermal conductance $H_{tr,is}$ is given by the equation:

$$H_{tr,is} = h_{is} \cdot A_{tot} \tag{3}$$

where $h_{is}$ is the thermal exchange coefficient between the nodes *s* and *a*, set to 3.45 W/m²K [3], and $A_{tot}$ is the whole area of all the surfaces which face the air-conditioned environment. The indoor air temperature is an input data and can be set as a constant value, or as a variable value to consider attenuate or intermittent operation. $\Phi_{sol}$ represents the incident solar radiation on the external surface of the envelope and, together with the internal energy gains, are divided among the three components on the internal surfaces ($\Phi_{st}$), on the effective mass node ($\Phi_m$) and on the indoor air node ($\Phi_{ia}$). With reference to Fig. 1, in a given hour, in order to evaluate the thermal/cooling load $\Phi_{HC}$ required to maintain the indoor set-point temperature, the three temperatures of the nodes *m*, *s* and *air* have to be determined.

The problem is solved by subsequent steps: by providing predicted climate data in a specific hour, the 5R1C model allows evaluation in advance of the correspondent thermal loads, by considering the thermal energy stored in the envelope in the previous time step. The equation system describing the electric circuit, in fact, is solved with hourly time-step by the Crank-Nicholson procedure [14]. The temperature of the effective mass $\theta_{m,t}$, is calculated starting from the previous value $\theta_{m,t-1}$ with the following relation:

$$\theta_{m,t} = \frac{\{\theta_{m,t-1}\left[\left(\frac{C_m}{3600}\right) - 0{,}5\ \times\left(H_{tr,3} + H_{tr,em}\right)\right] + \Phi_{m,tot}\}}{\left[\left(\frac{C_m}{3600}\right) + 0{,}5\ \times\left(H_{tr,3} + H_{tr,em}\right)\right]} \tag{4}$$

For t=1, the value of $\theta_m$ in the prior hour is an initial condition and it is given as input data from the users. The following relations can determine the various global thermal exchange coefficients that appears in Eq. (4):

$$\phi_{m,tot} = \phi_m + H_{tr,em}\cdot\theta_e + \frac{H_{tr,3}\cdot\left(\Phi_{st} + H_{tr,w}\cdot\theta_e + H_{tr,1}\cdot\left\{\left[\Phi_{ia} + \frac{\Phi_{HC,nd}}{H_{ve}}\right] + \theta_{sup}\right\}\right)}{H_{tr,2}} \tag{5}$$

$$H_{tr,1} = \frac{1}{\frac{1}{H_{ve}} + \frac{1}{H_{tr,is}}} \tag{6}$$

$$H_{tr,2} = H_{tr,1} + H_{tr,w} \tag{7}$$

$$H_{tr,3} = \frac{1}{\frac{1}{H_{tr,2}} + \frac{1}{H_{tr.ms}}} \tag{8}$$

$$\Phi_m = 0.5\cdot\frac{A_m}{A_t}\cdot(\Phi_{int} + \Phi_{sol}) \tag{9}$$

$$\Phi_{ia}=0.5\cdot\Phi_{int} \tag{10}$$

$$\Phi_{st} = 0.5\cdot(1 - \frac{A_m}{A_t} - \frac{H_{tr,w}}{9.1\cdot A_t}\cdot(\Phi_{int} + \Phi_{sol})) \tag{11}$$

The effective mass node temperature is determined as the average value between the previous hours (*t-1*) and the current hour at the generic time-step *t*, with:

$$\theta_m = \frac{(\theta_{m,t} + \theta_{m,t-1})}{2} \tag{12}$$

The surface temperature is a function of the effective mass temperature determined with the prior equation:

$$\theta_s = \frac{\{H_{tr,ms}\,\theta_m + \Phi_{st} + H_{tr,w}\,\theta_e}{\left(H_{tr,ms} + H_{tr,w} + H_{tr,1}\right)} + \frac{H_{tr,1}\left[\theta_{sup} + \frac{\left(\Phi_{ia} + \Phi_{HC,nd}\right)}{H_{ve}}\right]}{\left(H_{tr,ms} + H_{tr,w} + H_{tr,1}\right)} \tag{13}$$

and, finally, the indoor air node temperature is:

$$\theta_{air} = \frac{(H_{tr,is}\,\theta_s + H_{ve}\,\theta_{sup} + \Phi_{ia} + \Phi_{HC,nd})}{H_{tr,is} + H_{ve}} \tag{14}$$

By providing in Eq. (14) the $\theta_{air}$ values and the numerical values of $\theta_s$ and $\theta_m$ evaluated by eq. (12) and (13), the final calculation of $\Phi_{HC,nd}$ can be carried out.

Table 1. Building thermal class in function of effective mass area $A_m$ (m²) and internal thermal capacity $C_m$ (J/K)

| Class | | Am | Cm |
|---|---|---|---|
| A | Very light | 2.5·Af | 80000·Af |
| B | Light | 2.5·Af | 110000·Af |
| C | Intermediate | 2.5·Af | 165000·Af |
| D | Heavy | 3.0·Af | 260000·Af |
| E | Very Heavy | 3.5·Af | 370000·Af |

## 3. The reference buildings

In order to assess the accuracy of the results provided by the simplified model, the calculation method has been applied to three different types of buildings. By analyzing buildings with different geometries, different heat capacities can be taken into account, and this offers the advantage to observe the effects linked to the variation of the thermal inertia on the results provided by the simplified method. Furthermore, it is possible to assess whether the use of a single capacity in the equivalent electric circuit is sufficient to model the transient thermal behavior of the building envelopes.

The three buildings taken into account are those introduced in the European TABULA project, in particular a single house (SH), a terrace house (TH) and a multifamily house (MH). Fig. 2 shows schematically for each building, a 3D drawing with correspondent plans and sections.

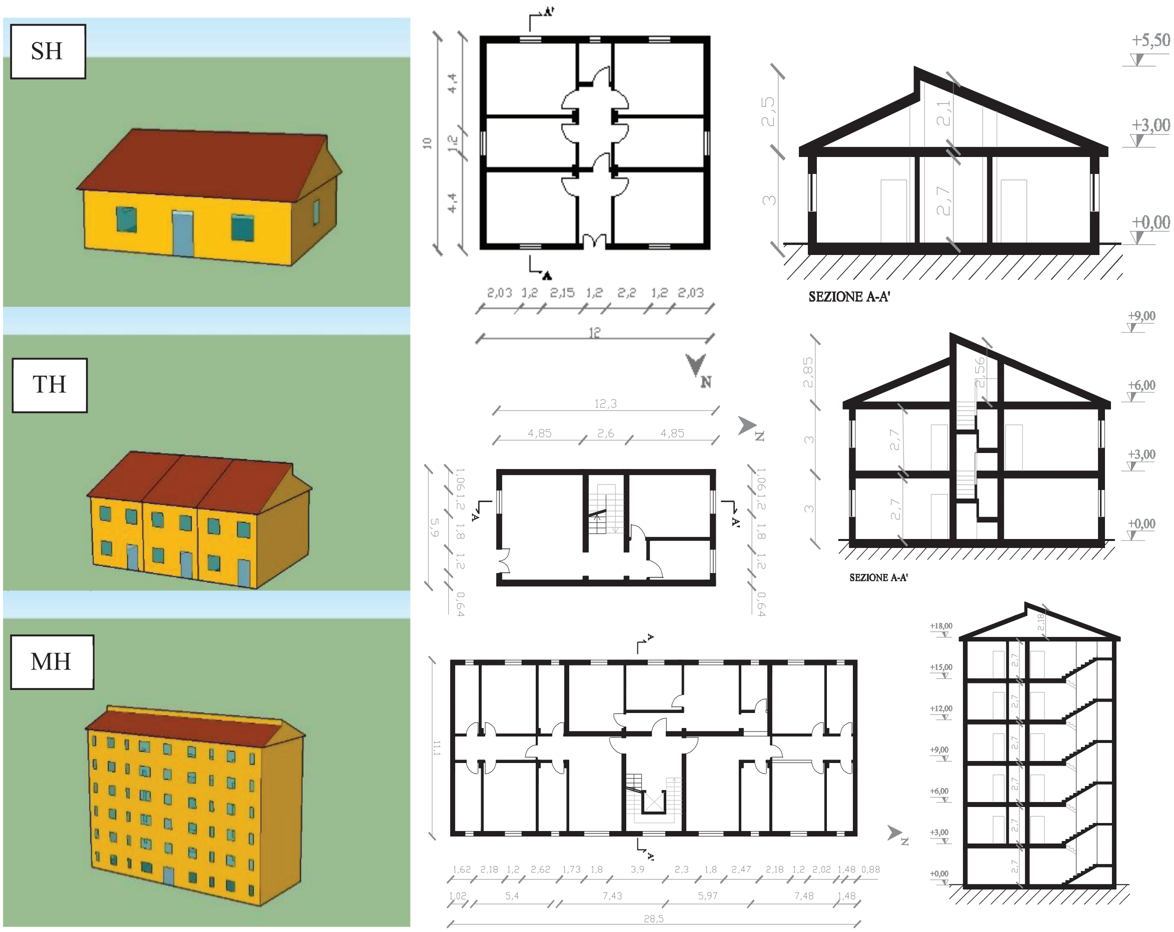


Fig. 2 – Typologies of building envelopes considered for the comparison between the simplified model and TRNSYS

## 4. Results and comparison with TRNSYS

By using real climatic data collected by the actinometric station of the University of Calabria (Lat. 39.36°N, Long. 16.26°E), located in South Italy and with typical Mediterranean weather conditions, fig. 3 shows the results obtained in winter by TRNSYS and by the simplified model for a week long period for a SH equipped with medium thermal inertia. The gap between the two thermal loads in regime conditions is very limited; however, substantial differences in the oscillations of the thermal loads are visible in presence of thermal gains. By increasing the thermal capacity of the building, the simplified model provides more pronounced thermal load oscillations. In the presence of solar gains, the load profiles are no longer in phase; qualitatively, the results obtained for a SH with medium thermal inertia provide load profiles that are rather consistent, especially in the initial phase where the load profiles obtained with the simplified model are very similar to that determined with TRNSYS. Completely different results were observed for the cooling loads: by using summer weather data, the cooling load profile obtained with the simplified model presents important oscillations and for any inertial class of the building envelope (see fig. 4 for SH with very high thermal inertia). The comparison with TRNSYS results seems to suggest that, in a Mediterranean context, the electric equivalent circuit is not accurate to describe the thermal transient behavior of the building envelope for summer weather conditions. The obtained summer load profiles, in fact, are never in phase, by observing differences more evident than the winter case. Moreover, other calculations carried out moving to continental climates, have shown that the results are more reliable for heavier inertial classes.

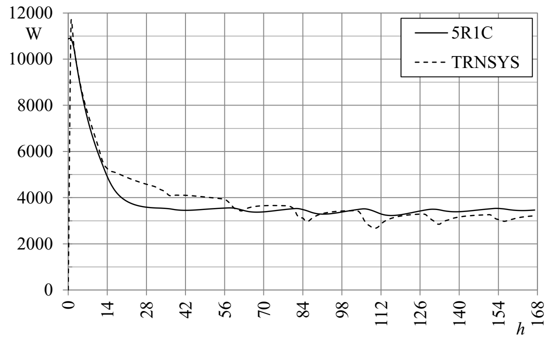


Fig. 3 – Heating load profiles for SH with C inertial class

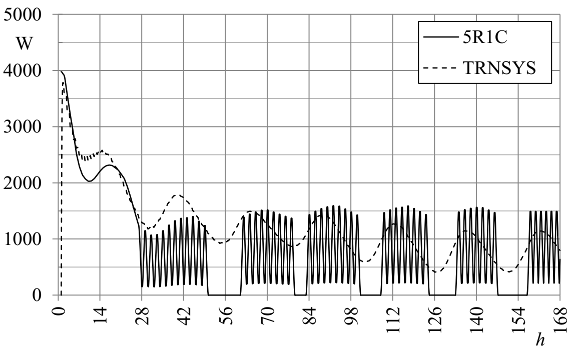


Fig. 4 – Cooling load profiles for SH with C inertial class

Concerning TH building models, the 5R1C method provides encouraging results but only for envelopes with heavy inertial class. The comparison with TRNSYS results, in fact (see fig. 5), shows thermal load profiles with more pronounced fluctuations than single house. These thermal load oscillations result limited for building with thermal inertia varying between the middle class and very heavy class. For an accurate evaluation of the thermal load in function of the time, it is evident that the obtained results are not accurate because the peaks concerning the two thermal profiles are never in phase. Regarding the initial transient phase, a good agreement is observable between the two profiles yet. In summer, the cooling loads provided by the simplified model for the TH envelope present considerable oscillations (fig. 6). However, by increasing the thermal capacity of the building envelope, the cooling load profile approaches those provided by TRNSYS. In fact, the gap between the two profiles is reduced by moving toward heavy inertial classes. In any case, the curves are not in phase so that the cooling load determined in a simplified way, depending on the case, is in advance or delay compared to the TRNSYS one.

For the MH building type, the simplified method 5R1C in winter does not provide reliable results for every inertial class of the envelope, and it provides the best results in a very heavy inertial class if compared with the TRNSYS profile. In fact, considerable differences in terms of both magnitude of the thermal peak load and in terms of time lag are observable (fig. 7). These deviations are more evident moving to continental climates, where the lowest outdoor temperatures further solicit the building envelope in the charging and discharge phases of thermal energy.

In addition, the differences measured between the two profiles decrease with the building thermal inertia growth, but in overall remain high. Regarding the initial transient phase, the 5R1C profile presents substantial deviations with those determined by TRNSYS, and in the subsequent period the thermal loads are never in phase. Contrarily, in summer the simplified model provides better trends: despite the cooling load fluctuations are evident, there is a good accordance between the two cooling load profiles. This accordance exists both in terms of cooling power peaks, as well as in terms of phase. The inertial class that best matches the two cooling load profiles is the medium inertial class. (fig. 8), while with the inertial class growth major deviation was detected. In general, the results provided by the 5R1C model seem to indicate that the increment of the building size involves beneficial effects in the summer period, compared instead with those observed for the single house and the terrace house, but only if the building envelope is not equipped with a significant thermal inertia.

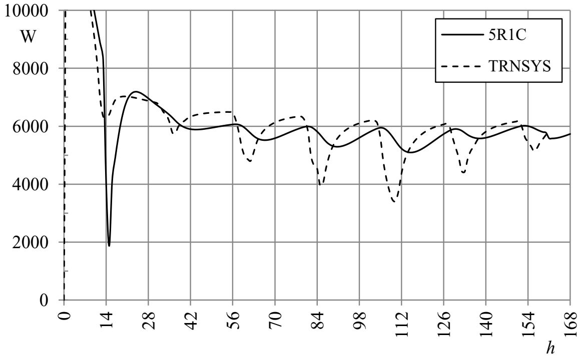

Fig. 5 – Heating load profiles for TH with D inertial class

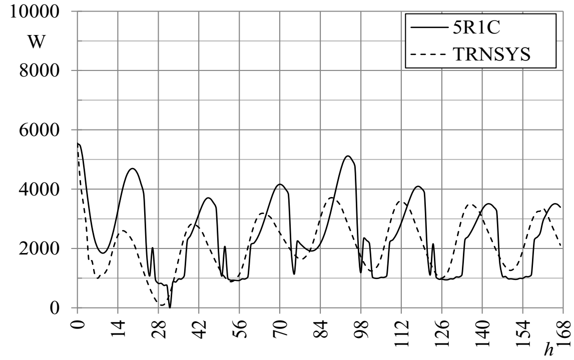

Fig. 6 – Cooling load profiles for TH with D inertial class

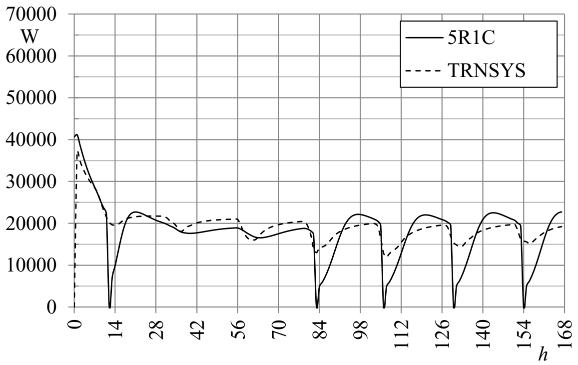

Fig. 7 – Heating load profiles for MH with E inertial class

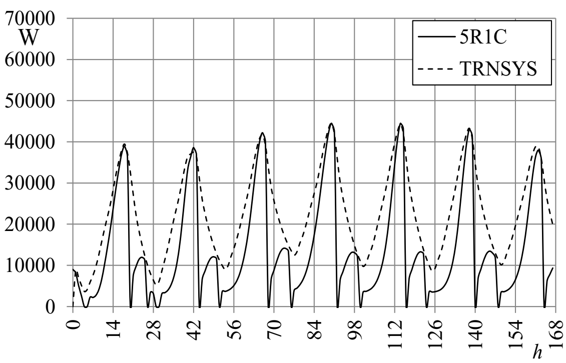

Fig. 8 – Cooling load profiles for MH with E inertial class

## 5. Conclusions

The development of novel smart grids requires the development of intelligent home automation systems for the rational exploitation of energy resources in buildings. Considerable energy savings in buildings equipped with multi-generator systems, or connected with a thermal network, can be achieved if these devices are able to program in advance the operation of thermal or cooling plants. The advanced knowledge of thermal loads represents a useful information for the correct operation of the home automation system. The possibility of knowing expected climatic data with a suitable reliability index allows the predictive evaluation of building thermal loads by dynamic simulation models. These models have to be easy to understand, with lumped parameters and approachable for non-expert users. Among these models, the 5R1C dynamic model described in EN ISO 13790 was tested. This simplified model was chosen because the standard EN ISO 13790 has been adopted as reference document for the evaluation of building energy performances in different countries. Regarding three different typologies of building envelope, described in the European project TABULA, the simplified model was applied and the obtained results compared with more reliable results provided by the TRNSYS simulation code. The comparison between the thermal and cooling load profiles obtained with the two codes, and by using real climatic data concerning a typical Mediterranean location, has provided non-generalizable results. The 5R1C model for a Single House in winter provided results that are in accordance with those provided by TRNSYS, especially in the initial transient phase for a building envelope equipped with a medium thermal inertia. Moreover, the gap between the two thermal loads is negligible in a regime phase but the thermal load oscillation observed with the simplified model, due to gains, is more attenuated compared to TRNSYS. Instead, in summer, the cooling loads profile are comparable, observing numerous fluctuations compared to the real ones, and a higher time shift between the obtained cooling load peaks was determined.

For a Terrace House, the simplified model in winter provides acceptable results in the initial transient phase, while a regime the time-shift is limited to few hours. The fluctuations of the thermal load concerning the simplified model are more attenuated compared to those determined by TRNSYS, but the gap registered at the end of simulation is negligible. In summer, the trend of the cooling loads is not relevant to the real profile, with differences that are not always negligible and with a high temporal shift between the cooling power peaks.

For a Multi-house Building, the simplified model reproduces the initial transient phase quite well, but does not sufficiently approximate the actual pattern of the thermal load over time, especially for buildings with elevated thermal inertia, and the time shift between the two profiles is too high. In summer, instead, the cooling load profiles are more in phase, showing a trend much more relevant to reality than that determined for the winter.

Therefore, the simplified method should be adopted with extreme caution as a predictive model of heating and cooling loads in buildings. This model, in fact, provides results that are in accordance with the real behavior of the building only for particular categories of envelope and under certain climatic conditions. The simulations conducted in this paper show that the simplified model 5R1C works well in winter for compact buildings, or for limited thermal inertia, especially when the same building is moved to continental climatic zones. On the contrary, for the same category of building, the simplified model provides not concordant results for the summer period. Moving towards larger envelopes, the thermal load profiles begin to diverge strongly, while qualitatively a good accordance between the cooling load profiles is observable.

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