Title

Improvement to EN ISO 52016-1:2017 hourly heat transfer through a wall assessment: the Italian National Annex

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Abstract

Energy efficiency in buildings is a crucial topic to reduce the worldwide energy consumptions and fight the climate change. A key aspect is the assessment of the heat transfer through the opaque elements of the building envelope. One way to do it is modelling the element as a resistors and capacitors network (RC), using the thermal-electrical analogy. In the hourly dynamic method introduced by the recently published standard EN ISO 52016-1:2017, each opaque element is modelled with a RC-network. Italy has implemented in the National Annex A of the Standard an alternative methodology for the definition of the number of nodes and position, based on the detailed layers' characteristics. In this work, the two methods are described and compared with the exact analytical solution for three cases under sinusoidal boundary conditions. In all the test cases, the results obtained applying the Italian Annex provide better results, with reduction of the error on the internal flux amplitude between 14% and 67%. In addition, it has been verified that the Italian model is actually well tuned. Indeed, the amplitude of the external flux is overestimated on average of only 3%, and the phase differences are limited (maximum ±1 hour). Lastly, also the effect of the change of number of nodes, and to move the nodes from the layers' mid-point to the interface, have been analysed, but none of these strategies were demonstrated able to increase significantly the model accuracy, which can be obtained only reducing the calculation timestep.

Keywords

heat transfer; building simulation; RC; EPBD; 52016

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1 Introduction

In the context of increasing attention to the environmental issues and energy policies, the interest towards energy strategies in the building sector is well-known. Modelling of buildings is a fundamental instrument to investigate the thermal behaviour and the energy uses. The approaches can be multiple and vary according to the specific purpose, level of accuracy and detail and computational effort required.

Currently, several international standards (e.g. EN ISO 13790:2008, EN 15265:2007, EN ISO 13791:2012, EN ISO 13792:2012, EN 15255:2007) describe a calculation method for different specific purposes. With the mandate M480, European Commission has instructed the CEN (European Committee for Standardization) to develop a set of EPB (Energy Performance of Buildings) standards [1], with the specific aim to define a harmonized methodology for the assessment of the energy performance of buildings, made of procedures unambiguous but also flexible and adaptable to national and regional specificities [2]. Among them, EN ISO 52016-1 [3] provides an hourly and monthly method, validated using relevant cases from the BESTEST series [4], for the calculation of the energy needs for heating, cooling and dehumidification, in addition to the calculation of the internal temperatures and the assessment of design heating or cooling loads. It is a simplified application of the generic method exposed in EN ISO 52017-1 [5] with specific boundary conditions and assumptions [6], conceived as a standard reference method, alternative to the use of dynamic building performance simulation tools, which requires a limited number of input data – avoiding the introduction of uncertainties and inaccuracy related to missing detailed data – and guarantees reproducibility and transparency [7].

This paper focuses on the analysis of methodologies to evaluate the heat transfer through opaque elements of the building envelope. A widely used approximate method is based on the thermal-electrical analogy. The heat transfer problem is modelled through a network of resistors and capacitors (RC-network) that represent thermal resistances and lumped capacitances of the building's elements. The mathematical description of this model consists of a set of first order differential equations, which are usually transformed in a set of algebraic equation thanks to the approximation of the ordinary derivative respect to the time with a finite difference. Several authors have investigated the accuracy and the application limits of RC-network representations both for sinusoidal heat flux input [8,9] and step heat flux input [10,11].

Considering the complexity of multilayer buildings' constructions, the definition of nodes number of the RC-network, and consequently the number of differential or algebraic equations to be solved, is a critical issue. Different approaches to identify the lumped parameters for the RC-network can be used, following numerical methods, optimization algorithms [12] or analytical procedures [13,14]. Indeed, improper identification could turn out in a not negligible error in terms of time lags and decrement factor, losing the insight linked of the properties of the wall layers (thickness, thermal diffusivity, heat capacity) investigated in [15].

According to EN ISO 52016-1, for the hourly calculation of the building's thermal behaviour each opaque element is modelled with a RC-network, whose number of nodes can range from one to five, independently from the actual number and characteristics of the layers. Therefore, to describe the building envelope, from one to five equations for each opaque element are necessary, in addition to two equations per window. Definitely, this model is more complex than the one prescribed in EN ISO 13790 [16] – with five thermal resistances and one capacity to describe the entire thermal zone –, whose accuracy has been tested in [17] for different climates and building envelope technologies, demonstrating that it is able to provide fairly good estimations of the building energy needs over the seasonal period, but it does not accurately follow the hourly fluctuations. At the same time, the model proposed in EN ISO 52016-1 could be not sufficiently accurate for an hourly based method, since the lack of detailed information regarding the elements' stratigraphy could result in significant errors in terms of phase shift. This error is much more important than the amplitude error, since an hourly dynamic model should be able to account for the mismatch between requirements and available power time profiles as much correctly as possible.

Nevertheless, EN ISO 52016 provides for the possibility of other methods to be included in the national annexes, once validated; thus, Italy has implemented in Annex A a different method that overcomes the default methodology and introduces a specific calculation procedure for the nodes number definition and positioning, dynamically calculated on the characteristics of each layer. Actually, this approach (Finite Volume) is close to the "Finite Difference" method, implemented in widely used building performance simulation tools as EnergyPlus [18].

In this work the results obtained with the two methods have been analysed, making a comparison with the harmonic exact solution obtained analytically according to EN ISO 13786:2017 [19].

2 Methodology

In this paper, the heat transfer in plane building elements has been analysed under sinusoidal boundary conditions: at the outer side sinusoidal variation of temperature is imposed, with an amplitude of 10°C and average value 0°C as shown in Figure 1, while at the inner side the temperature has been set constantly at 0°C. The zero value for the inside and outside average (steady) temperature has been chosen to concentrate the attention on the dynamic component only.

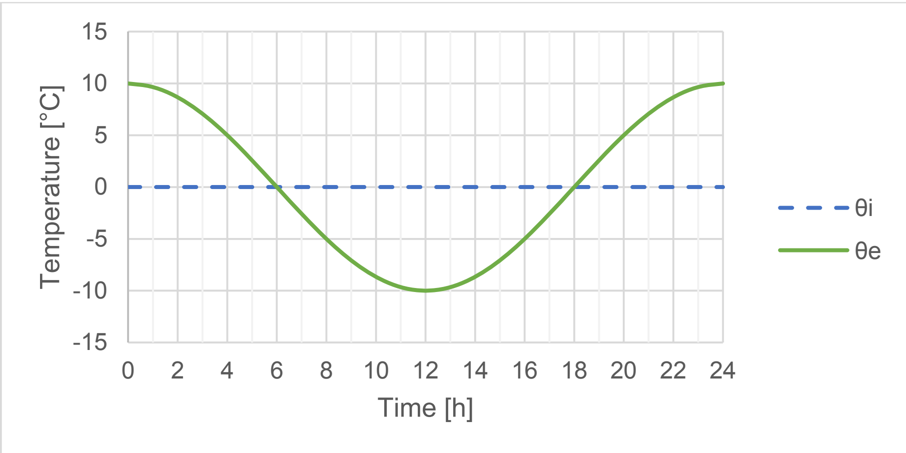

Figure 1: Temperatures imposed at the inner (θ_i) and outer sides (θ_e)

The building elements are composed of plane, parallel and homogeneous layers, thus heat flow has been assumed one-dimensional and thermal bridges' effects have been neglected. In addition, solar radiation and internal heat are not considered, because the quality assessment of the conductive models does not depend on the amount and typology of considered boundary conditions.

The construction test cases are defined in Table 1 in terms of layers' thermal conductivity λ [W/(m K)], density ρ [kg/m^3], specific heat capacity c [J/[kg K)], thickness d [m] and thermal resistance R [m^{2}K/W]. Wall W1 is the multilayer component reported in Annex D of EN ISO 13786:2007 [20], test case W2 is a typical masonry wall with exterior insulation while case W3 is a flat roof stratigraphy.

Table 1: Thermal properties of materials for the test cases

Test case	Materials	λ [W/m/K]	ρ [kg/m³]	c [J/kg K]	d [m]	R [m²K/W]
W1	Internal surface					0.130
	Concrete	1.800	2400	1000	0.200	0.111
	Thermal insulation	0.040	30	1400	0.100	2.500
	Coating	1.000	1200	1500	0.005	0.005
	External surface					0.040

W2	Internal surface					0.130
	Internal Plaster	0.530	1500	1000	0.015	0.028
	Masonry	0.230	750	1000	0.350	1.522
	Insulation	0.036	20	1450	0.060	1.667
	External Plaster	0.530	1500	1000	0.010	0.019
	External surface					0.040
W3	Internal surface					0.100
	Internal Plaster	0.530	1500	1000	0.015	0.028
	Hollow Bricks-Concrete slab	0.740	1150	1000	0.240	0.324
	Impact sound insulation layer	0.040	40	1000	0.008	0.200
	Lightened CLS underlayer	0.150	600	1000	0.060	0.400
	Insulation	0.036	20	1450	0.110	3.056
	Waterproof barrier	0.200	1050	1000	0.004	0.020
	External surface					0.040

For the three test cases, the results produced using the methods of the EN ISO 52016-1:2017 and the UNI EN ISO 52016-1:2017 Annex A have been compared with the exact solution, obtained following the analytical procedure of EN ISO 13786, in terms of amplitude and phase difference of the internal and external fluxes and surfaces temperatures.

Subsequently some remarks on the methodology proposed in the Italian Annex have been made, demonstrating its accuracy in comparison to a model with one capacity node per layer, but also highlighting the space discretization limits.

3 Description of the Methods used

3.1 The harmonic analytical solution according to EN ISO 13786

The standard EN ISO 13786:2017 provides a method to calculate the dynamic thermal behaviour of a building component. In particular, in Section 7 a simplified calculation procedure is provided for plane multi-layer components, based on the detailed characteristics of the building component and the period of the variations at the surfaces, in this case P = 24 h = 86400 s.

The temperature in zone *n* and the heat flow density are described by Eq. 1 and Eq. 2.

$$\theta_n(t) = \bar{\theta}_n + \left|\hat{\theta}_n\right| \cos(\omega t + \psi) \quad \text{Eq. 1}$$

$$q_n(t) = \bar{q}_n + |\hat{q}_n| \cos(\omega t + \varphi) \quad \text{Eq. 2}$$

where $\bar{\theta}$ and $\bar{q}$ are the average values, $\left|\hat{\theta}\right|$ and $|\hat{q}|$ are the amplitudes (modulus of the complex amplitude), ω is the angular frequency, and ψ and φ are the phase differences.

The value of the density of heat flow on both sides of a wall is obtained as:

$$q_n(t) = \bar{q} + Re\left(\hat{q}_n \cdot e^{j\omega t}\right) = U \cdot (\bar{\theta}_E - \bar{\theta}_I) + Re\left(\hat{q}_n \cdot e^{j\omega t}\right) \quad \text{Eq. 3}$$

where the mean value $\bar{q}$ is linked to the mean value of the temperatures at the two sides of the component, while the complex amplitude $\hat{q}$ is obtained as a function of the temperatures on both sides of a wall, according to the following steps:

- calculation of the penetration depth δ (Eq. 4) and definition of the ratio ξ (Eq. 5) for each layer.

$$\delta = \sqrt{\frac{\lambda}{\rho \cdot c} \cdot \frac{T}{\pi}} \quad \text{Eq. 4}$$

$$\xi = \frac{d}{\delta} \quad \text{Eq. 5}$$

- calculation of the heat transfer matrix Z_i of each layer i

$$\boldsymbol{Z_i} = \begin{bmatrix} Z_{11}^i & Z_{12}^i \\ Z_{21}^i & Z_{22}^i \end{bmatrix} \quad \text{Eq. 6}$$

where:

$$Z_{11}^i = Z_{22}^i = \cosh\xi \cdot \cos\xi + j \cdot \sinh\xi \cdot \sin\xi$$

$$Z_{12}^i = -\frac{\delta}{2\lambda}\{\sinh\xi \cdot \cos\xi + \cosh\xi \cdot \sin\xi + j \cdot [\cosh\xi \cdot \sin\xi - \sinh\xi \cdot \cos\xi]\} \quad \text{Eq. 7}$$

$$Z_{21}^i = -\frac{\lambda}{\delta}\{\sinh\xi \cdot \cos\xi - \cosh\xi \cdot \sin\xi + j \cdot [\sinh\xi \cdot \cos\xi + \cosh\xi \cdot \sin\xi]\}$$

- calculation of the heat transfer matrix of the building component from external to internal environment multiplying the layers' heat transfer matrices, including the boundary layers, in the correct order (from outside N to inside 1)

$$\boldsymbol{Z} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \boldsymbol{Z}_{s,EXT} \cdot \left(\prod_{i=N}^{1} \boldsymbol{Z}_i\right) \cdot \boldsymbol{Z}_{s,IN} \quad \text{Eq. 8}$$

where the heat transfer matrices of the boundary layers are obtained from the surface resistance $R_{s,i}$ as:

$$\boldsymbol{Z}_{s,i} = \begin{bmatrix} 1 & -R_{s,i} \\ 0 & 1 \end{bmatrix} \quad \text{Eq. 9}$$

- calculation of the thermal admittances Y_{11} and Y_{22} and the periodic thermal transmittance Y_{12}

$$Y_{11} = -\frac{Z_{11}}{Z_{12}} \quad \text{Eq. 10}$$

$$Y_{22} = -\frac{Z_{22}}{Z_{12}}$$

$$Y_{12} = -\frac{1}{Z_{12}}$$

- calculation of the variation of the heat flow density on both sides in function of the variations of temperatures:

$$\begin{bmatrix} \hat{q}_E \\ -\hat{q}_I \end{bmatrix} = \frac{1}{Z_{12}} \begin{bmatrix} -Z_{11} & 1 \\ 1 & -Z_{22} \end{bmatrix} \cdot \begin{bmatrix} \hat{\theta}_E \\ \hat{\theta}_I \end{bmatrix} = \begin{bmatrix} Y_{11} & -Y_{12} \\ -Y_{12} & Y_{22} \end{bmatrix} \cdot \begin{bmatrix} \hat{\theta}_E \\ \hat{\theta}_I \end{bmatrix} \quad \text{Eq. 11}$$

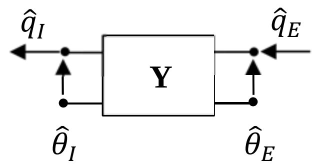

Figure 2: Equivalent quadrupole

3.2 The R-C method

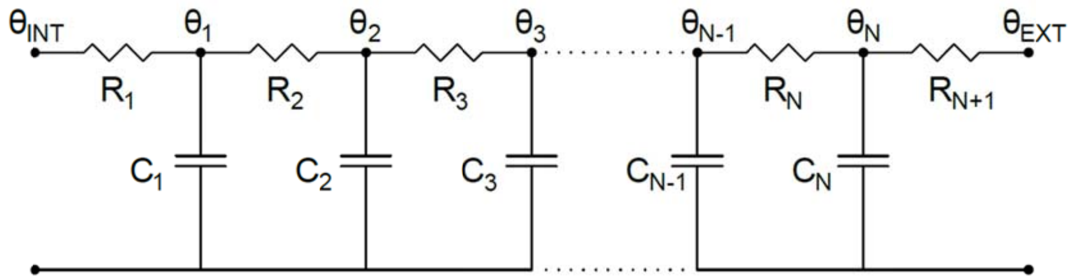

Figure 3: Generic Resistor-Capacitor network

According to thermal-electrical analogy, a multi-layer wall can be analysed as a Resistor-Capacitor (RC) network, whose number of resistors and capacitors connected in series has to be properly defined, as it is addressed in the following paragraphs.

The state-space representation of the system is given by the matrix Eq. 12, whose integration provides the temperatures at the building elements' nodes.

$$\frac{d\boldsymbol{x}}{dt} = \mathbf{A} \cdot x + \boldsymbol{b} \quad \text{Eq. 12}$$

$$\boldsymbol{x} = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \vdots \\ \vdots \\ \theta_N \end{bmatrix}$$

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & 0 & 0 & \cdots & 0 \\ a_{21} & a_{22} & a_{23} & 0 & \cdots & 0 \\ 0 & a_{32} & a_{33} & a_{34} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & a_{N(N-1)} & a_{NN} \end{bmatrix}$$

$$a_{ii} = -\frac{\frac{1}{R_i} + \frac{1}{R_{i+1}}}{C_i}$$

$$a_{i(i-1)} = \frac{1}{C_i \cdot R_i}$$

$$a_{i(i+1)} = \frac{1}{C_i \cdot R_{i+1}}$$

$$b = \begin{bmatrix} \frac{\theta_{int}}{C_1 \cdot R_1} \\ 0 \\ 0 \\ \vdots \\ \vdots \\ \frac{\theta_{ext}}{\kappa C_N \cdot R_{N+1}} \end{bmatrix}$$

Usually Eq. 12 is integrated numerically and, among all possible methods, the transformation into an algebraic system of equations is obtained using a backward finite difference approximation for the time derivative. A fully implicit numerical scheme is then obtained.

3.2.1 EN ISO 52016-1:2017 method

The model for building construction elements in EN ISO 52016-1:2017 is based on a predefined lumped parameters approximation: the wall RC-network is made of 5 nodes interconnected by 4 resistances and connected to one (minimum) to 5 (maximum) capacitances, in addition to the indoor and outdoor nodes and the radiative and convective resistances.

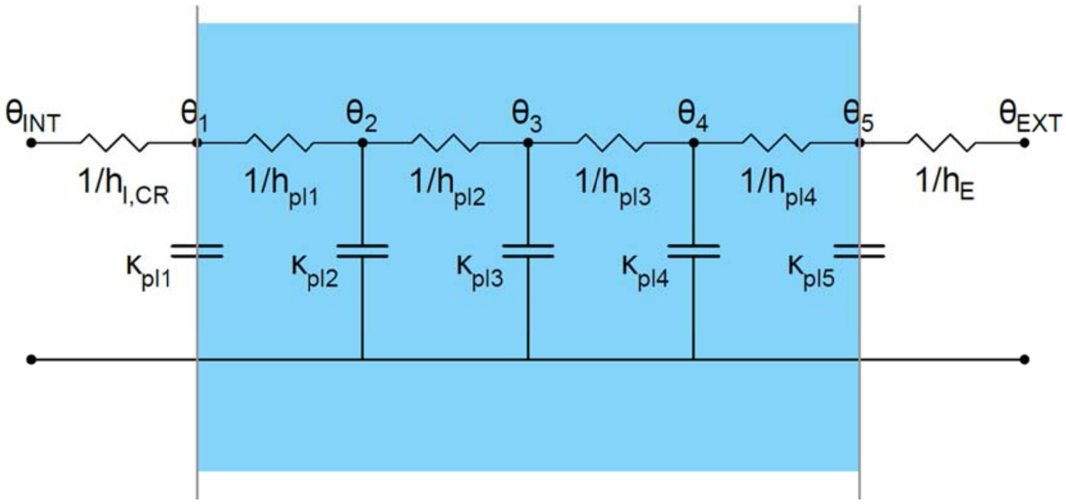

Figure 4: RC network of lumped parameters model proposed in EN ISO 52016

The nodes position is fixed independently from the number and characteristics of each layer (ρ, λ, c), just on the basis of the thermal resistance of opaque building element, and a thermal capacitance to the node is associated or not in function of the building wall classification only.

The thermal physics wall input quantities are then:

- $R_{c;eli}$ = thermal resistance of opaque building element *eli* [m^2K/W]
- $\kappa_{m;eli}$ = areal heat capacity of the opaque element *eli* [J/m^2K]
- wall class.

Specifically, the conductance between nodes *pli* and node *pli-1* are fixed according to Eq. 13 and Eq. 14, while the areal capacitance of the nodes is defined according to the predefined "classes" of mass position as described in

Table 2.

$$h_{pl1;eli} = h_{pl4;eli} = \frac{6}{R_{c;eli}} \qquad \text{Eq. 13}$$

$$h_{pl2;eli} = h_{pl3;eli} = \frac{3}{R_{c;eli}} \qquad \text{Eq. 14}$$

Table 2: Values of the nodal thermal capacities for each class of mass position, as defined in EN ISO 52016

Class		$\kappa_{pl1;eli}$	$\kappa_{pl2;eli}$	$\kappa_{pl3;eli}$	$\kappa_{pl4;eli}$	$\kappa_{pl5;eli}$
I	mass concentrated at the internal side	0	0	0	0	$\kappa_{m;eli}$
E	mass concentrated at the external side	$\kappa_{m;eli}$	0	0	0	0
IE	mass divided over internal and external side	$\kappa_{m:eli}/2$	0	0	0	$\kappa_{m;eli}/2$
D	mass equally distributed	$\kappa_{m:eli}/8$	$\kappa_{m:eli}/4$	$\kappa_{m;eli}/4$	$\kappa_{m:eli}/4$	$\kappa_{m:eli}/8$
M	mass concentrated inside	0	0	$\kappa_{m:eli}$	0	0

The basic areal capacity value in input to Table 2 has to be given in Table A.14 or taken form Table B.14 (default values) of EN ISO 52016-1:2017, as rough function of the wall weight (very light 50 000 J/m^{2}K, light 75 000 J/m^{2}K, medium 110 000 J/m^{2}K, heavy 175 000 J/m^{2}K, very heavy 250 000 J/m^{2}K).

3.2.2 Italian Annex

In the Italian Annex model, the number of nodes is not fixed but has to be determined according to the actual wall layers number and characteristics. For each layer *j* the number of nodes has to be calculated using the Eq. 16.

$$N_{d_j} = \max\left[1; \mathrm{Int}\left(\sqrt{\frac{\mathrm{Fo}_{ref}}{\mathrm{Fo}_j}} + 0.999999\right)\right] \qquad \text{Eq. 15}$$

In Eq. 16 the reference Fourier number is set at $\mathrm{Fo}_{ref} = 0.5$ and the layer Fourier number is defined in Eq. 16.

$$\mathrm{Fo}_j = \frac{\lambda_j}{\rho_j \cdot c_j} \cdot \frac{\Delta t}{d_j^2} \qquad \text{Eq. 16}$$

This means that there is at least one node per layer and the total number of nodes to be considered is the sum of the nodes of each layer, in addition to two nodes for the external and internal surfaces.

Each node *pli* (except for the surface ones) is located in the middle of the layer or sub-layer of thickness Δx (Eq. 17), as in Figure 5, always having an areal thermal capacity κ (Eq. 18). The internodal conductive resistances are obtained accordingly using the thermal conductivity and related material thickness of the actual layers crossed by.

$$\Delta x = \frac{d_j}{N_{d_j}} \qquad \text{Eq. 17}$$

$$\kappa_{pli;eli} = \rho_j \cdot c_j \cdot \frac{d_j}{N_{d_j}} \qquad \text{Eq. 18}$$

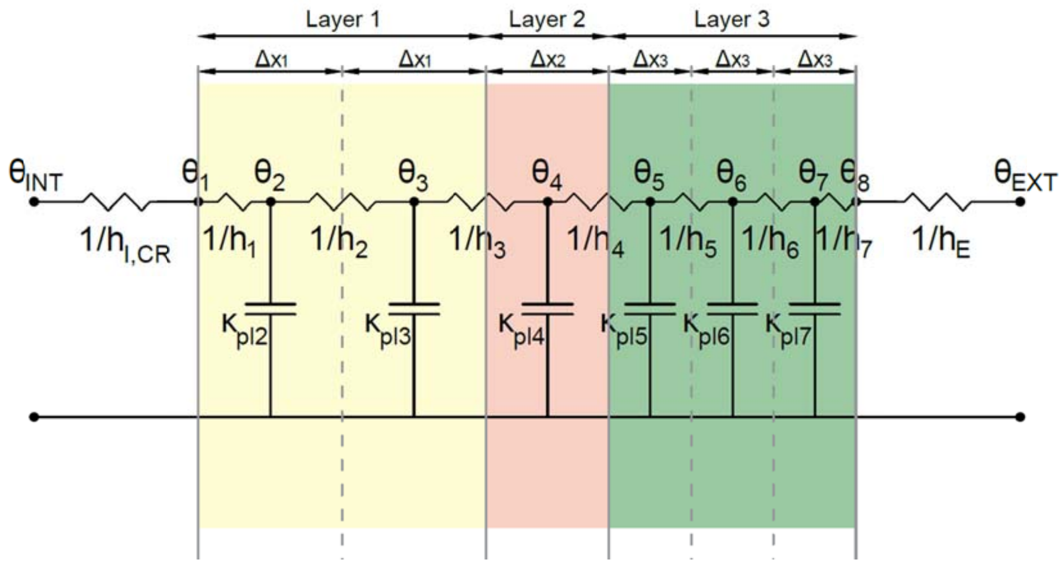

Figure 5: RC network of lumped parameters model of the Italian Annex (example of a 3-layer wall)

4 Results and discussion

4.1 Results comparison of EN ISO 52016 and Italian Annex methods with the analytical solution

When assessing the performance of the EN ISO 52016-1:2017 default model, the physical areal thermal capacity of the actual wall has been used to try to have the best as possible result to be able to judge the model and exclude the obvious uncertainties introduced by the roughly tabulated values previously cited. Also, to avoid erroneous chooses of thermal capacity distributions, all schemes related to each class of mass position have been used, looking for the best result among them.

In Figure 6 and Figure 7, for each RC model analysed, the sinusoidal amplitude and phase of the internal and external thermal fluxes are plotted for the three construction test cases.

For the test wall W1, where the massive layer is at the inner side, the results for the class I (mass concentrated at the internal side) are actually those closer to the analytical solution among the ones obtained using the International standard approach. Nevertheless, the internal flux amplitude is overestimated of the 27% and the external one is underestimated of the 56%, while the phase shifts lead to time lags of -3 and 4 hours respectively.

In the test cases W2 and W3, the EN ISO 52016 solution that better approximate the analytical results of the internal flux is given by class D (mass equally distributed among the nodes), with amplitude reductions of the 46% and 90% respectively and time shifts of 2 hours. For the external fluxes, this class of mass distribution presents good approximation of the trend but with significant amplitude differences.

With the method introduced by the Italian annex, the RC-networks, obtained from the detailed layers' distribution and material, are composed of 6 capacity nodes for wall W1 and 11 for cases W2 and W3. In all the test cases, the results obtained provide a more accurate approximation than the ones got with the default method, with reduction of the error on the internal flux amplitude between 14 and 67% compared to the previously mentioned classes. In addition, in comparison with the exact solution, the amplitude of the external flux overestimated on average of the 3%, and the phase differences are limited (maximum ± 1 hour).

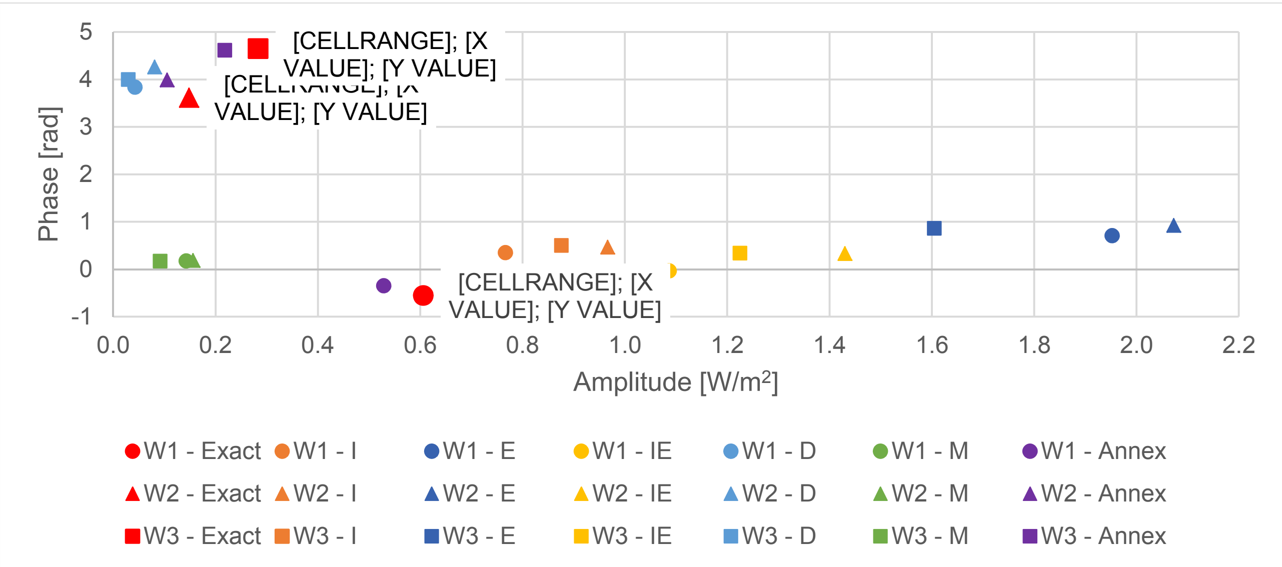

Figure 6: Internal flux sine amplitude and phase

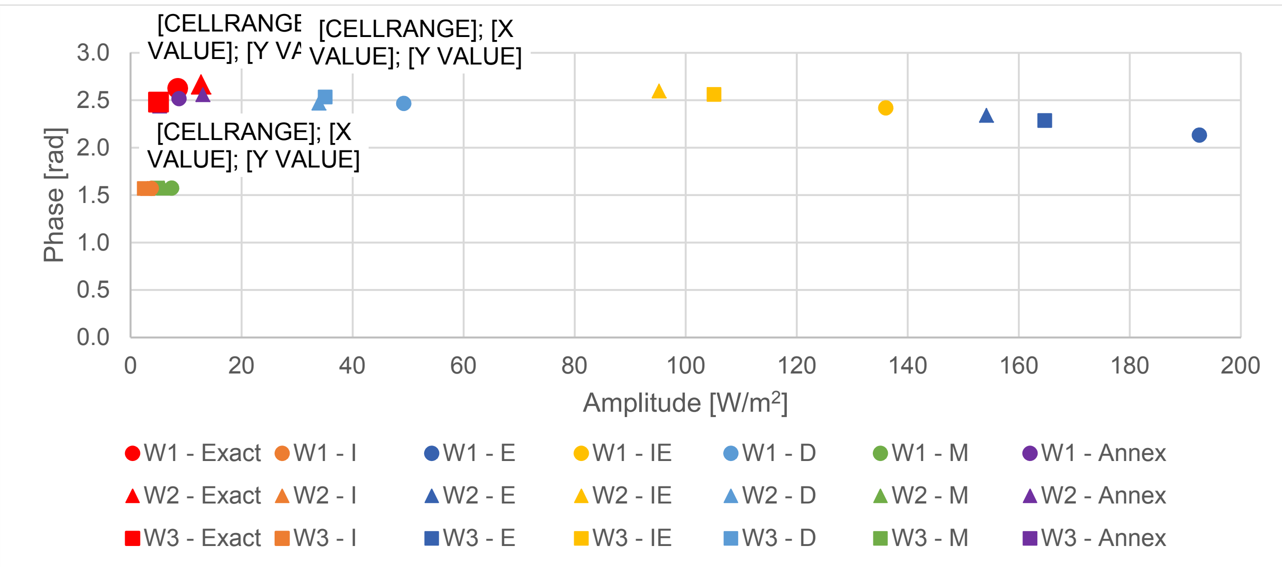

Figure 7: External flux sine amplitude and phase

For a comparison of the model results in terms of the internal and external surface temperatures, the charts in Figure 8 and Figure 9 have been plotted. The trends of the internal surface temperature reported in Figure 8 are qualitatively analogous to the one obtained for the internal flux (Figure 6). Regarding the external surface temperature, for all the construction test cases, good approximation is given by models M and I, in addition to the Annex one, with errors in the amplitude between -1% and 1% and no error on the phase.

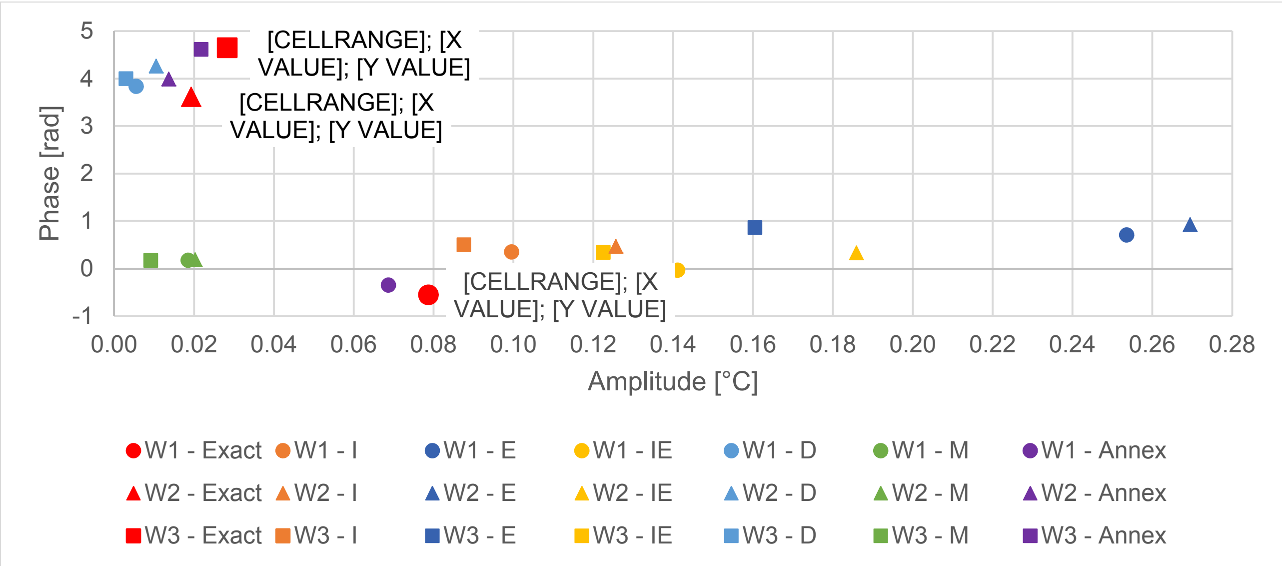

Figure 8: Internal surface temperature sine amplitude and phase

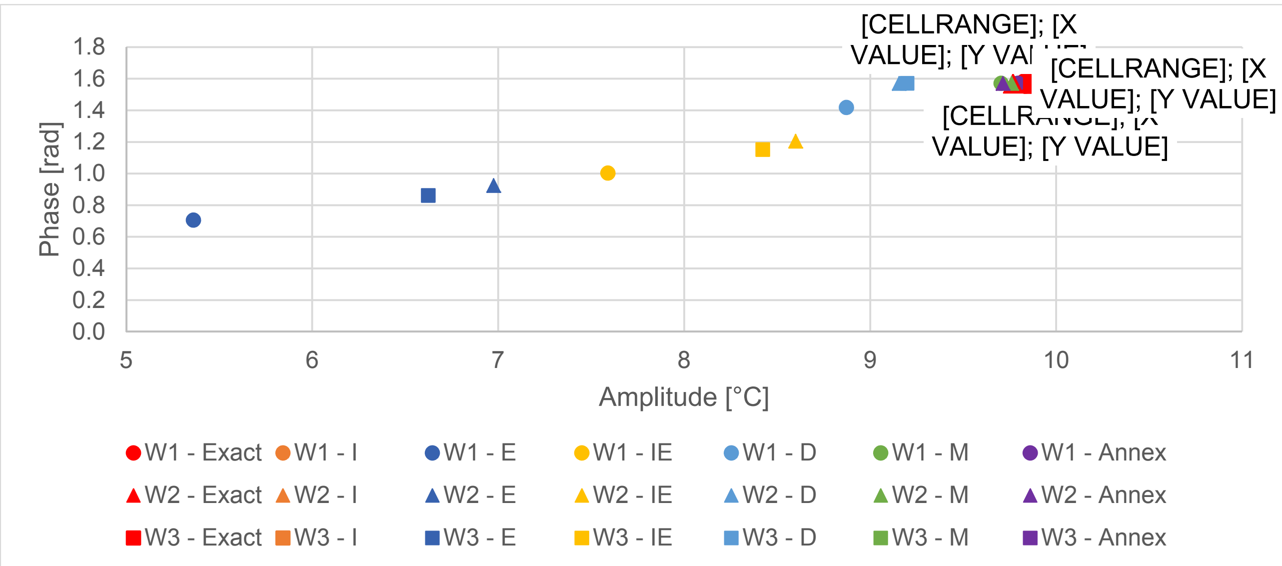

Figure 9: External surface temperature sine amplitude and phase

To better display the results previously examined, Figure 10 reports for the wall W1 the variations along 24 hours of internal and external heat flux densities and surface temperatures. Even from a qualitatively analysis, it is clear that none of the models provides a good approximation of the exact solution for all the variables considered except the Annex one.

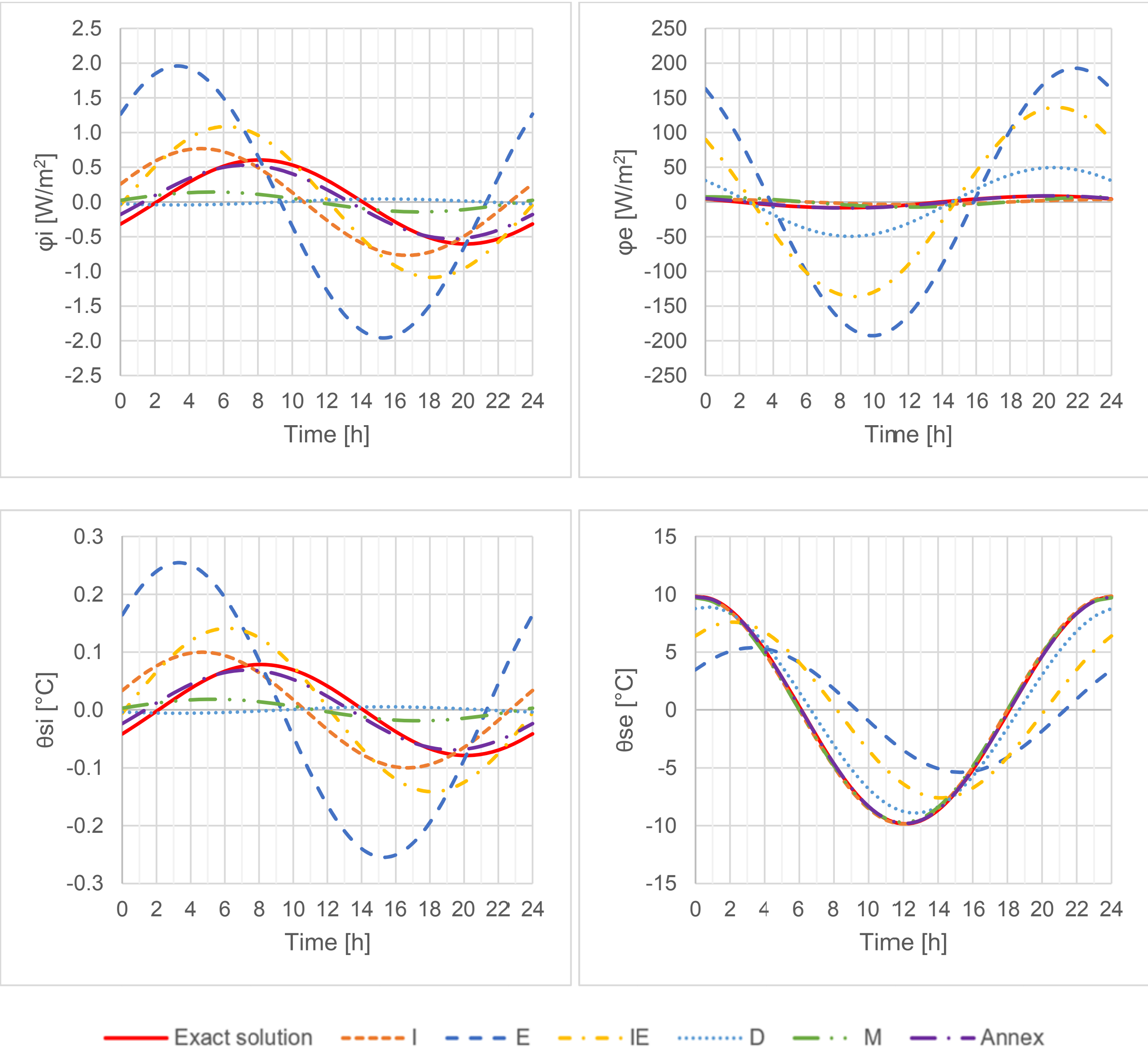

Figure 10: Time variations over 24h of the internal (top left) and external (top right) flux density and internal (lower left) and external (lower right) surface temperature for the test wall W1

4.2 Remarks on Italian annex methodology

Focusing on the methodology proposed in the Italian annex, the automatic nodes number determination (each with a capacity) through the reference Fourier number set to 0.5 has been investigated to assess its impact on the results accuracy. Thus, the accuracy given by a number of nodes lower (one node per layer in the model "1 node") or higher (doubling the number of nodes in the model "Double") than prescribed has been checked.

From Figure 11 and Figure 12, it is clear that using one capacity node per layer the results differ from the Annex model, going away from the analytic solution, in particular concerning the phase, thus increasing the time lag between the sinusoidal curves. On the other hand, doubling the number of nodes calculated according to the procedure exposed in Section 3.2.2 does not considerably improve the results accuracy; the errors in the amplitude are reduced of at maximum 3% compared to Annex model and the time lags are substantially unvaried.

Actually, being the time derivative approximated with a finite difference, the time discretization is also important for accuracy. Thus to get closer to the exact solution it is not sufficient to increase the space discretization, but it is necessary to act on the time discretization, as shown with the additional model "dt = 0.25h" where a timestep of 0.25 h has been applied to the method of the Italian Annex, obtaining results even closer to the analytic solution.

In addition, in the model called "Interface" the configuration proposed in the Italian Annex has been modified, placing the nodes at the layer/sublayer interfaces, rather than at the mid-point, but keeping the same methodology of nodes calculation and resistances and capacities allocation. It can be observed how the results obtained with this model present negligible differences (maximum 2%) in comparison to the Annex model.

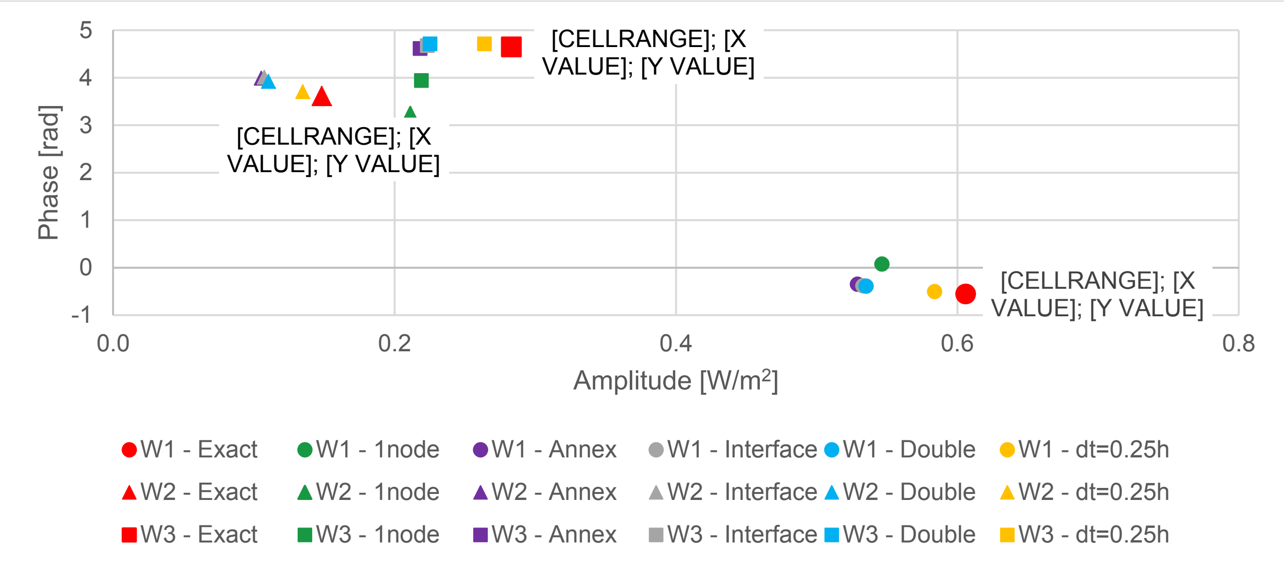

Figure 11: Internal flux sine amplitude and phase

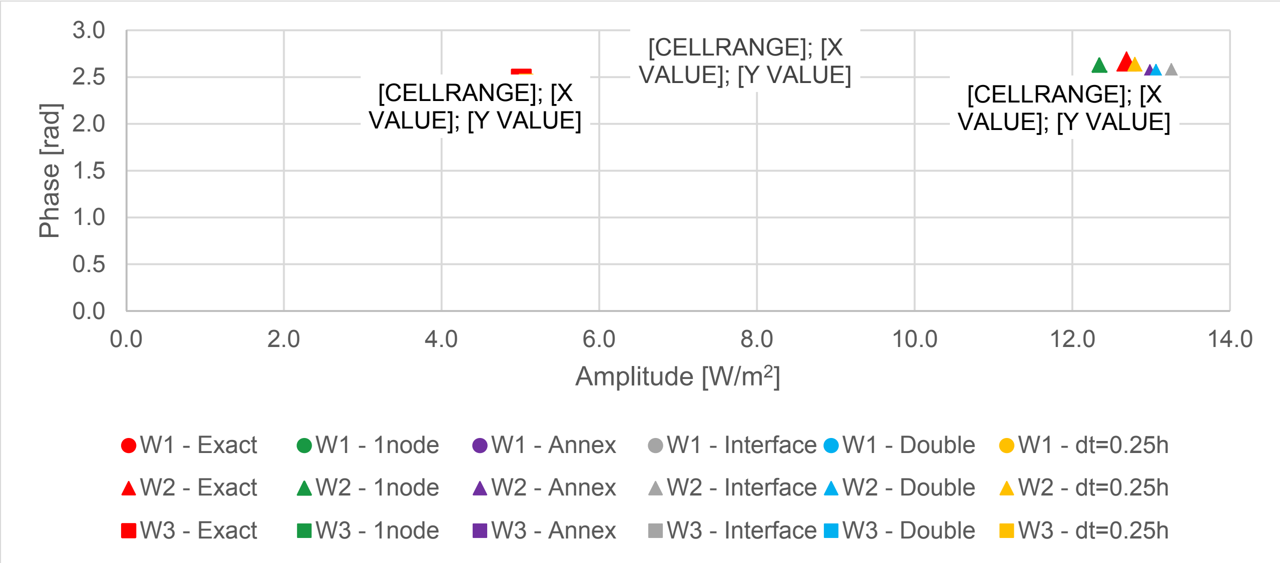

Figure 12: External flux sine amplitude and phase

5 Conclusions

In this work, the validity and accuracy of the opaque constructions' lumped parameters approximation proposed by EN ISO 52016-1:2017 have been tested under sinusoidal boundary conditions. The peculiarity of this method is the limited input data needed: the model requires only the global construction characteristics of thermal resistance and capacity, in addition to the class of mass position. This kind of simplification approach – which may seem convenient in the cases where detailed technical data are not available, as often happens for existing buildings – have been tested, demonstrating that it brings to results not consistent with the exact solution obtained with the analytical procedure of EN ISO 13786. The mismatches identified in the fluxes and temperatures profiles are incompatible with an hourly dynamic method, where the hourly variations have to be considered for the evaluation of the dynamic interactions.

As a consequence, Italy has implemented the standard with a National Annex that proposes an alternative method for the definition of the construction RC-network based on the actual layers' material and distribution. The analyses performed have demonstrated that this alternative method provides a more accurate approximation than the one proposed in the main text of the International Standard. However, the results still present a margin of error, which, as has been showed, cannot be filled only increasing the space discretization, but the time dependency of the problem has to be considered acting on the time discretization.

Nomenclature

c	Specific heat capacity [J/kg/K]
Fo	Layer Fourier number
d	Thickness of a layer [m]
h	Heat transfer coefficient [W/m^2/K]
j	Unit on the imaginary axis for a complex number [$j = \sqrt{-1}$]
q	Density of heat flow rate [W/m^2]
R	Thermal resistance [m^{2}K/W]
P	Period of the variations [s]
Y	Matrix of admittances
Z	Heat transfer matrix
δ	Periodic penetration depth of a heat wave in a material [m]
θ	Temperature [°C]
κ	Areal heat capacity [J/m^2/K]
λ	Thermal conductivity [W/m/K]
ξ	Ratio of the thickness of the layer to the penetration depth [-]
ρ	Density [kg/m^3]
Δt	Timestep [s]
Δx	Thickness of the layer material associated to each capacity node [m]

References

[1] EPB Center, (n.d.). https://epb.center/.

[2] D. van Dijk, M. Spiekman, D. Van Orshoven, W. Plokker, Subset of EPB standards on the energy use and the thermal performance of buildings and building elements, REHVA Eur. HVAC J. 52 (2015).

[3] EN ISO 52016-1:2017 - Energy performance of buildings - Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads - Part 1: Calculation procedures, (n.d.).

[4] D. van Dijk, M. Spiekman, L. Hoes - Van Oeffelen, EPB standard EN ISO 52016: Calculation of the building's energy needs for heating and cooling, internal temperatures and heating and cooling load,

REHVA Eur. HVAC J. 53 (2016) 18–22.

[5] EN ISO 52017-1:2017 - Energy performance of buildings - Sensible and latent heat loads and internal temperatures – Part 1: Generic calculation procedures., (n.d.).

[6] D. van Dijk, M. Spiekman, EN ISO 52016 and 52017 : Calculation of the building's energy needs for heating and cooling, internal temperatures and heating and cooling load, REHVA Eur. HVAC J. 53 (2016) 27–30.

[7] D. van Dijk, EPB standards: Why choose hourly calculation procedures?, REHVA Eur. HVAC J. 55 (2018) 6–12. https://www.rehva.eu/fileadmin/REHVA_Journal/REHVA_Journal_2018/RJ1/RJ.06-12/06-12_RJ1801.pdf.

[8] K.M. Letherman, A rational criterion for accuracy of modelling of periodic heat conduction in plane slabs, Build. Environ. 12 (1977) 127–130. doi:10.1016/0360-1323(77)90041-5.

[9] M.G. Davies, Optimum design of resistance and capacitance elements in modelling a sinusoidally excited building wall, Build. Environ. 18 (1983) 19–37. doi:10.1016/0360-1323(83)90015-X.

[10] P. Butler, K.M. Letherman, A criterion for the accuracy of modelling of transient heat conduction in plane slabs, Build. Environ. 15 (1980) 143–149. doi:10.1016/0360-1323(80)90032-3.

[11] M.G. Davies, A design procedure to model a transiently excited wall, Appl. Math. Model. 7 (1983) 182–188. doi:10.1016/0307-904X(83)90007-0.

[12] J. Wang, H. Chen, Y. Yuan, Y. Huang, A novel efficient optimization algorithm for parameter estimation of building thermal dynamic models, Build. Environ. 153 (2019) 233–240. doi:10.1016/J.BUILDENV.2019.02.006.

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

[14] A.P. Ramallo-González, M.E. Eames, D.A. Coley, Lumped parameter models for building thermal modelling: An analytic approach to simplifying complex multi-layered constructions, Energy Build. 60 (2013) 174–184. doi:10.1016/J.ENBUILD.2013.01.014.

[15] H. Asan, Numerical computation of time lags and decrement factors for different building materials, Build. Environ. 41 (2006) 615–620. doi:10.1016/J.BUILDENV.2005.02.020.

[16] EN ISO 13790:2008 - Energy performance of buildings - Calculation of energy use for space heating, (n.d.).

[17] J. Vivian, A. Zarrella, G. Emmi, M. De Carli, An evaluation of the suitability of lumped-capacitance models in calculating energy needs and thermal behaviour of buildings, Energy Build. 150 (2017) 447–465. doi:10.1016/J.ENBUILD.2017.06.021.

[18] U.S. Department of Energy, EnergyPlus: Energy Simulation Software, (n.d.).

[19] EN ISO 13786:2017 - Thermal performance of building components - Dynamic thermal characteristics - Calculation methods, (n.d.).

[20] EN ISO 13786:2007 - Thermal performance of building components — Dynamic thermal characteristics — Calculation methods, (n.d.).

Appendix

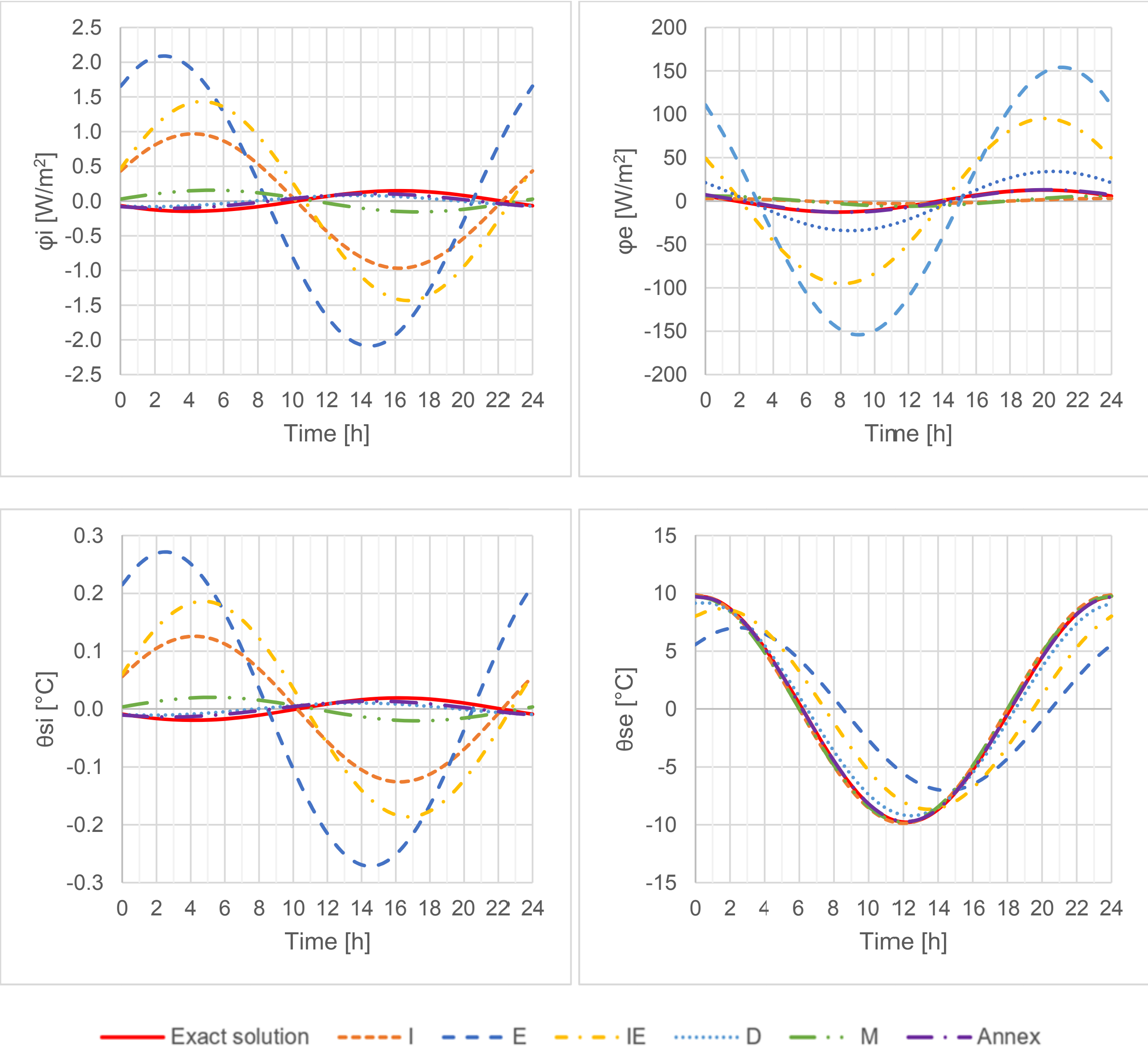

Figure 13: Time variations over 24h of the internal (top left) and external (top right) flux density and internal (lower left) and external (lower right) surface temperature for the test wall W2

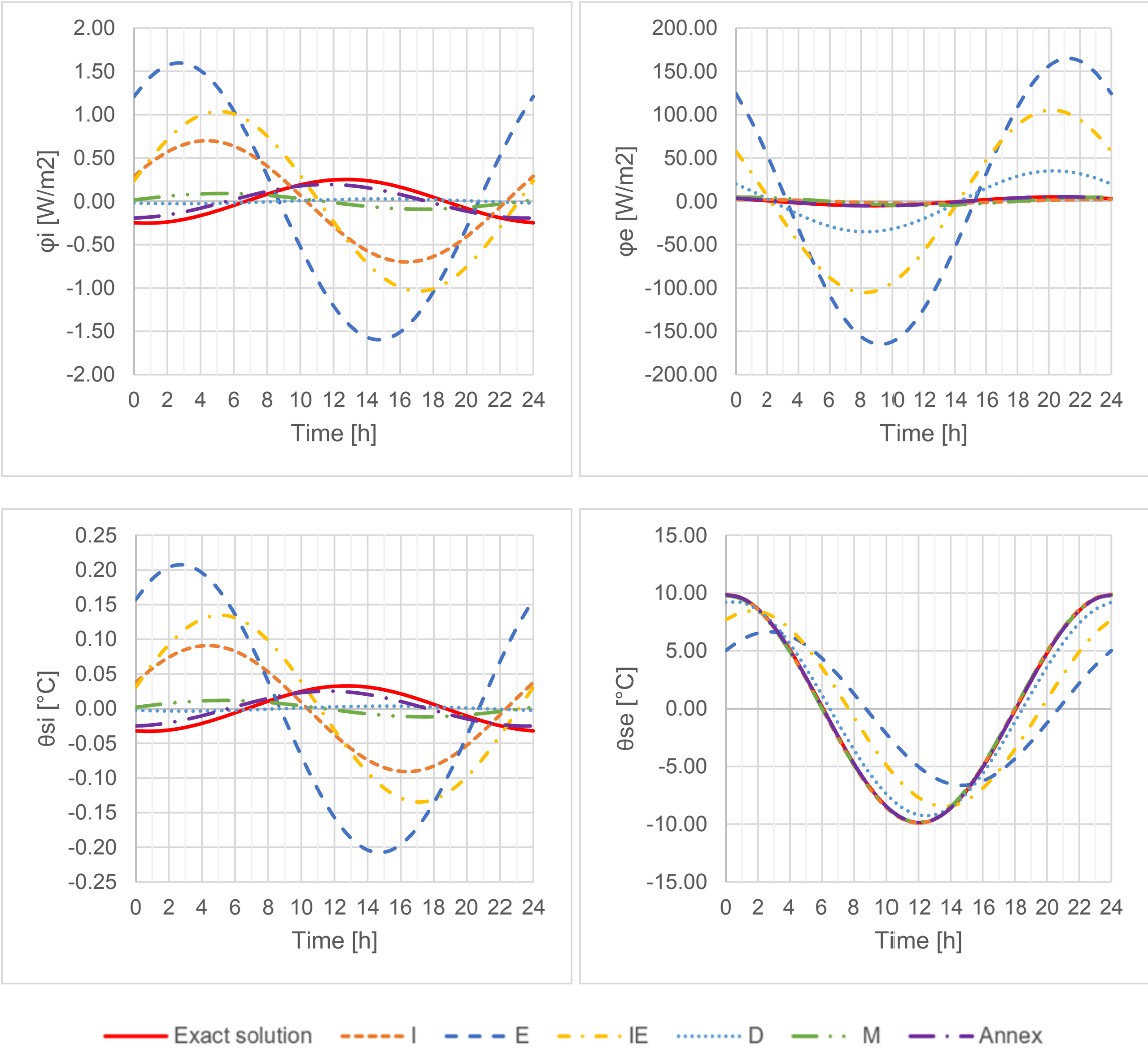

Figure 14: Time variations over 24h of the internal (top left) and external (top right) flux density and internal (lower left) and external (lower right) surface temperature for the test wall W3

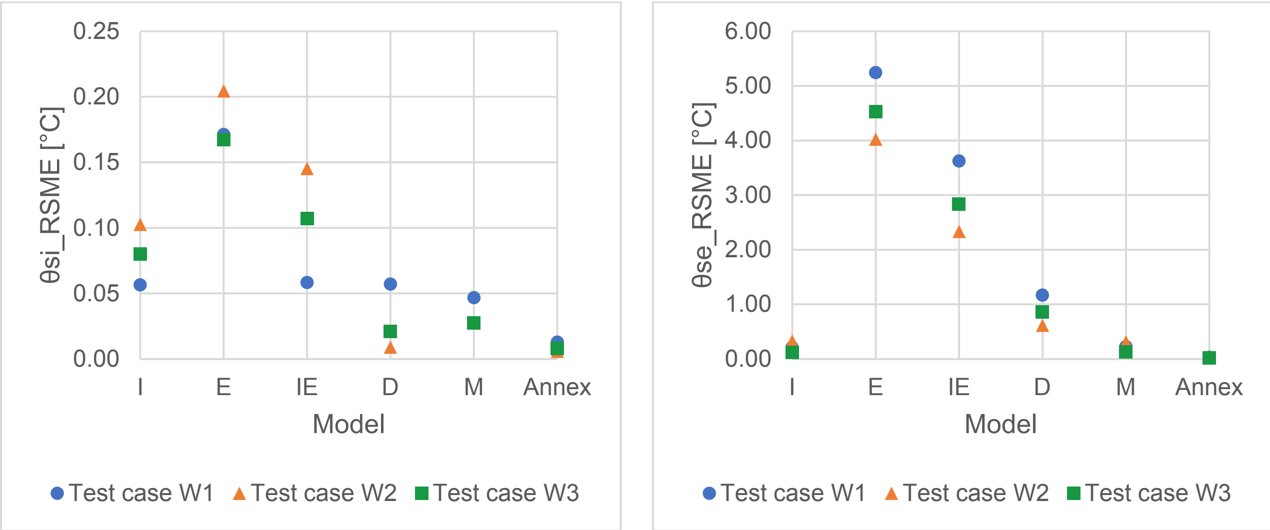

Figure 15: Root mean square error of the internal (right) and external (left) surface temperature