EQUIVALENT WALL METHOD FOR DYNAMIC CHARACTERIZATION OF THERMAL BRIDGES

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ABSTRACT

Although there are specific rules in the standard ISO 10211 for the characterization of thermal bridges, they are mainly focused on steady state calculations to obtain the linear thermal transmittance (Ψ) or the temperature factor at the internal surface (f_{Rsi}). These parameters are respectively indicators of the additional heat flow and the risk of internal surface condensation of thermal bridges.

However, in the calculations of building energy demand the dynamic thermal aspects of the envelope take a very important role. Moreover, a high percentage of the envelope is influenced by thermal bridges. Therefore it is necessary to take into account the implicit inertia of thermal bridges for accurate calculations.

This paper presents a methodology based on thermoelectric analogy to calculate an equivalent wall of three homogeneous layers, which have the same dynamic thermal behaviour as the thermal bridge. Furthermore, each thermal bridge is associated with an influence area within the envelope, so that they can be easily implemented in building energy simulation programs where the heat flow is usually considered one-dimensional.

KEYWORDS: Thermal bridges, equivalent wall, thermoelectric analogy, unsteady state, inertia.

1. Introduction

There are three main aspects that can be used for energy impact reduction: the control of emissions, use of renewable energy sources and increased energy efficiency. Energy conservation, defined as the strategy to adjust and optimize the energy use per person without affecting the socio-economic development, leads to a secure energy and desirable environmental goals.

The greatest potential for energy conservation in buildings is based on the reduced use of heating and cooling systems, which in Spain is more than 47% of building energy consumption [1], being even higher in the European Union.

There are three main characteristics which complicate the calculation of the energy demand: variables that change unsteadily, heat flow associated with non-linear temperature expressions and different heat transfer mechanisms which interact between them in complex ways [2].

To overcome these difficulties, building energy simulation (BES) programs have evolved, in part due to advances in computer technologies, adjusting the mathematical algorithms to achieve more accurate energy efficient design. It is necessary to conduct a comprehensive building analyse, because different aspects to consider are closely related, such as indoor air quality, noise or energy saving.

However, today is the day that is not yet properly calculated the impact of thermal bridges (TBs) in buildings energy demand. As far as energy saving is concerned it can only be asserted that the proportion of TBs impact increases when the insulation level of the envelope grows [3]. On the other hand, the influence on the phenomena related to the internal surface condensation and mould growth must also be considered [4].

Implementing correctly TBs in buildings energy demand models means a major effort by the designer that often is not rewarded. The research community in BES is constantly working to reduce energy demand differences between simulated values using computer tools and the real ones based on the use of the dwelling. There have been several studies to verify that these predictive tools offer high quality results [5].

Mainly there are two ways for the correct implementation of TBs in BES. On the one hand there is the possibility of incorporating 2D or 3D heat conduction capabilities into the existing programme structure [6]; although further improvements in solution speed and ease of problem specification is required before it can be routinely applied. On the other hand a homogeneous multilayer equivalent wall can be calculated that behaves similarly to the TB constructive solution. This latter option is analysed in this paper. Thus one-dimensional heat flow can be calculated instead implementing more complex models.

2. Objectives

The main goal is to introduce a methodology to implement TBs in the BES dynamic calculations taking into account the effects of thermal mass of each TB. Usually as a first approximation for the estimation of TBs, the value of linear thermal transmittance (Ψ) is used, which computes the additional heat flow of a specific TB, Eq. (1). But Ψ is a parameter calculated in steady state, so it does not consider the inertial aspects of TBs. Similarly it would be like trying to calculate the energy demand of a building considering only the thermal transmittance values (U) of the envelope elements.

However, nowadays it is totally analysed and demonstrated the importance of thermal inertia in the calculation of energy demand [7],[8].

$$\Psi = L_{2D} - \sum_{j=1}^{N} U_j \cdot l_j \qquad (1)$$

To include the effect of TBs taking into account not only the additional heat flow, but also their intrinsic inertia, a methodology to obtain a dynamic equivalent wall is defined, as well as its corresponding influence area (area of the envelope to which the thermal properties of the equivalent wall is assigned), which allows a simple implementation in BES software.

Summarizing, the issues discussed are as follow:

- Analyse the variety of TBs in a real building placed in Vitoria-Gasteiz (Basque Country).
- Steady state thermal characterization of the TBs by calculating the linear thermal transmittance (Ψ).
- For each type of TB its influence area is defined.
- Definition of a methodology to achieve a dynamic equivalent wall for a TB.

3. Equivalent wall method

Basically the concept of equivalent wall is based on defining a multilayer wall with the same steady and dynamic thermal behaviour as the original solution to be modelled. So the aim would be to calculate the equivalent thermal properties, such as conductivity (λ), density (ρ) and specific heat (c_p) for the different homogeneous layers of the equivalent wall. These data could be entered in BES programs for a direct response factors or conduction transfer coefficients calculation.

Once the equivalent wall is calculated, one-dimensional heat flow can be assumed for the TB. After getting the average value of parameters such as heat flow or surface temperatures in the influence area, a similar behaviour of the TB is achieved. The creator of the equivalent wall concept Kossecka defines it as follows: *"The thermally equivalent wall is a simple structure that has the same dynamic behaviour of a complex structure and can be used as a substitute for it in building energy simulation design"* [9].

Currently there are different methods for obtaining the characteristic parameters of the equivalent wall. Kossecka uses the definition of the *structural factors* to get response factors, and from them to calculate if necessary, the conduction transfer function coefficients [10]. In [3], Mao defines different types of TBs in the frequency domain. A method based on finite differences is used here to characterize TBs by amplitude and phase lag when it is excited by sinusoidal temperatures with different frequencies. Then an equivalent electrical circuit is defined through a frequency and lumped parameters transformation (ω-RC), from which the thermal properties can be obtained.

4. Preliminary considerations

To characterize a TB by numerical calculation, taking into account not only the heat loss that would result in steady state but also the inertial effect, the cut-off planes of the constructive solution must be fixed for the geometry definition. The standard ISO 10211 [11] locates the cut-off planes at least to 1 m distance from the central element if there is no nearer symmetry plane. It will be shown that shorter distance of these cut-off planes to a certain limit does not decrease accuracy in the Ψ value calculation, although it has influence on the dynamic response.

If only Ψ is used for characterizing the TB in BES programs there is no problem to identify the length which corresponds to the TB, but the error of a dynamic calculation using stationary parameters must be consider [12]. On the other hand, if the TB inertial properties are going to be implemented, the difficulty stays in the definition of its influence area.

ISO 13786 [13] indicates that for the dynamic characterization of a TB cut-off planes should be placed according to the specifications of the ISO 10211. The problem is to define the area to be assigned in the BES software to implement the TB. For example to characterize a 0.3x0.3 m^2 pillar TB, 2.3 m wide geometry is needed according to the standard. If a smaller surface is assigned in the BES software, such as the corresponding to the width of the pillar (0.3 multiplied by the pillar length), it would be an error of under estimating the real impact of the TB.

This is because when considering large distance for the cut-off planes, the influence of the homogeneous part of the wall over the TB has much weight, so the average heat flow is lower than if closer cut-off planes are chosen. When the area of influence assigned in the BES program is different to that used for the dynamic characterization of the TB an error is made [12].

5. Tools used in the study

5.1. Thermal bridge characterization in steady state

To obtain the linear thermal transmittance (Ψ) for each TB found around the building envelope, there are some possibilities:

I. Use of TB catalogues or handbooks that collect many constructive solutions with the corresponding Ψ values [14].
II. Use finite element, finite difference or finite volume programs where the calculation methodologies are more complex, but the achieved accuracy and flexibility are much higher.
III. Use of specific programs for the calculation of TBs. The most common are THERM or KOBRA.

The option of using catalogues with different construction details is initially the most attractive because of its simplicity. However, the variety of TBs in buildings is large, so taking Ψ values from catalogues normally leads to deviations from the real ones. Summarizing, the main drawback is that catalogues do not offer the flexibility to fit Ψ values to the real TBs details given in a building.

The possibility of using numerical methods programs such as FLUENT, FEMLAB, HEAT3, VOLTRA... allows any type of TB characterization from the point of view of material properties, geometry and boundary conditions. This fact results in a wide range of possibilities for heat transfer analysis considering steady or unsteady states and obtaining highly accurate values. The problem is the time consuming task of learning and familiarizing with the program user environment.

The last option is to employ specific software for the calculation and review of TBs. This combines the advantages of the above two alternatives, being more rigid than the numerical programs and not as simple as the use of a catalogue.

In addition, some TB configurations that appear in buildings are not described neither in the catalogue or the KOBRA program itself, which limits the possibilities to choose a simpler tool. Since it is necessary to develop the equivalent wall transient methodology simulations, the Computational Fluid Dynamics FLUENT 6.2 program [15] is to be used.

5.2. System identification methods

Thermoelectric analogy is used in the proposed methodology to obtain an equivalent RC circuit of the TB. From the analog electric circuit the thermal properties of the equivalent wall can be calculated. The resistances and capacities of the electric circuit are estimated by means of a system identification tool. Therefore, after the transient simulations are carried out by FLUENT, a system identification tool is used to estimate the parameters of the equivalent RC circuit.

For the latter purpose there are several tools available. The most used identification software is the Matlab ”System identification toolbox”, although there are more specific tools applied to heat transfer models. This is the case of Continuous Time Stochastic Modelling (CTSM) and Logical R Determination (LORD) tools.

In the case of CTSM, the system identification process is performed by searching the objective function that with the highest probability fits to the objective function dependent on the parameters to be identified. For this purpose the *prediction error method* is applied. LORD is based on a similar process, but in this case the search of dependent function parameters which minimize residuals respect to the objective function is made by applying the *output error method.*

In both cases it is necessary to define the lower and upper limits of the identification parameters. Regarding to the searching of minimum residuals, LORD presents a methodology based on Nelder-Mead and Monte Carlo methods [16] which allow fixing broader initial ranges, resulting in more robustness for the system identification process. For this reason the chosen program for this study is LORD [17].

6. Simulation characteristics

Numerical calculations are performed through the finite volume software FLUENT 6.2, which solves the simplified equation of energy Eq. (2) for each time step and at each node defined by the mesh. The mesh is generated using GAMBIT 2.2. The simplicity of the geometries allows rectangular and structured 5 mm size elements achieving optimal mesh quality.

$$\frac{\partial}{\partial t}(\rho \cdot h) = \nabla(\lambda \nabla T) \qquad (2)$$

where,

ρ is the density [kg/m^3]

h is the enthalpy [J/kgK]

λ is the thermal conductivity [W/mK]

T is the temperature [K]

6.1. Steady state

The calculation consists of applying a temperature difference of 20K between inner and outer environments using as surface thermal resistances the ones specified in ISO 6946 [18]. The aim of simulations in steady state is double.

Firstly is to calculate the value of Ψ for the geometry under ISO 10211 standard (hereafter referred as *standard)* and then compare it with the value obtained in the geometry where the cut-off planes are redefined according to the proposed methodology (hereafter referred as *proposed).* The condition is that both solutions must have similar Ψ value to consider that they have the same behaviour in steady state.

Secondly the same simulation is used for the definition of the proposed cut-off planes. The evolution of the inner surface contour temperature is analysed in section 7.

6.2. Unsteady state

A dynamic simulation is carried out in each TB analysing both the standard and proposed solutions. The simulation consists on exciting the outer surface according to the temperature of the Fig. 1 and keeping the indoor environment at the constant temperature of 293K.

The outer temperature excitation, composed by a set of harmonic signals of different periods and amplitudes, is used to optimize the process of system identification method. This type of temperature is represented by a variety of excitations under which the building envelope may be affected and simplifies the data analysis to obtain the thermal properties of the equivalent wall due to its variability. Moreover, the sudden variations of the transient excitation signals makes that the parameter estimation results will be conservative compared to more conventional outer temperature excitations. This is, if the equivalent wall behaves like the TB under the excitement of Fig. 1, it will in general do it for any excitement, as will be demonstrated in section 9.1.

The aim of the equivalent wall is that the interior heat flow and both the inner and outer surface temperatures must be similar to the average values obtained from the simulation model of the TB with the proposed geometry.

7. Redefinition of the cut-off planes

A steady state simulation is made with the geometry defined by ISO 10211. In this case the interesting result is not the transferred total heat flow to obtain Ψ but the inner surface temperature profile through which the new adiabatic cut-off planes are fixed according to the next definition:

Cut-off planes: It is considered that for a correct dynamic thermal characterization of a TB, only its area of influence must be taken into account. The location of the cut-off planes are replaced where the inner surface temperature deviates more than $\Delta T=0.2$ K from the temperature given in the cut-off planes defined by ISO 10211, when a 20 K temperature difference is applied between the environments.

The choice of $\Delta T<0.2$ K value is based on the fact that for this temperature difference the isotherms are basically parallel to the wall surfaces, resulting in a one-dimensional heat flow. This means that from the ISO 10211 cut-off planes to the proposed cut-off planes the TB has no influence. Therefore it is concluded that replacing cut-off planes at the previously defined zone involves no error for the characterization in steady state and is more convenient for the dynamic characterization [19].

In simulations carried out with the proposed geometry the average heat flow of the TB is higher than that achieved with the standard geometry. The advantage of this method is that the calculated influence area can be used directly in BES programs to include the impact of TBs.

8. Thermo-electrical analogy

After checking the similarity of the stationary response between the standard and proposed models by comparing the Ψ value, the dynamic simulation is carried out to obtain the interior heat flow and the inner and outer surface temperatures. These signals are the output to the system identification tool to calculate the equivalent wall properties based on a thermoelectric analogy which is represented in Table 1. As input signals the outdoor and indoor temperatures are used, which are known parameters in BES software.

When working with heat flow per square meter, the thermal resistance (R_t) and capacity (C) are also obtained per square meter. Thermal conductance (H) is inversely proportionate to thermal resistance ($H=1/R_t$). It is easier to specify the state equations using the conductance.

To find the thermal properties that characterize each of the layers of the equivalent wall, the electrical circuit must be defined to optimally represent the dynamic thermal behaviour of a TB. The parameters of this electrical circuit (H and C) are identified by LORD.

This tool solves the state differential equations obtained from the considered thermoelectric analogue circuit. The electrical circuit can be developed with different number of conductances and capacities. The larger the number of thermal capacities the better the results fit the output variable but the less significant the identified parameters are. To choose the most appropriate option three-layer equivalent wall configuration is chosen, which according to Carpenter [20] is the best option regarding to compromise between accuracy and computational effort. In addition Nygaard Nielsen [21] according to Eq. (3) estimates the number of capacities needed for the definition of the number of lumped parameters needed to represent each layer based on its thermal resistance and inertia.

$$N = \sqrt{\frac{2 \cdot R \cdot C \cdot f}{\pi}} \tag{3}$$

where,

N is the number of capacities to be defined for one layer

R is the thermal resistance of the layer [m^2K/W]

f is the frequency, chosen for daily variations [s^{-1}]

Referring to the most resistive or inertial layers, according to Eq. (3) it follows that with 4 capacities (5 conductances) distributed with the same value an optimal result will be achieved.

The equivalent electric circuit to be used for the characterization of TBs is illustrated in Fig. 2, where the conductances are given in W/m^2K and capacities in J/m^2K. So $H_{2-1}=1/R_{out}$ and $H_{18-17}=1/R_{in}$, being R_{out} and R_{in} the surface thermal resistances indicated in ISO 6946 in m^2K/W and used in the simulations. The alternating voltage V_{out} and direct voltage V_{in} represent respectively the outer temperature (which varies with time) and inner temperature (constant).

The state equations are set out applying Kirchoff's current law at each node, knowing that:

In conductances → $$i = \Delta V \cdot H \tag{4}$$

In capacities → $$i = C \cdot \frac{dV}{dt} \tag{5}$$

Finally, the thermal properties λ, ρ and c_p, are calculated for each layer of the equivalent wall. As shown in Table 1, there is a direct relationship between the electrical resistance of the circuit and the thermal resistance of each layer. The thermal conductivity of the layer is calculated depending on the fixed thickness of the layer (d), $R_t=d/\lambda$. The total equivalent wall thickness is considered to be distributed in three equally thick layers, being the thickness of a layer one third of the base wall of the simulated constructive solutions (0.25 m).

The information on ρ and c_p of each layer is given implicitly by the capacity. Regarding to thermal inertia the need is to know the heat capacity (product of density and specific heat), so that a constant value can be fixed for the specific heat and thus obtain the density value, or vice versa. Hence, a value of c_p=1000 J/kgK is set for all the layers of the equivalent wall.

9. Methodology to calculate the equivalent wall

The aim of the equivalent wall methodology applied to TBs is to implement their impact in BES taking into account their thermal inertia and simplifying data introduction to the program. Each type of TB will have different properties that make it unique.

The steps to obtain the equivalent wall from the constructive solution of a TB are as follows:

1. Determine the TBs location in the building envelope.
2. Define the geometry of each TB and the thermal properties of the materials (λ , ρ and c_p).
3. Following the indications of the standard ISO 10211, the geometry and the mesh is defined in each TB using the pre-processor GAMBIT which generates the *.msh file that can be read by FLUENT to solve the heat transfer equations.
4. The first simulation consists of applying a 20 K temperature difference between environments. The total heat flux Ψ can be obtained according to Eq. (1). Then the inner surface temperature profile is plotted to redefine the cut-off planes according to section 7. Over this new geometry, which is considered to be the influence area of the TB, the dynamic characterization will be carried out.

5. The new geometry of the TB is drawn again in GAMBIT, this time considering only the influence area. Once the mesh is exported to FLUENT, the steady state simulation is carried out to verify that the Ψ value is similar to that calculated from the standard geometry. If Ψ value is similar, it means that the simulated influence area has the same steady behaviour as the standard geometry.

6. With the proposed geometry a dynamic simulation is performed, exciting the TB with temperatures of Fig. 1, in order to obtain the evolution of interior heat flow and inner and outer surface temperatures.

7. Using thermoelectric analogy, the equivalent circuit of three layers is assessed imposing surface temperatures and interior heat flow as outputs. Each layer is defined by five thermal resistances and four capacities distributed equally. This identification is done with the system identification program LORD, which as a result returns the values of resistances and capacities of the equivalent circuit.

8. From thermal resistances and capacities thermal properties (λ, ρ, c_p) are calculated in each of the three layers of the equivalent wall. One more dynamic simulation is performed to validate that the equivalent wall behaves like the TB. Residuals of the interior heat flow and surface temperatures are analysed.

9. Once the characteristics of the equivalent wall are known as well as its influence area, TBs dynamic behaviour can be implemented in BES programs.

9.1. An explanatory example of the methodology

To validate numerically the proposed methodology the procedure is explained step by step using a TB as example. The chosen TB is the slab face between façade and floor meeting defined by the geometry of Fig. 3 and characterized by the thermal properties of Table 2.

To define the proposed cut-off planes, the inner surface temperature is analysed when applying a temperature difference of ΔT=20 K between environments. The cut-off planes are applied in the area where the temperature varies more than 0.2 K from the cut-off planes set by ISO 10211. Fig. 4 shows the temperature distribution in both the wall and the floor area.

In particular for this TB the geometry changes from 2.375 m to 0.655 m height and from 1.250 m to 0.868 m width (Fig. 5).

Fig. 6 shows the comparative evolution of interior heat flow between the standard and the proposed geometries when the transient temperature conditions of Fig. 1 are applied. Differences between the two curves are the reason why the cut-off planes are redefined to calculate the equivalent wall. By reducing the distance between the cut-off planes, the behaviour of the TB is closer to the real one according to the area to be implemented in BES programs.

Obviously, Fig. 6 shows that the impact of the TB per unit area in dynamic regimen is higher when the homogeneous wall area is reduced. However, the steady state characteristics of the standard and the proposed geometries are similar, as shown by the Ψ values of the equation Eq. (6). Also the isotherm distribution is shown in Fig. 7 due to a steady state simulation with a ΔT=20 K and compared with the same scale of temperature.

$$\begin{aligned} \Psi_{\text{standard}} &= 0.633\,\frac{\mathrm{W}}{\mathrm{m\,K}} \\ \Psi_{\text{proposed}} &= 0.620\,\frac{\mathrm{W}}{\mathrm{m\,K}} \end{aligned} \tag{6}$$

The glass fiber sheets, which are placed to minimize the influence of the slab face TB, produce higher impact on the two-dimensional heat flow deforming more the isotherms.

After verifying the similarity in steady state response, the dynamic simulation is carried out to supply data for the system identification program LORD. The software gives the values of resistances and capacities of the equivalent wall and then thermal properties of the layers can be calculated (Table 3).

Results are checked by repeating the transient simulation for the equivalent wall and comparing with the proposed TB (Fig. 8). Surface temperatures and interior heat flow of the equivalent wall line up with those obtained from the TB constructive solution. The deviations in the results can be analysed more accurately with the residuals values of Fig. 8d.

When the whole procedure is finished, all the information needed to implement the corresponding TB to a BES program is achieved. The area of influence to be implemented would be the corresponding to the product between the length along which the slab face TB is given and the height of the proposed geometry (0.655 m).

The methodology has been developed for an atypical dynamic temperature excitation. A typical exterior temperature excitation used in building physics calculations is the sol-air temperature **Error! Reference source not found.**. It is therefore advisable to check that the equivalent wall works not only to the excitation of Fig. 1, but also does for other transient conditions. This verification is carried out with the weather data from Vitoria-Gasteiz for an average day of summer and winter (Fig. 9).

After confirming that interior heat flow and surface temperatures fit to the real constructive solution for sol-air excitation (Fig. 10), the defined equivalent wall methodology for TBs is validated to evaluate their real impact in BES programs.

9.2. Other thermal bridges

It has been demonstrated the validity of the methodology to characterize the equivalent wall for the slab face TB. The next step is to analyse the results for other types of TBs.

Below there are other 10 constructive solutions of TBs with the same basis wall of the slab face TB (Fig. 11).

Firstly the steady state thermal performance is analysed and the Ψ value is compared with that obtained according to standard ISO 10211 (Table 4).

Secondly the residuals of the interior heat flow and surface temperatures are shown in Fig. 12 due to the dynamic response to the excitation of Fig. 1.

In the residual results the same scale for axes have been used when possible for an easier analysis, but in the low inertia TBs heat flow and temperatures are higher, leading to greater values of residuals. To compare the different magnitudes of interior heat flow, Fig. 13 shows the response of all the evaluated TBs and also the response of the basis wall (homogeneous) as reference.

Each TB has different characteristics, resulting in different responses to the same excitation (Fig. 13). When the impact of TBs are assessed in BES using the value of Ψ, two different constructive solutions with the same Ψ involve the same thermal behaviour. However, it has been shown that the inertia of the TBs plays an important role in energy calculations, so it is necessary to include its effect.

10. Conclusions

A methodology has been developed to calculate an equivalent wall with the same dynamic thermal behaviour of a TB. The calculated equivalent wall has the same average interior heat flow and surface temperatures of the analysed TB, but with one-dimensional heat flow which allows implementing this solution in BES programs. Thus, not only the additional heat flow of the TB would be taken into account, but also its inertial effects. The methodology can be applied to any type of TB.

One of the innovations of the proposed methodology is that for the dynamic characterization of a TB, cut-off planes must be relocated modifying ISO 10211 specification. By comparison of linear thermal transmittance (Ψ) it is shown that the proposed geometry behaves similarly to the standard geometry at steady state. The highest deviation is given in the meeting between façade and the roof TB with a difference of $\Delta\Psi$=0.019 W/mK (3.5% error). Furthermore, relocating the cut-off planes the influence area of the TB is defined so that the simulated geometry corresponds to the area to be implemented in BES programs.

On the other hand, despite the proposed and standard geometries have the same behaviour in steady state, it is shown that in dynamic regime it is different. In conclusion ISO 13786 approach for the dynamic characterization of the TBs under estimates their dynamic impact. Summarizing, if the cut-off planes are replaced according to the proposed method and thus the influence of the homogeneous part of the constructive solution is reduced, differences are noticed in the transient behaviour of the TB, but stationary properties are kept.

The thermal properties of the equivalent wall are calculated using thermoelectric analogy and solving the state equations by system identification methods. For any TB a generic equivalent wall of three layers is assigned with five resistances and four capacities in each layer. Notice that for each TB a different electrical circuit can be designed, simpler or more complicated, but the aim is to make the method general.

The residuals of interior heat flows and surface temperatures for different TBs are presented to a random outdoor temperature excitation. The worst result occurs in the blind box and lintel TB, which is a low inertia TB. In this case, the average residual for inner surface temperature, outer surface temperature and interior heat flow are 0.5 K, 1.4 K and 4.06 W/m^2 respectively. In the rest of TBs the residuals are much lower, being respectively the inner surface temperature, outer surface temperature and interior heat flow residuals, 0.1 K, 0.6 K and to 0.45 W/m^2.

The next step would consist of implementing the equivalent wall thermal properties in BES programs to analyse the TB impact in a building. Results could be compared with other methodologies which use Ψ as a parameter to evaluate TBs impact.

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TABLES CAPTION

Electrical circuit			Heat Transfer		
Parameter	**Symbol**	**Units**	**Parameter**	**Symbol**	**Units**
Electrical current	I	A	Heat flux	Q	W
Potential difference	ΔV	V	Temperature difference	ΔT	K
Electrical resistance	R	Ω	Thermal resistance	R_t	K/W
Capacitance	C	F	Thermal capacity	C	J/K

Table 1 – Thermoelectric analogy

Layer	Material	Thickness [m]	λ [W/mK]	ρ [kg/m^3]	c_p [J/kgK]
1	Perforated brick	0.115	0.667	1140	1000
2	Mortar	0.015	1.000	1700	1000
3	Polyurethane	0.040	0.028	30	800
4	Air cavity	0.020	0.118	1.23	1006
5	Ceramic block	0.045	0.445	1000	1000
6	Plaster	0.015	0.300	900	1000
7	Parquet	0.010	0.130	500	1600
8	Glass fiber	0.020	0.050	104	840
9	Mortar	0.050	1.000	1700	1000
10	Long hollow brick	0.310	1.128	1040	1000

Table 2 – Thermal characteristics of the slab face TB

Layer	Thickness [m]	λ [W/mK]	ρ [kg/m^3]	c_p [J/kgK]
1	0.083	0.650	1459.2	1000
2	0.083	0.158	1958.4	1000
3	0.083	0.067	0.5	1000

Table 3 – Thermal properties of the equivalent wall for the slab face TB

TB	1	2	3	4	5	6	7	8	9	10
$\Psi_{standard}$ [W/mK]	1.30	0.15	0.08	0.64	0.53	0.07	-0.07	0.36	0.26	0.47
$\Psi_{proposed}$ [W/mK]	1.29	0.14	0.08	0.65	0.51	0.06	-0.08	0.36	0.26	0.47
$\Delta\Psi\cdot 10^3$ [W/mK]	0.89	9.01	0.57	-4.05	18.8	12.6	9.98	1.42	1.37	-0.08

Table 4 – Ψ comparison between the standard and proposed geometry

List of Figure Captions

FIGURES CAPTION

Figure 1 – Thermal boundary conditions for dynamic calculations

Figure 2 – Electric circuit model for three layers equivalent wall

Figure 3 – Constructive solution of the slab face TB

Figure 4 – Inner surface temperature distribution in the slab face TB

Figure 5 – Slab face geometry for the proposed method

Figure 6 – Interior heat flow comparison between the standard and proposed geometry

Figure 7 – Isotherms in the slab face TB a) standard geometry b) proposed geometry

Figure 8 – Comparison between the proposed slab face TB and its equivalent wall a) outer temperature b) inner temperature c) interior heat flow d) residuals

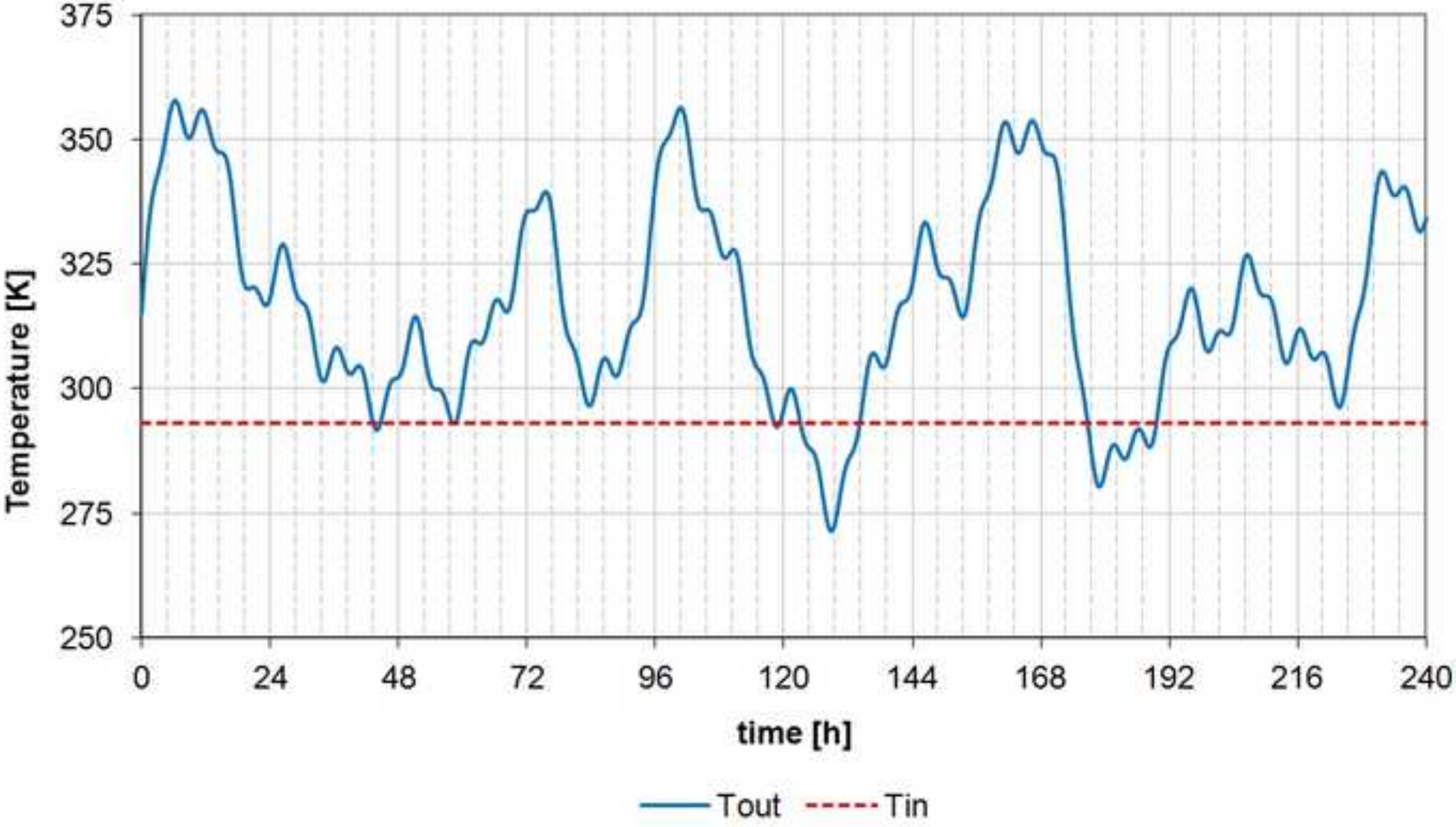
Figure 9 – Winter and summer typical sol-air temperature in Vitoria-Gasteiz

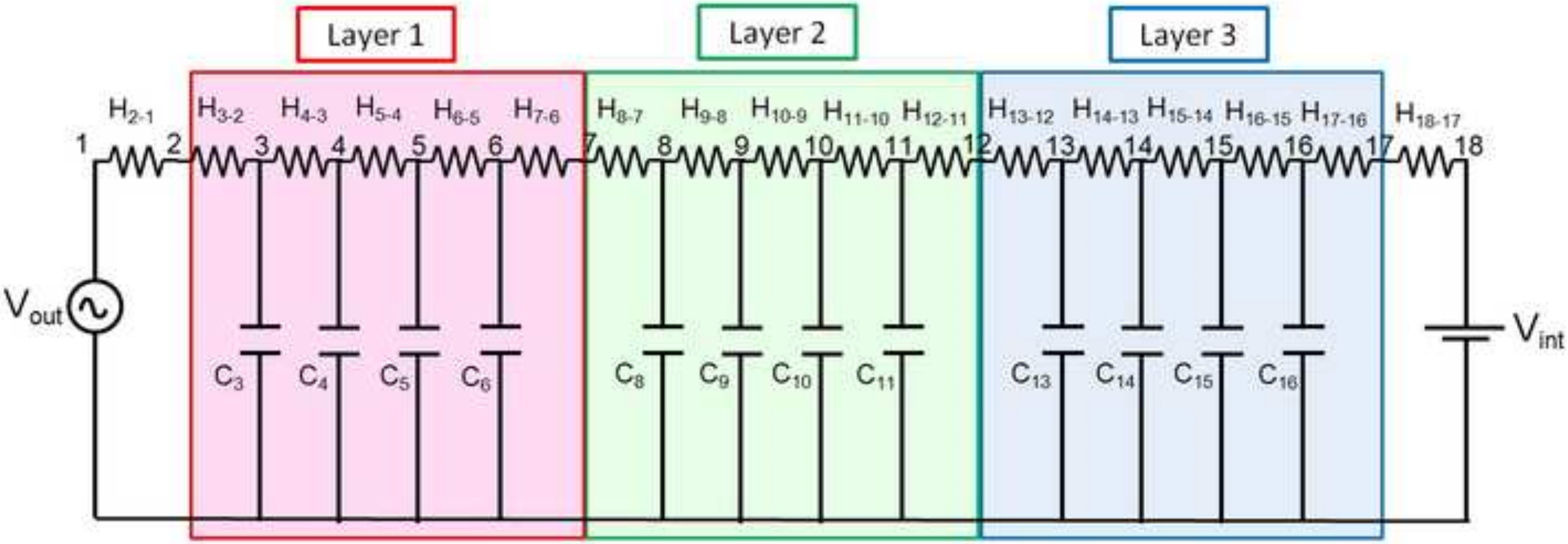
Figure 10 – Residual comparison between the slab face TB and its equivalent wall for a sol-air excitacion

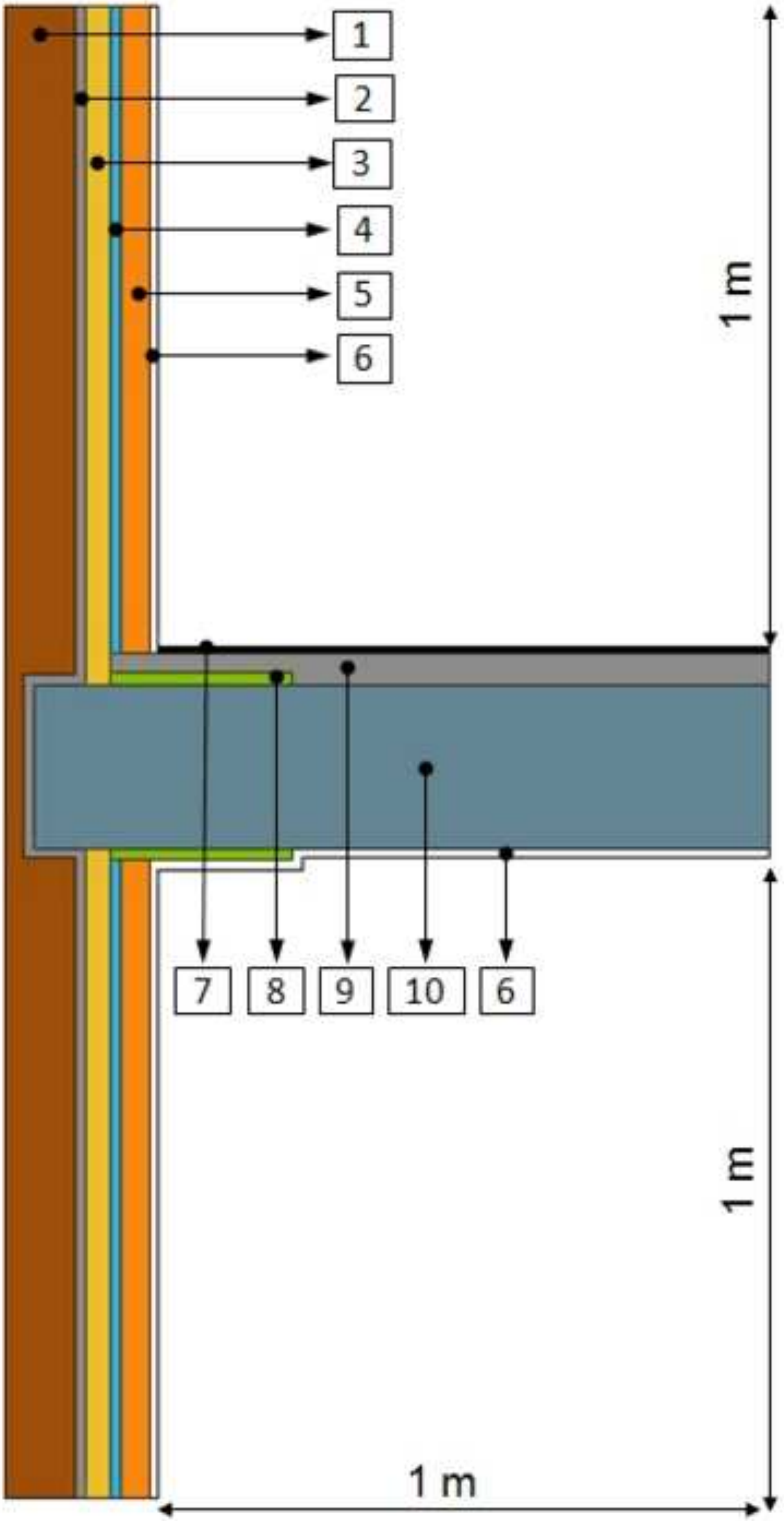
Figure 11 – Constructive solutions of the analyzed TBs

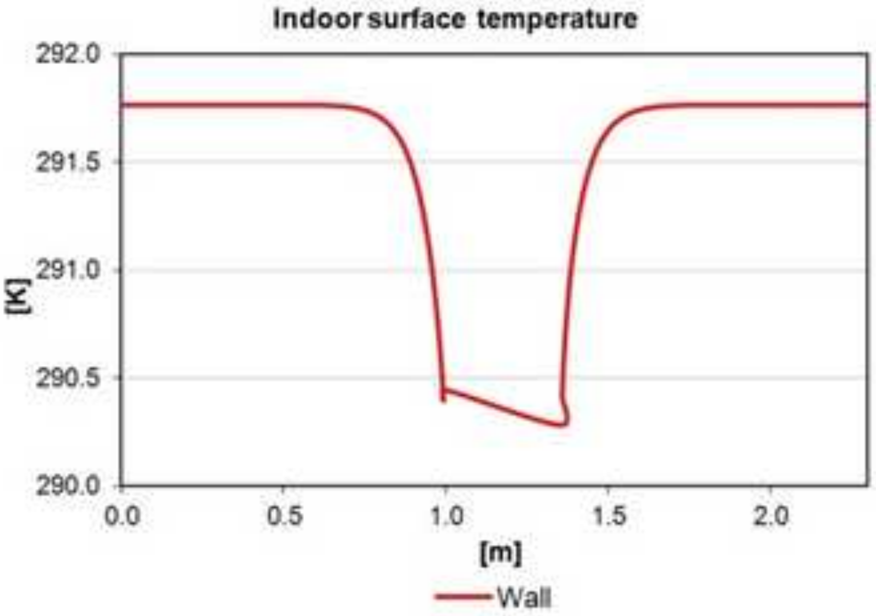
Figure 12 – Residuals of the analysed TBs

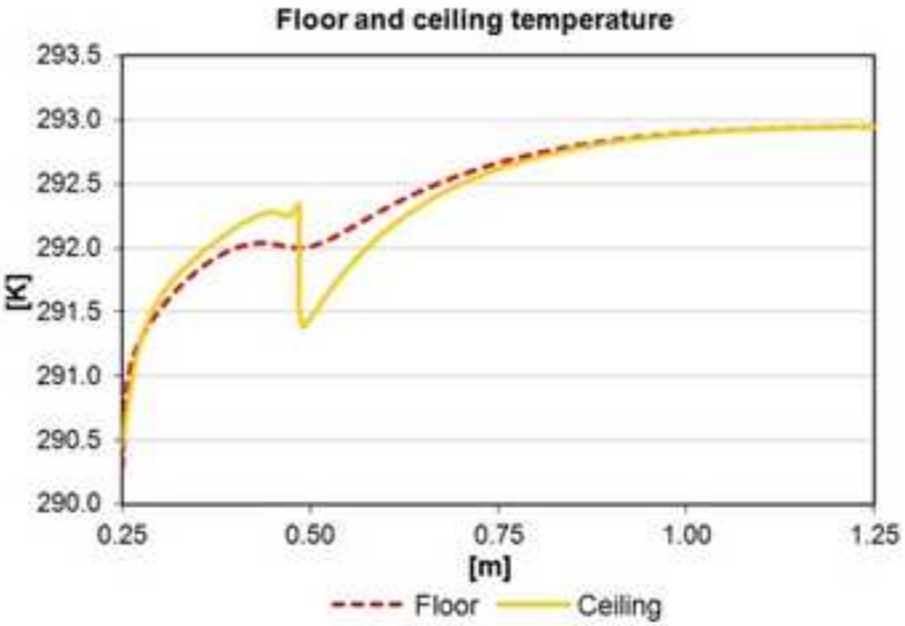
Figure 13 – Interior heat fluxes of the thermal bridges and the homogeneous wall

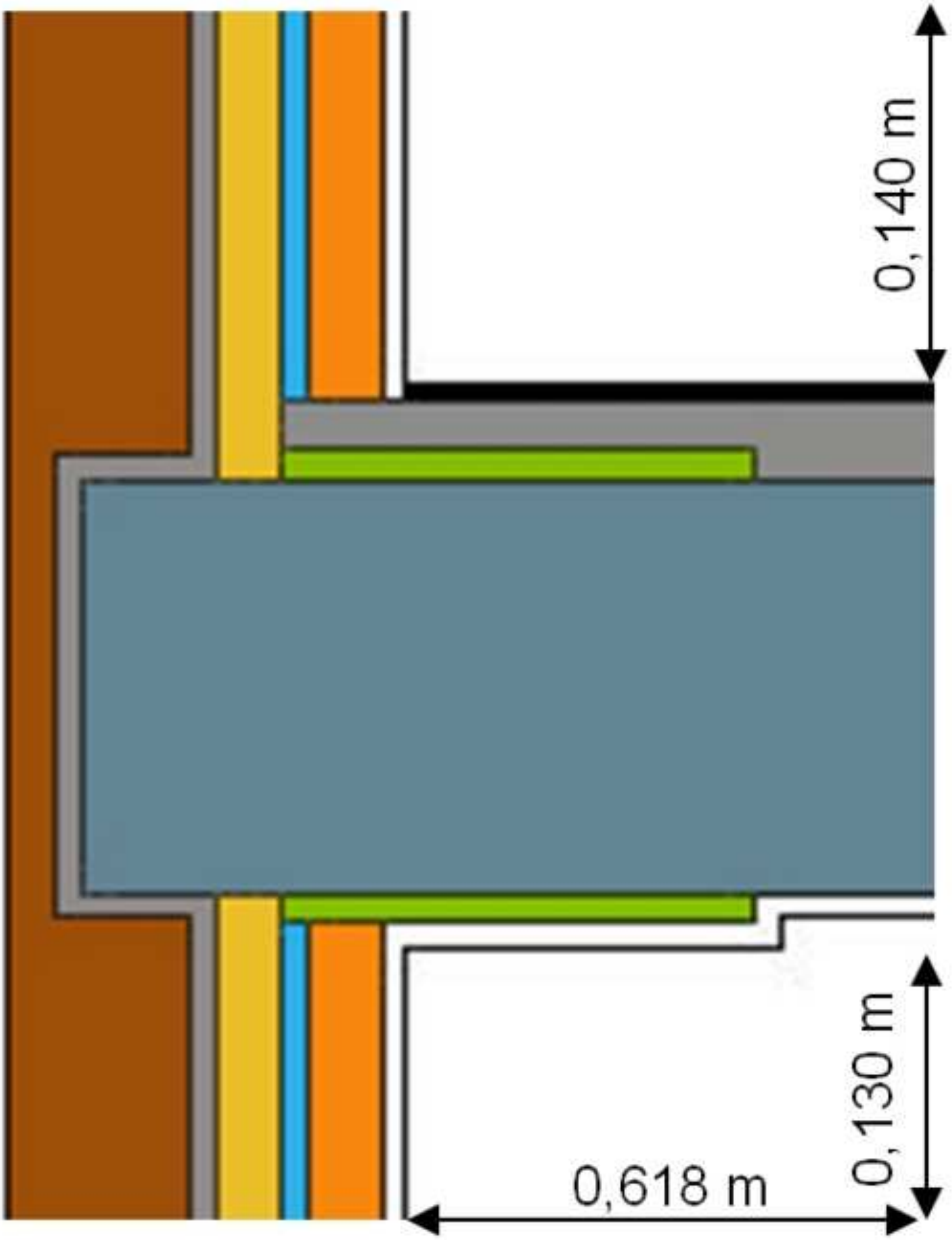

375
350
325
300
275
250
Temperature [K]
0
24
48
72
96
120
144
168
192
216
240
time [h]
Tout
Tin

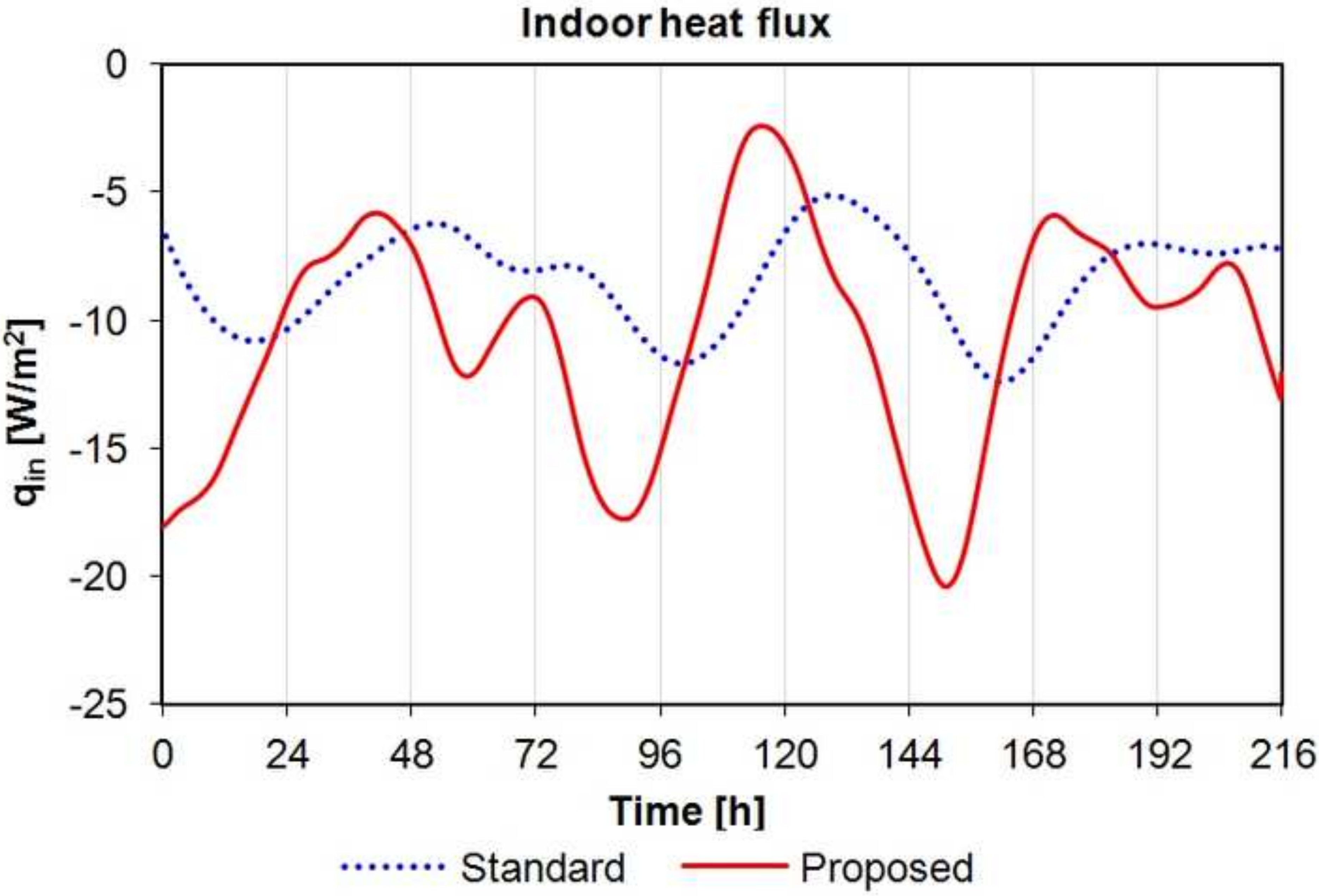

Layer 1
Layer 2
Layer 3
H2-1
H3-2
H4-3
H5-4
H6-5
H7-6
H8-7
H9-8
H10-9
H11-10
H12-11
H13-12
H14-13
H15-14
H16-15
H17-16
H18-17
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Vout
C3
C4
C5
C6
C8
C9
C10
C11
C13
C14
C15
C16
Vint

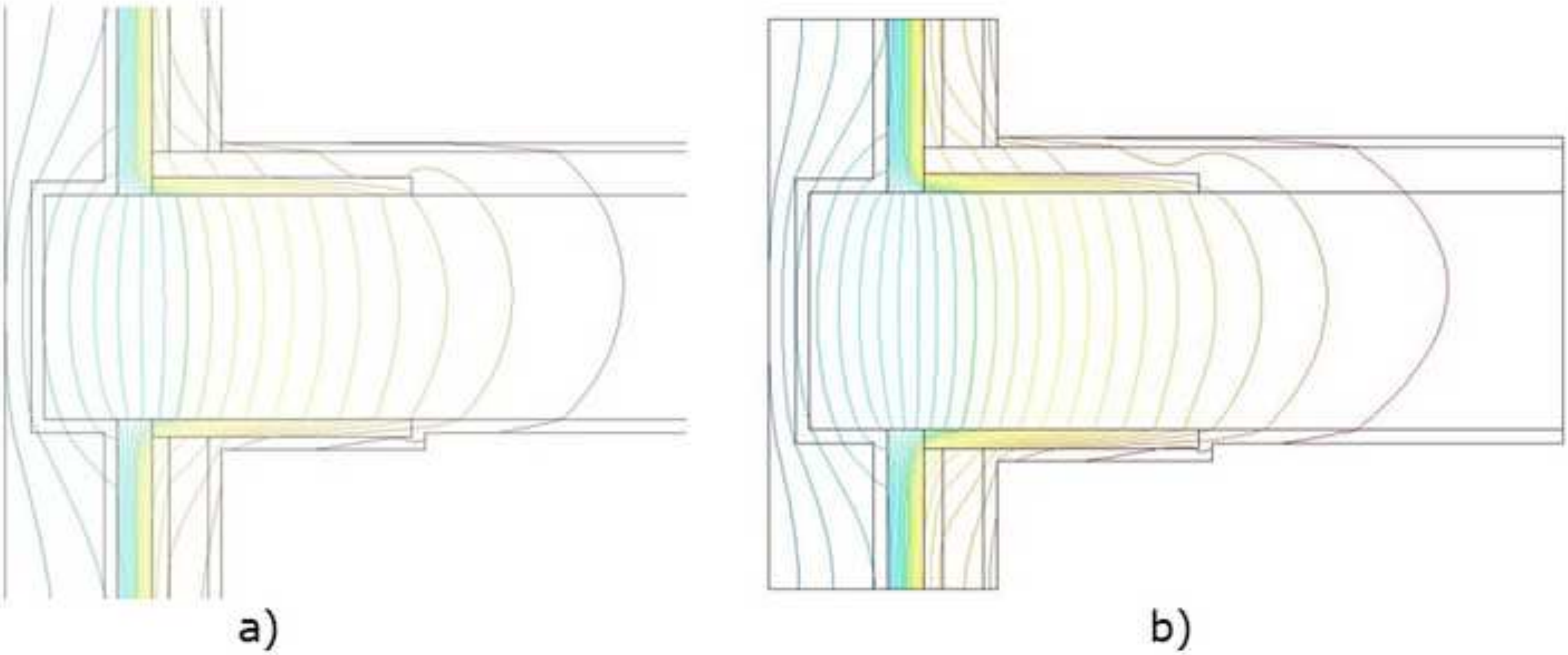

1
2
3
4
5
6
1 m
7
8
9
10
6
1 m
1 m

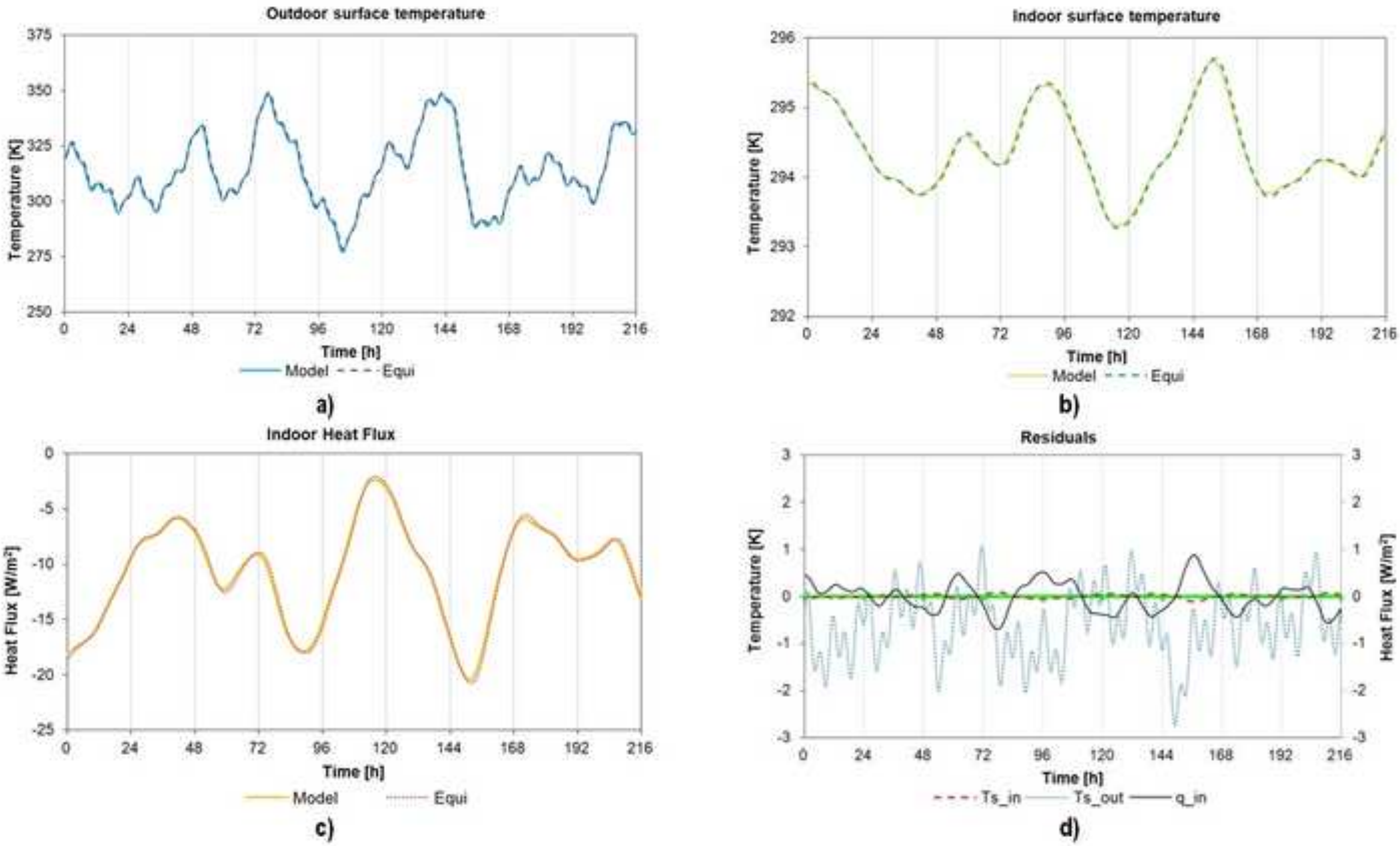

Indoor surface temperature
292.0
291.5
291.0
290.5
290.0
[K]
0.0
0.5
1.0
1.5
2.0
[m]
Wall

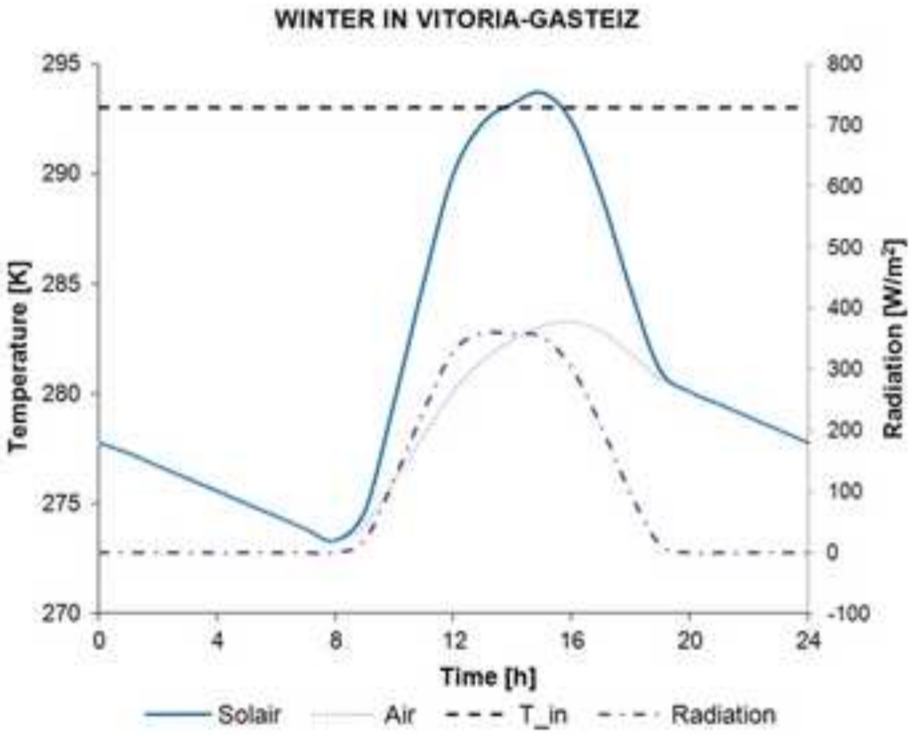

Floor and ceiling temperature
293.5
293.0
292.5
292.0
291.5
291.0
290.5
290.0
[K]
0.25
0.50
0.75
1.00
1.25
[m]
Floor
Ceiling

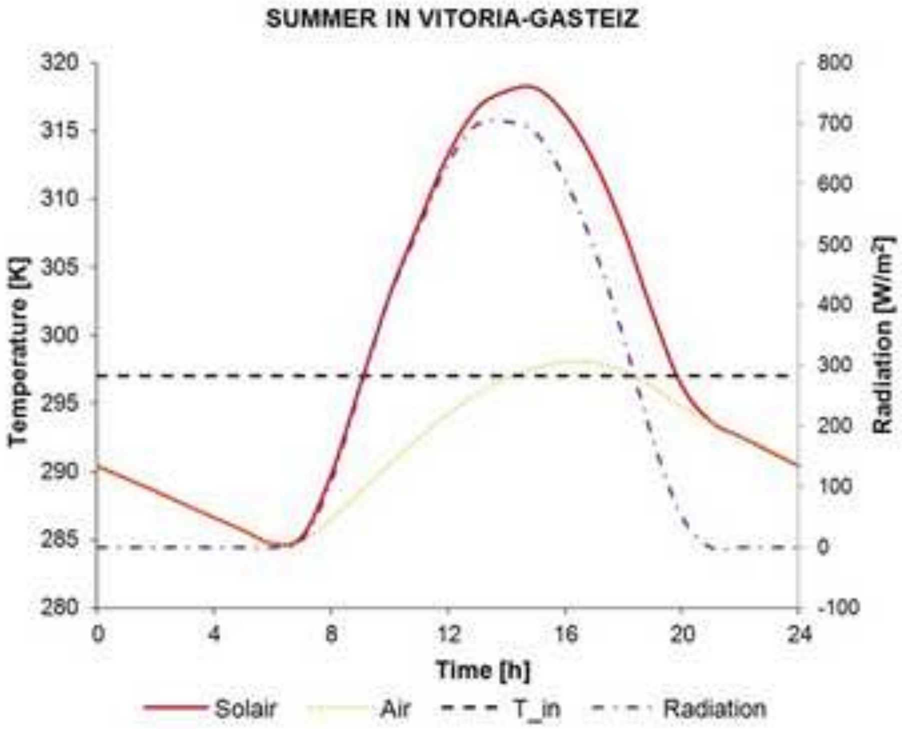

0,140 m
0,130 m
0,618 m

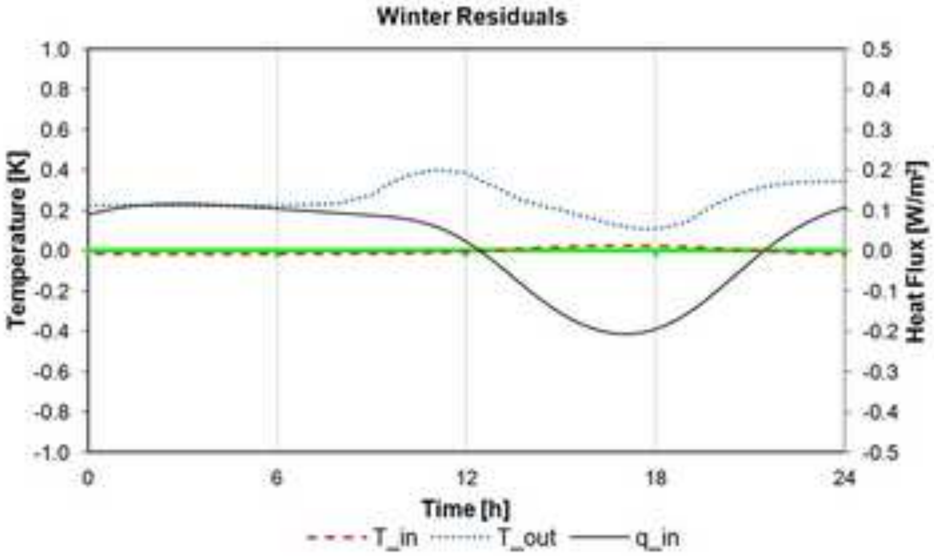

Indoor heat flux
0
-5
-10
-15
-20
-25
q_{in} [W/m^2]
0
24
48
72
96
120
144
168
192
216
Time [h]
Standard
Proposed

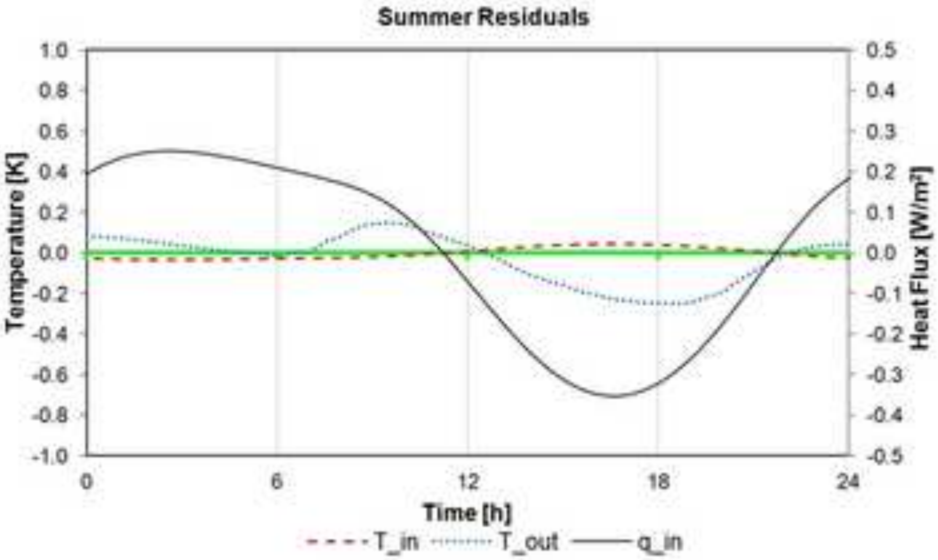

a)
b)

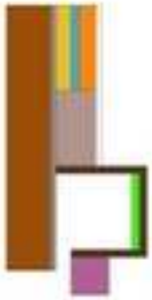

Outdoor surface temperature
Temperature [K]
375
350
325
300
275
250
0
24
48
72
96
120
144
168
192
216
Time [h]
Model
Equi
a)
Indoor surface temperature
Temperature [K]
296
295
294
293
292
0
24
48
72
96
120
144
168
192
216
Time [h]
Model
Equi
b)
Indoor Heat Flux
Heat Flux [W/m²]
0
-5
-10
-15
-20
-25
0
24
48
72
96
120
144
168
192
216
Time [h]
Model
Equi
c)
Residuals
Temperature [K]
Heat Flux [W/m²]
3
2
1
0
-1
-2
-3
0
24
48
72
96
120
144
168
192
216
Time [h]
Ts_in
Ts_out
q_in
d)


WINTER IN VITORIA-GASTEIZ
Temperature [K]
295
290
285
280
275
270
Radiation [W/m^2]
800
700
600
500
400
300
200
100
0
-100
0
4
8
12
16
20
24
Time [h]
Solair
Air
T_in
Radiation

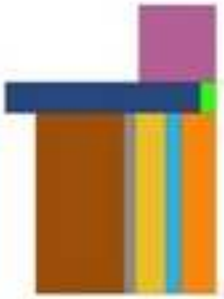

SUMMER IN VITORIA-GASTEIZ
Temperature [K]
320
315
310
305
300
295
290
285
280
Radiation [W/m^2]
800
700
600
500
400
300
200
100
0
-100
0
4
8
12
16
20
24
Time [h]
Solair
Air
T_in
Radiation


Winter Residuals
Temperature [K]
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Heat Flux [W/m²]
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
0
6
12
18
24
Time [h]
T_in
T_out
q_in

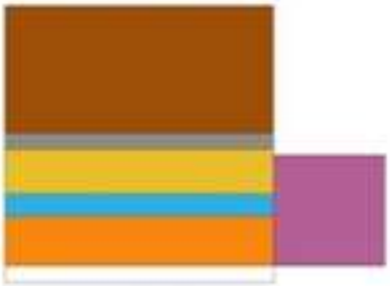

Summer Residuals
Temperature [K]
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Heat Flux [W/m²]
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
0
6
12
18
24
Time [h]
T_in
T_out
q_in



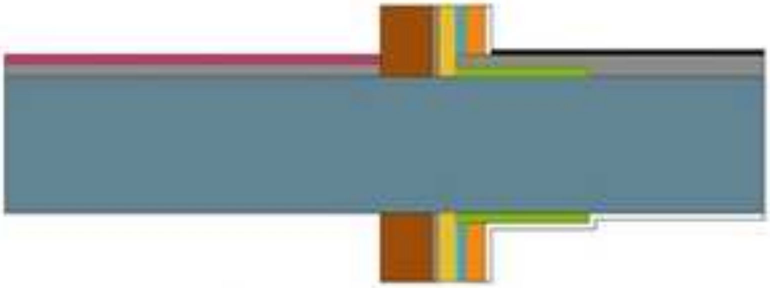
TB1: Blind box and lintel



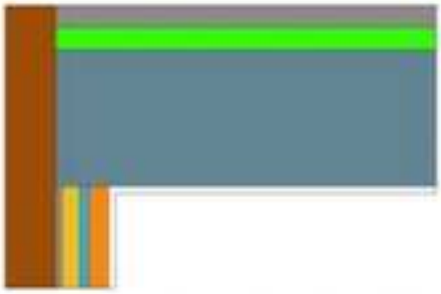
TB2: Windowsill



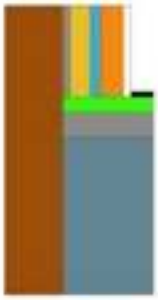
TB3: Window jamb



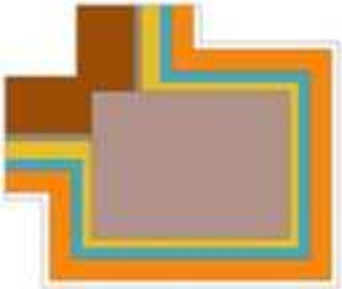
TB4: Balcony



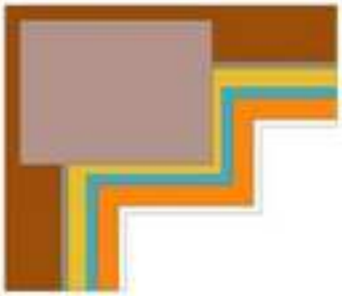
TB5: Façade+Roof



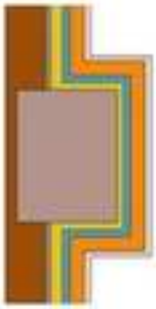
TB6: Façade+Floor



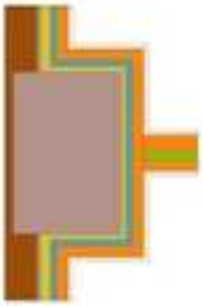
TB7: Pillar in recess corner



TB8: Pillar in projected corner

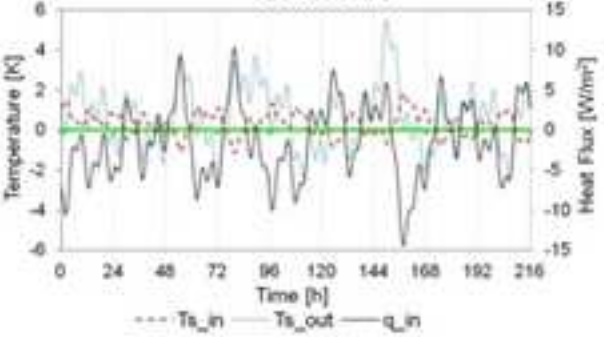


TB9: Pillar

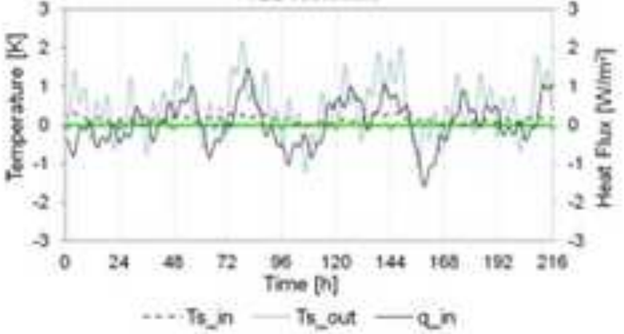


TB10: Pillar+Internal wall

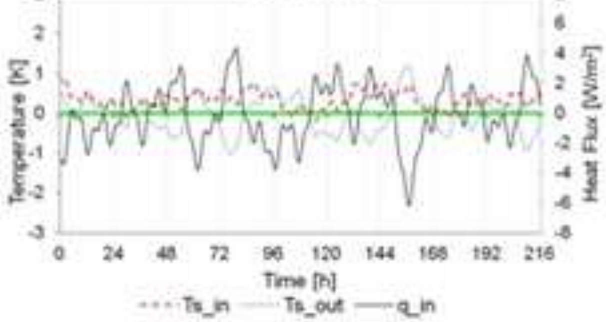
TB1 Residuals



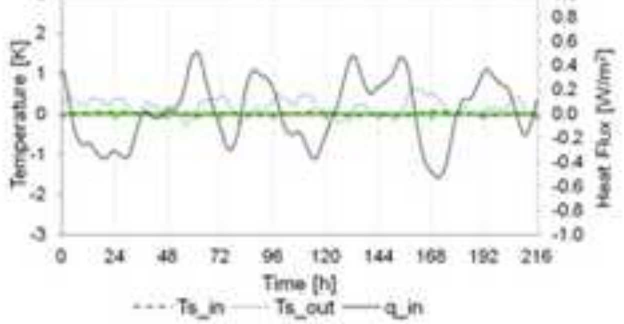
TB2 residuals



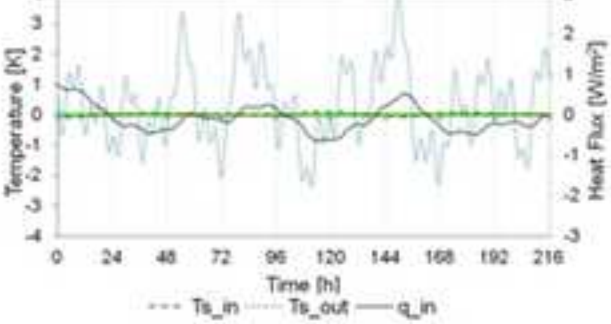
TB3 residuals



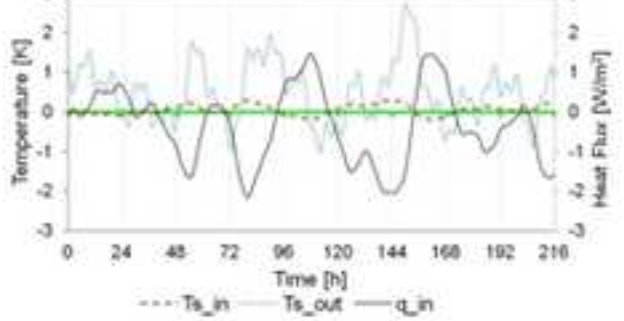
TB4 residuals



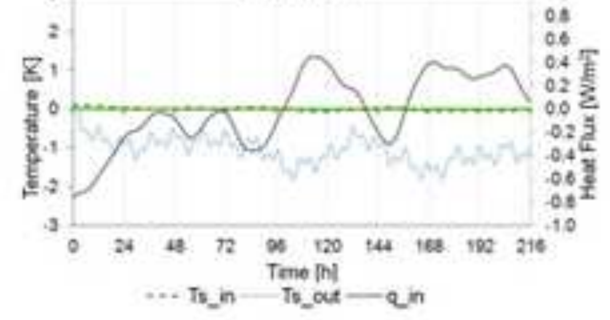
TB5 residuals



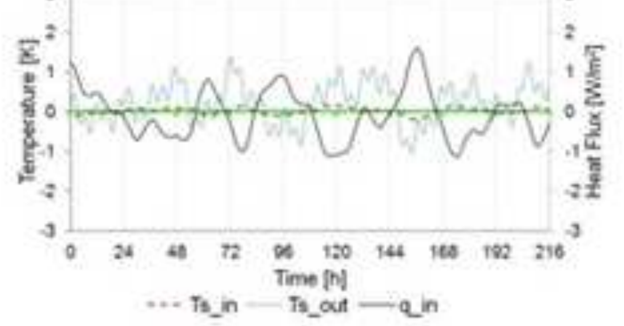
TB6 residuals



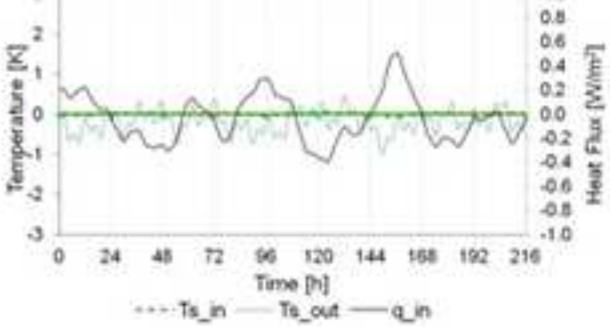
TB7 residuals



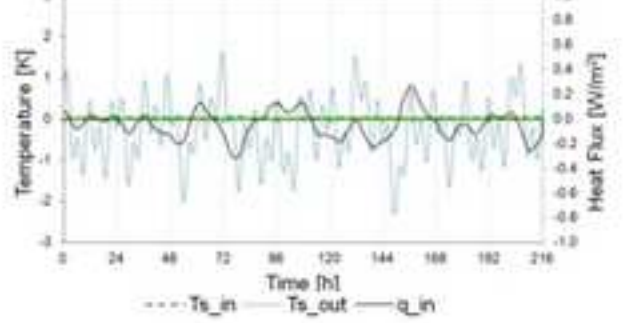
TB8 Residuals

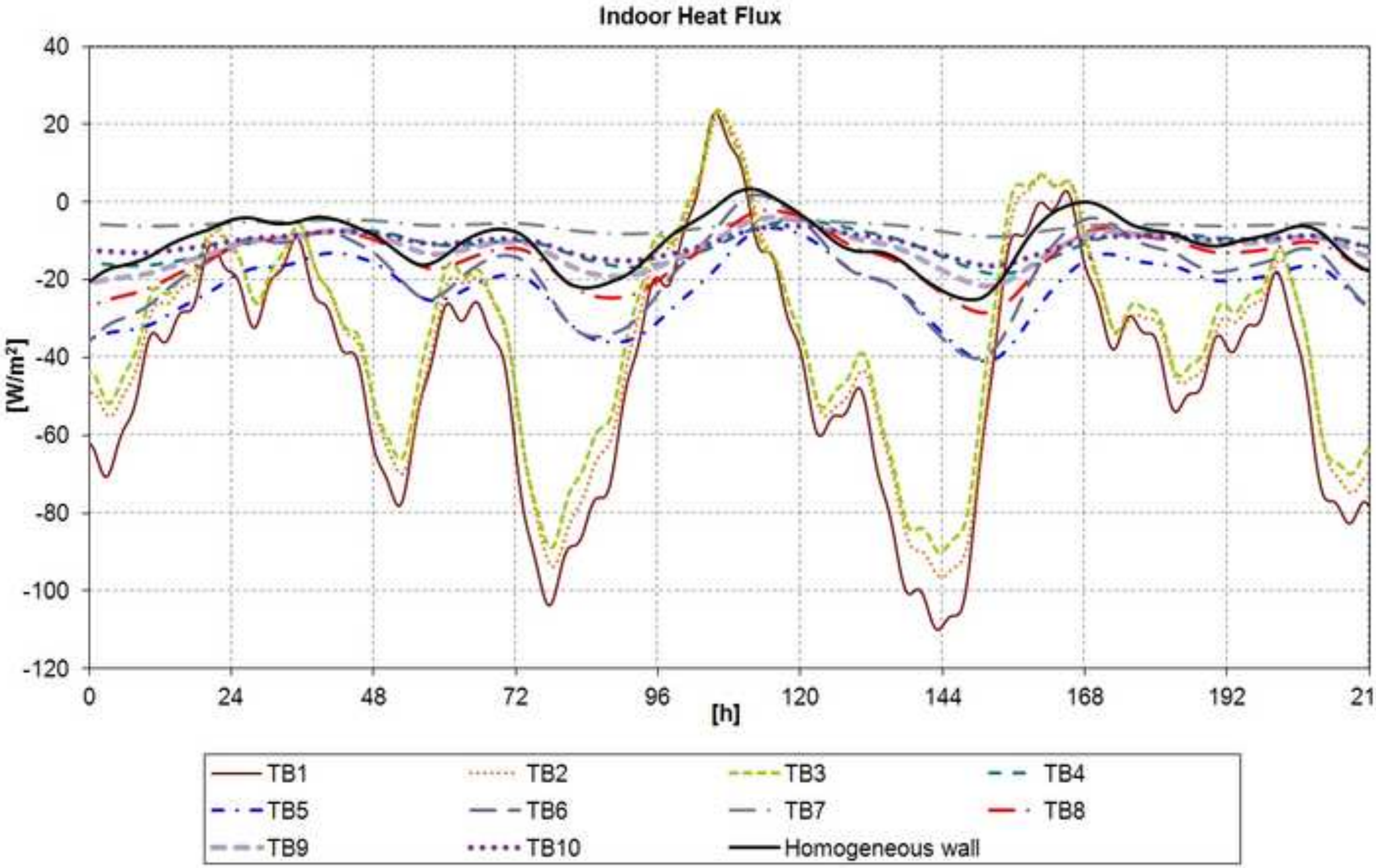


TB9 residuals



TB10 residuals




Indoor Heat Flux
40
20
0
-20
-40
-60
-80
-100
-120
[W/m²]
0
24
48
72
96
120
144
168
192
216
[h]
TB1
TB2
TB3
TB4
TB5
TB6
TB7
TB8
TB9
TB10
Homogeneous wall

***Highlights (for review)**

- An equivalent wall methodology for thermal bridges is developed.
- The influence area of the thermal bridges is redefined by the cut-off planes.
- The equivalent wall can easily be implemented in building energy simulations.
- Eleven types of thermal bridges have been evaluated for the methodology validation.