Simulation Tests for the Determination of the U-Value of Walls by Using Response Factors Theory with Noisy Boundary Conditions

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Abstract

The thermal behaviour of buildings' opaque components is still one of the most important aspects in the overall energy performance of a building. In the framework of the reduction of greenhouse gas emissions and global energy consumptions, the optimization of the walls' composition can lead to more sustainable and highly-efficient buildings, both for new and existing constructions. One of the parameters describing the thermal performance of a building's wall is the thermal transmittance or U-value. The determination of the U-value is usually done through analytical methods according to the Standard UNI EN 6946, especially when components are characterized by simple geometries and uniform layers. However, when such a hypothesis does not stand anymore, experimental procedures in controlled environments must be adopted, e.g., climatic chambers. Stationary methodologies, like the ones suggested either by the standard UNI 1934 or the UNI EN ISO 8990, are extremely accurate and reliable, but the main drawback is the long-time procedure required, especially for highly-insulated walls with larger thicknesses. To overcome this issue and to save both time and energy required to run the experiment, techniques based on the response factors theory have been recently gained interest with the aim of finding an alternative methodology to the standard time-consuming one, without compromising the accuracy of results. The simple application of a triangular temperature solicitation at one side of the wall, allows the determination of the thermal response of the wall in time, as well as, the assessment of the U-value, within a significant shorter time. Besides, such dynamic methods are capable of considering also the thermal capacity of the wall, which also influences its thermal performance. Nevertheless, the technique relies on very strict experimental conditions, e.g., high signal to noise ratios.

For this reason, this work investigates the effect that noisy boundary conditions, in terms of temperature, have on the determination of the thermal transmittance of walls. To do this, simulation tests in dynamic regime were developed in a COMSOL Multiphysics® environment. By applying multiple levels of noise to the boundary conditions, simulations are run and results in terms of perturbated heat fluxes and computed U-values are analysed. Results are then compared to the reference U-value obtained through a steady-state simulation. The main outcomes of this research can lead to practical guidelines for an alternative experimental technique aimed at measuring thermal transmittances of opaque buildings' components in controlled ambient conditions.

1. Introduction

The opaque envelope of a building plays a pivotal role in its energy performance, particularly during winter when the minimization of the heat loss is crucial. Due to the important impact that buildings have on energy consumptions (Eurostat, 2022; González-Torres et al., 2022), an effective thermal insulation within the envelope reduces heating demands, ensuring indoor thermal comfort. Conversely, in summer, the envelope must not only prevent heat from entering but it also acts as a thermal reservoir, absorbing and releasing heat to regulate indoor temperatures and reduce cooling needs, according to the thermal capacity of the component.

The design of an optimized thermal envelope is a fundamental step in energy efficient and sustainable buildings, like in new constructions, but also in buildings' retrofitting.

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One of the main thermal properties describing the buildings' thermal performance is the thermal transmittance, or the U-value. The current procedure to assess such a property is through an analytical way according to the EN 6946:2018 (CEN, 2018) where the thermal transmittance is computed by either knowing or assuming thermal conductivities and thickness of the composing layers of the wall. Nevertheless, often this information is not known, e.g., in retrofit design, or even if data are known, the analytical procedure cannot be applied because of significant irregular geometries and not-uniform layers, e.g., prefabricated walls with frames.

For this reason, experimental procedures in controlled environments, like laboratories, are preferable. The most adopted and extremely reliable techniques to measure the U-value of a building's envelope components are hot-boxes according to the Standards EN ISO 8990: 1996 (CEN, 1996), UNI EN 1934:2000 (Ente nazionale italiano di unificazione, 2000). These procedures rely on the stabilization of two chambers, where a sample is interposed, and steady-state variables like surface temperatures and heat flux are recorded and elaborated to compute the U-value of the wall. Despite the extremely accurate and reliable procedure, the main disadvantages that can be pointed out by adopting hot-boxes are, at first, the absence of other information related to the components' behaviour in non-stationary regime, like dynamic ones. In addition, such procedures often require a considerable amount of time to be concluded according to the thermal inertia of the wall. As a matter of fact, thick walls characterized by a significant thermal inertia may require more than one week to stabilize itself.

In order to reduce test time and to gain additional information on the tested wall, recent unconventional procedures have appeared based on the Response Factors theory of Mitalas & Stephenson (1967). Wall response factors describe the response of the wall when it is excited by a triangular unitary pulse in temperature on one side, and on both the excited and non-excited sides, the heat flux is obtained (Davies, 2004). Some authors like Sala et al. (2008) have exploited such technique in order to measure experimentally response factors of a hollow brick wall in laboratory conditions, which later on, they could be exploited in dynamic energy simulations. Other authors like Rasooli et al. (2016) implemented the response factors method with the aim to compute the in-situ thermal resistance of existing buildings' walls in order to overcome the difficulty of keeping constant boundary conditions. Satisfactory results were obtained in terms of accuracy with respect to stationary methods, i.e., less than 2%. Martín et al. (2010) developed a methodology for the calculation of response factors through experimental tests which was validated through simulations. They proposed a methodology in which response factors of a wall can be obtained without requiring the corresponding material properties. Besides this, they assessed the U-value, showing an accuracy of the procedure of about 10%.

According to the literature, impulsive procedures (or, dynamic procedures) have been investigated and adopted in order to overcome stationary methods, which require a long time and which they do not add anything more to the simple stationary characterization of the wall. However, studies focus either on just experimentally determining response factors or on in-situ measurements.

For these reasons, this research work aims to propose an alternative methodology for the determination of the U-values of walls by adopting the Response Factors theory, which has been tested by running simulation tests of two wall typologies with opposite thermal characteristics. Results in terms of U-values obtained with the dynamic method are compared with the stationary one, with and without noisy boundary conditions. Results show how the proposed methodology can be adopted to assess the U-value of walls with errors lower than 1%, and it was also possible to characterize the wall in a transient regime. The noise does not affect the method in a significant way when adopted on walls with a lower thermal resistance and a high thermal capacity (e.g., brick walls), while, for walls with a higher values of thermal resistance and lower thermal capacities (like cross laminated timber walls), in order to determine the U-value through a dynamic way with an error below 10%, internal boundary conditions must not oscillate more than ±0.4 K of the average value. The work points out the efficacy of the dynamic procedure, as well as its resilience against noisy boundary conditions that can be further adopted in real experimental procedure in hot-box apparatuses.

2. Methodology

2.1 Geometrical Model

The two components adopted for testing the proposed methodology are two walls, with different characteristics in terms of thermal resistance and thermal capacity, that are a 25 cm of clay brick masonry wall and a 10 cm cross-laminated timber (CLT) wall. Their thermal-physical properties are: *(i)* the density equal to 1840 kg m^{-3} (clay bricks) and 420 kg m^{-3} (CLT), *(ii)* the thermal conductivity equal to 0.80 W m^{-1} K^{-1} (clay bricks) and 0.12 W m^{-1} K^{-1} (CLT) and, *(iii)* the specific heat equal to 1800 J kg^{-1} K^{-1} and 1600 J kg^{-1} K^{-1}, for the clay brick masonry wall and the CLT walls, respectively.
The geometrical model of the two analyzed walls was developed in a COMSOL Multiphysics® environment (v. 5.6). The space domain of each element was discretized according to the default size settings with an extremely fine mesh (maximum size of 1.05 cm and minimum size of 0.002 cm:), chosen after a preliminary sensitivity analysis conducted on each wall where results showed that the numerical model of the time-dependent problem required a finer mesh than the normal one.

2.2 Simulation Tests

For each wall, two sets of simulations were run. At first, a stationary simulation for determining the U-value of the wall by imposing constant boundary conditions at the two surfaces equal to 20 °C (internal air temperature) and 0 °C (external air temperature). The thermal transmittance, named U_s, expressed in W m^{-2} K^{-1}, was determined according to Eq. 1.

$$U_s = \frac{\Phi}{(\mathrm{T_i} - T_e)} \tag{1}$$

Where Φ is the heat flux across the wall in W m^{-2}, T_i and T_e are respectively the internal and external air temperatures (°C). The stationary numerical model was solved by means of the Backward differentiation formula with a relative tolerance equal to 10^{-3}.
The second regime that was simulated is a time-dependent simulation called "dynamic", in which a triangular profile was applied to the external temperature of each wall, where the temperature followed a first increasing ramp from the initial temperature of 16 °C to 26 °C in one hour (+10 K of temperature increase). Then, the first step was followed by a second decreasing ramp till the initial temperature of 16 °C, with duration of one hour (i.e., -10 K h^{-1}). The third and last part of the temperature profile was kept constant equal to 16 °C. At the opposite side, the internal temperature was maintained constant equal to 16 °C. The simulation time-step was equal to 1 minute and the total duration of the simulation was set equal to four days. Such a value was chosen to be sufficient to the heat flux of the non-excited side to return to zero, for both walls. For the resolution of the time-dependent problem, it was necessary to change solver and choose a more suitable one for non-stationary problems. For this reason, the numerical model was solved by means of the Runge-Kutta method, where the relative and the absolute tolerances were set equal to 10^{-4} and 10^{-5}. In order to compute the U-value of the wall by exploiting the dynamic test, the heat flux at the non-excited side was obtained and divided by the magnitude of the temperature increase of the triangular ramp (i.e., 10 K) in order to obtain a unitary heat flux Φ_u, expressed in W m^{-2} K^{-1}. The Response Factors theory adopted in this work relies on a unitary impulse applied to one surface, but since the theory is derived from the Fourier Conduction Equation and the Laplace Transform (Hittle, 1992), the superimposition principle is valid and it was possible to apply a higher pulse in order to obtain a significant response on the opposite side that otherwise would be negligible.

The unitary heat flux Φ_u was then fitted as a function of the time *t* (min) in MATLAB® environment using the fitting function reported in Eq. 2. Parameters a, b, c and d were determined by minimizing the root-mean-square error between simulation results and the fitting function.

$$\Phi_u(t) = \begin{cases} 0 & if\ t < d \\ a \cdot e^{-b \cdot \ln\left(\frac{t-d}{c}\right)^2} & if\ t \geq d \end{cases} \qquad (2)$$

After that, the U-value of each wall, i.e., U_d, was computed by performing the integral of the unitary heat flux in time, obtaining Eq. 3.

$$U_d = a \cdot c \cdot \pi^{\frac{1}{2}} \cdot b^{-\frac{1}{2}} \cdot e^{\frac{1}{4 \cdot b}} \qquad (3)$$

This value was then compared to the stationary U-value. In both simulation regimes the internal surface thermal resistance was set equal to 0.13 m^2 K W^{-1}, while the external equal to 0.04 m^2 K W^{-1}, according to the Standard EN 6946: 2018 (CEN, 2018).

2.3 Analysis of Noisy Boundary Conditions

In order to evaluate the effect that noise applied to the temperature boundary conditions can have on the determination of the U-value with a dynamic test, the same time-dependant simulations described before were run as before but applying a random noise function to the temperature profiles. In particular, the noise function was initially defined as a random trend with mean equal to zero and maximum intensity equal to ±1.0 K, and then, different intensities were applied to it by scaling the random profile in order to obtain different noise magnitudes, which were equal to ±0.2, ±0.4, ±0.6, ±0.8, and ±1.0 K. The noise was applied at first on the external boundary condition ("External" case), after that, at the internal one (named "Internal" case) and finally on both sides ("Both" case). The previously described procedure was repeated, and the dynamic U-value was determined for each noise level.

3. Results and Discussion

Fig. 1 and Fig. 2 show results in terms of unitary heat flux obtained at the non-excited side from dynamic simulation tests and the fitted trend for the clay brick masonry wall and of the cross laminated timber wall (CLT wall), respectively. It can be pointed out that the fitting function expressed in Eq. 2 accurately represents the trend of the simulation test. As a matter of fact, root mean square errors are 0.06 and 0.08 W m^{-2} K^{-1} for the clay brick masonry wall case and for the CLT wall case, respectively. In the case of the CLT wall, it can be noticed that the peak of the unitary heat flux is poorly fitted with respect to the other wall. This could be explained by the sharper shape of the CLT wall thermal response. Fitting parameters for the unitary heat flux at the internal side of the clay brick masonry wall are equal to a = 0.184, b = 0.944, c = 4.811 and d = 1.369. While, as regards the CLT wall, parameters are equal to a = 0.250, b = 1.515, c = 2.336 and d = 0.719.
By exploiting Equation (3) for the determination of the thermal transmittance by means of the dynamic test, results of U_d are reported for the clay brick masonry wall and the CLT wall, as well as the percentage deviation of such value than the stationary U-value, i.e., U_s.

Clay brick masonry wall
U_d = 2.098 W m^{-2} K^{-1} (+0.34%, U_s = 2.091 W m^{-2} K^{-1})

CLT wall
U_d = 0.994 W m^{-2} K^{-1} (-0.77%, U_s = 1.001 W m^{-2} K^{-1})

Results in terms of "dynamic" U-values show extremely good agreement with the stationary values, with deviations lower than 1%, a threshold that is definitely lower than the maximum standard measurement uncertainty of U-values (around 10%). A slightly higher deviation is shown for the CLT wall, but this is due to the poorer fitting procedure the proposed methodology relies on (see Equation 3). Probably, the narrower shape of the unitary heat flux of the CLT wall results more difficult to be fitted by the optimization algorithm than the one of the Clay Brick Masonry walls.

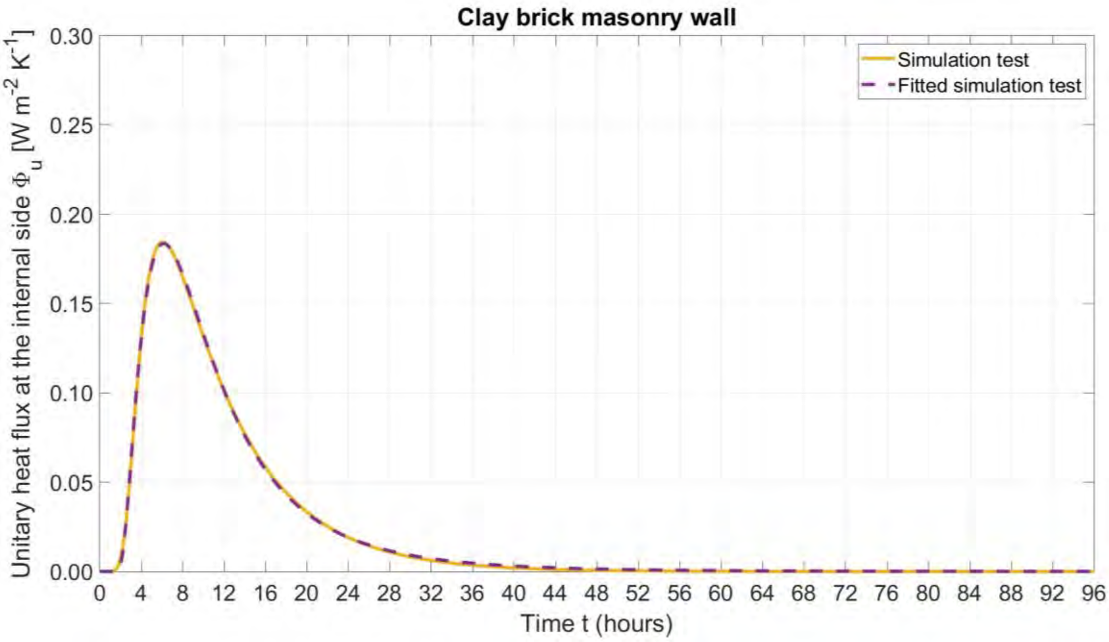

Fig. 1 – Unitary heat flux at the internal side Φ_u expressed in W m^{-2} K^{-1} as a function of the time t, expressed in hours. The yellow line represents the simulation test, while, the dashed purple line represents the fitting function with parameters equal to a = 0.184, b = 0.944, c = 4.811 and d = 1.369. Root mean square error equal to 0.06 W m^{-2} K^{-1} (clay brick masonry wall)

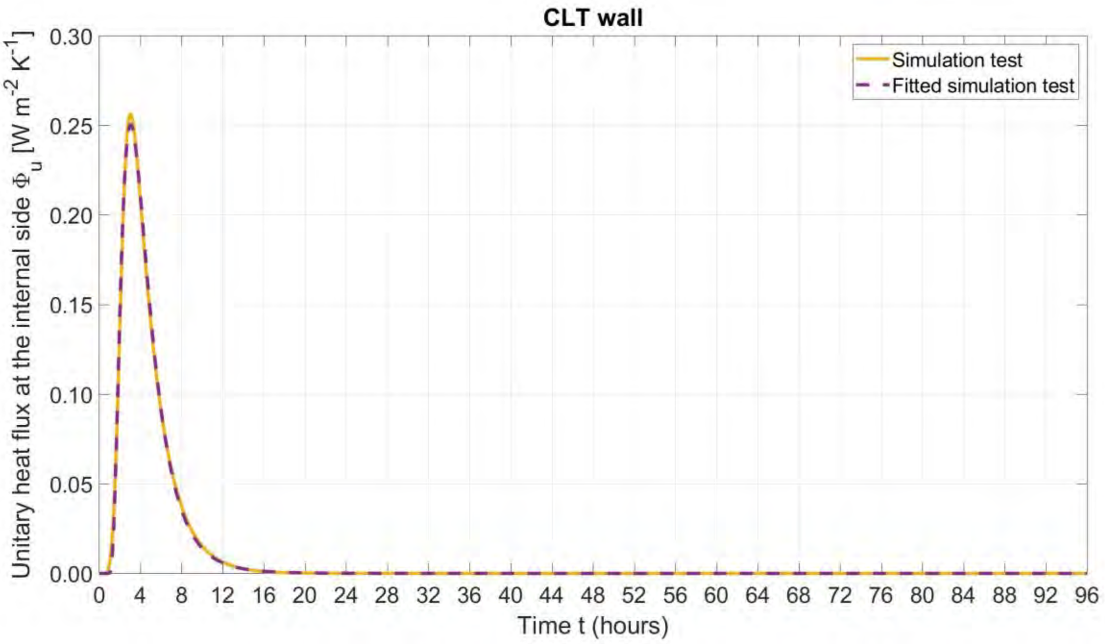

Fig. 2 – Unitary heat flux at the internal side Φ_u expressed in W m^{-2} K^{-1} as a function of the time t, expressed in hours. The yellow line represents the simulation test, while, the dashed purple line represents the fitting function with parameters equal to a = 0.250, b = 1.515, c = 2.336 and d = 0.719. Root mean square error equal to 0.08 W m^{-2} K^{-1} (CLT wall)

Moving forward to the analysis of noise, which means how the noise applied to the temperature boundary conditions affects the dynamic methodology for determining the U-value of walls, Fig. 3 and Fig. 4 are given. They show the percentage error compared to the case without noise of the thermal transmittance U_d computed with the dynamic method, obtained at different noise levels applied at the external side (blue dot), internal side (yellow hexagram) and on both sides (black asterisk).

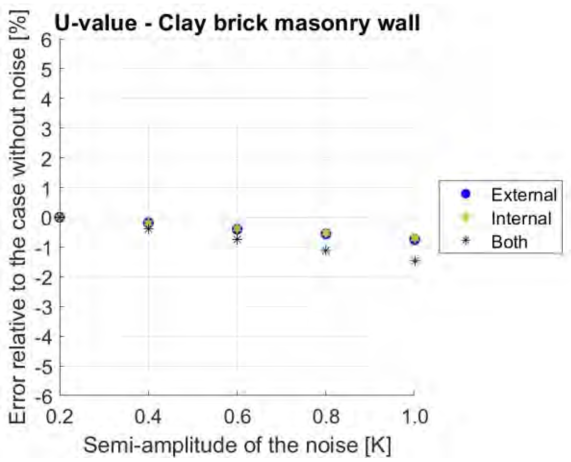

Fig. 3 – Error in the evaluation of the thermal transmittance U_d in percentage terms as a function of the noise level applied at the external side (blue dot), internal side (yellow hexagram) and on both sides. (black asterisk). Case of the clay brick masonry wall

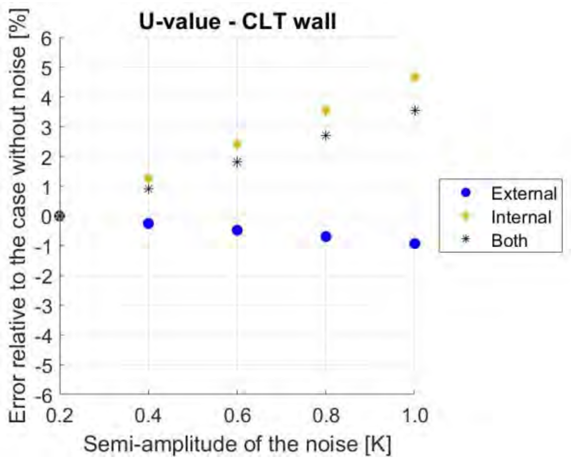

Fig. 4 – Error in the evaluation of the thermal transmittance Ud in percentage terms as a function of the noise level applied at the external side (blue dot), internal side (yellow hexagram) and on both sides. Case of the CLT wall

As expected, the results show how noise does have an effect on the methodology for the estimation of the U-value of both walls. Nevertheless, the maximum deviation reached in the computation of the U-value with the proposed dynamic method is about +5% than the case without noise and this occurs for the CLT wall with semi-amplitude of the noise equal to ±1.0 K. In the other cases analyzed, deviations stay below this level.

As regards the side of the application of the noise, it can be noticed that when the noise is applied to the external air temperature, errors are the lowest ones registered. For instance, the maximum error reached is -1.0% than the case without noise in correspondence to the highest semi-amplitude of the noise for both walls. A slightly higher deviation is obtained for the CLT wall in the “External” case, and this could be due to the poorer fit of the unitary heat flux discussed before. However, such differences can be considered negligible with respect to other sources of uncertainty present when performing such tests in real conditions. When the noise is applied at the constant internal temperature, results show a different behavior. In particular, it can be noticed that by increasing the noise magnitude, the error increases more than the case without noise but with a more significant impact, especially for the CLT wall. The U-value is overestimated with a +4.6% than the zero-noise case when the noise-amplitude reaches the maximum value. However, when focusing on the clay brick masonry wall, the error on the U-value with the same noise conditions is comparable with the “External” case. This result can be explained by the specific shape of the unitary heat flux adopted as input of the optimization algorithm. The heat flux on the non-excited side of the CLT wall is sharper and it is characterized by a higher and narrower peak than the one of the clay brick masonry wall, because of the lower thermal capacity of the former than the latter. This makes it more difficult for the optimization algorithm to estimate the fitting’s parameters under noisy boundary conditions. The last analysis performed in this work focuses on the noise applied on both sides of the walls. Results show how by applying the same noise on both sides there is a summation effect in the clay brick masonry wall, where the two errors of the “Internal” and “External” cases, both negative, are summed showing a maximum deviation of -1.5%

than reference U-value obtained without noise. On the contrary, the summation effect in the CLT wall causes a slight decrease in the noise effect on the results of the optimization algorithm, obtaining results still closer to the “Internal” case.

4. Conclusion

The research presented herein focuses on the determination of the U-value of walls using the Response Factors theory. The study aimed to assess the efficacy and resilience of a dynamic methodology in comparison to traditional stationary methods, particularly in the presence of noisy boundary conditions. Through simulation tests conducted in the COMSOL Multiphysics® environment, the research investigated the impact of varying levels of noise on the determination of thermal transmittance.

Results of this study revealed promising outcomes in terms of accuracy and efficiency. The dynamic methodology demonstrated the capability to assess U-values with errors lower than 5%, highlighting its potential for practical applications in experimental procedures. By applying a triangular temperature solicitation at one side of the wall, the methodology allowed for the determination of thermal response over time and the assessment of U-values, which duration is usually lower than a standard test. This dynamic approach not only provided accurate results but also offered insights into the transient behaviour of walls, which is crucial for understanding the thermal performance of building components.

Furthermore, the work examined the resilience of the dynamic methodology against noisy boundary conditions applied on both sides in terms of temperature. Simulations showed that for both walls with lower thermal resistance and higher thermal capacity, such as brick walls, as well as, for those walls with slightly higher thermal resistance and lower thermal capacity, the method was acceptably robust against noise, with minimal impact on the accuracy of U-value determination, especially for the clay brick masonry wall. Higher deviations were obtained for the CLT wall when the noise is applied at the internal side and errors relative to the zero-noise case reached about +5.0%, depending on the specific shape of the response heat flux at the non-excited side, which is directly determined by the thermo-physical properties of the analysed wall. Still, the magnitude of the impact is not significant compared to the sources of uncertainty present under real ambient conditions.

Overall, research findings provide valuable insights and practical guidelines for measuring the thermal transmittance of opaque building components. The dynamic methodology based on Response Factors theory offers a promising alternative to traditional stationary methods, offering a more efficient and time-saving approach without compromising accuracy. The study's results pave the way for the adoption of dynamic procedures in real experimental settings, such as hot-box apparatuses, enhancing the understanding of building thermal performance and contributing to the design of more sustainable and energy-efficient buildings. The dynamic methodology presented in this research holds great potential for advancing the field of building energy performance assessment, offering a reliable and efficient approach for determining the U-value of walls in the presence of noisy boundary conditions, like in real experimental procedures. Additionally, this methodology can support decision-making procedures when it comes to a more detailed building component design by enabling faster thermal characterization of components.

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Nomenclature

Symbols

CLT	Cross Laminated Timber
e	Euler’s number
Φ	Heat flux (W m^{-2})
Φ_u	Unitary heat flux (W m^{-2})
ln	Natural logarithm
t	Time (min)
T	Temperature (°C)
U_d	Thermal transmittance obtained with the dynamic test (W m^{-2} K^{-1})
U_s	Thermal transmittance obtained with the steady-state test (W m^{-2} K^{-1})

Subscripts/Superscripts

a	Parameter 1
b	Parameter 2
c	Parameter 3
d	Parameter 4
e	External
i	Internal

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