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A comparison of standardized calculation methods for in situ measurements of façades U-value

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Abstract

In recent years, a growing concern has been how to determine the actual thermal behaviour of façades in their operational stage, in order to establish appropriate energy-saving measures. This paper aims at comparing standardized methods for obtaining the actual thermal transmittance of existing buildings' façades, specifically the average method and the dynamic method defined by ISO 9869-1:2014, to verify which best fits theoretical values. The paper also aims to promote the use of the dynamic method, and facilitate its implementation. Differences between the theoretical U-value and the measured U-value obtained using the average and dynamic methods were calculated in three case studies, and then compared. The results showed that differences between the theoretical and the measured U-value were lower when the dynamic method was used. Particularly, when testing conditions were not optimal, the use of the dynamic method significantly improved the fit with the theoretical value. Moreover, measurements of the U-value using the dynamic method with a sufficiently large dataset showed a better fit to the theoretical U-value than the results of other dynamic methods proposed by authors. Further research should consider the optimum size of the dataset to obtain a measured U-value that is correctly adjusted to the theoretical U-value.

Keywords: U-value calculation; thermal transmittance; average method; dynamic method; in-situ measurements; façade

1. Introduction

Horizon 2020, the European Union Framework Programme for Research and Innovation available from 2014 to 2020 [1], emphasizes the need to bridge the gap between the predicted and actual energy performance of buildings, to increase the energy performance of existing buildings, and achieve the European Union's "20-20-20" energy efficiency target. Construction is considered the biggest potential sector for energy savings, as buildings are responsible for 41% of total final energy consumption in Europe [2], and residential buildings in particular have potential energy saving of 27% [3].

Façades play an important role in buildings' energy demand, and thermal transmittance is a fundamental parameter to characterise the thermal performance of building envelopes [4–7].

The causes of the energy performance gap can be grouped into three categories, associated with the design stage, the construction stage and the operational stage [8]. According to De Wilde [8], causes in the design stage are (1) miscommunication between the client and the design team, or between members of the design team, about a future building's performance targets, (2) differences between the actual performance of the equipment and the specifications of the manufacturer, (3) the use of incorrect methods, tools or component models in the modelling and simulation process, (4) misalignment between design and prediction, as detailed design calculations are not formally tested for errors and accuracy and, as Williamson [9] pointed out, (5) the fact that present approaches do not take system performance deterioration into account, which leads to a mismatch between prediction and measurement. Relating to the construction process, the author highlighted as the main causes of performance gap (1) the fact that the quality of buildings does not meet specifications and (2) discrepancy between the design and the actual building due to change orders and value engineering. Finally, regarding the operational stage, the author highlighted as roots of the performance gap (1) a difference between occupant behaviour and the assumptions made in the design stage, (2) assumptions about the performance of technological developments, and (3) the use of uncertainty in experimental data. Thus, accuracy in the determination of the actual thermal behaviour of façades in the operational stage has become a widespread concern in recent years, to establish appropriate measures for energy efficiency improvement.

Currently, several approaches are used to determine the thermal transmittance of existing buildings' façades: (1) procedures based on classifying buildings by typologies or by historical analysis [10,5], (2) procedures based on design data, and (3) procedures based on experimental methods.

Procedures based on classifying buildings by typologies or by historical studies are usually general in nature, and take into account all existing buildings. This leads to imprecise values for the composition of façades and for the thermal properties of their materials [5].

Reliable design data can be obtained from executive projects or specific technical building reports. If the procedure described in ISO 6946:2007 [11] is applied, the theoretical U-value of façades can be determined.

Experimental methods are based on measurements of in situ data. These measurements can be conducted by destructive procedures, such as the endoscope and sampling methods, or non-destructive procedures, such as the heat flow meter method [12], the quantitative thermography method, or other methods developed by researchers. The endoscope method involves measuring the thickness of the layers in the wall, and is often combined with the extraction of samples to analyse the properties of the materials, for the subsequent calculation of thermal transmittance, according to ISO 6946:2007 [5,11,4]. The heat flow meter method is a non-destructive method standardized by ISO 9869-1:2014 [12] that consists of monitoring the heat flux rate passing through the façade and the indoor and outdoor environmental temperatures to obtain the thermal transmittance. The ISO 9869-1:2014 standard [12] defines two methods for the analysis of data: the average method and the dynamic method. The quantitative thermography method provides a measure of the overall transmittance of façades in a short period of time. There is increasing interest in this method [13,14,7,6]. Finally, some authors have developed their own methods, based on in situ measurements to calculate the thermal behaviour of façades.

To conduct research on the behaviour of façades, authors such as Desogus et al. [4], Baker [15], Asdrubali et al. [16], Ficco et al. [5] and Evangelisti et al. [17] used the average method defined by ISO 9869:1994, in which the measured values of thermal behaviour are compared with theoretical ones obtained from design data or endoscope analysis. The disparity in the results obtained by the authors is noteworthy. Desogus et al. [4] analysed a ceramic single-skin wall and obtained differences of -8.1% between the U-value calculated using the destructive method and the measured U-value with a differential environmental temperature of 10ºC, and -18.9% with a differential temperature of 7ºC. In a study by Asdrubali et al. [16] on buildings designed using principles of bio-architecture, the differences between the theoretical and the measured U-values ranged from 4% to 75%. A study carried out by Evangelisti et al. [17] on three conventional façades obtained differences between the theoretical U-value and the measured U-values ranging from +17% to +153%. The authors stated that these differences may be due to unknown composition of the wall or to an inaccurate thermal conductivity value.

Other authors, such as Peng and Wu [18], Jimenez et al. [19], Biddulph et al. [20], Guillén et al. [21] and Tadeu et al. [22], introduced their own methods for obtaining values of thermal transmittance or thermal resistance, and compared their results with values obtained using existing methods, including the standardized average method and methods defined by other authors. Peng and Wu [18] presented three methods for the analysis of in situ data to determine the thermal resistance of buildings (R-values): the synthetic temperature method, the surface temperature method and the frequency response method introduced by the authors. They obtained differences between the three methods and the design value ranging from 2.8% to 7.04% in a western wall, and from 6.1% to 24.4% in a southern wall. Jimenez et al. [19] applied three linear models to the same datasets to estimate the U value of the component: deterministic and lumped RC models using LORD software, linear transfer function models using the MATLAB System Identification Toolbox, and linear continuous-time state space models based on stochastic differential equations analysed using CTSM. The authors found that at least one model gave appropriate results in each approach. Biddulph et al. [20] proposed a combination of a simple lumped thermal mass model and Bayesian analysis. In the study, a non-thermal mass model and a single thermal mass model were compared to the averaging method of estimating U-values. The study showed that the averaging method and the two models gave similar results for all the walls measured. Guillén et al. [21] presented a model for thermal transmittance through different façades, and validated it using two types of walls: a conventional façade and a ventilated façade. The numerical results were compared with experimental measurements of temperature through the wall, and the modelled temperatures were compared with those expected by applying ISO 13786:2007. The results validated the numerical model representing the temperature in every layer of the façades. Tadeu et al. [22] proposed and validated, numerically and experimentally, an iterative model to evaluate the thermal resistance of multilayer walls in the dynamic state. The results showed good agreement between the thermal resistance evaluation given by the iterative model and the expected value, and the relative errors between the results, design value, and the result obtained by the new method were below 8%.

Very few initiatives used the standardized dynamic method defined by ISO 9869-1:2014 [12] to calculate the thermal transmittance of façades because, as Ficco et al. [5] states, dynamic methods are more complex than the average method. This is the case of Mandilaras et al. [23]. The authors studied the actual in situ hydrothermal performance of a full-scale envelope with two types of insulation: expanded polystyrene (EPS) and a vacuum insulation panel (VIP). They determined the experimental R-value using the dynamic method of ISO 9869:1994 and compared it with the theoretical estimation of R-value according to ISO 6946:2007 [11] and numerical simulations. In this study, the authors obtained differences between the theoretical and the measured U-values according to the dynamic method, ranging from 1.2% in the envelope insulated with expanded polystyrene to 22.1% in the envelope insulated with vacuum insulation panel.

In this context and for first time, this paper aims to compare two standardized methods (the average method and the dynamic method) for obtaining the actual thermal transmittance of existing buildings' façades, to check which best fits the theoretical values. Furthermore, the paper describes in detail how to apply the dynamic method, and includes a flowchart of the programmed spreadsheet of the dynamic method, to facilitate its use.

This paper is structured into the following sections: method, case studies and discussion, conclusions and further research.

2. Method

The method for comparing standardized methods for obtaining façades' thermal transmittance consists of three steps:

- Firstly, the theoretical U-value is determined according to ISO 6946:2007 [11]. In order to obtain an accurate value, a preliminary analysis of the executive project of the building under study and subsequent testing on site are necessary.
- Secondly, the in-situ U-value is determined according to ISO 9869-1:2014 [12]. In this step, in-situ measurements must be conducted, taking into account recommendations for the monitoring of façades related to equipment and conditions. Then, the data must be analysed using the average method and the dynamic method.
- Thirdly, the differences between the theoretical U-value and the U-values measured by the average method and the dynamic method should be calculated.

2.1 Determination of theoretical U-value according to ISO 6946:2007

The thermal transmittance of an element is the inverse of its thermal resistance. The theoretical total thermal resistance (R_T) of a construction element comprised of uniform layers perpendicular to the heat flux is calculated according to the following expression [11]:

$$R_T\left(\frac{\mathrm{m}^2\cdot\mathrm{K}}{W}\right)=\frac{1}{U}=R_{si}+R_1+R_2+\cdots+R_N+R_{se} \tag{1}$$

where $R_1 + R_2 + \ldots + R_N$ are the design thermal resistances of each layer (from 1 to N) and R_{si} and R_{se} are the interior and exterior superficial resistances, respectively.

According to ISO 6946:2007 [11], the design values of the interior and exterior superficial resistances (R_{si} and R_{se}) for horizontal heat flux are 0.13 and 0.04 respectively. The thermal resistance (R) of a uniform layer is obtained as follows:

$$R\left(\frac{\mathrm{m}^2\cdot\mathrm{K}}{W}\right)=\frac{d}{\lambda} \tag{2}$$

where d is the thickness of the layer in the element, and λ is the design thermal conductivity of the material.

To determine the theoretical U-value in the three case studies, the design data for façades is obtained by means of the buildings' executive projects, ISO 6949:2007 [11], and the Spanish Technical Building Code's Catalogue of Building Elements [24].

2.2 Determination of in-situ U-value according to ISO 9869-1:2014

To measure the in-situ thermal transmittance of a plane building component consisting of opaque layers perpendicular to the heat flow, ISO 9869-1:2014 [12] describes the heat flow meter measurement method. This standard defines the process of wall monitoring (the apparatus to be used, its installation, and the measurement procedures) and the analysis of data (average method and dynamic method, and associated uncertainty).

2.2.1 Process monitoring and data acquisition

The instrumentation must be selected appropriately to obtain the thermal transmittance of the façades in the case studies. The equipment consists of a heat flux meter plate (HFP01, Hukseflux), an inside air temperature sensor (T107, Campbell Scientific, Inc.), an indoor acquisition system (CR850, Campbell Scientific, Inc.) and its batteries, and an outside air temperature sensor and its acquisition system (TF-500, PCE-T390, PCE Iberica, SL). The main specifications of the equipment are:

- The heat flux meter plate (HFP01, Hukseflux) has a thickness of 5.0 mm, a diameter of 80.0 mm, and a guard made of a ceramic-plastic composite. It has a range of ±2000 W/m², accuracy of ±5%, and sensitivity of 61.68 μV/(W/m^2).
- The inside air temperature sensor (107, Campbell Scientific, Inc.) consists of a thermistor encapsulated in epoxy-filled aluminium housing. It has a temperature measurement range from -35° to +50°C and accuracy of ±0.5°C.
- The inside acquisition system (CR850, Campbell Scientific, Inc.) consists of measurement electronics encased in a plastic shell with an integrated wiring panel that uses an external power supply. The CR850 stops working when the primary power drops below 9.6 V, which reduces the possibility of inaccurate measurements. The datalogger has an input voltage range of ±5 Vdc and an analog voltage accuracy of ± (0.06% of reading + offset) at 0° to 40°C.
- The outside air temperature sensor, consisting of a thermocouple (type K) and its acquisition system (TF-500, PCE-T390, PCE Iberica, SL) have a range from -50º to +999.9 °C and accuracy of ± (0.4 % + 0.5 ºC).

The design of the monitoring process followed the guidelines of ISO 9869-1:2014 [12]. Sensors were installed in a representative part of the façade, avoiding the borders between the opaque part of the wall and the vicinity of defects. The location was investigated by thermography, as recommended in ISO 9869-1:2014 [12], Asdrubali et al. [16], Ahmad et al. [25] and Evangelisti et al. [17], with an infrared thermographic camera (FLIR E60bx Infrared Camera). The heat flux meter plate was installed directly on the internal part of the wall, as this is the most thermally stable area. To ensure good thermal contact between the entire area of the sensor and the wall surface, a layer of thermal interface material (silicon grease) was applied carefully. To avoid direct solar radiation and thus obtain accurate results, only north-facing walls were monitored. Moreover, weather conditions were observed during the data collection process, and monitoring was not carried out on rainy days or during episodes of strong winds. Furthermore, the data collection process was conducted in different environmental conditions that ensured that the indoor temperature was always higher than the outdoor temperature. Optimal environmental conditions involve differences between indoor and outdoor environmental temperatures not lower than 10ºC. The test lasted 72 hours in all case studies. The indoor datalogger was configured to sample data every 1 second and store the 5-minutes averaged data in its memory [4,17,26].

2.2.2 Analysis of data using the average method

The average method assumes that transmittance (*U*) can be obtained by dividing the mean density of the heat flow rate by the mean temperature difference [12], assuming a steady state heat flow where thermal mass is neglected [20], as in the following equation:

$$U\left(\frac{\mathrm{W}}{\mathrm{m}^2\cdot\mathrm{K}}\right)=\frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n}\left(T_{ij}-T_{ej}\right)} \tag{3}$$

where q is the density of the heat flow rate per unit area, T_i is the interior environmental temperature, and T_e is the exterior environmental temperature and the index j enumerates the individual measurements.

The combined standard uncertainty of measurements is calculated according to ISO/IEC Guide 98-3:2008 [27], taking into account the accuracy of the equipment (sensors and acquisition systems), with a coverage factor (k), where k =2 corresponds to a level of confidence of 95%. The uncertainty (σU) is obtained according to the following expression:

$$\begin{aligned}\sigma U^2 &= \left(\frac{\delta U}{\delta q}\right)^2\cdot\sigma q^2+\left(\frac{\delta U}{\delta T_i}\right)^2\cdot\sigma T_i^2+\left(\frac{\delta U}{\delta T_e}\right)^2\cdot\sigma T_e^2= \\ &= \left(\frac{1}{T_i-T_e}\right)^2\cdot\sigma q^2+\left(\frac{-q}{(T_i-T_e)^2}\right)^2\cdot\sigma T_i^2+\left(\frac{q}{(T_i-T_e)^2}\right)^2\cdot\sigma T_e^2\end{aligned} \tag{4}$$

where σq is the uncertainty associated with the heat flow rate measuring equipment, σT_i is the uncertainty associated with the environmental indoor temperature measuring equipment, and σT_e is the uncertainty associated with the environmental outdoor temperature measuring equipment.

2.2.3 Analysis of data using the dynamic method

According to the dynamic analysis method described by ISO 9869-1:2014 [12], the heat flow rate q_i at a time t_i is a function of the temperatures at that time and at all preceding times, and is calculated using the following equation:

$$\begin{aligned}q_i\left(\frac{\mathrm{W}}{\mathrm{m}^2}\right) &= U\cdot\left(T_{Ii}-T_{Ei}\right)+K_1\cdot\dot{T}_{Ii}-K_2\cdot\dot{T}_{Ei}+\sum_n P_n\sum_{j=i-p}^{i-1}T_{Ij}\cdot\left(1-\beta_n\right)\cdot\beta_n\cdot(i-j) \\ &+\sum_n Q_n\sum_{j=i-p}^{i-1}T_{Ij}\cdot\left(1-\beta_n\right)\cdot\beta_n\cdot(i-j)\end{aligned} \tag{5}$$

where T_{Ii} and T_{Ei} are the indoor and outdoor ambient temperatures taken at the times t_i, and $\dot{T}_{Ii}$ and $\dot{T}_{Ei}$ are the time derivative of the indoor and outdoor temperatures. K_1, K_2, P_n and Q_n are variables of the wall that do not have any specific definition, and depend on the time constant τ_n. The coefficients β_n are exponential functions of the time constant τ_n, where $\beta_n=\exp\left(-\frac{\Delta t}{\tau_n}\right)$, and the time constants τ_n are unknown parameters found by looking for the best estimate of $\vec{Z}$ by varying the time constants.

To properly represent the interrelation between q, T_I and T_E, one to three (m) time constants must be taken ($\tau_1 = r\tau_2 = r^2\tau_3$), where r is the ratio between time constants. This results in $2m+3$ unknown parameters in Eq. (5). Using enough sets of data (more than $2m+3$) at various times, an overdetermined system of linear equations is created as follows:

$$\vec{q} = (X) \cdot \vec{Z} \tag{6}$$

where $\vec{q}$ is a vector with M components that are the heat flow data measurements (q_i), (X) is a rectangular matrix with M lines (number of equations) and $2m+3$ columns, and $\vec{Z}$ is a vector with $2m+3$ components, which are the unknown parameters. The set of equations gives an estimate $\vec{Z}*$ of the vector $\vec{Z}$ (see Eq. (7)), and for each value of $\vec{Z}*$ the estimate $\vec{q}*$ is obtained.

$$\vec{Z}* = [(X)' \cdot (X)]^{-1} \cdot (X)' \cdot \vec{q} \tag{7}$$

where $(X)'$ is the transposed matrix of (X), and the first component of $\vec{Z}*$ is the best estimate of thermal transmittance.

In this study, three time constants were taken and nine unknown parameters were obtained. Using all the measurements stored every five minutes, 856 equations were defined. To solve the overdetermined system of linear equations, a classic least squares fit was used. The best estimate of $\vec{Z}$ is the one that calculates the smallest square deviation between $\vec{q}$ and its estimate $\vec{q}*$ (S^2).

To solve the system of equations optimally, an Excel worksheet was programmed using the Solver tool [28]. The model is comprised of two decision variables (the time constant τ_1 and its ratio r), the objective of minimizing the deviation between $\vec{q}$ and its estimate $\vec{q}*$ (S^2), and two constraints consisting of bound variables ($\Delta t/_{10} < \tau_1 < p \cdot \Delta t/_{2}$ and $3 \leq r \leq 10$). The most appropriate solution is obtained by iterating and varying the unknown time constant (τ_1) and its ratio (r). Figure 1 shows a flowchart of the programmed spreadsheet to solve the system.

To evaluate the quality of results, uncertainty is calculated according to the following equation [12]:

$$I = \sqrt{\frac{S^2 \cdot Y(1,1)}{M - 2m - 4}} \cdot F(P, M - 2m - 5) \tag{8}$$

where S^2 is the total square deviation between $\vec{q}$ and its estimate $\vec{q}*$, $Y(1,1)$ is the first element of the matrix $(Y) = [(X)' \cdot (X)]^{-1}$, M is the number of equations, and m the number of time constants. F is the significance limit of the Student's t-distribution, where P is the probability, and $M-2m-5$ is the degree of freedom. In the study, a level of confidence of 95% is adopted.

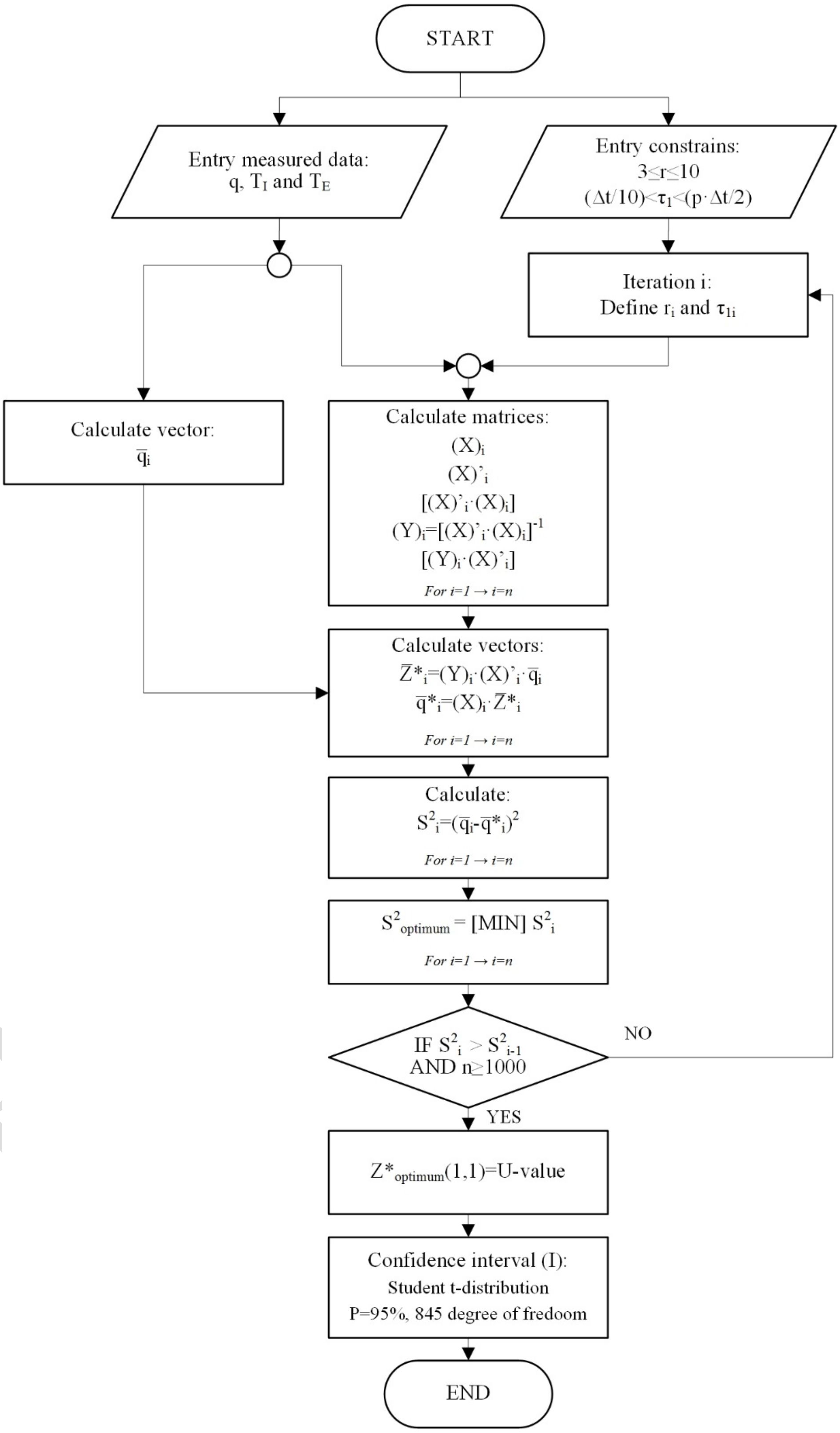

Figure 1. Flowchart of the programmed spreadsheet of the dynamic method, based on least squares adjustment

2.3 Calculation of differences between U-values measured using the average method and the dynamic method and theoretical U-values

To assess the adjustment between the average method and the dynamic method, used for calculating the measured thermal transmittance of façades according to ISO 9869:2014 [12], the relative differences between the theoretical U-value and the measured U-value were calculated in each case using the following expressions:

$$Difference\ U_t - U_{M-Av}(\%) = \frac{(U_t - U_{M-Av})}{U_t} \times 100 \tag{9}$$

$$Difference\ U_t - U_{M-Dyn}(\%) = \frac{(U_t - U_{M-Dyn})}{U_t} \times 100 \tag{10}$$

where U_t is the theoretical thermal transmittance of the façade, $U_{M\text{-}Av}$ is the measured thermal transmittance of the façade using the average method, and $U_{M\text{-}Dyn}$ is the measured thermal transmittance of the façade using the dynamic method.

3. Case studies and discussion

Three façades of three buildings in Catalonia, northeast Spain, were selected as case studies. The façades were typical of Spanish constructions. According to Gaspar et al. [29], Façade 1 and Façade 3 are classified as double-skin façades with non-ventilated air cavities and internal insulation, finished with continuous covering, and Façade 2 as a single-skin façade without an air cavity or insulation, finished with continuous covering.

Façade 1 was built in 1992. The façade has a total thickness of 0.31 m and a theoretical thermal transmittance of 0.72 W/m²·K. Façade 2 was built in 1960. The wall has a total thickness of 0.16 m and theoretical thermal transmittance of 2.35 W/m²·K. Finally, Façade 3 was built in 2007. This façade has a total thickness of 0.30 m and a theoretical thermal transmittance of 0.49 W/m²·K. The composition of the façades is shown in Figure 2 by means of a schematic section. Table 1 describes in detail the materials used in the layers of the façade, as well as its thickness and thermal conductivity. This information was obtained from executive projects and building reports.

Eq. 1 and Eq. 2 were used to calculate the theoretical U-value of the three case studies. Nominal design data on the thermal resistance of the non-ventilated air cavity and the interior and exterior superficial resistances were obtained from ISO 6946:2007 [11]. Nominal design data on the thermal resistance of the hollow and perforated brick walls were obtained from the Spanish Technical Building Code's Catalogue of Building Elements [24]. The theoretical U-value were 0.72 W/m²·K for Façade 1, 2.35 W/m²·K for Façade 2, and 0.49 W/m²·K for Façade 3. The thermal resistance of each layer and the theoretical U-value are summarized in Table 1.

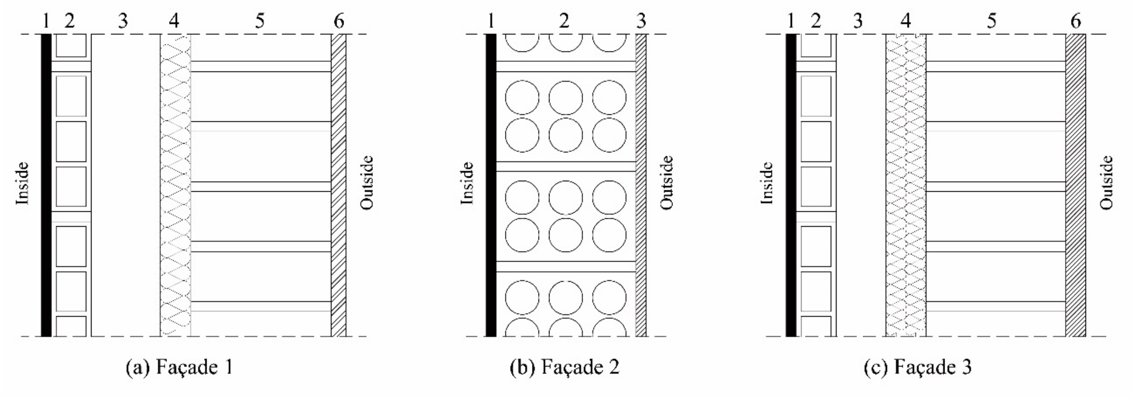

Figure 2. Schematic sections of the façades

Façade type	Num. layer[a]	Material layer (inside-outside)	Thickness (m)	Thermal conductivity (W/m·K)	Thermal resistance (m²·K/W)	Total thickness (m)	Theoretical U-value (W/m²·K)
Façade 1	1	Gypsum plaster	0.01	0.570	0.018	0.31	0.72
	2	Hollow brick wall	0.04		0.090		
	3	Non-ventilated air cavity	0.07		0.130		
	4	Extruded polystyrene	0.03	0.039	0.769		
	5	Perforated brick wall	0.14		0.210		
	6	Pebbledash coating	0.02	1.300	0.012		
Façade 2	1	Gypsum plaster	0.01	0.570	0.018	0.16	2.35
	2	Hollow brick wall	0.14		0.230		
	3	Mortar plaster	0.01	1.300	0.008		
Façade 3	1	Gypsum plaster	0.01	0.570	0.018	0.30	0.49
	2	Hollow brick wall	0.04		0.090		
	3	Non-ventilated air cavity	0.05		0.110		
	4	Polyurethane insulation	0.04	0.028	1.429		
	5	Perforated brick wall	0.14		0.210		
	6	Mortar plaster	0.02	1.300	0.015		

[a] The number of layer refers to the numbering of layers illustrated in Figure 2.

Table 1. Composition of the façades

The three case studies are north-facing façades and were monitored for 72 hours to determine their thermal performance values. Façade 1 was monitored from 5–8 December 2015, Façade 2 from 25–28 January 2016, and Façade 3 from 3–6 April 2016. During the process of monitoring the façades, data on indoor and outdoor temperatures and heat flow rate were taken at five-minute intervals. In case study 1, the range of indoor temperatures fluctuated between 14.9ºC and 19.3ºC with an average of 17.8ºC, the outdoor temperature ranged from 3.2ºC to 12.5ºC with an average of 7.7ºC, and the heat flux rate oscillated between 5.3 and 15.3 W/m² with a mean value of 7.6 W/m². As shown in Figure 3, in case study 2 the indoor temperature varied from 18.0ºC to 22.3ºC with an average of 20.0ºC, the outdoor temperature was between 6.8ºC and 16.6ºC with an average value of 16.5ºC, and the heat flux rate fluctuated between 7.3

and 39.7 W/m² with a mean value of 22.2 W/m². Finally, in case study 3 the indoor temperature ranged between 16.3ºC and 16.6ºC with an average of 16.5ºC, the outdoor temperature was between 11.0ºC and 16.1ºC with an average of 13.7ºC, and the heat flow rate fluctuated between 1.0 and 2.4 W/m² with a mean value of 1.7 W/m².

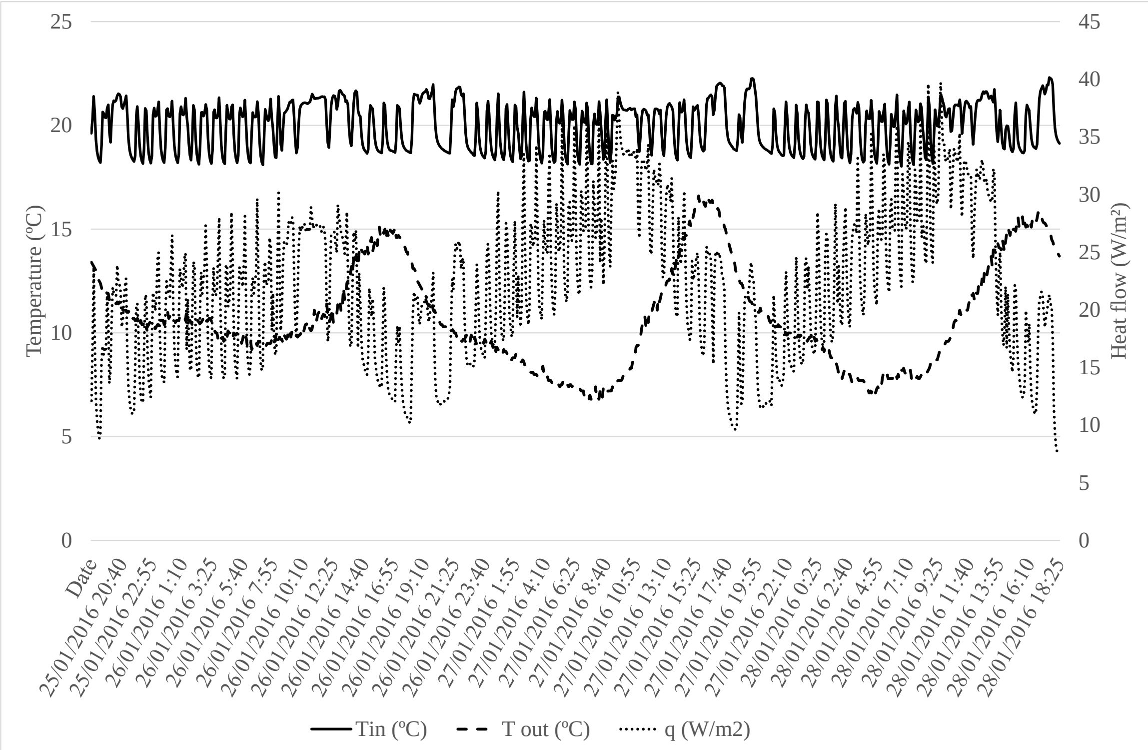

Figure 3. Data obtained from the process of monitoring Façade 2 for the period 25–28 January 2016

The collected datasets of 865 readings were used to calculate the values of the façades' thermal transmittance and uncertainty, using the average method and the dynamic method for the three façades following the indications in Section 2. To apply the dynamic method, three time constants were adopted.

In the first case study, the measured U-value analysed with the average method and its uncertainty was 0.75±0.03 W/m²·K, and the measured U-value analysed with the dynamic and its uncertainty was 0.71±0.01 W/m²·K. The results obtained for Façade 2 were 2.40±0.09 W/m²·K with the average method, and 2.37±0.04 W/m²·K with the dynamic method. Finally, the results for Façade 3 were 0.59±0.03 W/m²·K with the average method, and 0.54±0.01 W/m²·K using the dynamic method. In all case studies, uncertainty related to a level of confidence of 95% was lower in the dynamic method than in the average method. The results of the data analysis are shown in Table 2.

Case study	Days	Duration (h)	ΔT average (K)	U_t (W/m²·K)	$U_{M-Av}\pm\sigma_{95\%}$ (W/m²·K)	$U_{M-Dyn}\pm I_{95\%}$ (W/m²·K)	Difference U_t - U_{M-Av} (%)	Difference U_t - U_{M-Dyn} (%)
Façade 1	from 12/05/2015 to 12/08/2015	72	10.1	0.72	0.75 ±0.03	0.71±0.01	-4.3%	0.4%
Façade 2	from 01/25/2016 to 01/28/2016	72	9.3	2.35	2.40 ±0.09	2.37±0.04	-2.0%	-0.7%
Façade 3	from 04/03/2016 to 04/06/2016	72	2.8	0.49	0.59±0.03	0.54±0.01	-20.4%	-9.6%

Table 2. Theoretical thermal transmittance and measured thermal transmittance using the average and dynamic methods, and differences between values for the three case studies

To check the correctness of both methods, the differences between the theoretical and the measured U-values using the average method and the dynamic method were calculated according to Eq. 9 and Eq. 10 respectively. Generally, the differences between the U-values measured using the dynamic method and the theoretical values were smaller than the differences between the U-values measured using the average method and the theoretical values. In Table 2, the differences between the U-values measured using both methods and the theoretical U-values are shown.

In Façades 1 and 2, the differences between the U-values measured using the average method and the theoretical U-values were lower than ±5%, which was an acceptable result. Specifically, the differences were -4.3% for Façade 1, and -2% for Façade 2. Notwithstanding, the U-value measured by the dynamic method was much tighter than that obtained using the average method, with differences of 0.4% in Façade 1, and -0.7% in Façade 2. These values are in line with the results obtained by Mandilaras et al. [23].

The results obtained for Façade 3 were not as tight as in the other case studies, possibly due to worse environmental conditions. In this Façade, there was a larger contrast between the theoretical U-values and the values measured using both methods. The average method led to differences with the theoretical U-value of -20.4%. With the dynamic method, the difference between the measured and theoretical U-value was reduced by more than -10%, to reach -9.6%.

Moreover, the measured U-value obtained by applying the standardized dynamic method with the defined dataset fitted to the theoretical U-value was more accurate than that derived from the other dynamic methods proposed by authors.

4. Conclusions and further research

This paper gives a detailed description of the implementation of the dynamic method. To facilitate its use, a flowchart of the programmed spreadsheet for the dynamic method is included. The measured thermal transmittance of existing façades using the standardized methods defined by ISO 9869-1:2014, the average method and the dynamic method were compared through three case studies. In each case study, the differences between the checked theoretical U-value and the U-value measured using the average method and the dynamic method were calculated, and the differences were compared.

The results for the three case studies showed that the difference between the theoretical and measured U-value is lower when the dynamic method is used. When the environmental conditions for carrying out in-situ measurements were optimal, as in the case of Façades 1 and 2, the differences were lower than ±5% when the average method was used, but lower than ±1% when the dynamic method was used. The results also showed that when testing conditions are not optimal, the use of the dynamic method can significantly improve the fit with the theoretical U-value, as in the case of Façade 3. Moreover, the U-value measured using the standardized dynamic method with a sufficiently large dataset showed a better fit to the theoretical U-value than other dynamic methods proposed by authors.

Further research should consider the optimum size of datasets to obtain a measured U-value that is correctly adjusted to the theoretical U-value and minimizes the complexity of the calculation. Some of the factors that could be taken into account to assess the size of datasets are the duration of the experimental campaign and the frequency of data collection.

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