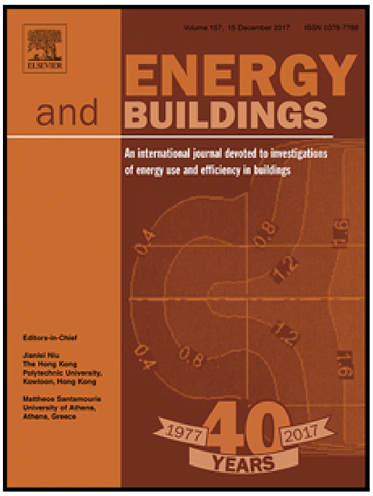

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Review of criteria for determining HFM minimum test duration

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Abstract

The actual thermal behaviour of façades is important to identify suitable energy-saving measures and increase the energy performance of existing buildings. However, the accuracy of in situ measurements of façades' U-values varies widely, mostly due to inadequate test durations. The aim of this paper was to evaluate the minimum duration of in situ experimental campaigns to measure the thermal transmittance of existing buildings' façades using the heat flow meter method, and to analyse the thermal performance of the façade during the test. Minimum test duration was determined according to data quality criteria, variability of results criteria, and standardized criteria for different ranges of theoretical thermal transmittance and for the same range of average temperature difference. Then, the minimum test duration results were compared. The findings show that ISO criteria are more sensitive and provide more accurate results, requiring a longer test duration. However, when certification is not required, the duration of the test could be reduced by applying data quality and variability of results criteria. The minimum duration of experimental campaigns depends on the theoretical thermal transmittance and the stability of climatic conditions. Moreover, results are more accurate when the dynamic method is used.

Keywords: U-value calculation, thermal transmittance, in situ measurements, experimental campaign, testing duration, façade

1. Introduction

The Energy Efficiency Directive 2012/27/EU [1] and the European Commission's Energy Efficiency Plan 2011 [2] affirm that construction is the biggest potential sector for energy saving. Buildings account for 40% of the EU's final energy demand [3]. Specifically, residential buildings are responsible for 25.4% of total final energy consumption in Europe [4] and have potential energy savings of 27%, according to the European Commission [5]. Horizon 2020, the European Framework Programme for Research and Innovation for 2014 to 2020, states that the most challenging aspect of reducing energy use in buildings is how to increase the rate, quality, and effectiveness of building renovation [3].

The thermal behaviour of building envelopes is a key factor to evaluate in the energy diagnosis of a building [6-13]. The thermal properties of building components must be characterized accurately to model residential energy consumption using the top-down and bottom-up techniques defined in Swan and Urgursal [14] and Aksoezen et al. [15]. Moreover, precise data is required to ensure a successful decision-making process during energy efficiency improvements to buildings [16,17]. Several approaches are used to determine the thermal transmittance of existing buildings' façades:

- Methods based on data obtained by historical analysis or by analogies with buildings of similar type [9,18]. These methods often lead to imprecise values because of the lack of reliable data on the composition of façades and the thermal properties of their materials [9].
- Methods based on design data, to determine the theoretical U-value of façades. These methods are standardized in ISO 6946:2007 [19], and data are obtained from executive projects or specific technical building reports.
- Methods based on experimental analysis, which use measurements of in situ data. These methods can involve destructive procedures, such as the use of endoscopes or sampling, or non-destructive procedures, such as the use of the heat flow meter, quantitative thermography, 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 [7,9,19]. The heat flow meter method consists of monitoring the heat flux rate through a façade and the indoor and outdoor environmental temperatures to obtain the thermal transmittance [20]. The ISO 9869-1:2014 standard [20] defines two methods for data analysis: the average method and the dynamic method. The average method assumes that the

transmittance can be obtained by dividing the mean density of heat flow rate by the mean temperature difference, and the dynamic method considers the thermal variations using the heat equation. 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 [13,21-28]. Finally, some authors have developed other methods, based on in situ measurements to calculate the thermal behaviour of façades [29].

2. Background

The heat flow meter method is one of the most widely used to measure in situ the actual thermal transmittance of façades. The standard [20] establishes that on-site measurements must have a minimum duration of 72 hours. However, depending on the stability of conditions, measurements may take longer than seven days. As stated by Peng and Wu [30], many difficulties may arise in on-site measurements in existing buildings, due to problems related to accurate measurement of temperatures and heat flux, because seasonal climatic conditions may be unfavourable [6,7,31-33]. Aspects related to the component being measured could influence the duration of experimental campaigns. For historic brick masonry, Lucchi [16] showed good thermal stability after 145 h of monitoring with an average temperature difference of 15ºC. For historic walls from 0.90 to 1.10 m thick, the duration of the test was extended to 14 days. In traditionally built walls, Rye and Scott [34] stated that a period of at least a week is required before the U-value estimate stabilises to within ±5% of the final value determined from about 27 days' data. In measurements of low U-value façades, Gaspar et al. [35] showed that for high ranges of temperature differences (around 20ºC) the test could be finished after 72 h, and as the temperature difference decreases, the test should be extended to 144 h. For light façades, ISO 9869-1:2014 [20] recommends analysing only the data acquired at night. For heavier façades, the standard indicates that the actual test duration should be determined by applying criteria to the values obtained during the test.

Some authors have used experimental campaigns of varying durations (from three days to one month) in comparisons of theoretical and measured U-value [20]. Asdrubali et al. [6] measured in situ thermal transmittance in buildings designed using bio-architecture principles, with calculated thermal transmittance ranging from 0.23 W/m²·K to 0.33 W/m²·K. The measurement acquisition time was 3 days if the indoor temperature was stable, and 7 days if not. The differences between theoretical and measured U-values using the average method ranged from 4% to 75%.

Baker [31] determined U-value from 10 days of data on the actual thermal performance of Scottish traditional construction techniques, to provide guidance for energy performance assessments. The calculated thermal transmittance of façades ranged from 0.30 W/m²·K to 2.65 W/m²·K. Results showed that 44% of wall measurements were lower than the theoretical U-value range, 42% were within the range, and 14% were higher than the theoretical range.

For an energy performance analysis of two houses, Bros-Williamson et al. [36] monitored in two periods of between 14 and 21 days the corresponding façades, which had theoretical U-values of 0.10 W/m²·K and 0.23 W/m^2·K. Results showed relative differences between the theoretical and measured U-values of 20%, 10%, 13%, and 65%, respectively.

Desogus et al. [7] carried out in situ measurements over 72 hours to compare two methods for measuring the building fabric's thermal resistance, in a wall with a calculated thermal resistance of 0.30 m²·K/W. The differences between the U-value calculated using a destructive method and the U-value measured using the average method were -8.1% when the temperature difference between the indoor and outdoor environment was 10ºC, and -18.9% when it was 7ºC.

In a study by Evangelisti et al. [37] on three conventional façades with calculated U-values ranging from 0.504 to 1.897 W/m²·K, the monitoring period was 7 days. The differences between the theoretical U-value according to ISO 6946 and the measured U-values using the average method ranged from +17% to +153%.

Ficco et al. [9] performed an experimental campaign in which seven envelope components were monitored for between 72 and 168 hours, with theoretical U-values ranging from 0.37 to 3.30 W/m^2·K. The authors estimated high relative in situ U-value uncertainties ranging from 8% in optimal operating conditions to about 50% in non-optimal operating conditions (average temperature difference values were lower than 10ºC, and there was low heat flow or heat flow inversion).

Li et al. [32] performed a study to provide additional evidence of real-world solid-walls' U-values and used two methods to reinterpret monitored data. The mean measured U-value was 1.29 W/m^2·K for walls that appeared to be of solid brick construction, and 1.34 W/m^2·K for stone, with standard deviations of about 0.35 and 0.38 W/m^2·K, respectively. The authors found that the transient analysis methodology developed by Biddulph et al. [38] could provide an estimate of the U-value using a much shorter time series than required in the average method following the ISO 9869:2014 standard [18].

Mandilaras et al. [39] investigated the thermal behaviour of a building envelope insulated with expanded polystyrene and a vacuum insulation panel with a theoretical estimation of R-value of 1.72 and 4.98 m²·K/W, respectively. The measurement period lasted approximately one month for each type of wall. The theoretical estimation of R-value was calculated according to ISO 6946 and numerical simulations, and the experimental determination of R-value was calculated using the dynamic method of ISO 9869:1994. The differences ranged from 1.2% in the envelope insulated with expanded polystyrene to 22.1% in the envelope insulated with a vacuum insulation panel.

Other authors used durations ranging from three to fourteen days in experimental campaigns to compare values of thermal transmittance obtained using the average method [20] and other techniques. Ahmad et al. [40] employed three sets of experimental data gathered during periods of 14, 10, and 6 days to evaluate the thermal performance of two exterior walls made from reinforced precast concrete panels, using the average method described in ASTM C1155 [41] and ISO 9869:1994 [20]. The results showed that the U-values were in a range of 1.402-1.490 W/m²·K with a mean of 1.456 W/m²·K, and a coefficient of variation of 3.39%. The authors concluded that a period of six days was sufficient to obtain in situ thermal performance parameters.

Biddulph et al. [38] performed measurements in 93 walls with calculated U-values ranging from 1.598 to 2.392 W/m²·K, to compare the average method of estimating U-values with a no thermal mass model and a single thermal mass model. The monitoring process lasted 14 days. The average method and the two models gave similar results for all the walls measured. The single thermal mass model achieved stability after three days, while the no thermal mass model required ten days.

Cesaratto and De Carli [42] evaluated the thermal conductance of 29 real buildings in a measurement campaign that lasted four days. They compared the reference thermal conductance values with those computed from the measurements. Most of the measurement results showed conductance values within a range of 0.3-1.1 W/m²·K. For new or refurbished buildings, the measured conductance value was found to be about 20% higher than the reference value.

Nardi et al. [23] presented experimental measurements of the thermal transmittance of buildings from different historical periods. The period of data acquisition was 144 hours for a wall with a theoretical U-value of 1.25 W/m^2·K, and 72 hours for walls with a theoretical U-value of 0.23 W/m^2·K and 0.51 W/m^2·K. The authors compared the non-invasive techniques of infrared technology and the heat flow meter method (using the average method from ISO 9869:1994) and calculated the U-value according to the ISO 6946:2007 standard. The results showed differences between the design and calculated U-values using the heat flow meter method of 7.1% for the wall with a theoretical U-value of 1.25 W/m^2·K, 82.6% for the wall with a theoretical U-value of 0.23 W/m^2·K, and 44.2% for the wall with a theoretical U-value of 0.51 W/m^2·K.

Deconinck and Roels [43] employed data from simulations to compare several semi-stationary and dynamic data analysis methods that are typically used for the thermal characterization of building components. The analysis considered the measurement time span and climatic conditions in a cavity wall with a thermal resistance of up to 4.002 m²·K/W. When the average method was used, the simulation results showed that in January, datasets of around 8 days or longer were required to obtain results within 10% accuracy, while datasets of around 20 days were required to obtain 5% accurate results. In April, around 12–14 days or longer were needed to obtain results in the 10% accuracy band. For the two summer scenarios, the results showed the limited validity of the average method, because summer periods are characterized by low heat flow rates and high capacitive functioning of the wall.

As shown in the literature review, differences between measured thermal properties and theoretical values vary widely. The variation could be influenced by the duration of the on-site tests, which ranged from three days to one month. The aim of this paper was to evaluate the minimum duration required of in situ experimental campaigns to measure the thermal transmittance of existing buildings' façades using the heat flow meter method, and to analyse the thermal performance of the façades during the test. Minimum test duration was determined according to data quality criteria, variability of results criteria, and standardized criteria, taking into consideration different values of thermal transmittance for the same range of average temperature difference. Data quality criteria indicate whether enough data have been obtained before disassembling the instrumentation, variability of results criteria express an estimation of the amount of random variation expected when the method is applied several times, and ISO criteria define the conditions that must be met before ending the test in heavy elements (which have a specific heat per unit area of more than 20 kJ/(m²·K). The minimum test durations using the three criteria were compared. The average and dynamic calculation methods were used for the analysis. This new approach consisting of analysing various criteria to finish the test will help to reduce practitioners' uncertainty about the duration of experimental campaigns for in situ measurements of façades' U-value.

The paper is organized as follows. After the introduction and the background, the third section describes the case studies and the method used in the research. The fourth section discusses the results, and the fifth section presents conclusions and future research issues.

3. Method

The method used to assess the minimum test duration required for in situ measurements of thermal transmittance of existing buildings' façades using a heat flow meter consisted of three steps:

- First, the façade's U-value was measured in situ in three case studies with different theoretical U-values. The monitoring process took into consideration guidelines associated with equipment and environmental conditions. Data were analysed in periods of 12-hour cycles, using the average method and the dynamic method.
- Second, the minimum test duration was evaluated by analysing data quality criteria, variability of results criteria, and ISO standard criteria.
- Third, the minimum test durations using different criteria were compared.

3.1 In situ measurement of the façade's U-value

This section describes the case studies, the monitoring process, and the data analysis.

3.1.1 Case studies

Three north-facing façades with different U-values were selected as case studies. The aim was to analyse the implications of the use of the two calculation methods on the duration of experimental campaigns in a façade with a high thermal transmittance value (Case study 1), a façade with a medium thermal transmittance value (Case study 2), and a façade with a low thermal transmittance value (Case study 3).

According to Gaspar et al. [44], Case study 1 is a single-skin façade with no air cavity or insulation, Case study 2 is classified as a double-skin façade with internal insulation but no air cavities, and Case study 3 is classified as a double-skin façade with a non-ventilated air cavity and internal insulation, finished with continuous covering. Façade 1 was built in 1960 and has a total thickness of 0.16 m. Façade 2 was built in 2006 and has a total thickness of 0.33 m. Façade 3 was built in 2005 and has a total thickness of 0.34 m. Table 2 describes in detail the layers and materials of the walls, as well as their thickness and thermal conductivity. The composition of façades was found to be in accordance with the executive project, as verified by the technical project manager or the facility manager. The total thickness of the wall was checked in situ.

The theoretical thermal transmittance of the façades was calculated as 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 obtained as follows [19]:

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

where $R_1 + R_2 + ... + R_N$ 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 [19], 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 calculated according to the following expression:

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

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

The theoretical U-value of the three case studies was obtained using Eq. 1 and Eq. 2. The design data for façades were obtained from the buildings' executive projects and reports. The technical project manager or the facility manager was asked whether the composition of the façades was as specified in the executive project. Afterwards, walls were inspected successively in situ by measuring the total thickness of the envelope. ISO 6949:2007 [19] and the Spanish Technical Building Code's Catalogue of Building Elements [45] were used to calculate theoretical values. Case study 1 had a theoretical thermal transmittance of 2.35 W/m²·K, Case study 2 of 0.52 W/m²·K, and Case study 3 of 0.36 W/m²·K. Although the goodness of the theoretical U-values was not absolutely certain, these values were used as a reference. Table 1 summarizes the thermal resistance of each layer and the theoretical U-value of the façades.

Case study	No. layer	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)
Case study 1	1	Gypsum plaster	0.01	0.570	0.018	0.16	2.35
	2	Single hollow brick wall	0.14		0.230		
	3	Mortar plaster	0.01	1.300	0.008		
Case study 2	1	Gypsum plaster	0.02	0.570	0.035	0.33	0.52
	2	Hollow brick wall	0.10		0.160		
	3	Extruded polystyrene	0.05	0.039	1.282		
	4	Perforated brick wall	0.14		0.210		
	5	Single-layer mortar plaster	0.02	0.340	0.059		
Case study 3	1	Mortar plaster	0.02	1.300	0.015	0.34	0.36
	2	Hollow brick wall	0.10		0.160		
	3	Polyurethane insulation	0.06	0.028	2.143		
	4	Perforated brick wall	0.14		0.210		
	5	Single-layer mortar plaster	0.02	0.340	0.059		

Table 1. Composition of the case studies

3.1.2 Monitoring process

Appropriate measuring equipment was required to obtain the actual thermal transmittance in the case studies. The equipment consisted of a heat flux meter plate, an inside air temperature sensor, an inside acquisition system and its batteries, and an outside air temperature sensor and its acquisition system (Fig. 1). The main specifications and a priori accuracy of the equipment are shown in Table 2.

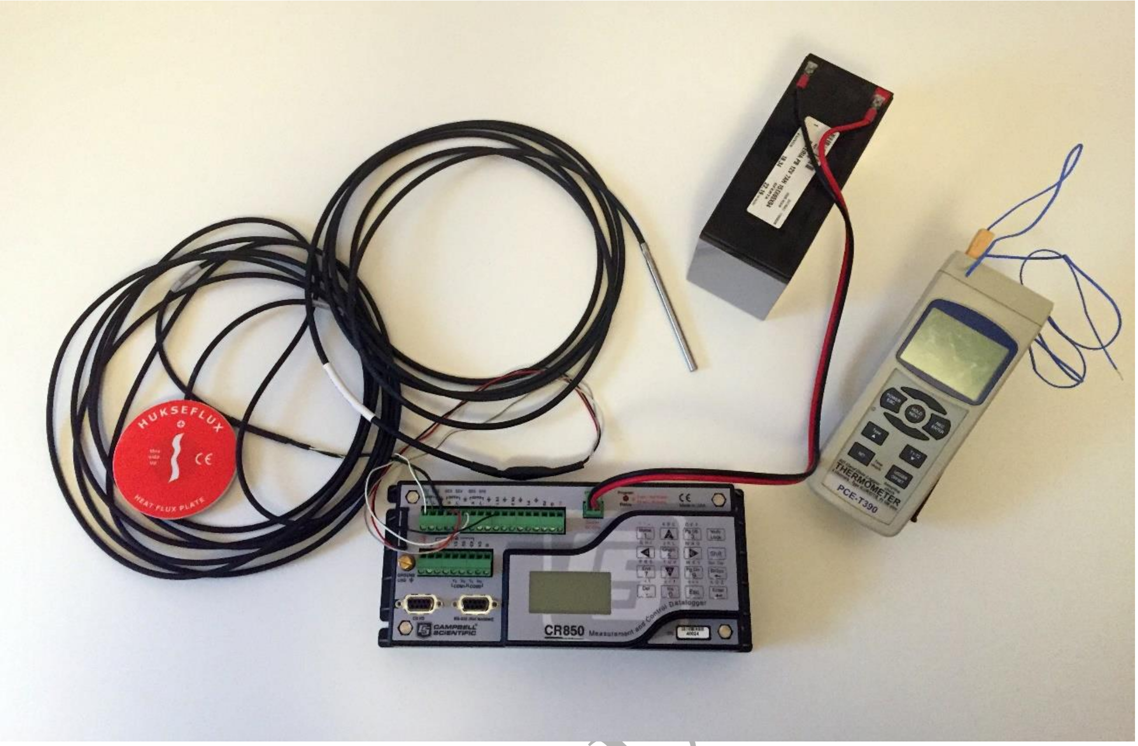


Fig. 1. View of the instrumentation used in the monitoring process

Type of equipment	Model and manufacturer	Range	A priori accuracy
Heat flux meter plate	HFP01, Hukseflux	±2000 W/m²	±5%
Inside air temperature sensor	T107, Campbell Scientific, Inc.	-35° to +50°C	±0.5°C
Inside acquisition system	CR850, Campbell Scientific, Inc.	Input ±5Vdc	±0.06% of reading
Outside air temperature sensor and its acquisition system	K-type, TF-500, PCE-T390, PCE Iberica, SL	-50º to +999.9°C	±(0.4% + 0.5ºC)

Table 2. Main specifications of the equipment

The location of the measured area was investigated by thermography, as recommended in ISO 9869-1:2014 [20] and considered in several studies such as Ahmad et al. [40], Asdrubali et al. [6], Evangelisti et al. [37], and Tejedor et al. [46], with an infrared thermographic camera (FLIR E60bx Infrared Camera). Sensors were mounted on a representative part of the wall. Corners in the opaque part, the vicinity of defects, and the direct influence of a heating or cooling device were avoided. Guattari et al. [47] and Evangelisti et al. [48] investigated the impact of heating systems on the in situ measurement of the thermal transmittance of façades. Only north-facing walls were monitored, to avoid direct solar radiation. In addition, the weather conditions were observed during the data collection process (Fig. 2). To avoid inaccurate measurements, indoor temperature was always higher than outdoor temperature, so the heat flow direction was stable, since changes in heat flow direction could lead to imprecise measurements, as stated by Tadeu et al. [33]. Moreover, a study by Atsonios et al. [49] showed that the direction of heat flow during the day strongly influenced the duration of the required measurement period and the variability of the results. Average differences between indoor and outdoor environmental temperatures were no lower than 10ºC. The heat flux meter plate was installed on the internal side of the wall, where the temperature was the most stable before and during the test. A layer of thermal interface material was carefully applied, to ensure adequate thermal contact between the entire area of the sensor and the wall surface. Data from the heat flux meter plate and temperature sensors were recorded for at least seven complete days (168 hours). Dataloggers were configured to sample data every 1 second and store the 30-minute averaged data in their memories.

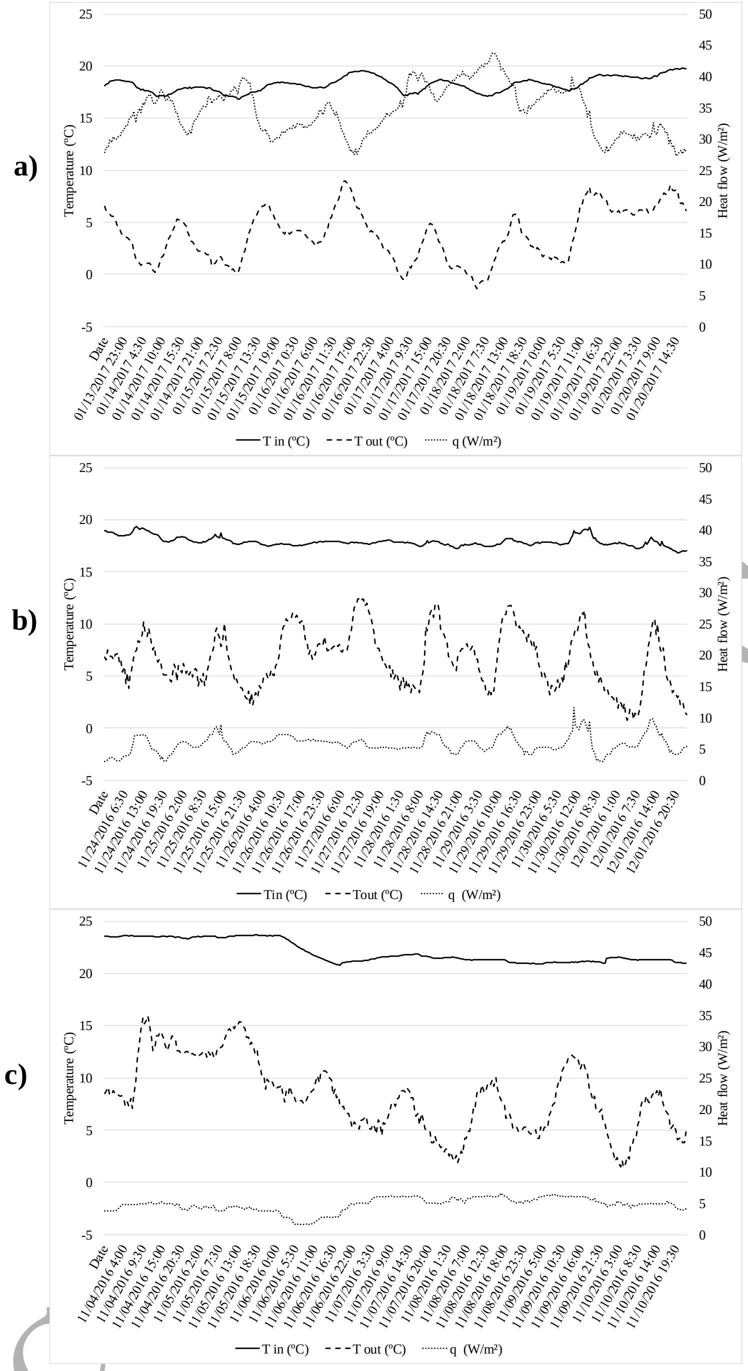


Fig. 2. Data obtained from the process of monitoring for a) Case study 1 for the period 13–20 January 2017, b) Case study 2 for the period 24 November to 01 December 2016, and c) Case study 3 for the period 03–10 November 2016

Case study 1 was monitored from 13–20 January 2017 (from 6 p.m. to 6 p.m.), Case study 2 from 24 November to 1 December 2016 (from 0:30 a.m. to 0:30 a.m.) and Case study 3 from 03–10 November 2016 (from 11 p.m. to 11 p.m.). Environmental conditions were optimal in Case studies 1 and 2. However, in Case study 3, it rained on the seventh day of the experimental campaign.

3.1.3 Data analysis

The average and dynamic methods were used to calculate the in situ thermal transmittance of façades [20]. Following Flanders' [50] indications for analysing data quality in the measurement of a façade's U-value, the thermal behaviour of the façades was analysed with data from consecutive cycles of 12 hours, using cumulative values. Therefore, the first cycle contained data on the first 12 hours tested, the second cycle contained data on the first 24 hours tested, the third cycle contained data on the first 36 hours tested, and the other cycles successively.

3.1.3.1 Data analysis using the average method

Using the average method, thermal transmittance (U) can be obtained by dividing the mean density of the heat flow rate by the mean temperature difference [20], assuming a steady state heat flow in which thermal mass is neglected [38], as in the following equation:

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

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

The combined standard uncertainty of measurements was calculated according to the Guide to the expression of uncertainty in measurement [51], and following the guidelines established in Gaspar et al. [52], considering the accuracy of the equipment indicated in the manufacturer's technical specifications (sensors and acquisition systems). The uncertainty ($u_c(U)$) was obtained according to the following expression:

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

where $u_c(q)$ is the uncertainty associated with the heat flow rate measuring equipment, $u_c(T_i)$ is the uncertainty associated with the environmental indoor temperature measuring equipment, and $u_c(T_e)$ is the uncertainty associated with the environmental outdoor temperature measuring equipment.

3.1.3.2 Analysis of data using the dynamic method

According to the dynamic analysis method described by ISO 9869-1:2014 [20], 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:

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

where T_{Ii} and T_{Ei} are the indoor and outdoor ambient temperatures taken at 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 dynamic characteristics of the wall without any particular significance and depend on the time constant τ_n. The coefficients β_n are exponential functions of the time constant τ_n, where $\beta_\mathrm{n} = \exp\left(-\frac{\Delta \mathrm{t}}{\tau_\mathrm{n}}\right)$, and the time constants τ_n are unknown parameters found by looking for the best estimate of $\vec{\mathrm{Z}}$ 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 data sets (more than $2m+3$) at various times, an overdetermined system of linear equations is created as follows:

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

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 (U, K_1, K_2, P_n and Q_n.) 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), the first component of $\vec{Z}*$ is the best estimate of thermal transmittance (U), and the other components are the best estimate of variables K_1, K_2, P_n and Q_n.

The guidelines of Gaspar et al. [52] were followed to apply the dynamic method with a programmed spreadsheet.

3.2 Analysis of minimum test duration

This section describes the method and criteria for analysing the minimum test duration in three ways: data quality, variability of results, and ISO standard.

3.2.1 Data quality criteria

In the average method, data quality criteria are obtained by computing the convergence factor (CU_n) of the resulting U-values following the equation [41,50]:

$$CU_n = \frac{U(t)-U(t-n)}{U(t)} \tag{8}$$

In the dynamic method, quality criteria to indicate confidence in the U-value estimation results are calculated according to the following equation [20,53]:

$$I = \sqrt{\frac{S^2 \cdot Y(1,1)}{M-2m-4}} \cdot F(P, M-2m-5) \tag{9}$$

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 $M\text{-}2m\text{-}5$ is the degree of freedom.

For the average method, in this study, when the convergence factor (CU_n) remains lower than 10% for at least three periods of length n (being n = 12 hours), the convergence criterion has been satisfied [50].

For the dynamic method, in this study, a confidence interval smaller than 5% of the thermal transmittance for $P = 0.95$ is adopted as a quality criterion [53].

3.2.2 Variability of results criteria

The variability of results or random error was analysed by calculating the relative standard deviation (the coefficient of variation) of the resulting U-values, as proposed in ASTM C1155 [41] and by Atsonios et al. [49]. The coefficient of variation was calculated following the expression:

$$Coefficient\ of\ variation\ [CV(\%)] = \sqrt{\frac{\sum_i^{i+(n-1)}(Um_i-\overline{Um})^2}{n-1}} \times \frac{1}{\overline{Um}} \times 100 \tag{10}$$

where $\overline{Um}$ is the average of *Um-values* of the façade during n cycles, and n is the number of cycles (n=3).

The random error of the results was estimated with a 95.4% confidence level, following the expression:

$$e(\%) = 2 \times CV(\%) \tag{11}$$

In this study, the coefficient of variation is expected to be 10% for the average method and 6% for the dynamic method [49], for a confidence level of 95.4%.

3.2.3 ISO criteria

The ISO 9869-1:2014 standard [20] establishes a minimum test duration of 72 hours when the temperature is stable around the heat flux meter plate. However, the actual duration depends on the values obtained during the course of the test. The ISO standard defines three conditions that must be met simultaneously to end the test. The first condition is that the test must have lasted 72 hours or longer (Eq. 12). The second condition is that the U-value obtained at the end of the test must not deviate more than

5% from the value obtained 24 hours earlier (Eq. 13). And the third condition is that the U-value obtained by analysing data from the first time period during *INT(2·D_T/3)* days must not deviate more than 5% from the value obtained from the data for the last period of the same duration (Eq. 14).

$$D_T\ (days) \geq 3 \tag{12}$$

$$\left| \frac{U_{m_i} - U_{m_{i-1}}}{U_{m_{i-1}}} \times 100 \right| \leq 5\% \tag{13}$$

$$\left| \frac{{U_m}_{i=1}^{INT(2\times\frac{DT}{3})} - {U_m}_{i=DT-INT(2\times\frac{DT}{3})+1}^{DT}}{{U_m}_{i=DT-INT(2\times\frac{DT}{3})+1}^{DT}} \times 100 \right| \leq 5\% \tag{14}$$

where D_T is the duration of the test in days, U_m is the measured thermal transmittance of the façade, the index *i* enumerates the cycle, and *INT* is the integer part.

4. Results and discussion

Experimental campaigns were conducted under real environmental conditions. All case studies had an average temperature difference of between 10ºC and 15ºC with a stable direction of heat flow. Thus, the average temperature difference was not a significant factor that influenced the thermal transmittance results. The average temperature differences are shown in Table 3.

During the data acquisition process, 337 datasets of readings for Case studies 1 and 3, and 385 for Case study 2 were collected to calculate the thermal transmittance and its associated uncertainty. The thermal transmittance was calculated for 12-hour test cycles, using the average and dynamic methods in the three case studies (Eq. 3 to Eq. 7). The results of the data analysis are depicted in Fig. 3, and are summarized in Table 3, where $U_{m\text{-}Av} \pm U_{(C)}$ is the measured thermal transmittance using the average method and its associated uncertainty, $U_{m\text{-}Dyn} \pm I95\%$ is the measured thermal transmittance using the dynamic method, and *Ut* is the theoretical thermal transmittance obtained using Eq. 1 and Eq. 2.

Uncertainties of measurement decreased as the tests were extended. The results are in line with those analysed from the literature in previous sections, in which periods of data acquisition that were too short led to highly inaccurate measurements [6,23].

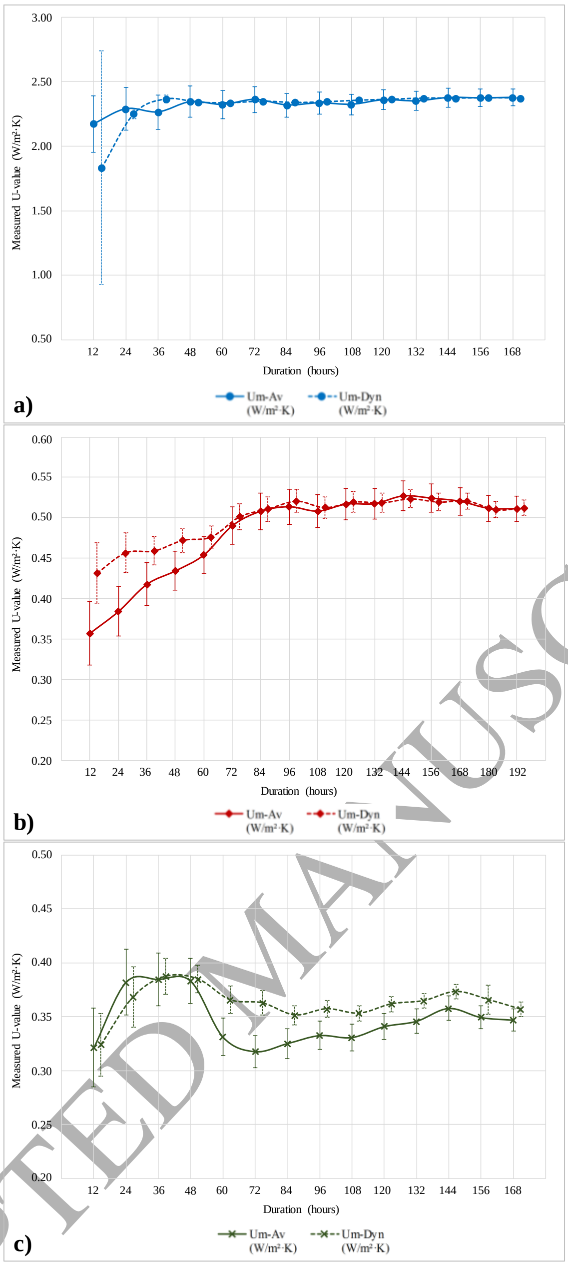


Fig. 3. Measured U-values and their associated uncertainties in a) Case study 1, b) Case study 2, and c) Case study 3

		Case study 1		**Case study 2**		**Case study 3**	
		$U_{m\text{-}Av} \pm U_{(C)}$ (W/m^2·K)	**$U_{m\text{-}Dyn}$ ±I95% (W/m^2·K)**	**$U_{m\text{-}Av} \pm U_{(C)}$ (W/m^2·K)**	**$U_{m\text{-}Dyn}$ ±I95% (W/m^2·K)**	**$U_{m\text{-}Av} \pm U_{(C)}$ (W/m^2·K)**	**$U_{m\text{-}Dyn}$ ±I95% (W/m^2·K)**
Duration of the test (hours)	**12 h**	2.17±0.22	1.83±0.90	0.36±0.04	0.43±0.04	0.32±0.04	0.32±0.03
	24 h	2.29±0.17	2.25±0.04	0.38±0.03	0.46±0.02	0.38±0.03	0.37±0.03
	36 h	2.26±0.13	2.36±0.03	0.42±0.03	0.46±0.02	0.38±0.02	0.39±0.02
	48 h	2.34±0.12	2.34±0.02	0.43±0.02	0.47±0.01	0.38±0.02	0.38±0.01

	60 h	2.32±0.11	2.33±0.01	0.45±0.02	0.48±0.01	0.33±0.02	0.37±0.01
	72 h	2.36±0.10	2.35±0.01	0.49±0.02	0.50±0.02	0.32±0.01	0.36±0.01
	84 h	2.32±0.09	2.34±0.01	0.51±0.02	0.51±0.02	0.33±0.01	0.35±0.01
	96 h	2.33±0.09	2.34±0.01	0.51±0.02	0.52±0.01	0.33±0.01	0.36±0.01
	108 h	2.32±0.08	2.35±0.01	0.51±0.02	0.51±0.01	0.33±0.01	0.35±0.01
	120 h	2.36±0.08	2.36±0.01	0.52±0.02	0.52±0.01	0.34±0.01	0.36±0.01
	132 h	2.35±0.07	2.37±0.01	0.52±0.02	0.52±0.01	0.35±0.01	0.36±0.01
	144 h	2.37±0.07	2.37±0.01	0.53±0.02	0.52±0.01	0.36±0.01	0.37±0.01
	156 h	2.37±0.07	2.37±0.01	0.52±0.02	0.52±0.01	0.35±0.01	0.37±0.01
	168 h	2.38±0.07	2.37±0.01	0.52±0.02	0.52±0.01	0.35±0.01	0.36±0.01
	180 h			0.51±0.02	0.51±0.01		
	192 h			0.51±0.02	0.51±0.01		
Measurement period		from 01/13/2017 to 01/20/2017		from 11/24/2016 to 12/01/2016		from 11/03/2016 to 11/09/2016	
ΔT average (K)		14.5		11.3		13.4	
Ut (W/m²·K)		2.35		0.52		0.36	

Table 3. Estimated theoretical thermal transmittance and measured thermal transmittance using the average and dynamic methods calculated in cycles of 12 hours

4.1 Data quality criteria

Data quality criteria for the average method were examined for the three cases through the convergence factor (Eq. 8). Fig. 4 presents the evolution of the convergence factor (CU) every 12 hours. In Case study 1, the CU remained below 10% for 3 consecutive periods of 12 hours after 24 hours of testing, so the test could be ended on the third day (24 + 36 hours). In Case study 2, the CU was kept below 10% for 3 consecutive periods of 12 hours after 24 hours of testing, so the test could be ended on the third day (24 + 36 hours). In Case study 3, the CU remained below 10% for 3 consecutive periods of 12 hours after 72 hours of testing, so the test could be ended on the fifth day (72 + 36 hours). Generally, façades with a high thermal transmittance value obtained a lower convergence factor than façades with low thermal transmittance.

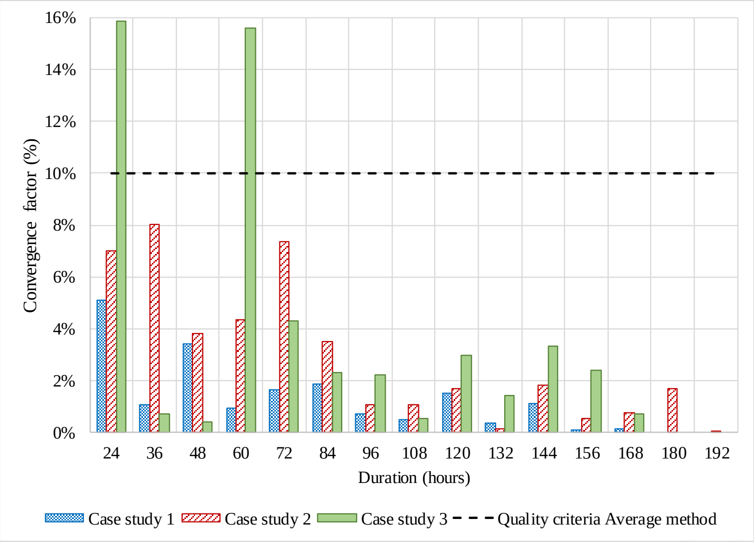


Fig. 4. Data quality criteria in Case study 1, Case study 2, and Case study 3 using the Average method

Data quality criteria for the dynamic method were examined for the three case studies through the confidence interval (Eq. 9). Fig. 5 presents the evolution of the confidence interval every 12 hours. The confidence interval remained below 5% from 24 hours in Case study 1. In Case study 2 and Case study 3, it remained below 5% from 36 hours. Generally, and particularly in initial cycles, façades with a high thermal transmittance value obtained lower confidence intervals than façades with low thermal transmittance.

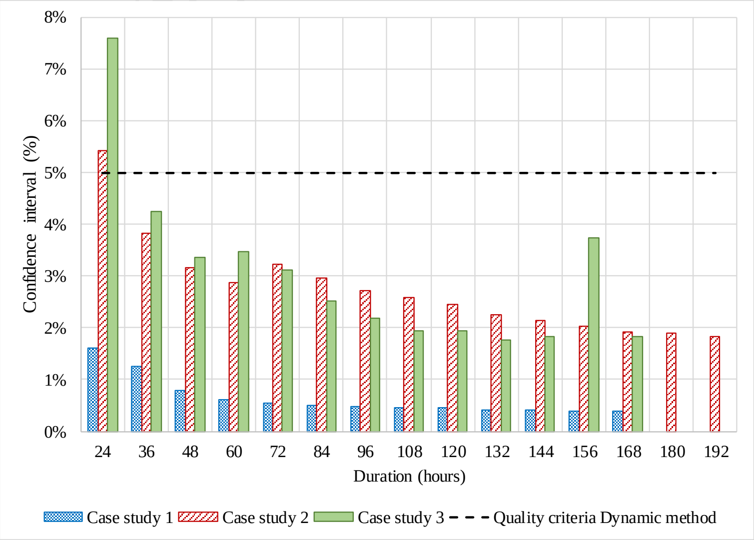
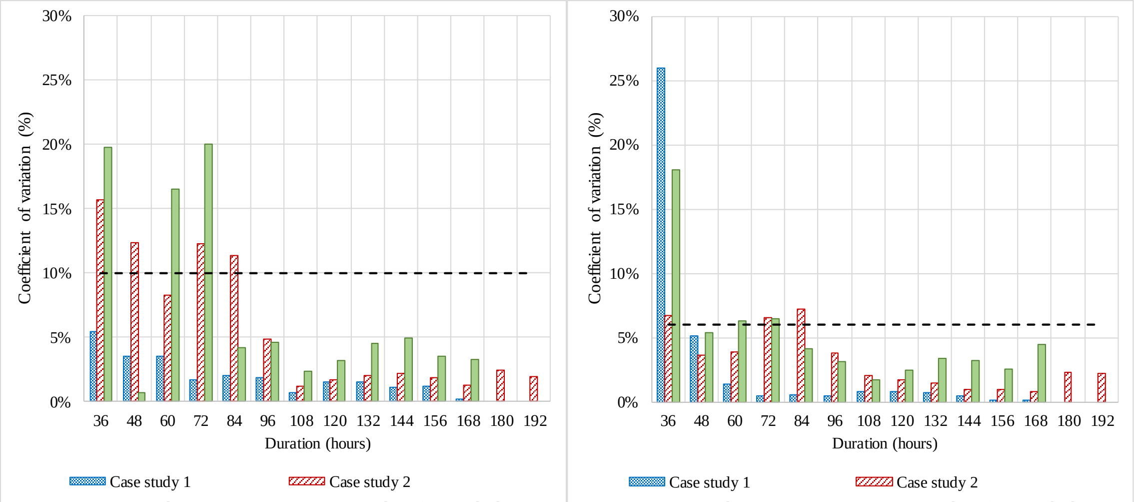


Fig. 5. Data quality criteria in Case study 1, Case study 2, and Case study 3 using the Dynamic method

4.2 Variability of results

The variability of results was examined for each calculation method in the three case studies through the coefficient of variation, following Eq. 10 and Eq. 11. The coefficients of variation in each cycle using the average and dynamic methods are depicted in Fig. 6. In Case study 1, the coefficient of variation of the results was lower than expected at 36 hours using the average method, and at 48 hours using the dynamic method. In Case study 2, the coefficient of variation of the results remained lower than expected from 96 hours onwards using both calculation methods. In Case study 3, the coefficient of variation of the results remained lower than expected from 84 hours using both calculation methods. Thus, the test could be stopped on the second day in Case study 1 and on the fourth day in Case studies 2 and 3.



a) **b)**

Fig. 6. Coefficients of variation in Case study 1, Case study 2, and Case study 3 using a) the Average method, and b) the Dynamic method

4.3 ISO criteria

The conditions for ending the test according to the ISO standard [20] were checked. The first condition is that the test must last at least 72 hours (Eq. 12). Therefore, the second and third conditions were checked from the third day (72 hours) onwards.

The second condition is that the U-value obtained at the end of the test must not deviate more than 5% from the value obtained 24 hours earlier (Eq. 13). In Case study 1, the test could be finished after 72 hours, given that the condition was fulfilled for all cycles for the two calculation methods. In Case studies 2 and 3, the minimum test duration of three days indicated in the ISO 9869-1:2014 standard [20] was not long enough. A minimum of 96 hours was required for the monitoring process, as the condition was fulfilled in the fourth 24-hour cycle for both calculation methods. Table 4 shows deviations of the U-value from the value obtained 24 hours earlier for the two calculation methods in the three case studies.

Number of cycles evaluated	**Related cycles in the evaluation**	**Case study 1**		**Case study 2**		**Case study 3**	
		Deviation in U_{m-Av} (%)	**Deviation in U_{m-Dyn} (%)**	**Deviation in U_{m-Av} (%)**	**Deviation in U_{m-Dyn} (%)**	**Deviation in U_{m-Av} (%)**	**Deviation in U_{m-Dyn} (%)**
3 (72 h)	3 vs. 2	0.7	0.3	12.8 *	6.2 *	17.1 *	5.8 *
4 (96 h)	4 vs. 3	1.1	0.2	4.8	3.9	4.7	1.5
5 (120 h)	5 vs. 4	1.0	0.8	0.6	0.2	2.5	1.3
6 (144 h)	6 vs. 5	0.7	0.4	2.0	0.7	4.9	3.2
7 (168 h)	7 vs. 6	0.0	0.0	1.3	0.5	3.0	4.4
8 (192 h)	8 vs. 7	--	--	1.7	1.6	--	--

* The cycle did not meet the second condition of test completion

Table 4. Deviation of the U-value from the value obtained 24 hours earlier, for the average and dynamic methods of calculation

The third condition for test completion is that the U-value obtained by analysing data from an initial period must not deviate more than 5% from the value obtained from data for the last period of the same duration (Eq. 14). The duration of the analysis period depends on the test duration and was calculated for each 24-hour cycle according to the expression: $INT(2 \cdot D_T/3)$ days. Thus, the analysis period for the third and fourth cycles was two days, for the fifth cycle was three days, for the sixth and seventh cycles was four days, and for the eighth cycle was five days. In accordance with this condition, the monitoring process in Case study 1 could be finished in 72 hours, using both calculation methods. In Case study 2, the test could not be finished until 192 hours when the average method was used, or until 168 hours when the dynamic method was used, because the condition was fulfilled in the eighth and seventh cycle, respectively. In Case study 3, the test could not be finished until 120 hours, because the condition was fulfilled in the fifth cycle. Additionally, verification of the condition showed non-optimal environmental conditions in the seventh cycle in Case study 3 when the average method was used. Table 5 shows, for the three case studies, the duration of analysis periods related to each cycle, the results of thermal transmittance during the initial and final analysis period for each cycle and for both calculation methods, and the deviations between the U-values obtained during the initial and final analysis period for each cycle, based on Eq. 14.

Case study	Duration of the test (days)	Duration of the analysis period (days)	Analysis period	U_{m-Av} (W/m²·K)	Deviation of U_{m-Av} between periods of analysis (%)	U_{m-Dyn} (W/m²·K)	Deviation of U_{m-Dyn} between periods of analysis (%)
Case study 1	3 (72 h)	2	Initial test period	2.34	2.3	2.34	1.5
			Final test period	2.40		2.37	
	4 (96 h)	2	Initial test period	2.34	0.8	2.34	0.6
			Final test period	2.33		2.35	
	5 (120 h)	3	Initial test period	2.36	0.3	2.35	1.1
			Final test period	2.37		2.37	
	6 (144 h)	4	Initial test period	2.33	2.4	2.34	1.7
			Final test period	2.39		2.38	
	7 (168 h)	4	Initial test period	2.33	2.2	2.34	2.0
			Final test period	2.39		2.39	
Case study 2	3 (72 h)	2	Initial test period	0.43	20.3 *	0.47	12.9 *
			Final test period	0.55		0.54	
	4 (96 h)	2	Initial test period	0.43	28.6 *	0.47	21.3 *
			Final test period	0.61		0.60	
	5 (120 h)	3	Initial test period	0.49	15.6 *	0.50	13.1 *
			Final test period	0.58		0.58	
	6 (144 h)	4	Initial test period	0.51	11.7 *	0.52	7.4 *
			Final test period	0.58		0.56	
	7 (168 h)	4	Initial test period	0.51	5.9 *	0.52	3.4
			Final test period	0.55		0.54	
	8 (192 h)	5	Initial test period	0.52	1.5	0.52	0.1
			Final test period	0.53		0.52	
Case study 3	3 (72 h)	2	Initial test period	0.38	33.8 *	0.38	7.9 *
			Final test period	0.29		0.36	
	4 (96 h)	2	Initial test period	0.38	31.1 *	0.38	10.9 *
			Final test period	0.29		0.35	
	5 (120 h)	3	Initial test period	0.32	0.3	0.36	1.2
			Final test period	0.32		0.36	
	6 (144 h)	4	Initial test period	0.33	4.2	0.36	4.9
			Final test period	0.35		0.38	
	7 (168 h)	4	Initial test period	0.33	8.6 **	0.36	1.0
			Final test period	0.36		0.36	

* The cycle did not meet the third condition of test completion.

** Measurements biased due to unfavourable climatic conditions.

Table 5. Deviation of U-values between the initial and final analysis period for each test duration for the average and dynamic methods of calculation

4.4 Comparison of results

Table 6 summarizes the minimum duration required for in situ experimental campaigns for the three case studies, according to the three criteria.

	Case study 1		Case study 2		Case study 3	
	Average method	**Dynamic method**	**Average method**	**Dynamic method**	**Average method**	**Dynamic method**
Data quality criteria	60 hours (3 days)	24 hours (1 days)	60 hours (3 days)	36 hours (2 days)	108 hours (5 days)	36 hours (2 days)
Variability of results criteria	36 hours (2 days)	48 hours (2 days)	96 hours (4 days)	96 hours (4 days)	84 hours (4 days)	84 hours (4 days)

ISO criteria	72 hours (3 days)	72 hours (3 days)	192 hours (8 days)	168 hours (7 days)	120 hours (5 days)	120 hours (5 days)
ΔT average (K)	14.5		11.3		13.4	
Ut (W/m²·K)	2.35		0.52		0.36	

Table 6. Minimum duration of the test according to the three criteria: data quality, variability of results, and ISO criteria for the average and dynamic methods of calculation in each case study

In Case study 1 (façade with high thermal transmittance), the conditions for ending the test were met on the third day (60 hours) for the average method and on the first day (24 hours) for the dynamic method, using data quality criteria. Using variability of results criteria, conditions for ending the test were met on the second day for both calculation methods, 36 hours for the average method, and 48 hours for the dynamic method. According to ISO criteria, conditions for ending the test were met on the third day (72 hours) for both calculation methods. The results were highly accurate with respect to the theoretical U-value. A systematic error (difference between theoretical and measured U-value) below 4% was obtained for the average method, and below 3% for the dynamic method, regardless of the criteria used. However, when ISO criteria were applied, the systematic error was lower than 0.5%.

In Case study 2 (façade with medium thermal transmittance), the test could be stopped on the third day (60 hours) for the average method and on the second day (36 hours) for the dynamic method, using data quality criteria. Using variability of results criteria, the test could be ended on the fourth day (96 hours) for both calculation methods. In accordance with ISO criteria, the test could be ended on the eighth day (192 hours) when the average method was used, and on the seventh day (168 hours) when the dynamic method was used. This increase in test duration may be due to a reduction in thermal transmittance with respect to Case study 1, greater sensitivity of the ISO criteria, and the fact that the average temperature difference was slightly lower than in the previous case, although it was higher than 10ºC. Taking the theoretical U-value as a reference, a systematic error of 13% was obtained for the average method using data quality criteria. This error was reduced below 2% by applying variability of results criteria and ISO criteria. For the dynamic method, the systematic error was reduced from 12% to 0.2% by applying variability of results criteria and ISO criteria.

In Case study 3 (façade with low thermal transmittance), conditions for ending the test were met on the fifth day (108 hours) for the average method, and on the second day (36 hours) for the dynamic method, using data quality criteria. Using variability of results criteria, conditions for ending the test were met on the fourth day (84 hours) for both calculation methods. With ISO criteria, the test could be finished on the fifth day (120 hours) for both calculation methods. Taking the theoretical U-value as a reference value, a systematic error of 9% for the average method and 7% for the dynamic method was obtained by applying data quality criteria. Using variability of results criteria, the systematic error was around 10% for the average method and around 3% for the dynamic method. Using ISO criteria, the systematic error for the average method was 6%, and 0.3% for the dynamic method.

5. Conclusions and further research

This paper evaluates the minimum duration of in situ experimental campaigns to measure the thermal transmittance of existing buildings' façades using the heat flow meter method. The evaluation takes into consideration criteria of data quality, variability of results, and the ISO standard for three values of thermal transmittance (a wall with a high U-value, a wall with a medium U-value, and a wall with a low U-value). In situ measurements were conducted under real conditions within the same range of average temperature difference (between 10ºC and 15ºC). Data were analysed in periods of 12-hour cycles, using the average and dynamic methods. Finally, the minimum duration of on-site tests following the three criteria were compared.

The findings show that the results were influenced by the measurand (the façade's theoretical U-value), regardless of the calculation method used. Generally, in initial cycles, façades with high thermal transmittance obtained a lower convergence factor, lower confidence interval, and lower variability of results than façades with low thermal transmittance.

Test completion results indicated that the ISO standard is robust, pursuing the minimum risk of error in the on-site measurement of the façade's thermal transmittance. The minimum test duration according to criteria of data quality and variability of results was found to be shorter than that using ISO criteria.

The calculation method influences the accuracy of results. The results obtained with the dynamic method were found to be more accurate than those obtained using the average method, especially for low thermal transmittances. Moreover, the use of the dynamic method could reduce the duration of the test. It should be taken into account that real-time monitoring could improve decision-making regarding the adjustment of the minimum duration of the on-site tests.

The findings indicate that when certification is not required in the assessment of the thermal performance of a façade, the minimum duration of the test could be reduced by applying data quality and variability of results criteria. When a highly accurate measurement is needed, the use of ISO criteria is recommended. Moreover, the findings appear to suggest that in future revisions of the standard, the minimum duration of the test could be discussed. However, further research should be conducted to readjust the criteria.

Nomenclature list

CU_n	convergence factor [%]
CV	coefficient of variation [%]
I	confidence interval [%]
q	heat flux [W/m^2]
R	theoretical thermal transmittance of a uniform layer [m^2·K/W]
Rt	theoretical total thermal transmittance [m^2·K/W]
T_{in}	indoor environmental temperature [ºC]
T_{out}	outdoor environmental temperature [ºC]
$U_{m\text{-}Av}$	measured thermal transmittance using the average calculation method [W/m^2·K]
$U_{m\text{-}Dyn}$	measured thermal transmittance using the dynamic calculation method [W/m^2·K]
Ut	theoretical thermal transmittance [W/m^2·K]
$U_{(C)}$	combined standard uncertainty of measurements [W/m^2·K]
ΔT	average temperature difference [K]

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