# Impact assessment of the façades' actual state on the energy performance gap of residential buildings

Thesis by publications

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“A person who never made a mistake

never tried anything new”.

Albert Einstein

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# Abstract

Bridging the gap between the predicted and actual energy performance of buildings is necessary to increase the energy performance of existing buildings and achieve the European Union's energy efficiency targets in the "2030 climate & energy framework". Construction is considered the sector with the most potential for energy saving. Specifically, buildings space heating has considerable potential for energy saving. Thermal transmittance is the fundamental parameter to characterise the heat losses of building envelopes. However, several research authors evidenced that assumptions regarding heat loss from a home pre-retrofit and post-retrofit were incorrect. In this sense, accurate on-site measurements are necessary to provide information on the actual thermal transmittance of façades.

The purpose of this thesis is to contribute to reduce the energy performance gap of residential buildings. Therefore, the aim of the thesis is to enhance the accuracy of in situ measurements of the actual thermal transmittance of façades of existing residential buildings using the heat flux meter method to ensure successful decision-making during the energy renovation processes of existing buildings, and to confirm energy performance strategies for new nearly zero-energy buildings.

The analysis of testing parameters for the in situ measurement process of the thermal transmittance are not fully specified by the standard ISO used extensively. Relating to calculation methods to conduct research on the thermal behaviour of façades, the standardised average method is widely used by authors. Very few initiatives used the standardised dynamic method because it is more complex than the average method. This research assesses the implications of using the different standardised calculation methods in order to verify which best fits theoretical values. Moreover, the usability of the standardised dynamic method is promoted and facilitated through a calculation procedure, defining a programmed spreadsheet accessible to practitioners.

The dissertation proposes a classification system of façades to facilitate the selection of façades to conduct a systematic analysis of the thermal performance of façades in the housing sector. The classification of façades of existing residential buildings for subsequent analysis is based on the characterization of the opaque part of façades.

The dissertation continues with the exploration of the boundaries of the requirements for using the standardised heat flow meter method to refine the testing conditions in low U-value façades. Façades with low thermal transmittance values are increasingly promoted due to comply with Directive 2010/31/EC targets. However, as several researchers shown, conducting accurate in situ measurement of low thermal transmittance façades is a challenging task. Investigating the limits of application of the HFM method for the in situ measurement of U-values in low thermal transmittance façades would allow to ensure compliance with policies to transition the existing building stock to nearly zero-energy buildings, and to confirm energy performance strategies for new nearly zero-energy buildings.

To enhance the usability of the heat flux meter method, the dissertation compares different criteria for determining conditions for stopping the test during in situ experimental campaigns when measuring the thermal transmittance of existing buildings’ façades using the heat flow meter method. This will help to reduce practitioners’ uncertainty about the duration of experimental campaigns for obtaining accurate actual thermal transmittance of existing buildings’ façades.

The dissertation concludes by outlining the main contributions of this research. The subjects that were raised during the research undertaken although they could not be addressed are commented and proposed as future work.

# Resum

Reduir la diferència entre el rendiment energètic previst i real dels edificis és necessari per tal d'augmentar el rendiment energètic dels edificis existents i assolir els objectius sobre eficiència energètica de la Unió Europea en el "Marc sobre clima i energia per al 2030". La construcció és considerada el sector amb més potencial d'estalvi energètic. Concretament, el condicionament tèrmic dels edificis mitjançant calefacció té un potencial d'estalvi energètic considerable. La transmitància tèrmica és el paràmetre fonamental per caracteritzar les pèrdues de calor a través de les envolvents de l'edifici. Tanmateix, diversos investigadors han demostrat que les hipòtesis sobre la pèrdua de calor dels edificis abans i després d'una rehabilitació no són correctes. En aquest sentit, es fa necessari realitzar mesures in situ amb elevada precisió per proporcionar informació sobre la transmitància tèrmica real de les façanes.

El propòsit d'aquesta tesi és contribuir a reduir la bretxa del rendiment energètic en els edificis residencials. Per això, l'objectiu d'aquesta dissertació és millorar la precisió en la realització de mesures in situ de la transmitància tèrmica real de les façanes dels edificis residencials existents usant el mètode estandarditzat del mesurador de flux de calor (HFM), per assegurar l'èxit en la presa de decisions durant els processos de renovació energètica dels edificis existents i confirmar estratègies d'eficiència energètica per a nous edificis de consum d'energia quasi nul.

L'anàlisi dels paràmetres d'assaig per a la mesura in situ de la transmitància tèrmica no està totalment especificada en l'estàndard ISO utilitzat extensivament. Pel que fa als procediments de càlcul per a determinar el comportament tèrmic de les façanes, el mètode que s'utilitza de forma més àmplia pels investigadors és el mètode de mitjanes estandarditzat. Poques iniciatives utilitzen el mètode dinàmic estandarditzat degut a la seva complexitat. La investigació avalua les implicacions d'utilitzar els diferents mètodes de càlcul estandarditzats per verificar quin s'ajusta millor als valors teòrics de referència. A més, es fomenta i facilita la usabilitat del mètode dinàmic estandarditzat mitjançant un procediment de càlcul, definint un full de càlcul programat accessible per als professionals.

La dissertació proposa un sistema de classificació de façanes per facilitar la selecció de façanes per a la seva posterior anàlisi del rendiment tèrmic de les façanes del sector de l'habitatge. La classificació de façanes d'edificis residencials existents es basa en la caracterització de la part opaca de les façanes.

La dissertació continua explorant els límits dels requisits per a la utilització del mètode HFM per a refinar les condicions d'assaig en les façanes amb baixa transmitància tèrmica. Les façanes amb valors baixos de transmitància tèrmica es promouen cada vegada més per tal de complir amb els objectius de la Directiva 2010/31/CE. Tot i així, tal com han demostrat diversos investigadors, realitzar mesures in situ precises en aquestes façanes és un repte. La investigació dels límits d'aplicació del mètode HFM per a la mesura in situ de la transmitància tèrmica en façanes amb baixa transmitància tèrmica permetria assegurar el compliment de les polítiques de transició d'edificis existents a edificis de

consum energètic quasi nul, i confirmar estratègies d'eficiència energètica per a nous edificis de consum energètic quasi nul.

Per millorar la usabilitat del mètode HFM, aquesta tesi analitza diferents criteris per a determinar les condicions d’aturada de l’assaig durant les campanyes experimentals per mesurar in situ la transmitància tèrmica de les façanes dels edificis existents mitjançant el mètode HFM. Els resultats ajudaran a reduir la incertesa sobre la durada de les campanyes experimentals per obtenir una transmitància tèrmica real precisa de les façanes dels edificis existents.

La tesi conclou resumint les principals aportacions d'aquesta investigació. Els temes que s’han plantejat durant la investigació realitzada, i que no s’han pogut abordar, es comenten i es proposen com a línies de treball futures.

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# Chapter 1. General introduction

This chapter provides an introduction to this thesis, which is focused on the subject of thermal performance of façades in existing residential buildings, as a fulfilment for the title of Doctor by the Universitat Politècnica de Catalunya. The chapter is divided in five parts. The first and second parts introduce preliminary notions on energy performance gap in buildings and actual trends on analysing façades for nearly zero-energy buildings. The third part presents a review of existing methods for determining the thermal performance of façades. The fourth part presents aspects that could affect the accuracy of in-situ measurements of façades' U-values using the heat flow meter (HFM) method, based on a critical literature review. The topic addressed in this thesis is introduced in the discussion of the implications in the fifth part.

## 1.1 Energy performance gap in buildings

The European Framework Programme for Research and Innovation available from 2014 to 2020, known as Horizon 2020 (European Commission, 2016a), 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 energy efficiency targets in the "2030 climate and energy framework" (European Council, 2014), based on the "20-20-20" energy efficiency targets (European Union, 2010) and in line with the longer term perspective set out in the Roadmap for moving to a competitive low carbon economy in 2050 (European Commission, 2011a). The "2030 climate and energy framework" sets three key targets for the year 2030:

- At least 40% cuts in greenhouse gas emissions (from 1990 levels),
- At least 27% share for renewable energy,
- At least 27% improvement in energy efficiency.

Construction is considered the sector with the most potential for energy saving (European Commission, 2011b; European Union, 2012). Currently, buildings account for 40% of the EU's final energy demand (European Commission, 2016a). Residential buildings are responsible for 25.4% of total final energy consumption in Europe (European Union, 2017). The breakdown of total household energy consumption by end-use in the European Union shows that 64.6% is used for space heating, 0.4% for space cooling, 13.8% for water heating, 14.1% electric appliances, 4.7% for cooking and 2.2% for lighting (Government of Spain, 2017), which is in accordance with a study by Gangolells et al. (2016). As noted, space heating accounts for a high proportion of energy consumption in residential buildings and consequently has considerable potential for energy saving. Two complementary building renovation strategies can be adopted: (1) a passive strategy, in which the energy demand is reduced by modifying construction elements, and (2) an active strategy, in which the energy efficiency of heating, ventilation, and air conditioning systems is enhanced.

Horizon 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 (European Commission, 2016a). In fact, according to the 2050 decarbonisation target, 97% of residential building stock needs to be upgraded to become highly energy efficient and obtain the Energy Performance Certificate (EPC) label A (BPIE, 2017). This is due, in part, to the average age of European residential building stock: more than 80% of residential buildings are over 25 years old (Table 1).

| Region | Floor space distribution | Average age of residential floor space | | |
|---|---|---|---|---|
| | | Pre 1960 | 1961-1990 | 1991-2010 |
| North and West | 50% | 42% | 39% | 19% |
| Central and East | 14% | 35% | 48% | 17% |
| South | 36% | 37% | 49% | 14% |

Table 1. Distribution of residential floor space by year of construction in the European Union 27, Switzerland and Norway (BPIE, 2011a).

The growing concern for energy efficiency leads some authors to question the concept of energy performance gap in buildings. There is no simple definition of performance gap in buildings, nor are there standards and regulations that characterize this gap (Jradi et al., 2018). Galvin (2014) defined the energy performance gap as overconsumption as a proportion (or percentage) of design consumption. Whilst de Wilde (2014) defined the energy performance gap as a mismatch between the predicted energy performance of buildings and actual measured performance.

An effort to characterize the energy performance gap in buildings has recently been made. De Wilde (2014) identified three different types of energy performance gap; (1) mismatch between "first principle" energy models, and measurements undertaken on actual buildings, (2) mismatch between machine learning approaches, and measurements from real buildings, and (3) mismatch between the energy ratings provided by compliance test methods and energy display certificates as enshrined in regulation. Burman (2016) and Van Dronkelaar et al. (2016) distinguished three types of energy performance gap; (1) a regulatory performance gap, comparing predictions from compliance modeling to measured energy use, (2) a static performance gap, comparing predictions from performance modeling to measured energy use, and (3) a dynamic performance gap, utilizing calibrated predictions from performance modeling with measured energy use taking a longitudinal perspective to diagnose underlying issues and their impact on the performance gap.

Energy performance gap causes are interrelated and connected, and could be grouped into three categories associated to building stages: causes that pertain to the design stage, causes rooted in the construction stage and causes that relate to the operational stage (de Wilde, 2014; Jradi et al., 2018; Menezes et al., 2012).

In relation to the design stage, de Wilde (2014) enumerated as a root (1) the miscommunication about performance targets for the future building between client and design team, or between members of the design team, (2) the difference of performance of equipment respect to specifications of the manufacturer, (3) the modelling and simulation process using incorrect methods, tools or component models, (4) the misalignment between design and prediction due to lack of formal error and accuracy testing of detailed design calculations, and, as Williamson (2010) pointed out, (5) the fact that present approaches do not take system performance deterioration into account, which will lead to a mismatch between prediction and measurement.

Relating to the construction process, de Wilde (2014) highlighted (1) the quality of buildings not being in accordance with the specification and (2) the discrepancy between design and actual building by change orders and value engineering as the main causes of performance gap. Jradi et al. (2018) disaggregated the causes of the construction process in six points; (1) mismatch between the quality at the building handover and the quality at the design stage, (2) changing requests from clients, (3) poor commissioning, (4) improper envelope assembly, (5) economically-driven decisions affecting materials and systems selection leading to design modifications, and (6) improper components and systems integration.

Finally, regarding to the operational stage, de Wilde (2014) pointed as roots of performance gap (1) the differences of occupant behaviour from the assumptions made in the design stage, and (2) the assumptions about the performance of technological developments, and (3) the use of uncertainty in experimental data. Jradi et al. (2018) detailed the causes of the operational stage in eleven points, (1) lack of continuous commissioning, (2) mismatch between design idealized assumptions and actual patterns, (3) faulty systems and components, (4) poor practice, (5) lack of maintenance and service, (6) occupants behaviour and activities, (7) lack of occupancy monitoring, (8) variation in systems operation modes and changes in the use of the building, (9) inappropriate building management and control strategies, (10) faulty sensors and meters, and (11) lack of customers and residents knowledge in terms of energy efficiency and building operation.

The actual thermal behaviour of building envelopes could contribute to the energy performance gap in buildings. Deviations between predicted and actual operating performance of envelopes are associated with factors in the design and construction stages (Kampelis et al., 2017). Moreover, assumptions related to energy efficiency improvements as a result of refurbishment of buildings are not always met (Farmer et al., 2017). Consequently, accurate in situ measurements of the actual thermal transmittance of façades become necessary.

## 1.2 Façades for nearly zero-energy buildings

To meet the 2020 energy targets, the Directive on energy performance of buildings establishes that by 31 December 2020 all new buildings must be nearly zero energy, and new public occupied or owned buildings must be nearly zero-energy buildings by 31 December 2018 (European Union, 2010). According to Erhorn and Erhorn-Kluttig (2015) about 40% of EU member states do not yet have a detailed definition of the nZEB. However, the definition of nearly zero-energy buildings has been widely studied (BPIE, 2015, 2011; D'Agostino, 2015; Pacheco and Lamberts, 2013; Szalay and Zöld, 2014). Most Member States use a primary energy use indicator in kWh/(m²·y), but other parameters are also employed, such as net and final energy for heating and cooling, CO2 emissions and the U-values of building envelope components (European Commission, 2016b). The use of the thermal transmittance of façades' components as a parameter to define nearly zero-energy buildings will increase the construction of buildings with very low U-value façades.

Existing approaches in literature reviews on nearly zero-energy buildings technologies can be summarized in three categories: passive energy-saving technologies, energy-efficient building service systems, and renewable energy production technologies (Cao et al., 2016). Focusing on passive energy saving technologies, Friess and Rakhshan (2017), Omrany et al. (2016) and Sadineni et al. (2011) reviewed various advanced wall technologies to improve the energy efficiency and comfort levels in buildings. According to Sadineni et al. (2011), the improvement of building envelopes primarily relies on reducing thermal transmittances, combined with passive heating or cooling (Cao et al., 2016).

Significant indicators of passive energy efficiency solutions such as the average wall U-values for nearly zero-energy buildings in the European residential building stock are being analysed by the project Zebra2020, cofounded by the Intelligent Energy Europe Programme of the European Union. This project monitored best cases of the nearly zero-energy buildings market transition with the aim of giving recommendations and strategies to accelerate the use of nearly zero-energy buildings while having a deep understanding of local contexts (European Union, 2014). The project Zebra2020 covered 88.6% of the European building stock and 89.1% of the European population (EU28 & Norway). Wall U-values of the monitored residential buildings range from 0.10 W/m²·K in Belgium and Sweden to 0.30 W/m²·K in Slovakia, 0.31 W/m²·K in Germany or 0.56 W/m²·K in Romania. The average thermal transmittance of residential nearly zero-energy building façades in Europe is summarized in Table 2 (European Union, 2014).

| **Country** | **Austria** | **Belgium** | **Czech Rep.** | **Denmark** | **France** | **Germany** | **Italy** | **Lithuania** | **Luxembourg** | **Netherlands** | **Norway** | **Poland** | **Portugal** | **Romania** | **Slovakia** | **Spain** | **Sweden** | **UK** | **EU17** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Average wall U-value (W/m²·K)** | 0.11 | 0.10 | 0.13 | 0.12 | 0.14 | 0.31 | 0.16 | 0.11 | 0.11 | 0.11 | 0.13 | 0.11 | n.a. | 0.56 | 0.30 | 0.18 | 0.10 | 0.13 | 0.17 |

Table 2. Average U-value of residential nearly zero-energy building façades in Europe (European Union, 2014).

Currently, there is great concern about the role of building envelopes in defining strategies for new nearly zero-energy buildings. There are numerous strategies available to design and construct building façades for low-energy or nearly zero-energy buildings. Several authors (Ascione et al., 2016b; Berry and Davidson, 2015; Buonomano et al., 2016; Charisi, 2017; Loukaidou et al., 2017; Micono and Zanzottera, 2015; Moran et al., 2017; Zakis et al., 2017) have studied the optimization of building envelope design for nearly zero-energy buildings through models and simulations in different climate zones. Ascione et al. (2016b) focused on the optimization of the building envelope design for nearly zero-energy buildings in the Mediterranean climate through energy simulations. Berry and Davidson (2015) explored the economic feasibility of the net zero-energy building policy in warm temperate climates based on energy monitoring evidence and construction economics. In order to achieve the NZEB goal, Buonomano et al. (2016) developed a computer model for predicting the energy demand of buildings integrating new technologies such as phase change materials, photovoltaic-thermal collectors, adjacent sunspaces and innovative daylighting control. Charisi (2017) conducted a study focusing on the potential reduction of energy demands in typical Greek residential building. The researcher modelled the effect of insulation, openings and shading devices of building envelopes on the energy demand. The model was examined in four climate zones using dynamic simulation software tools. In order to achieve nearly-zero energy buildings in the climate conditions of Cyprus, Loukaidou et al. (2017) conducted a cost-optimal analysis of thermal features of the building envelope, including thermal insulation on wall, roof and ground floor and optimal window properties. Micono and Zanzottera (2015) checked the results of the simulation of an office building in Northern Italy taking into consideration variations occurred during the construction phase to guarantee the energy performances forecasted. Moran et al. (2017) conducted a study to determine the optimal strategy to design a nearly zero-energy building in a temperate oceanic climate, such as Ireland. Eight different versions of a modelled semi-detached house were investigated with two different building fabrics, airtightness and ventilation strategies employed. The analysis was focused on the life cycle cost and environmental analysis of nearly zero-energy buildings using various heat sources. To optimality design of eleven nearly zero-energy new buildings types in cold climate conditions, Zakis et al. (2017) coupled evolutionary algorithms with a building dynamic simulation engine. The multi-objective computer model took into account life cycle cost and performance modulation.

Energy renovation measures for existing building stock to bring it up to the nearly zero-energy building level were also analysed by several authors (Albadry et al., 2017; Brandão De Vasconcelos et al., 2016; Corrado et al., 2016a, 2016b; Ferreira et al., 2016; Hou et al., 2016; Kuusk and Kalamees, 2015) through energy simulation tools. Albadry at al. (2017) proposed a validated guideline to achieve net zero-energy buildings through retrofitting existing residential buildings using photovoltaic panels in Egypt. Brandão De Vasconcelos et al. (2016) identified cost-optimal packages of energy efficient solutions from among a set of possible refurbishment measures taking into consideration different discount rates and building orientations. The research was applied to a Portuguese reference building. Corrado et al. (2016b) showed the approach and the methodology adopted in the European Project, RePublic_ZEB, for the assessment of retrofit measures suitable to reach nearly zero-energy buildings. In order to reach the nearly zero-energy target for buildings that represent the national residential building stock in Italy, Corrado et al. (2016a) identified packages of energy efficiency measures to apply. Ferreira et al. (2016) compared cost-optimal renovation packages with nearly zero-energy building levels of energy performance in building renovation of modelled representative buildings of Portuguese residential building stock. Based on site surveys and expert interviews, Hou et al. (2016) conducted a comparative analysis on incentive policies to implement commercial building energy efficiency retrofit programs in China. Kuusk and Kalamees (2015) discussed energy renovation scenarios from major renovation to nearly zero-energy building level for apartment buildings in a cold climate (Estonia).

Due to deviations between predicted and actual energy consumption in nearly zero-energy buildings, energy performance strategies for both new and existing buildings need to be checked. Some authors (Ascione et al., 2016a; Kampelis et al., 2017; Kneifel and Webb, 2016; Ulpiani et al., 2017; Zavrl and Stegnar, 2017; Zhou et al., 2016) have modelled differences between forecasted and actual energy consumption. Ascione et al. (2016a) created a numerical model to investigate deviations between the expected and the measured electric usage in the areas of heating and domestic hot water, ventilation, lighting, equipment and auxiliaries, yield of the photovoltaic system. The modelled building was a two-storey nZEB situated in Berlin. Kampelis et al. (2017) investigated the operational performance of industrial, residential and research/educational buildings with the use of simulation tools. Researchers evaluated the significance for smart near-zero energy buildings energy efficient technologies, renewable energy technologies, storage and smart monitoring and controls. In order to determine if building designs reach target energy efficiency improvements, Kneifel and Webb (2016) developed a statistically derived regression model to predict energy performance of a net-zero energy building. Ulpiani et al. (2017) conducted an experimental study focused on the energy benefits achieved by coupling an energy efficient building with a sunspace in winter season and Mediterranean climate. The monitoring phase was used to calibrate the simulation model and provide on-site validated data for subsequent assessments and comparisons. Zavrl and Stegnar (2017) investigated the calculated and metered energy use of monitored apartments in a highly energy efficient apartment building Eco Silver House committed to meet the national nearly zero energy buildings requirements. Zhou et al. (2016) investigated the operational performance of an occupied net zero energy office building in Tianjin, China, during a year. Results showed that energy consumption of the case building was much higher than the energy generated from the solar photovoltaic system selected according to the simulated energy consumption of the building at design phase. The researchers highlighted that during the design process of net zero-energy buildings, it was imperative to ensure that the energy simulation accurately reflects how the building will actually operate once occupied.

Deviations between a building's overall energy efficiency target and its actual operating performance are associated with factors in the design and construction of the building envelope and systems or in the management procedures affecting the operational phase of the building (Kampelis et al., 2017). Therefore, in situ measurements are needed to assess the actual performance of building envelopes and ensure that they reach the nearly zero-energy building level.

The literature review revealed that only a few researchers (Albatici et al., 2015; Asdrubali et al., 2014; Bros-Williamson et al., 2016; Mandilaras et al., 2014; Nardi et al., 2015; Samardzioska and Apostolska, 2016) have measured in situ the actual thermal transmittance of façades with low U-values. As shown in Table 3, these researchers encountered difficulties in the measurements, as they frequently obtained high deviations from theoretical U-values. Albatici et al. (2015) validated quantitative infrared thermography for the evaluation of building thermal transmittance by assessing two walls with low U-values (0.17 $W/m^2 \cdot K$ and 0.18 $W/m^2 \cdot K$), using the standardized average calculation method (ISO, 2014) to obtain the HFM measured U-value. Asdrubali et al. (2014) presented the results of in situ thermal transmittance measurements performed on six energy efficient buildings funded by the Umbria Region in Italy. The buildings were constructed between 2007 and 2008, and their calculated thermal transmittance using the standardized average calculation method (ISO, 2014) ranged from 0.23 $W/m^2 \cdot K$ to 0.33 $W/m^2 \cdot K$. For the energy performance analysis of two houses, Bros-Williamson et al. (2016) monitored over two periods the corresponding façades, which had theoretical U-values of 0.10 $W/m^2 \cdot K$ and 0.23 $W/m^2 \cdot K$. In a study about the thermal behaviour of a building envelope with varying insulation conducted by Mandilaras et al. (2014), the authors analysed performance with a vacuum insulation panel and compared it with a theoretical estimation of R-value of 4.98 $m^2 \cdot K/W$, which is equal to thermal transmittance of 0.20 $W/m^2 \cdot K$. The experimental determination of R-value was calculated using the dynamic method of ISO 9869:1994. In a comparison of experimental measurements of thermal transmittance using infrared technology, the heat flow meter method and the calculated U-value (ISO, 2007), Nardi el al. (2015) analysed a wall with a theoretical U-value of 0.23 $W/m^2 \cdot K$. Authors used the standardized average calculation method to obtain the measured U-value. Finally, Samardzioska and Apostolska (2016) conducted a study on façades with a new construction system. The thermal transmittance of the wall with the new construction system was 0.22 $W/m^2 \cdot K$, according to calculations using analytical software. Authors performed measurements on the walls of three buildings whose façades had been constructed using the new system. To obtain the calculated thermal transmittances, they used the standardized average calculation method, but excluded results obtained on one day on the first and third building. Absolute values of relative differences between the design and measured thermal transmittance obtained by the existing literature approaches are summarized in Table 3.

| Authors in the literature review | Design thermal transmittance ($W/m^2 \cdot K$) | HFM-measured thermal transmittance ($W/m^2 \cdot K$) | Absolute value of relative deviation (%) |
|---|---|---|---|
| Albatici et al. (2015) | 0.17 | 0.18 | 6% |
| | 0.18 | 0.18 | 1% |
| Asdrubali et al. (2014) | 0.23 | 0.22 | 4% |
| | 0.25 | 0.34 | 36% |
| | 0.27 | 0.34 | 26% |
| | 0.30 | 0.37 | 23% |
| | 0.32 | 0.56 | 75% |
| | 0.33 | 0.39 | 18% |
| Bros-Williamson et al. (2016) | 0.10 | 0.12 | 20% |
| | 0.10 | 0.11 | 10% |
| | 0.23 | 0.26 | 13% |
| | 0.23 | 0.38 | 65% |
| Mandilaras et al. (2014) | 0.20 | 0.26 | 28% |
| Nardi el al. (2015) | 0.23 | 0.42 | 83% |
| Samardzioska and Apostolska (2016) | 0.22 | 0.23 | 3% |
| | 0.22 | 0.35 | 59% |
| | 0.22 | 0.23 | 4% |

Table 3. Calculated and measured low thermal transmittance walls in a literature review.

As shown in the literature review, conducting accurate in situ measurement of low thermal transmittance façades is a challenging task.

## 1.3 Approaches to determine the thermal performance of façades

The thermal performance of building envelopes is a key factor that should be evaluated to obtain an accurate energy diagnosis of buildings (Asdrubali et al., 2014; Desogus et al., 2011; Evangelisti et al., 2015b; Ficco et al., 2015; Hughes at al., 2013; Sunikka-Blank and Galvin, 2012; Symonds et al., 2016;

Zheng et al., 2013). Thermal properties of the building components must be characterized accurately to ensure successful decision-making during energy efficiency improvements to buildings (Lucchi, 2017; Sassine, 2016). Classifying the opaque part of façades is essential to facilitate a systematic analysis of the thermal performance of façades in the housing sector.

Assumed U-values of walls have been a significant source of uncertainty in estimations of energy savings and carbon emissions (Li et al., 2015). Evidence suggests that assumptions regarding heat loss from a home pre-retrofit and post-retrofit are incorrect (Farmer et al., 2017). Therefore, accurate on-site measurements are necessary to provide information on the actual thermal transmittance of façades.

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 (Ballarini et al., 2014; Ficco et al., 2015), (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 (Ficco et al., 2015).

Reliable design data can be obtained from executive projects or specific technical building reports. If the procedure described in ISO 6946:2007 (ISO, 2007) 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 (ISO, 2014), 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 (Desogus et al, 2011; Ficco et al., 2015; ISO, 2007). The heat flow meter method is a non-destructive method standardized by ISO 9869 (ISO, 2014) 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 standard 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 (Albatici et al., 2015; Chaffar et al., 2014; Nardi et al., 2015; Zheng et al., 2013). Finally, some authors have developed their own methods, based on in situ measurements to calculate the thermal behaviour of façades.

As seen, several methods can be used for the in situ measurement of thermal transmittance of existing buildings' façades. One of the most common is the heat flow meter method standardized by

ISO 9869 (ISO, 2014). However, on-site measurements in existing buildings may encounter many difficulties, leading to inaccurate measurements (Peng and Wu, 2008).

## 1.4 Aspects affecting the accuracy of the in-situ measurement of façades' U-values

Aspects that could affect the accuracy of the in-situ measurement of façades' U-values have been analysed based on the existing literature, and can be classified into four groups: equipment-related factors, environmental factors, the component being measured, and measurement and calculation procedures (Figure 1).

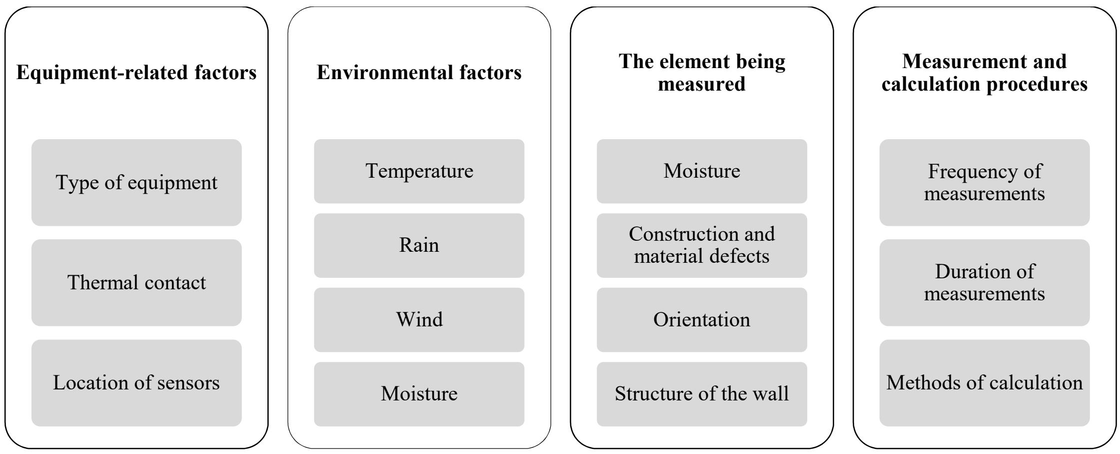


Figure 1. Summary of aspects that could affect the measurement of the thermal transmittance of façades.

### 1.4.1 Equipment-related factors

Several authors have analysed the impact of equipment-related factors (type of equipment and its installation) on the in situ measurement of the thermal transmittance of façades through the heat flux meter (HFM) method. Relating to the type of equipment, Trethowen (1986) studied measurement errors using surface-mounted heat flux sensors. The author affirmed that measurement errors could be reduced by increasing the size of the sensor, the surface resistance, the thermal resistance of the wall under test and the edge guarding, and by decreasing the sensor's contact resistance and the conductivity and thickness of the surface layer of substrate. Ficco et al. (2015) described uncertainty contributions to the in situ U-value caused by temperature sensors, the heat flux meter, and the data acquisition system. Cesaratto et al. (2011) analysed the heat flux perturbation caused by the presence of heat flux meters and considered the non-ideal adhesion of the heat flux meter to the internal surface. They discussed the problem of analysing input data with a significant drift in temperature. The results showed relative deviation with respect to the nominal value of around -15% when simulations were carried out with input data that was not affected by a drift in temperature, while this entity reached a peak value of -21% for simulations with input data affected by a non-negligible drift in temperature. Tadeu et al. (2015) declared that to obtain accurate results, the heat flow meter and temperature sensors should be mounted to ensure good thermal contact with the surface, and their colour and emissivity should be similar to that of the building element surface.

Regarding the installation of sensors, Peng and Wu (2008) considered that heat flow meters need to be plastered onto the surface or embedded in specimens to increase the accuracy of in situ measurements of the thermal resistance of building constructions. Meng et al. (2015) studied the influence of the location of thermocouples and heat flow meters, and of the size, shape and pasting angle of heat flow meters on the measurement accuracy of the wall’s U-value using the heat flow meter method. Results showed that the measurement error could be up to 6% when the thermocouples were improperly pasted, and up to 26% when the heat flow meters were improperly pasted. The authors stated that for symmetrical structural walls, greater accuracy could be obtained when the heat flow meter was on the inner surface, while for asymmetrical structural walls, measurements were more accurate when the heat flow meter was on the side with the greatest thermal resistance. The authors also considered that it was important to select the pasting angle, size and shape of the heat flow meter based on the wall structure, especially when heat flux meters were pasted near a mortar joint. Research results showed that the U-value was most accurate when heat flow meters were located 20-32 mm away from the mortar joint. In a study conducted by Ahmad et al. (2014), the authors found that a measurement location close to a joint between two interlocked wall panels resulted in a higher U-value. Li et al. (2015) indicated that it was difficult to conduct measurements in occupied buildings, due to factors such as rough internal surfaces and the need to avoid damage to the wall surfaces. Guattari et al. (2017) investigated the best position for installing the heat flux plate, considering the influence of internal heat sources on thermal resistance evaluation.

### 1.4.2 Environmental factors

The analysis of aspects related to the environment took into account the variability of weather conditions and focused on temperature. Authors such as Ahmad et al. (2014), Albatici et al. (2015), Ficco et al. (2015), Nardi et al. (2015), Peng and Wu (2008) and Tadeu et al. (2015) stated that variability in climatic conditions (rain, wind, moisture and temperature) during the monitoring process could introduce uncertainties in the measurements. Regarding temperature, Asdrubali et al. (2014), Desogus et al. (2011) and Li et al. (2015) found that measurement uncertainty was reduced if the temperature difference between the indoor and outdoor environment was above 10ºC, and if the temperature of the internal surface was kept as constant as possible (Asdrubali et al., 2014). Tadeu et al. (2015) noted that a temperature difference between the indoor and outdoor environment of less than 10ºC may not be enough to obtain accurate results.

### 1.4.3 The element being measured

Aspects related to the component being measured include an analysis of moisture, construction and material defects, orientation and structure of the wall. The moisture-related phenomena in the wall was considered a cause of differences between the measured value and the design value (Cesaratto and De Carli, 2013; Peng and Wu, 2008; Tadeu et al., 2015). Other causes of differences between the measured and design value were construction and material defects such as thermal bridges (Peng and Wu, 2008), the presence of heterogeneities due to errors that occurred during building operations (Asdrubali et al., 2014; Cesaratto and De Carli, 2013; Tadeu et al., 2015), overestimation of the performance data declared by producers of building materials (Asdrubali et al., 2014), unknown stratigraphy of the inner part of the wall or an inaccurate thermal conductivity value (Evangelisti et al., 2015), aging of the materials, envelope deterioration and poor maintenance of envelopes (Bros-Williamson et al., 2016; Tadeu et al., 2015). Regarding wall orientation, Ahmad at al. (2014) stated that walls exposed to solar radiation resulted in greater heat flux. Relating to the structure of the wall, Desogus et al. (2011) affirmed that heat loss measurement uncertainty was higher for well-insulated walls, i.e. those with an R-value equal to 4 $m^2 \cdot K/W$. Mandilaras et al. (2014) stated that the measured R-value could be significantly lower than the design value when high performance insulation materials were introduced in external thermal insulation composite systems.

For assessing the impact of theoretical U-value on the measurement of the actual thermal transmittance of façades an analysis of previous studies based on in situ measurements of façades' U-value using the heat flux meter standardized methods was conducted. A thorough literature review was conducted, and two research studies, Baker (2011) and Ficco et al. (2015), were selected for the availability of data on in situ measurements (the walls' theoretical U-value and the average temperature difference). The study performed by Ficco et al. (2015) was conducted with three different heat flux meters. In each case study, only the value that best fit the theoretical U-value was analysed. Only case studies with heavy elements, which have a specific heat capacity per unit area of more than 20 $kJ/m^2 \cdot K$, were selected. From the study performed by Baker (2011), only case studies conducted on north-facing walls were selected. Finally, a total of 18 case studies from the literature review were analysed. Figure 2 shows the relative differences between theoretical and measured U-values, in relation to the average temperature difference and the theoretical U-value of the selected case studies. As shown, no trend between the temperature difference or the theoretical U-value and the relative differences between U-values can be observed. The Pearson correlation coefficient indicated that there were weak associations between the variables. As a result of this preliminary evaluation and taking into consideration the stratigraphy of the walls, other parameters related to the thermal performance of the wall, such as thermal capacity, may influence measurement accuracy. Researchers such as Aste et al. (2009), Di Perna et al. (2011), Olsthoorn et al. (2017), Reilly and Kinnane (2017) and Siddiqui et al. (2017) studied how the thermal capacity of walls affected energy performance and comfort in buildings. However, the impact of the thermal capacity of the wall on the accuracy of in situ measurements of façades' U-value has not been analysed in depth.

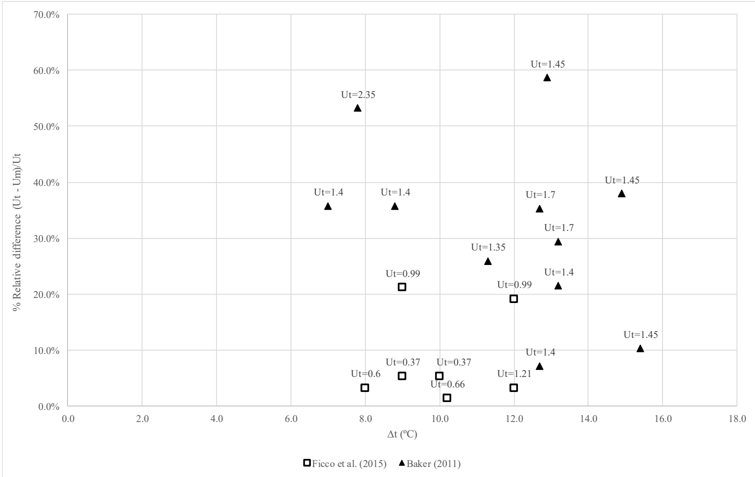


Figure 2. Relation between average temperature difference and theoretical U-value, and absolute relative differences between U-values in case studies from the literature review.

## 1.4.4 Measurement and calculation procedures

The analysis of measurement and calculation procedures has focused on the study of methods of calculation and duration of measurements, since the frequency of data collection was analysed by Ficco et al. (2015). The authors stated that sampling frequency ranging from 30 to 60 minutes did not seem to affect measurement accuracy.

***Methods of calculation***

The literature shows that the data analysis method affects the value of the measured U-value obtained with the heat flow meter (Albatici et al., 2015; Nardi et al., 2015; Peng and Wu, 2008).

To conduct research on the behaviour of façades, authors such as Desogus et al. (2011), Baker (2011), Asdrubali et al. (2014), Ficco et al. (2015), Evangelisti et al. (2015a) and Lucchi (2017) 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. (2011) 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. (2014) 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. (2015a) 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. Lucchi (2017) compared the standard procedures normally used in Italy by energy auditors and simulators for assessing the thermo-physical behaviour of traditional masonries. The results showed that measured U-values are better than standard and calculated values, which tend to overestimate the thermal performance of historic brick masonries.

Other authors, such as Biddulph et al. (2014), Guillén et al. (2014), Jimenez et al. (2009), Peng and Wu (2008) and Tadeu et al. (2015), 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. Biddulph et al. (2014) 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. (2014) 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. Jimenez et al. (2009) 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. Peng and Wu (2008) 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. Tadeu et al. (2015) 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 to calculate the thermal transmittance of façades because, as Ficco et al. (2015) states, dynamic methods are more complex than the average method. This is the case of Atsonios et al. (2017), Deconinck and Roels (2106) and Mandilaras et al. (2014). Atsonios et al. (2017) examined the measuring period and the variability of the results of four available standardized methods for the R-value measurement, as described in ISO 9869 (ISO, 2014) and ASTM C1155 (ASTM, 2007). They concluded that the Average and Summation methods require a high temperature difference between the indoor and outdoor surfaces of the tested wall to provide R-values in a short measuring period with low variability. The required measuring period for the Dynamic and the Sum of Least Square methods appeared to be independent of the measuring conditions. Deconinck and Roels (2106) compared several semi-stationary and dynamic data analysis methods that are typically used for the thermal characterization of building components from on-site measurements, depending on the measurement timespan and climatic conditions. They concluded that semi-stationary methods perform as well as dynamic analysis methods when winter datasets are considered. In contrast, for spring and summer datasets, only dynamic methods lead to reliable estimation results. Mandilaras et al. (2014) 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 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.

***Duration of experimental campaigns***

Relating to the duration of experimental campaigns, within the extended heat flow meter method, the standard (ISO, 2014) establishes that on-site measurements must have a minimum duration of 72 hours, but, depending on the stability of conditions, measurements may take longer than seven days. As stated by Peng and Wu (2008), on-site measurements in existing buildings may encounter many difficulties, due to problems related to accurate measurement of temperatures and heat flux, because seasonal climatic conditions may be unfavourable (Asdrubali et al., 2014; Baker, 2011; Desogus et al., 2011; Li et al., 2015; Tadeu et al., 2015). In fact, ISO 9869-1:2014 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 in comparisons of the theoretical U-value and the measured U-value (ISO, 2014). These ranged from three days to one month. Asdrubali et al. (2014) 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. They found that the differences between theoretical and measured U-values using the average method ranged from 4% to 75%. Baker (2011) 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 the energy performance analysis of two houses, Bros-Williamson et al. (2016) 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/m²·K. Results showed relative differences between theoretical and measured U-values of 20%, 10%, 13% and 65%, respectively. Desogus et al. (2011) carried out in situ measurements that lasted 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. (2015b) 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. (2015) 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/m²·K. The authors estimated high relative in situ U-value uncertainties ranging from 8% in optimal operative conditions to about 50% in non-optimal operative conditions (average temperature difference values were lower than 10ºC, and there was low heat flow or heat flow inversion). Li et al. (2015) 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/m²·K for walls that appeared to be of solid brick construction, and 1.34 W/m²·K for stone, with standard deviations of about 0.35 and 0.38 W/m²·K, respectively. The authors found that the transient analysis methodology developed by Biddulph et al. (2014) could provide an estimate of the U-value using a much shorter time series than the average method following the standard ISO 9869-1:2014. Mandilaras et al. (2014) 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 measuring 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 9869-1:1994. 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 measured values of thermal transmittance obtained using the average method (ISO, 2014) and other techniques. Ahmad et al. (2014) used three sets of experimental data obtained during a period 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 (ASTM, 2007) and ISO 9869 (ISO, 2014). 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. (2014) 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. Results showed that 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 (2013) 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 based on the measurements. Most of the measurement results showed conductance values within a range of 0.3-1.1 $W/m^2 \cdot K$. For new or refurbished buildings, the measured conductance value was found to be about 20% higher than the reference value. Deconinck and Roels (2016) employed data from simulations to compare several semi-stationary and dynamic data analysis methods typically used for the thermal characterization of building components in function of the measurement time span and climatic conditions in a cavity wall with a thermal resistance of up to 4.002 $m^2 \cdot K/W$. Relating to the average method, 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 between the 10% accuracy bands. 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. Nardi et al. (2015) 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 $W/m^2 \cdot K$, and 72 hours for walls with a theoretical U-value of 0.23 $W/m^2 \cdot K$ and 0.51 $W/m^2 \cdot K$. The authors compared the non-invasive techniques of infrared technology and the heat flow meter method (the average method according to ISO 9869:1994) and calculated the U-value according to standard ISO 6946:2007. The results showed differences between 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 $W/m^2 \cdot K$, 82.6% for the wall with a theoretical U-value of 0.23 $W/m^2 \cdot K$, and 44.2% for the wall with a theoretical U-value of 0.51 $W/m^2 \cdot K$.

As shown in the literature, the duration of the on-site tests conducted by researchers, which ranged from three days to one month, could influence on the wide variation between measured thermal properties and theoretical values.

## 1.5 Implications and justification of the thesis

Bridging the gap between the predicted and actual energy performance of buildings is necessary to increase the energy performance of existing buildings and achieve the European Union's "2030 climate and energy framework" (European Council, 2014) energy efficiency targets. Construction is considered the sector with the most potential for energy saving (European Commission, 2011b; European Union, 2012). Specifically, buildings space heating accounts for a share of 64.8% of total household energy consumption by end-use in the European Union (Government of Spain, 2017), having considerable potential for energy saving.

Thermal transmittance is the fundamental parameter to characterise the heat losses of building envelopes. Evidence suggests that assumptions regarding heat loss from a home pre-retrofit and post-retrofit are incorrect (Farmer et al., 2017). Therefore, accurate on-site measurements are necessary to provide information on the actual thermal transmittance of façades.

For the in situ measurement of façades' thermal transmittance standard ISO (ISO, 2014) is used extensively. Although this standard describes the apparatus to be used, the calibration procedure for the apparatus, the installation and measurement procedures, and the analysis of the data, some testing parameters for the measurement process are not fully specified. The literature shows that several factors affect the accuracy of in situ measurements of façades' thermal transmittance using the heat flow meter method. These factors include equipment, environmental conditions, the element to be analysed and the measurement and calculation procedures. Regarding calculation methods to conduct research on the thermal behaviour of façades, the standardised average method is widely used by authors. Other authors introduce their own calculation methods. However, very few initiatives used the HFM standardised dynamic method because, as Ficco et al. (2015) states, dynamic methods are more complex than the average method. For this reason, this dissertation proposes a calculation procedure for the dynamic method with accessible tools to facilitate its implementation. This can help to obtain more accurate measurements and adjust the conditions of experimental campaigns. Moreover, this dissertation assesses the implications of using the different standardised calculation methods for in situ measurement of façades' U-value using the HFM method.

To facilitate the selection of façades to conduct a systematic analysis of the thermal performance of façades in the housing sector, characterizing the opaque part of façades becomes basic. The classification of façades of existing residential buildings for subsequent analysis is not an easy task, since there are several proposals of classification. National and regional regulations and codes for buildings and construction processes do not provide a classification system, but they do describe national construction systems in detail. Otherwise, existing classifications of façades in housing stock such as OmniClass (OmniClass Construction Classification System Development Committee, 2006), UniClass (Crawford et al. 1997) or Uniformat (The Construction Specifications Institute, 2010), among others, do not define in detail the constructive composition of the opaque part of façades. For this reason, a classification system of façades is developed in this dissertation.

In order to comply with Directive 2010/31/EC (European Union, 2010) and "2030 climate and energy framework" (European Council, 2014) targets, façades with low thermal transmittance values are increasingly promoted. As shown in the literature review, conducting accurate in situ measurement of low thermal transmittance façades is a challenging task. In order to improve the accuracy of the in situ measurement of the actual thermal transmittance in façades with low thermal transmittance using the heat flow meter method, this dissertation explores the boundaries of the requirements for using the standardised heat flow meter (HFM) method to refine the testing conditions in low U-value façades. This would allow to ensure compliance with policies to transition the existing building stock to nearly zero-energy buildings, and to confirm energy performance strategies for new nearly zero-energy buildings.

In relation to measurement procedures, the ISO standard establishes a minimum test duration of 72 hours when the temperature is stable around the heat flux meter plate, regardless of the magnitude of the thermal transmittance of façades. As shown in the literature review, inadequate test durations could lead to wide variations in the accuracy of in situ measurements of façades' U-values. However, no studies in the existing literature provide guidance on the duration of tests on façades based on the value of theoretical thermal transmittance or according to the calculation method used. To enhance the usability of the heat flux meter method for the in situ measurement of the actual thermal transmittance of façades of existing residential buildings, this dissertation analyses different criteria for determining the conditions for stopping the test during in situ experimental campaigns to measure the thermal transmittance of existing buildings' façades using the heat flow meter method. This will help to reduce practitioners' uncertainty about the duration of in situ experimental campaigns for obtaining the actual thermal transmittance of existing buildings' façades.

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# Chapter 2. Purpose, aim and objectives, scope, research methodology, structure and publications

This chapter outlines the purpose, aim and objectives of this thesis, formulated from the discussion presented in Chapter 1, sets out the scope of the work, its limitations and delimitations, and summarizes the methodology implemented. Additionally, it describes the structure of the document and includes the list of publications derived from this work.

## 2.1 Purpose, aim and objectives

The purpose of this thesis is to contribute to reduce the energy performance gap of residential buildings. Therefore, the aim of the thesis is to enhance the accuracy of in situ measurements of the actual thermal transmittance of façades of existing residential buildings using the heat flux meter method to ensure successful decision-making during the energy renovation processes of existing buildings, and to confirm energy performance strategies for new nearly zero-energy buildings.

The objectives of this dissertation are listed below:

Objective 1: To propose a calculation procedure for the dynamic calculation method for the in situ measurement of the actual thermal transmittance of façades of existing residential buildings using the heat flux meter method with accessible tools to facilitate its use.

Objective 2: To improve the accuracy of the in situ measurement of the actual thermal transmittance in façades with low thermal transmittance using the heat flow meter method.

Objective 3: To enhance the usability of the heat flux meter method for the in situ measurement of the actual thermal transmittance of façades of existing residential buildings providing best practices in conducting in situ experimental campaigns.

## 2.2 Scope of the research, limitations and delimitations

The scope of this research focuses on the improvement of the accuracy of in situ measurements of the actual thermal transmittance of façades of existing residential buildings using the heat flux meter method to ensure successful decision-making during the energy renovation processes of existing buildings, and to confirm energy performance strategies for new nearly zero-energy buildings.

In the Implication and justification of the thesis section, the necessity of conducting accurate in situ measurements of the actual thermal transmittance of existing façades is presented.

The dissertation includes a literature review that deals with factors affecting the accuracy of in situ measurements of façades' thermal transmittance using the heat flow meter method. These factors include equipment, environmental conditions, the element to be analysed and the measurement and calculation procedures.

Regarding the calculation procedures, the dynamic calculation method is found to be more complex than the average method, so very few initiatives used the dynamic method. For this reason, a proposal of calculation procedure for the dynamic method for the in situ measurement of the actual thermal transmittance of façades using the heat flux meter method with accessible tools to facilitate its use is done. Moreover, this research assesses the implications of using the different standardised calculation methods for in situ measurement of façades' U-value using the heat flux meter method, and selects the optimal method, through in situ experimental campaigns.

To facilitate the selection of case studies to conduct in situ experimental campaigns in façades with different theoretical thermal transmittance, this research includes the definition of a classification system of façades characterizing the opaque part of façades. It takes into account the most common Spanish housing façades, considering both solid walls and cavity walls, and containing both traditional technologies such as brick walls and concrete block walls, and industrialised technologies such as concrete panels.

The dissertation includes an analysis of the limits of testing conditions for applying the heat flux meter method for in situ measurement of low thermal transmittance façades to improve the accuracy of measurements. The research focuses on the study of operational conditions that are not fully specified in the ISO standard: average temperature difference, test duration and accuracy of equipment. The analysis is conducted through in situ experimental campaigns in a building mock-up constructed to investigate the boundaries of the requirements for using the heat flux meter method for the in situ measurement of U-values in low thermal transmittance façades.

To enhance the usability of the heat flux meter method for the in situ measurement of the actual thermal transmittance of façades with different theoretical U-values, this dissertation analyses criteria for determining the conditions for stopping the test during the experimental campaigns to measure the thermal transmittance of existing buildings' façades using the heat flow meter method. The analysis took into consideration criteria of data quality, variability of the results and ISO standard for different values of thermal transmittance in a same range of average temperature difference.

## 2.3 Overview of the research methodology

The research methodology guides the course of activities to be undertaken during the research.

This dissertation starts with a literature review in order to contextualize the current state of research with regard to energy performance gap in existing residential buildings, and the necessity of conducting accurate in situ measurements of the actual thermal transmittance of façades.

To select the case studies for conducting in situ experimental campaigns, it has been necessary to establish a classification system of façades. The first draft of the classification system is based on literature review and national and regional regulations and codes related to buildings and construction processes. After that, the classification system is validated in a workshop hold with a panel of experts composed of practitioners from the construction industry who are specialised in existing buildings.

To plan the experimental campaigns, a selection of different case studies has been made according to the aforementioned objectives. Then, the monitoring process has been programmed taking into account the following test conditions:

- Only north-facing walls has been monitored, to avoid direct solar radiation.
- Weather conditions have been observed during the data collection process. The monitoring process has not been carried out on rainy days or during episodes of strong winds.
- Indoor temperature has been always higher than outdoor temperature, so the heat flow direction has been stable. This condition has been maintained throughout the monitoring process. Thus, the monitoring period is practically limited to the coldest months, during the winter period.

To compare existing standardised calculation methods for the in situ measurement of the actual thermal transmittance of façades of existing residential buildings using the heat flux meter method, three façades with different U-values have been selected as case studies. In the comparison of calculation methods, the impact of theoretical U-value on the accuracy of the in situ measurement of façades U-values has been assessed. Then, a procedure for the dynamic calculation method for the in situ measurement of the actual thermal transmittance of façades using the heat flux meter method with accessible tools has been proposed to facilitate and promote its use.

A building mock-up with low U-value panels has been monitored to explore the boundaries of the requirements for using the heat flux meter method to improve the accuracy of the in situ measurement of the actual thermal transmittance in façades with low thermal transmittance. The monitoring process has been conducted in a low U-value panel during three periods to achieve different ranges of average temperature difference in order to analyse the impact of temperature differences and duration of the experimental campaigns on the accuracy of in situ U-value measurements. Moreover, to refine the testing conditions during experimental campaigns the impact of the a priori accuracy of equipment on accuracy of thermal transmittance measurements has been simulated.

To enhance the usability of the heat flux meter method for the in situ measurement of the actual thermal transmittance of façades, three façades with different U-values have been selected and monitored during at least a week within the same range of temperature difference. Then, three different criteria to determine conditions for stopping the test have been analysed and compared: data quality criteria, variability of the results criteria and ISO criteria.

Figure 3 illustrates the planned activities to achieve the research aim and objectives.

| Research purpose and aim | |
|---|---|
| The purpose of this thesis is to contribute to reduce the energy performance gap of residential buildings. Therefore, the aim of the thesis is to enhance the accuracy of in situ measurements of the actual thermal transmittance of façades of existing residential buildings using the heat flux meter method to ensure successful decision-making during the energy renovation processes of existing buildings, and to confirm energy performance strategies for new nearly zero-energy buildings. | |
| **Research objectives** | **Related tasks** |
| **Objective 1:**<br><br>To propose a calculation procedure for the dynamic calculation method for the in situ measurement of the actual thermal transmittance of façades of existing residential buildings using the heat flux meter method with accessible tools to facilitate its use. | **Task 1**<br>Definition of a classification system of façades in existing Spanish residential buildings to facilitate the selection of façades with different theoretical thermal transmittance.<br>**Task 2**<br>Comparison of existing standardised calculation methods for the in situ measurement of the actual thermal transmittance of façades of existing residential buildings using the heat flux meter method.<br>**Task 3**<br>Proposal of a calculation procedure for the dynamic calculation method for the in situ measurement of the actual thermal transmittance of façades using the heat flux meter method with accessible tools to facilitate its use. |
| **Objective 2:**<br><br>To improve the accuracy of the in situ measurement of the actual thermal transmittance in façades with low thermal transmittance using the heat flow meter method. | **Task 4**<br>Assessment of the impact of operational conditions of experimental campaigns on the accuracy of the in situ measurement of the actual thermal transmittance in façades with low U-values using the heat flux meter method:<br>**Task 4.1**<br>Assessment of the impact of testing duration<br>**Task 4.2**<br>Assessment of the impact of average temperature difference<br>**Task 4.3**<br>Assessment of the impact of a priori accuracy of equipment |
| **Objective 3:**<br><br>To enhance the usability of the heat flux meter method for the in situ measurement of the actual thermal transmittance of façades of existing residential buildings providing best practices in conducting in situ experimental campaigns. | **Task 5**<br>Assessment of the impact of theoretical U-value on the accuracy of the in situ measurement of the actual thermal transmittance of façades of existing residential buildings using the heat flux meter method.<br>**Task 6**<br>Comparison of conditions for ending the test duration of experimental campaigns for the in situ measurement of the actual thermal transmittance of façades using the heat flux meter method. |

Figure 3. Overview of the research methodology.

## 2.4 Structure of the document

This is an article-based thesis consisting of a set of papers conducted as part of the thesis research. The document is structured by five chapters, as follows:

Chapter 1 presents a critical literature review discussing concepts of energy performance gap in existing residential buildings, actual trends on analysing façades for nearly zero-energy buildings, existing methods for determining the thermal performance of façades and factors affecting the accuracy of in situ measurement of façades' U-value using the heat flux meter method. Having outlined the main barriers to accurately in situ measure the thermal transmittance of existing façades, this chapter serves as justification of the research undertaken within this thesis.

Chapter 2 presents the purpose, the main aim and the objectives of the research project raised from the results of the previous chapter, specifies the scope of the work, its limitations and delimitations, summarizes the research methodology, outlines the structure of this dissertation and enumerates the list of publications derived from the research.

Chapter 3 presents a general discussion of the main contributions resulting from the research done. It is structured following the objectives stated in the previous chapter. Moreover, presents conclusions regarding the stated objectives and presents suitable areas for further research.

Chapter 4 corresponds to the full version of the published publications.

Chapter 5 corresponds to the full version of the publications under revision.

A separate bibliography is included in Chapter 1 and Chapter 3 at the References section. Each paper included in Chapter 4 and Chapter 5 follows its own numbering of sections, figures, tables, equations and references.

## 2.5 List of publications

The publications derived from this thesis are grouped into published and submitted papers.

<u>Published papers:</u>

Journal paper I.

Gaspar K., Casals M, Gangolells M. Classifying system for façades and anomalies. *Journal of Performance of Constructed Facilities*, 2016, 30(1): 1-10. <doi: 10.1061/(ASCE)CF.1943-5509.0000693>.

- Area: Construction and Building technology
- Quartile: Q2
- Rank: 30/61
- JCR Impact factor: 1.192 (2016)
- Number of cites: 5 (Scopus), 4 (Web of Science)
- This publication covers task 1 of the research methodology.

Journal paper II.

Gaspar K., Casals M., Gangolells M. A comparison of standardized calculation methods for in situ measurements of façades U-value. *Energy and Buildings*, 2016, 130(15): 592-599. <http://dx.doi.org/10.1016/j.enbuild.2016.08.072>.

- Area: Construction and Building technology
- Quartile: Q1
- Rank: 5/61
- JCR Impact factor: 4.067 (2016)
- Number of cites: 11 (Scopus), 6 (Web of Science)
- This publication covers tasks 2, 3 and 5 of the research methodology.

Journal paper III.

Gaspar K., Casals M., Gangolells M. In situ measurement of façades with a low U-value: Avoiding deviations. *Energy and Buildings*, 2018, 170: 61–73. <doi:10.1016/j.enbuild.2018.04.012>.

- Area: Construction and Building technology
- Quartile: Q1
- Rank: 5/61
- JCR Impact factor: 4.067 (2016)
- Number of cites: - (Scopus), - (Web of Science)
- This publication covers tasks 4.1, 4.2 and 4.3 of the research methodology.

<u>Submitted papers:</u>

Journal paper IV.

Gaspar K., Casals M., Gangolells M. Review of criteria for determining HFM minimum test duration. Submitted to *Energy and Buildings* in April 2018.

- This publication covers tasks 5 and 6 of the research methodology.

# Chapter 3. General discussion and conclusions

This chapter discusses the main contributions resulting from the combination of the written publications. The discussion is structured in three sections, corresponding to the specific objectives detailed in Chapter 2:

- Proposal of a calculation procedure for the dynamic calculation method for the in situ measurement of the actual thermal transmittance of façades of existing residential buildings using the heat flux meter method with accessible tools to facilitate its use. It stars by defining a classification system for façades. Then, comparing standardised calculation methods for in situ measurements of façade's U-value using the heat flux meter. And finally, proposing a calculation procedure to facilitate the implementation of the dynamic calculation method.
- Improvement of the accuracy of the in situ measurement of the actual thermal transmittance of façades in low U-value façades using the heat flow meter method, by exploring the limits of application of the heat flux meter method for the in situ measurement of façades' U-value in façades with low thermal transmittance.
- Enhancement of the usability of the heat flux meter method for the in situ measurement of the actual thermal transmittance of façades of existing residential buildings providing best practices in conducting in situ experimental campaigns, by analysing conditions for ending the test duration of experimental campaigns during the in situ measurements of façade's thermal transmittance of existing residential buildings using the heat flux meter method to provide best practices in conducting in situ experimental campaigns.

Afterwards, conclusions are summarized. During the research undertaken, interesting questions were raised although they could not be addressed. These issues are presented as possible paths to continue the research on this field.

## 3.1 Proposing a calculation procedure for the dynamic calculation method for the in situ measurement of the actual thermal transmittance of façades

### 3.1.1 Classification system of façades in existing Spanish residential buildings

Aiming to establish a classification system between typologies of façades and corresponding defects in existing Spanish residential buildings to facilitate subsequent systematic analysis of existing building façades, an initial façade classification proposal was developed according to the literature review and the national and regional regulations and codes related to buildings and construction processes. This literature review and analysis of regulations and codes are widely described in Journal Paper I.

As a result of a workshop held with a panel of experts composed of practitioners from the construction industry who are specialised in existing buildings, the proposed classification of façades in existing residential buildings was revised, enhanced and validated.

The classification of façades in existing residential buildings in Spain was organised into four levels; (1) number of skins of the façade, (2) existence of air cavity, (3) existence of insulation, and (4) type of external wall covering. Table 4 presents the resulting façade classification for existing residential buildings in Spain.

| Number of skins | | Air cavity | | Insulation | | Wall covering | |
|---|---|---|---|---|---|---|---|
| F.1 | Single skin | AC.1 | Without air cavity | I.1 | Without insulation | WC.1 | Faced |
| | | | | | | WC.2 | Continuous covering |
| | | | | | | WC.3 | Non-continuous covering |
| | | | | I.3 | External | WC.2 | Continuous covering |
| | | AC.2 | With external ventilated air cavity | I.1 | Without insulation | WC.3 | Non-continuous covering |
| | | | | I.3 | External | WC.3 | Non-continuous covering |
| F.2 | Double skin | AC.1 | Without air cavity | I.2 | Internal | WC.1 | Faced |
| | | | | | | WC.2 | Continuous covering |
| | | | | | | WC.3 | Non-continuous covering |
| | | AC.2 | With external ventilated air cavity | I.1 | Without insulation | WC.3 | Non-continuous covering |
| | | | | I.2 | Internal | WC.3 | Non-continuous covering |
| | | AC.3 | With internal ventilated air cavity | I.1 | Without insulation | WC.1 | Faced |
| | | | | | | WC.2 | Continuous covering |
| | | | | | | WC.3 | Non-continuous covering |
| | | | | I.2 | Internal | WC.1 | Faced |
| | | | | | | WC.2 | Continuous covering |
| | | | | | | WC.3 | Non-continuous covering |
| | | AC.4 | With non-ventilated air cavity | I.1 | Without insulation | WC.1 | Faced |
| | | | | | | WC.2 | Continuous covering |
| | | | | | | WC.3 | Non-continuous covering |
| | | | | I.2 | Internal | WC.1 | Faced |
| | | | | | | WC.2 | Continuous covering |
| | | | | | | WC.3 | Non-continuous covering |

Table 4. Classification of façades in existing residential buildings in Spain.

A system for classifying anomalies was developed and codified on the basis of the literature review. The initial proposal was comprised of a one-level category with nineteen anomalies that covered all of the defects found in the review. During the workshop, the initial anomaly classification was analysed, enhanced and validated by the same panel of experts, using the same methodology as that applied in the façade classification for existing residential buildings.

The resulting anomaly classification had eight categories: (1) adhesion failure, (2) cracking, (3) dampness, (4) deformation, (5) degradation of material, (6) detachment, (7) oxidation and corrosion, and (8) rupture. These categories covered potential damage that can affect the state of conservation of elements or materials in the façades of existing residential buildings. Table 5 presents the anomaly classification for closures in residential buildings and its definition.

| Category | | Definition |
|---|---|---|
| D.1 | Adhesion failure | Lack of junction between a material that mainly serves as a coating and its support, without detachment. |
| D.2 | Cracking | Longitudinal division that affects the surface of a construction element, and can be continuous, non-continuous or involves the total thickness of the element. |
| D.3 | Dampness | Presence of water in higher proportions than expected in a material or a building element. |
| D.4 | Deformation | Loss of the original shape of the element. |
| D.5 | Degradation of material | Reduction in the quality of an element, without affecting its functionality. This may occur as a result of staining, erosion, dirtiness, etc. and is due mainly to a lack of maintenance. |
| D.6 | Detachment | Lack of continuity of a coating on the wall, as a result of either constant degradation of a material or adhesion failure. |
| D.7 | Oxidation and corrosion | Chemical reaction generally produced in metals by the presence of oxygen. The reaction is usually increased by moisture. In corrosion, the material is gradually destroyed. |
| D.8 | Rupture | Absence of material that is not caused by continuous degradation, and appears in bulky items. |

Table 5. Classification of anomalies damaging façades in existing residential buildings in Spain.

In a second workshop with the same panel of experts, the relationship between façades and the anomalies that affect, or can affect, each type of façade were analysed, to facilitate an accurate, systematic analysis of the energy impact of façades on building thermal performance. The resulting classification of anomalies that affect, or have the potential to affect, the state of conservation of each type of façade is summarized in Table 6.

| Façade classification for existing residential buildings [a] | | | | Anomaly classification for façades in existing residential buildings [b] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Number of skins** | **Air cavity** | **Insulation** | **External wall covering** | **D.1** | **D.2** | **D.3** | **D.4** | **D.5** | **D.6** | **D.7** | **D.8** |
| F.1 | AC.1 | I.1 | WC.1 | | x | x | x | x | | x | x |
| | | | WC.2 | x | x | x | x | x | x | x | |
| | | | WC.3 | x | x | x | x | x | x | x | x |
| | | I.3 | WC.2 | x | x | x | x | x | x | x | |
| | AC.2 | I.1 | WC.3 | x | x | x | x | x | x | x | x |
| | | I.3 | WC.3 | x | x | x | x | x | x | x | x |
| F.2 | AC.1 | I.2 | WC.1 | | x | x | x | x | | x | x |
| | | | WC.2 | x | x | x | x | x | x | x | |
| | | | WC.3 | x | x | x | x | x | x | x | x |
| | AC.2 | I.1 | WC.3 | x | x | x | x | x | x | x | x |
| | | I.2 | WC.3 | x | x | x | x | x | x | x | x |
| | AC.3 | I.1 | WC.1 | | x | x | x | x | | x | x |
| | | | WC.2 | x | x | x | x | x | x | x | |
| | | | WC.3 | x | x | x | x | x | x | x | x |
| | | I.2 | WC.1 | | x | x | x | x | | x | x |
| | | | WC.2 | x | x | x | x | x | x | x | |
| | | | WC.3 | x | x | x | x | x | x | x | x |
| | AC.4 | I.1 | WC.1 | | x | x | x | x | | x | x |
| | | | WC.2 | x | x | x | x | x | x | x | |
| | | | WC.3 | x | x | x | x | x | x | x | x |
| | | I.2 | WC.1 | | x | x | x | x | | x | x |
| | | | WC.2 | x | x | x | x | x | x | x | |
| | | | WC.3 | x | x | x | x | x | x | x | x |

[a] Façade codes can be found in Table 4.
[b] Codification of anomalies for façades obtained from Table 5.

Table 6. Relationship between façades and anomalies that affect their state of conservation.

The proposed classification system could help to structure analysis on the gap between the predicted and actual energy performance of existing residential buildings by selecting the case studies.

### 3.1.2 Comparing standardised calculation methods for in situ measurements of façade's U-value using the heat flux meter method

To check which of the two standardized calculation methods (the average method and the dynamic method) best fits the theoretical U-value, three north-facing façades of three buildings in Catalonia, northeast Spain, were selected as case studies. The composition of the façades is shown in Figure 4 by means of a schematic section. Table 7 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.

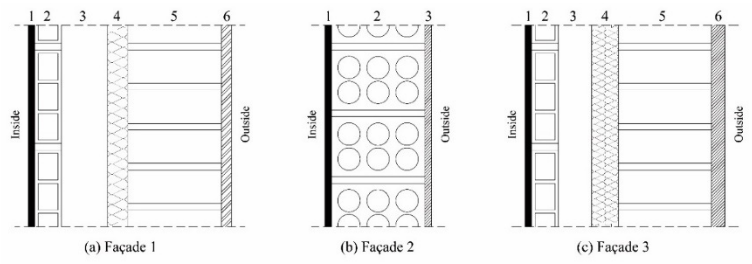



Figure 4. Schematic sections of the façades.

| 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 7.

Table 7. Composition of the façades.

Journal Paper II describes extensively the process monitoring and data acquisition, the analysis of data using the average and the dynamic calculation methods over façades with different U-values, and the methodology followed.

The results of the data analysis are shown in Table 8. 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 method 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.

| 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 8. 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, relative differences between the theoretical and the measured U-values using the average method and the dynamic method were calculated. 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 8, the relative 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. (2014).

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%.

The dynamic calculation method resulted to be the method that best fits the theoretical thermal transmittance. 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.

### 3.1.3 Proposal of calculation procedure for the HFM dynamic calculation method

Journal paper II describes extensively the analysis of data using the dynamic calculation method.

A calculation procedure to solve the system of equations of the dynamic method optimally, programming an Excel worksheet using the Solver tool (Frontline Systems, 2015) is proposed to facilitate its use. The model is comprised of:

- Two decision variables (the time constant *τ1* and its ratio *r*),
- The objective of minimizing the deviation between $\vec{q}$ and its estimate $\vec{q}*$ ($S^2$),
- 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 (*τ1*) and its ratio (*r*). Figure 5 shows a flowchart of the programmed spreadsheet to solve the system.

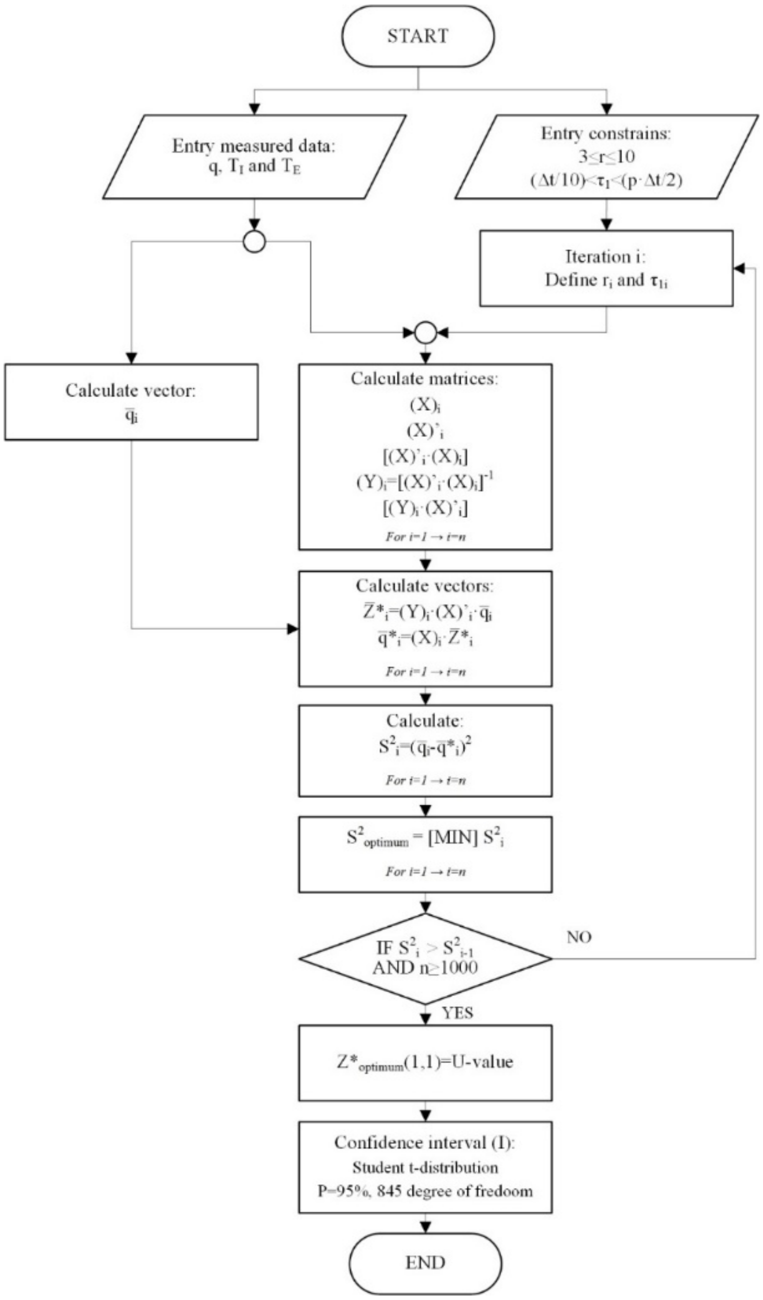



Figure 5. Flowchart of the programmed spreadsheet of the dynamic method, based on least squares adjustment.

## 3.2 Improving the accuracy of the in situ measurement of the actual thermal transmittance in façades with low thermal transmittance

A building mock-up with an area of 12 m² was constructed to investigate the limits of application of the heat flux meter method for the in situ measurement of U-values in low thermal transmittance façades, to verify the actual energy performance of new or refurbished building façades. Journal Paper III describes the composition of the building mock-up, the process monitoring and data acquisition, and the methodology followed.

Three variables were assessed to refine the standardised test conditions in façades with low thermal transmittance: the average temperature difference, the test duration and the a priori accuracy of equipment.

### 3.2.1 Average temperature difference

To analyse the impact of the average temperature difference on the accuracy of the U-value measurement, three periods of 168 hours with favourable weather conditions (no rain and no strong wind) and varying average temperature differences were selected. Measurements were classified into three intervals of temperature difference: less than 13ºC, from 13ºC to 19ºC, and higher than 19ºC. The measured thermal transmittance of the wall was determined in consecutive cycles of complete days, using cumulative values.

Measured U-values and their corresponding uncertainties obtained in each cycle for the intervals of temperature difference are depicted in Figure 6 and summarized in Table 7. The higher the temperature difference, the lower the deviation obtained between theoretical and measured U-values:

- A temperature difference between 11ºC and 13ºC led to high deviations of 10% and above between theoretical and measured U-value in initial cycles. Based on the results of U-value measurements, and their associated uncertainty, the test should have a minimum duration of 7 days.
- With a temperature difference ranging from 13ºC to 19ºC, relative differences between U-values were above 5% in initial cycles. It was found that the test should have a minimum duration of 4 days to minimize deviations and uncertainties associated to the measurement.
- When the temperature difference was above 19ºC, deviations between theoretical and measured U-value were above 5% in initial cycles. The minimum duration of the test was found to be 3 days to obtain reasonable deviations and uncertainties associated to the measurement.

Accordingly, to accurately measure in situ low U-value façades, temperature differences must be much higher than 10ºC.

Uncertainties of measurements decreased as the test was extended and when temperature difference increased. In the interval of temperature difference ranging from 11ºC to 13ºC, the uncertainty of measurements decreased when the duration of the test was extended, from ±0.032 W/m²·K in the first cycle to ±0.018 W/m²·K in the seventh cycle. In the interval ranging from 13ºC to 19ºC, results obtained in the third cycle were acceptable but uncertainty associated with the measurement was very high (±0.030 W/m²·K). However, when the test was extended 24 hours, the uncertainty was significantly reduced (±0.016 W/m²·K). In the range of temperature difference above 19ºC, the improvement neither in the result nor in the uncertainty of measurements would justify extending the test beyond 72 hours.

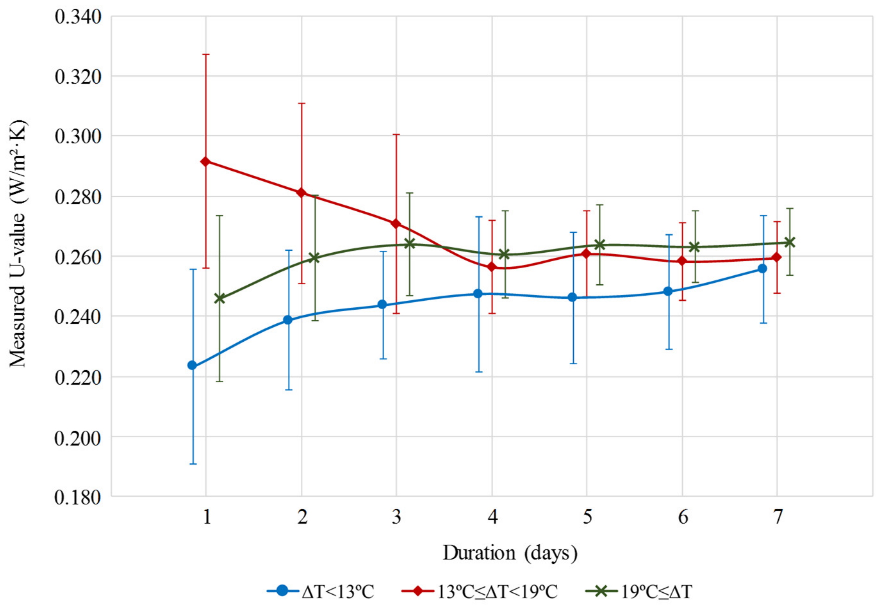



Figure 6. Measured U-values and their associated combined uncertainties in each interval of temperature difference for the seven cycles of test duration.

### 3.2.2 Test duration

The impact of the test duration was analysed to determine how the accuracy of theoretical and measured thermal transmittance varied as the test evolved. The variability of results was analysed by calculating the coefficient of variation of the resulting U-values, as proposed in ASTM standard (ASTM, 2007) and by Atsonios et al. (2017). The condition for ending the test was that the coefficient of variation of the U-value obtained at the end of the test must not deviate more than 1% from the value obtained 48 hours earlier.

In Table 9, the measured thermal transmittances and their associated uncertainties, the absolute values of the relative difference between theoretical and measured U-value, and the coefficient of variation are summarized for the results obtained in each cycle.

| | ΔT<13ºC | | | 13ºC≤ΔT<19ºC | | | 19ºC≤ΔT | | |
|---|---|---|---|---|---|---|---|---|---|
| Number of cycles (duration) | Um±$u_c(U)$ (W/m²·K) | $\left\|\frac{(U_t-U_m)}{U_t}\right\|$ (%) | Cv (%) | Um±$u_c(U)$ (W/m²·K) | $\left\|\frac{(U_t-U_m)}{U_t}\right\|$ (%) | Cv (%) | Um±$u_c(U)$ (W/m²·K) | $\left\|\frac{(U_t-U_m)}{U_t}\right\|$ (%) | Cv (%) |
| 1 (24h) | 0.223±0.032 | 15.9% | -- | 0.292±0.036 | 9.8% | -- | 0.246±0.028 | 7.4% | -- |
| 2 (48h) | 0.239±0.023 | 10.1% | -- | 0.281±0.030 | 5.8% | -- | 0.259±0.021 | 2.3% | -- |
| 3 (72h) | 0.244±0.018 | 8.3% | 4.4% | 0.271±0.030 | 1.9% | 3.9% | 0.264±0.017 | 0.6% | 3.6% |
| 4 (96h) | 0.247±0.026 | 6.9% | 1.8% | 0.256±0.016 | 3.4% | 4.7% | 0.261±0.015 | 1.9% | 0.9% |
| 5 (120h) | 0.246±0.022 | 7.3% | 0.8% | 0.261±0.014 | 1.8% | 2.8% | 0.264±0.013 | 0.7% | 0.7% |
| 6 (144h) | 0.248±0.019 | 6.6% | 0.4% | 0.258±0.013 | 2.8% | 0.8% | 0.263±0.012 | 0.9% | 0.6% |
| 7 (168h) | 0.256±0.018 | 3.7% | 1.9% | 0.259±0.012 | 2.3% | 0.5% | 0.265±0.011 | 0.3% | 0.3% |

Table 9. Measured U-values and their associated combined uncertainties, deviation between theoretical and measured U-value, and coefficient of variation of the measured thermal transmittance in the three intervals of temperature difference.

The results obtained in the experimental campaign showed that the test could not be stopped before 72 hours, since neither measurements nor its associated uncertainty would be acceptable. The duration of the test should be consistent with the temperature difference:

- For the interval of temperature difference above 19ºC, the test could be finished after 72 hours according to the standard and after 96 hours considering the variability of results criteria, with a deviation between theoretical and measured U-value of 1.9%.
- For the interval of temperature difference ranging from 13ºC to 19ºC, considering the variability of results criteria the test could be finished after 144 hours and meet the conditions for ending the test established in the standard, obtaining a deviation between theoretical and measured U-value of 2.8%.
- For the interval of temperature difference ranging from 11ºC to 13ºC, considering the variability of results criteria the test could be finished after 120 hours and meet the conditions for ending the test established in the standard, obtaining a deviation between theoretical and measured U-value of 7.3%.

### 3.2.3 Accuracy of equipment

In the assessment of the impact of the a priori accuracy of equipment on the measurement, the interval of temperature difference above 19ºC was selected, since it led to more accurate results, lengthening the test to 21 days.

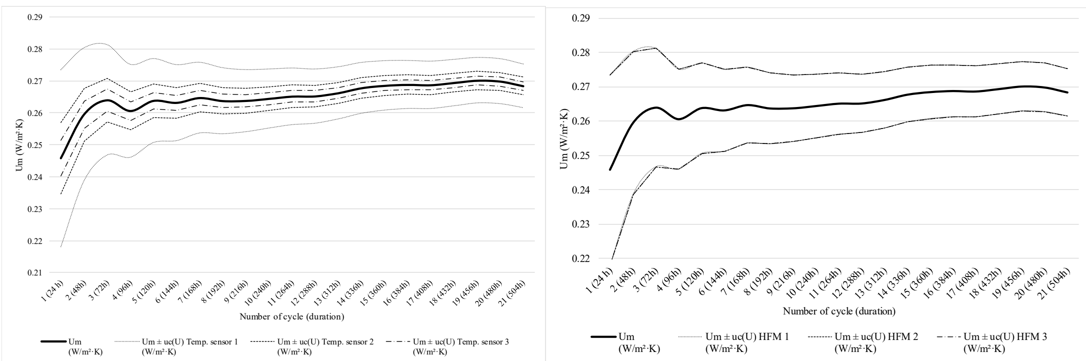
The measurement uncertainty was simulated in two situations; (1) in the first situation, the original a priori accuracy of the heat flow meter was kept constant and three scenarios for the temperature sensors' accuracy were considered, and (2) in the second situation, the original a priori accuracy of the inside and outside temperature sensors was kept constant and three scenarios for the heat flux meter accuracy were considered. Table 10 details the a priori accuracy of the selected equipment for the two situations and the three scenarios.

| Situation | Type of equipment | Equipment accuracy scenario 1 | Equipment accuracy scenario 2 | Equipment accuracy scenario 3 |
|---|---|---|---|---|
| 1 | Heat flux meter plate | ±5% * | ±5% | ±5% |
| | Inside and outside air temperature sensor | ±0.5°C * | ±0.2°C | ±0.1°C |
| 2 | Heat flux meter plate | ±6% | ±5% * | ±3% |
| | Inside and outside air temperature sensor | ±0.5°C | ±0.5°C * | ±0.5°C |

* Specifications of apparatus used for the experimental campaign.

Table 10. A priori accuracy of equipment in the two situations for the three scenarios.

The measured thermal transmittance and its associated uncertainty in both situations for the three scenarios for each cycle is depicted in Figure 7. In the first situation, temperature sensors that were more accurate resulted in lower uncertainty of measurements. However, the relation was not linear. The impact of equipment accuracy on the trueness of results was high in the first cycle of tests, and decreased when the test was extended (Figure 7a). The selection of ambient temperature sensors had a considerable impact on the uncertainty of measurements, especially in the initial cycles of the test. The second situation took into account the specifications of equipment commonly used in studies of the in situ measurement of thermal transmittance (Hukseflux Thermal Sensors, 2016; GreenTEG, 2016). The most widely used heat flux meters by researchers for in situ measurements of façade's U-value are highly accurate (Ahmad et al., 2014; Asdrubali et al., 2014; Ficco et al., 2015; Mandilaras et al., 2014). Consequently, the change of scenario does not have a significant impact on the uncertainty of measurements, as shown in Figure 7b, where lines corresponding to the three scenarios overlapped.



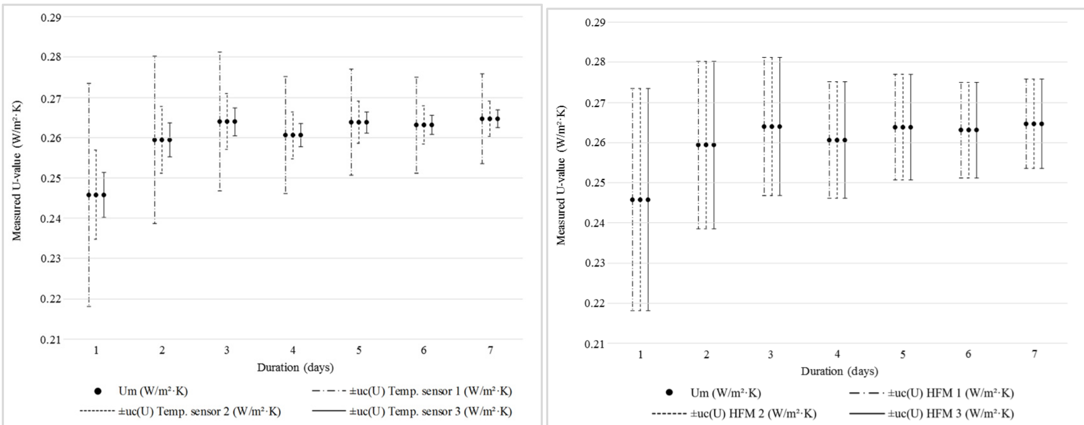

**a)** **b)**

Figure 7. Results of thermal transmittance and its associated combined uncertainty in a) situation 1, and b) situation 2.

The accuracy of the temperature sensors plays a very important role in the total uncertainty of the measurement when low thermal transmittance façades are measured for the interval of temperature difference above 19ºC and using an accurate heat flux meter (Ficco et al., 2015). When the accuracy of the heat flux meter was kept constant at ±5%, with temperature sensors that had an accuracy of ±0.5ºC, the simulated uncertainty of measurements was ±0.017 W/m²·K at 72 hours of test duration and meeting the conditions for ending the test according to the standard. When the accuracy of temperature sensors was ±0.2ºC, the simulated uncertainty was reduced to ±0.007 W/m²·K, and with temperature sensors with an accuracy of ±0.1ºC the simulated uncertainty was reduced to ±0.003 W/m²·K (Figure 8a).

Selecting a heat flux meter with high performance is essential to obtain accurate results. When the accuracy of the temperature sensors was kept constant at ±0.5ºC, with a heat flux meter that had an accuracy of ±6%, the simulated uncertainty of measurements was ±0.017 W/m²·K at 72 hours of test duration and meeting the conditions for ending the test according to the standard. The simulated uncertainty of measurements did not differ significantly when accurate heat flux meters were used (with accuracies ranging from ±5% and ±3%) (Figure 8b).

The selected heat flux meters, commonly used by researchers, were already very accurate (ranging from ±3% to ±6%), and the improvement of the measurement uncertainty by changing the sensor was not significant. Whereas the uncertainty of the U-value measurements can be significantly reduced by using temperature sensors with high accuracies (±0.1ºC or ±0.2ºC).




**a)** **b)**

Figure 8. Uncertainty related to equipment in a) situation 1, and b) situation 2.

## 3.3 Enhancing the usability of the heat flux meter method for the in situ measurement of the actual thermal transmittance of façades

Conditions for ending the test of in situ experimental campaigns to measure the thermal transmittance of existing buildings' façades using the heat flow meter method were analysed taking into consideration criteria of data quality, variability of results and 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). Journal Paper IV widely describes the composition of the case studies, the process monitoring and data acquisition, the analysis of data using the average and the dynamic calculation methods, the criteria for analysing the minimum test duration in three ways and the methodology followed.

Table 11 summarizes the thermal resistance of each layer and the theoretical U-value of the case studies.

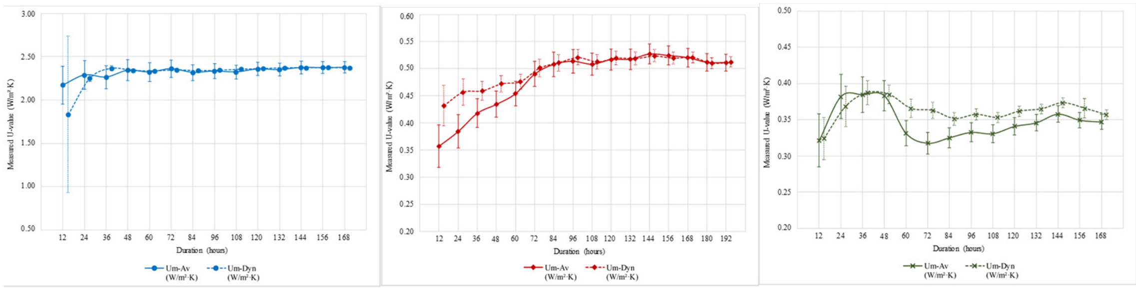
| Case study | No. layer | Material layer (inside-outside) | Thickness (m) | Thermal conductivity (W/m·K) | Thermal resistance (m²·K/W) | Total thickness (m) | Theoretical U-value (W/m²·K) |
|---|---|---|---|---|---|---|---|
| Case study 1 | 1 | Gypsum plaster | 0.01 | 0.570 | 0.018 | 0.16 | 2.35 |
| | 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 11. Composition of the case studies.

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 and dynamic methods were used to calculate the in situ thermal transmittance of façades (ISO, 2014). Following Flanders (1985) 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. The results of the data analysis are summarized in Table 12 and are depicted in Figure 9.

Uncertainties of measurement decreased as the tests were extended. The results are in line with those analysed from the literature, in which periods of data acquisition that were too short led to highly inaccurate measurements (Asdrubali et al., 2014; Nardi et al., 2015).




**a)** **b)** **c)**

Figure 9. 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 | |
|---|---|---|---|---|---|---|---|
| | | $U_{m\text{-}Av}$ ±$U_{(C)}$ (W/m²·K) | $U_{m\text{-}Dyn}$ ±I95% (W/m²·K) | $U_{m\text{-}Av}$ ±$U_{(C)}$ (W/m²·K) | $U_{m\text{-}Dyn}$ ±I95% (W/m²·K) | $U_{m\text{-}Av}$ ±$U_{(C)}$ (W/m²·K) | $U_{m\text{-}Dyn}$ ±I95% (W/m²·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/m²K)** | | 2.35 | | 0.52 | | 0.36 | |

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

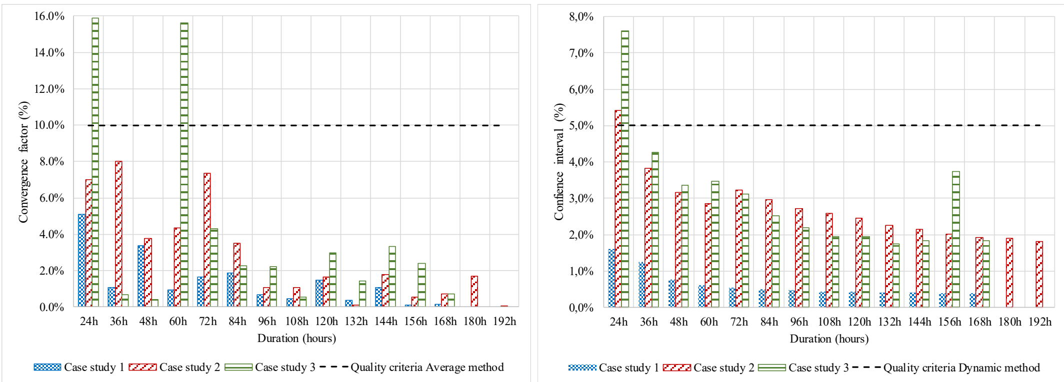
### 3.3.1 Data quality criteria

Data quality criteria for the average method were examined for the three cases through the convergence factor (ASTM, 20077; Flanders, 1985). 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 (Flanders, 1985).

Figure 10a 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.

Data quality criteria for the dynamic method were examined for the three case studies through the confidence interval (ISO, 2014; Roulet et al., 1985). In this study, a confidence interval smaller than 5% of the thermal transmittance for $P = 0.95$ is adopted as a quality criterion (Roulet et al., 1985).

Figure 10b 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.




**a)** **b)**

Figure 10. Data quality criteria in Case study 1, Case study 2 and Case study 3 using a) the Average method, and b) the Dynamic method.

### 3.3.2 Variability of results

The variability of results was examined for each calculation method in the three case studies through the coefficient of variation, as proposed in standard ASTM (ASTM, 2007) and by Atsonios et al. (2017). In this study, the coefficient of variation is expected to be 10% for the average method and 6% for the dynamic method (Atsonios et al., 2017), for a confidence level of 95.4%.

The coefficients of variation in each cycle using the average and the dynamic methods are depicted in Figure 11. 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.

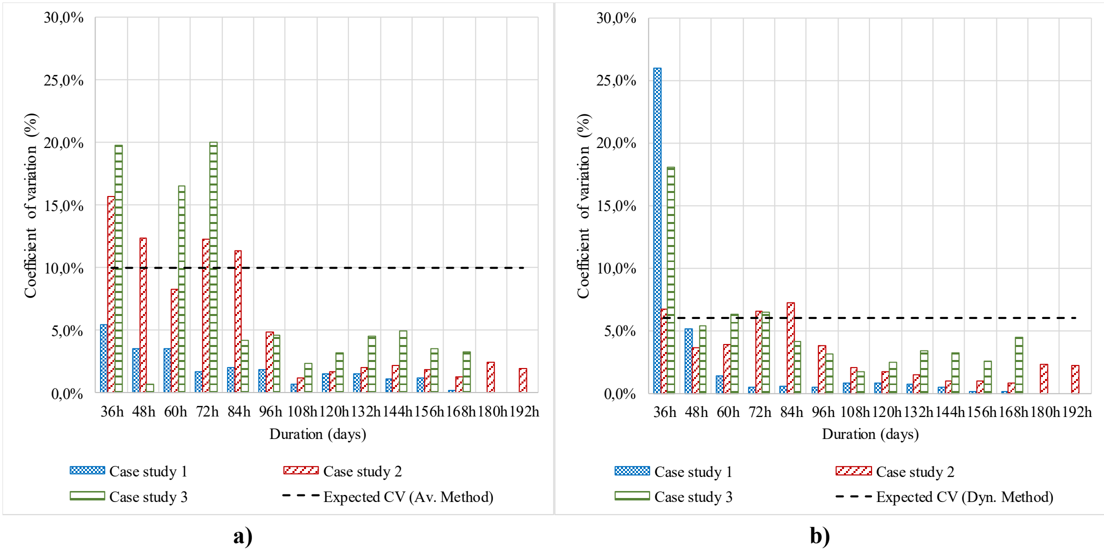



Figure 11. Coefficients of variation in Case study 1, Case study 2 and Case study 3 using a) the Average method, and b) the Dynamic method.

### 3.3.3 ISO criteria

The conditions for ending the test according to the ISO standard (ISO, 2014) were checked. The first condition is that the test must last at least 72 hours. 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. 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 standard (ISO, 2014) 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 13 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 13. 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. 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·$D_T$/3)* 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 14 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.

| 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 14. Deviation of U-values between the initial and final analysis period for each test duration for the average and dynamic methods of calculation.

### 3.3.4 Comparison of results

The minimum duration required for in situ experimental campaigns for the three case studies, according to the three criteria, is summarized in Table 15.

| | 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/m²K)** | 2.35 | | 0.52 | | 0.36 | |

Table 15. 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.

Results in Case study 1 showed that:

- Using data quality criteria, 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 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.
- Using 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, applying ISO criteria the systematic error was lower than 0.5%.

Results in Case study 2 showed that:

- Using data quality criteria, 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 variability of results criteria, the test could be ended on the fourth day (96 hours) for both calculation methods.
- Using 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, to greater sensitivity of the ISO criteria, and to 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%, using data quality criteria, to 0.2% by applying variability of results criteria and ISO criteria.

Results in Case study 3 showed that:

- Using data quality criteria, 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 variability of results criteria, conditions for ending the test were met on the fourth day (84 hours) for both calculation methods.
- Using 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.

## 3.4 Conclusions and further research

The principal findings and implications of this dissertation are presented below, demonstrating how the objectives stated at the beginning have been achieved by the undertaken research.

The first objective of this thesis was to propose a calculation procedure for the dynamic calculation method for the in situ measurement of the actual thermal transmittance of façades of existing residential buildings using the heat flux meter method with accessible tools to facilitate its use. To achieve this objective, three tasks have been done; 1) definition of a classification system of façades in existing Spanish residential buildings to facilitate the selection of façades with different theoretical thermal transmittance, 2) comparison of existing standardised calculation methods for the in situ measurement of the actual thermal transmittance of façades of existing residential buildings using the heat flux meter method, and 3) proposal of a calculation procedure for the dynamic calculation method for the in situ measurement of the actual thermal transmittance of façades using the heat flux meter method with available tools to promote its use.

In this sense, in Journal Paper I a classification system for façades in existing Spanish residential buildings was developed for the first time. The key features of the developed classification system are summarized below:

- The façade classification for existing residential buildings was based on the opaque part of closures and organised into four levels: number of skins, existence of an air cavity, existence of insulation and type of external wall covering. The research covered original buildings in the Spanish area and did not take into account any measures to upgrade the façades. Twenty-three types of façades were identified, depending on the type of material and thickness of the different layers comprising the building closures.
- The classification of anomalies had eight categories: adhesion failure, cracking, dampness, deformation, degradation of material, detachment, oxidation and corrosion, and rupture. Each category includes a definition to clarify its meaning.
- The interviews conducted to validate the classifications revealed that:
  - The classifications were comprehensive, which refers to the extent to which the classifications can cover all the main categories and issues associated with types of façades and anomalies.
  - The classifications were functional, which refers to the extent to which the classifications can be used by different technicians to obtain the same results.
  - The classifications were suitable, which refers to the extent to which the classification facilitates energy studies.
- To determine the types of anomalies that affect, or have the potential to affect, the state of conservation of each type of façade, a relationship between both classifications was established. This relationship was validated by the same panel of experts in a second workshop.
- The classification system can be applied to most Spanish buildings. The comprehensiveness of the classification system was demonstrated with a case study, using real data on 154 public housing buildings. All the closures in the sample of buildings were covered by the classification system, and all the façades in the classification system were found in the sample of buildings. Furthermore, all the anomalies affecting façades in the sample of buildings were found in the classification system, and all the types of anomalies established in the classification system were identified in the sample of façades.

In Journal Paper II a comparison of 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, was made to verify which best fits theoretical values. Then, a calculation procedure to solve the system of equations of the dynamic method optimally using a spreadsheet was proposed to facilitate its use. The main contributions in this area are summarized below:

- The results 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 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.
- The measured thermal transmittance using the standardized dynamic method with a sufficiently large dataset showed a better fit to the theoretical thermal transmittance than other dynamic methods proposed by authors.
- A description of the implementation of the dynamic method is detailed. To facilitate its implementation, a flowchart of the programmed spreadsheet for the dynamic method is included.

The second objective of this thesis was to improve the accuracy of the in situ measurement of the actual thermal transmittance in façades with low thermal transmittance using the heat flow meter method, exploring the boundaries of the requirements for using the heat flux meter method to refine the testing conditions. In this sense, in Journal Paper III conditions for applying the ISO standardised HFM method for in situ measurement of thermal transmittance in low U-value façades were refined. The research focused on the study of operational conditions that are not fully specified in the standard; 1) average temperature difference, 2) test duration, and 3) a priori accuracy of equipment. The main contributions in this area are summarized below:

- In the in situ measurement of low U-value façades, low thermal flux is obtained, decreasing the accuracy of the measurement. To reduce this deviation, temperature differences should be increased. However, achieve average temperature differences equal or greater than 19ºC may be a limitation in real conditions. Possibly, for low U-value façades greater deviations have to be assumed. Specifically, in the conducted experiment, deviations of 1.9% were obtained with temperature differences above 19ºC, and they increased to 7.3% with temperature differences ranging from 11ºC to 13ºC.
- The duration of the test should be consistent with the temperature difference between the indoor and outdoor environments during the experimental campaign. In the range of temperature differences equal or greater than 19ºC accurate results are obtained from a test duration of 72 hours. Whilst for lower ranges of temperature difference the duration of the test should be extended between 24 and 48 hours.
- The analysis of in situ measurements of façades' U-values in the existing literature revealed that specific heat flow meters were used, with good technical performance and relatively high costs. However, the accuracy of the temperature sensors varied widely. Therefore, to reduce the uncertainty of measurements, practitioners could save on the acquisition of heat flow meters with accuracies of ±5% to ±6%, and invest in the acquisition of temperature sensors with accuracies between ±0.1ºC and ±0.2ºC.
- Since the heat flux meter method is a widely used technique for in situ measurement of the thermal transmittance of façades, this research aims to help avoid errors in its use when façades

with a low U-value are measured. The findings complement those stated in ISO 9869-1:2014 and in the existing literature.

The third objective of this thesis was to enhance the usability of the heat flux meter method for the in situ measurement of the actual thermal transmittance of façades of existing residential buildings providing best practices in conducting in situ experimental campaigns. To achieve this objective, two tasks have been done; 1) assessment of the impact of theoretical U-value on the accuracy of the in situ measurement of the actual thermal transmittance of façades of existing residential buildings using the heat flux meter method, and 2) comparison of conditions for ending the test duration of experimental campaigns for the in situ measurement of the actual thermal transmittance of façades using the heat flux meter method.

In this sense, in Journal Paper IV different criteria for determining the conditions for stopping the test of in situ experimental campaigns to measure the thermal transmittance of existing buildings' façades using the heat flow meter method were analysed. The analysis took into consideration criteria of data quality, variability of the results and ISO standard. In situ measurements were conducted under real conditions within the same range of average temperature difference (between 10ºC and 15ºC). The main contributions on this area are summarized below:

- 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.
- 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 criteria of data quality and variability of results.
- When a highly accurate measurement is needed, the use of ISO criteria is recommended.

In Journal Paper II and Journal Paper IV the impact of theoretical U-value on the accuracy of the in situ measurement of the actual thermal transmittance of façades of existing residential buildings using the heat flux meter method was assessed. The main contributions on this area are summarized below:

- Regarding the calculation methods, the results showed that façades with a high thermal transmittance obtained acceptable differences between theoretical and measured thermal transmittance using both calculation methods, the average and the dynamic methods. However, it is recommended to use the dynamic method in façades with low thermal transmittance since it reduces the differences between theoretical and measured thermal transmittance with respect to the average method.

- In relation to the conditions for ending de test, the findings showed that 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. Thus, façades with high thermal transmittance require shorter test durations than façades with low thermal transmittance.

The main contributions of this dissertation are presented below:

- A classification system of façades is developed in the dissertation. This classification system can be applied to most existing Spanish buildings. The findings help in the selection of case studies for subsequent analysis on the thermal performance of façades of existing residential buildings.
- Regarding the comparison of standardised calculation methods for in situ measurements of façade's U-value using the heat flux meter method, the results showed that the use of the dynamic calculation method could lead to more accurate measurements. However, this calculation method is more complex and consequently its use is not extended. This dissertation proposes a calculation procedure to solve the system of equations of the dynamic method optimally, programming a spreadsheet using accessible tools for practitioners to facilitate its use.
- With respect to the exploration of boundaries of requirements for in situ measuring the façades' U-value applying the heat flux meter method in low U-value façades, practitioners will be able to improve the design of experimental campaigns required in energy audits of low U-value façades. Specifically, when they verify compliance with energy performance policies in façades retrofitted to attain nearly zero-energy buildings, and corroborate energy performance of façade strategies for new nearly zero-energy buildings. Depending on the accuracy of measurements required, this dissertation guides on conditions of environmental temperatures, duration of the test and accuracy of equipment required.
- Concerning the analysis of different criteria for determining conditions for ending the test of experimental campaigns during in situ measurements of façades' U-value using the heat flux meter method, the results showed that the accuracy of in situ measurement of façades' thermal transmittance could be improved taking into account the theoretical thermal transmittance of the façade, the calculation method and the requirements of the energy audit.
- This dissertation provides parameters to be taken into consideration for future revisions of the standard. The minimum duration of the standardised HFM test could be discussed in future revisions of the ISO standard. The discussion could take into account parameters such as

average temperature difference between indoor and outdoor ambient, composition of the façade and accuracy of equipment, among others. However, it would be reasonable to conduct further research to readjust the criteria.

### 3.4.1 Further research

Some interesting issues emerged during the development of this research were not addressed within this dissertation, since the level of analysis they would require is beyond the scope of this dissertation. The most interesting and urgent research questions seeking for answers and explanations are listed below.

- A real-time monitoring system could improve decision-making regarding the adjustment of the minimum duration of the on-site tests, depending on the temperature difference, the thermal flux and the calculation method used. It should be considered for the in situ measurement of façades with very low thermal transmittance, since their use is increasing worldwide to meet Directive 2010/31/EC and "2030 climate and energy framework" targets.
- The dissertation could not cover the analysis of the impact of all constructive characteristics of façades on the in situ measurement accuracy of the façades' thermal transmittance using the heat flux meter method. In this sense, two parameters are proposed to be studied in future research:
    - Analysing how the thermal capacity of walls affects the measurement accuracy of the actual thermal transmittance of existing buildings' façades using the heat flow meter method should be considered. Literature review reveals that several factors that could influence the accuracy of the in-situ measurement of façades' U-value have been analysed. However, studies on the impact of the thermal capacity of façades on the accuracy of in situ measurements of façades' U-values are not yet conclusive.
    - Evaluations of the thermal performance of façades in existing buildings have tended to focus on the composition of their layers and are based on a building's age rather than the state and conservation status of the façades. However, the conservation state of the building envelope might have a significant effect on the thermal behaviour of the building. The implications of the deterioration of façades over time for energy consumption could be investigated because this is not a well-researched issue, and no thermal simulation program probably takes this or other known unknowns into account.

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# Chapter 4. Publications: Published papers

This chapter reproduces the published journal papers derived from this thesis. Each paper follows its own numbering of sections, figures, tables, equations and references.

Journal paper I:

Gaspar K., Casals M, Gangolells M. Classifying system for façades and anomalies. *Journal of Performance of Constructed Facilities*, 2016, 30(1): 1-10. <doi: 10.1061/(ASCE)CF.1943-5509.0000693>.

- Area: Construction and Building technology
- Quartile: Q2 (30/61)
- JCR Impact factor: 1.192 (2016)
- Number of cites: 5 (Scopus), 4 (Web of Science)

Journal paper II:

Gaspar K., Casals M., Gangolells M. A comparison of standardized calculation methods for in situ measurements of façades U-value. *Energy and Buildings*, 2016, 130(15): 592-599. <http://dx.doi.org/10.1016/j.enbuild.2016.08.072>.

- Area: Construction and Building technology
- Quartile: Q1 (5/61)
- JCR Impact factor: 4.067 (2016)
- Number of cites: 11 (Scopus), 6 (Web of Science)

Journal paper III:

Gaspar K., Casals M., Gangolells M. In situ measurement of façades with a low U-value: Avoiding deviations. *Energy and Buildings*, 2018, 170: 61–73. <doi:10.1016/j.enbuild.2018.04.012>.

- Area: Construction and Building technology
- Quartile: Q1 (5/61)
- JCR Impact factor: 4.067 (2016)
- Number of cites: - (Scopus), - (Web of Science)

## 4.1 Journal paper I. Classifying System for Façades and Anomalies

*Published in Journal of Performance of Constructed Facilities, 2016, 30(1):1-10. <doi: 10.1061/(ASCE)CF.1943-5509.0000693>.*

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**Abstract**

Façades play an important role in buildings' energy demand, and their state of conservation obviously influences thermal performance. The energy performance gap in existing residential buildings due to façade conservation status has not been analyzed in depth. In order to facilitate the systematic analysis of this influence, a system for classifying façades and their corresponding anomalies was developed for the first time. The classification system includes 23 types of façades and eight types of anomalies. It was verified by a panel of experts, and a case study was carried out with a sample of 154 buildings. An analysis of the results showed that the classification system is useful for a future analysis of the energy performance gap in existing residential buildings

*CE Database subject headings:* classification, anomalies, residential buildings, Spain

*Author keywords:* residential building stock, façade, anomaly, classification system

## 1. Introduction

Interest in improving buildings' energy performance has been growing, as buildings are responsible for 41% of total final energy consumption in Europe (European Union 2013). In order to achieve the European Union's "20-20-20" energy efficiency target, two documents have been published recently: the European Commission's Energy Efficiency Plan 2011 (European Commission 2011) and Directive 2012/27/EU on energy efficiency (European Union 2012). Both documents highlight construction as the biggest potential sector for energy saving. According to the European Commission (European Commission 2006), potential energy savings of 27% can be made in residential buildings. To reach energy efficiency targets, Horizon 2020, the European Union Framework Programme for Research and Innovation for 2014 to 2020, stresses the need to close the gap between the predicted and actual energy performance of existing buildings (European Commission 2014).

According to Balaras et al. (2005), the existing building stock in Europe is estimated at 150 million dwellings. Approximately 70% of the residential building stock is over 30 years old, and about 35% is more than 50 years old. In Spain, the existing residential building stock stood at around 9.7 million dwellings, about 56% of which were built before 1980 (Instituto Nacional de Estadística 2013), when the NBE CT-79 (Spain 1979) basic building regulations on thermal conditions in buildings came into effect (Gangolells and Casals 2012).

NBE CT-79 (Spain 1979) establishes five areas (V-Z) according to the mean minimum temperature in January, and uses this classification to set maximum heat transmission coefficients for individual closures (Gangolells and Casals 2012). NBE CT-79 (Spain 1979) was repealed by the Technical Building Code (Spain 2006), which was adopted as a result of the transposition of 2002/91/EC, the first Energy Performance of Buildings Directive (EPBD) (European Union 2002). The Technical Building Code (Spain 2006) establishes five areas (A-E) according to the winter climate zone, taking into account solar radiation and heating/cooling degree-days based on 20ºC. This classification is used to set the maximum heat transmission coefficients for individual closures (Gangolells and Casals 2012). Table 1 shows typical *U-values* for the façades of these buildings.

The breakdown of total household energy consumption by end-use in the European Union is as follows: 68% for space heating, 12% for water heating, 4% for cooking and 15% for lighting and electric appliances (Lapillonne et al. 2012). The breakdown of the total energy consumption by end-use in Spain is as follows: 47% for space heating, 27.4% for water heating, 24.5% for lighting and electric appliances, and 1.1% for space cooling (IDAE 2011). As observed, space heating is responsible for a high proportion of energy consumption in residential buildings, and consequently has considerable potential for energy saving. Two methods can achieve energy savings in residential building stock: (1) reduce the energy demand by modifying construction elements (passive method), and (2) enhance the energy efficiency of heating, ventilation, and air conditioning systems (active method).

In existing residential buildings, the gap between predicted and actual energy performance due to façade state and conservation status has not been analysed in depth. According to Williamson (2010), deterioration over time could have a significant impact on energy consumption. However, this is not a well-researched issue, and no thermal simulation program takes this or other known unknowns into account.

Façades play an important role in buildings' energy demand. To date, evaluations of the thermal performance of façades in existing buildings have tended to focus on the composition of the layers and are based on a building's age rather than the envelope degradation and the façades' conservation status. However, according to Rodrigues et al. (2013), the conservation state of the building envelope might have a significant effect on a building's thermal behaviour. To analyse the influence of envelope degradation on buildings' energy performance, first the relationship between types of façades and the types of anomalies that may affect an envelope's conservation status must be established. No relevant contributions on this area were found in the literature. Thus, the aim of this paper was to develop a classification system for types of façades and the types of anomalies that can affect conservation status, to facilitate a systematic analysis of the influence of closures' state of conservation on the thermal performance of buildings in the Spanish housing sector.

The method used to determine and validate the classification system is explained in the second section following this introduction. In the third section, a case study is presented to verify the system. Finally, the conclusions are given in the fourth section, and suggestions are made for future research.

## 2. Method

First, a thorough literature review was carried out on existing classifications of façades, and of the anomalies that can damage these closures. As a result of this analysis, several types of façades and anomalies were proposed. The proposal was later refined and validated by a panel of experts. Then, again with the help of experts, a system was established for classifying façade types and associated types of anomalies that affect the state of conservation of closures in existing residential buildings. Finally, a case study was performed to verify the approach (Fig. 1).

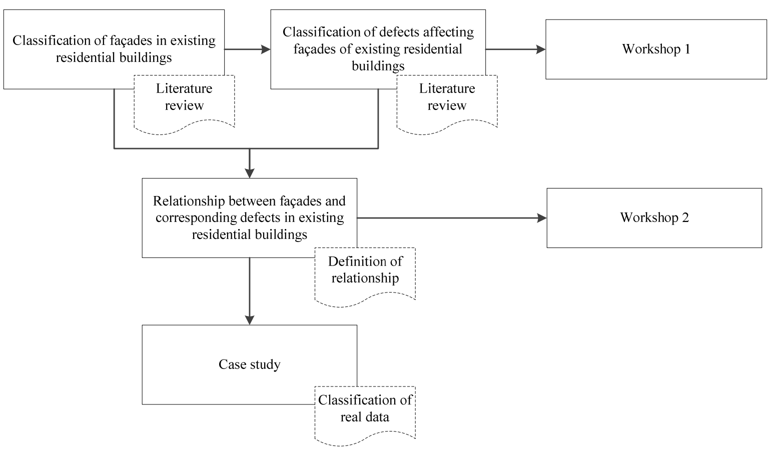


Fig. 1. Research methodology

### 2.1 Classification of façades in existing residential buildings

The first step in characterising the opaque part of façades in existing Spanish residential buildings was to analyse national and regional regulations and codes for buildings and construction processes. According to Jørgensen (2011), these regulations and codes do not provide a classification system, but they do describe Spanish construction systems in detail. A catalogue of building elements was developed (IETcc 2010) to promote compliance with the general habitability design requirements of the Technical Building Code in Spain (Spain 2006). Façades were categorised into twenty types according to the main characteristics of the wall covering, air cavity and insulation. The types vary according to the main skin's material, the inner skin's material, the existence of intermediate cladding, the existence of inner cladding, and the existence and type of air cavity and internal partitions. Spanish building types were characterised by the *Instituto Valenciano de la Edificación* (IVE) as part of the Tabula Project (Loga et al. 2012) for energy performance assessment of national building stock. In addition, a catalogue of construction solutions for energy building renovation (Valencia Institute of Building 2011) has been drawn up by the IVE, detailing a wide range of construction elements that can be found in thermal envelopes in Spanish buildings from the 1940s to the 1980s. The catalogue contains a classification of types of existing façades according to the number of skins, air cavity, insulation and wall covering.

In the second step, existing classifications of façades in the housing stock were analysed. First, classifications related to the construction industry were reviewed. Several classifications such as OmniClass (OmniClass 2006) and UniClass (Crawford et al. 1997) have been developed that take as a reference the standard ISO 12006-2:2001 (ISO 2001), where the "element" is the basis for classification. According to Jørgensen (2011), "element" is defined as part of a construction entity that, alone or in combination with other parts, fulfils a predominant function. Both UniClass and OmniClass are faceted classifications for the architectural, engineering and construction industry that are designed within the parameters of ISO 12006-2 (ISO 2001) and organised in tables. OmniClass (OmniClass 2006) is focused on US terminology and practise, and consists of fifteen tables representing different facets of construction information. UniClass (Crawford et al. 1997) is the equivalent classification for the United Kingdom. It is also structured into fifteen tables representing different aspects of construction information. The Danish DBK classification (BIPS 2006) is also based on ISO 12006-2:2001 parameters, but the top part of the table is organised by systems and the function of components are listed in a sub-table (Jørgensen 2011). Other existing classifications are not based on ISO 12006-2:2001 (ISO 2001). This is the case of UniFormat (The Construction Specifications Institute 2010) in the United States of America and Canada, and BSAB 96 (Svensk Byggtjänst 1999) in Sweden. UniFormat (The Construction Specifications Institute 2010) is a standard method for organising construction information around the physical part of systems and assemblies, which are characterised by their function without identifying the technical or design solutions that may have been used. According to Jørgensen (2011), BSAB 96 (Svensk Byggtjänst 1999) has separate entries for the classification of composite elements and that of systems compared to elements, and consequently there are conflicting classification requirements.

The third step involved a literature review. Monjo (2005) carried out a general analysis of the evolution of construction systems for buildings' closures. Adell and Vega (2005) undertook a specific analysis of types of reinforced brick façade (supported, suspended and prefabricated). Eicker et al. (2008) reviewed façade systems and the energy performance of single and multiple-skin glazed façades with sun-shading systems in non-residential buildings. Chan et al. (2009) evaluated the energy performance of double-skin façades with various configurations including glazing type, glazing position and glazing layers. Some authors focused their research on residential buildings. Chandra (1980) classified four walls in hot dry climates on the basis of their thermal performance index (precast and cast-in-place walls). In order to analyse the influence of external walls' thermal inertia on the energy performance of well-insulated buildings, Aste et al. (2009) established twenty-four construction systems for opaque vertical walls grouped into three categories: (1) single layer massive walls, (2) walls with insulation outside, in the middle, inside or on both sides, and (3) light walls mainly based on insulation materials. Pulselli et al. (2009) evaluated three building envelope technologies from an environmental perspective, namely: a traditional air-cavity wall, a plus-insulated wall (with an external cork covering), and a ventilated wall (with external brick panels fixed on extruded frames). To gain fundamental insight into how to improve insulation performance with arrangements of wall layers, Bond et al. (2013) defined four primary configurations of multi-layered walls with fixed volumes of insulation and thermal mass, in which only the layer distribution varied. Sadineni et al. (2011) reviewed building envelope components for passive building energy savings. They defined four advanced wall technologies (passive solar walls, lightweight concrete walls, ventilated or double-skin walls, and walls with latent heat storage), and three conventional walls (wood-based walls, metal-based walls and masonry walls). Other authors focused on local façade systems. Theodosiou and Papadopoulos (2008) studied four scenarios with two configurations of wall thermal insulation that are frequently used in typical Greek buildings (double wall and single wall), in order to investigate the impact of thermal bridges on energy consumption. Yu et al. (2009) systematically evaluated the energy and thermal performance of residential envelopes in six typical multi-skin external walls in China. Aldawi et al. (2012) investigated the thermal performance of a new house wall envelope in Australia and defined a conventional house wall system (brick veneer and wood frame wall) and an alternative house wall system (reinforced concrete panel with insulation). Finally, Cuerda et al. (2014) developed a system for classifying the façades of buildings erected between 1950 and 1980, in a specific neighbourhood in Madrid (Spain).

In conclusion, existing classifications do not define the construction composition of the opaque part of façades. Some authors have carried out specific studies on façade classifications, without covering the entire range of façades in Spanish residential buildings. Consequently, a façade classification for housing stock in Spain was developed.

An initial façade classification proposal was developed by the research team according to the literature review and the national and regional regulations and codes related to buildings and construction processes. The initial classification system was composed of four levels, and took into account: (1) the materials in the core fabric and the external wall covering as the main level, (2) the existence of an air cavity and its position and type, when applicable, (3) the existence and position of insulation, and finally (4) the type of external wall covering system, since this is the part of the closures that is in direct contact with the aggressiveness of the external environment and, therefore, more susceptible to degradation processes. A workshop was held with a panel of experts to analyse, enhance and validate the proposed classification. The panel was composed of practitioners from the construction industry who are specialised in existing buildings: two professors from the Department of Architectural Technology II at the *Universitat Politècnica de Catalunya·BarcelonaTech* (UPC), two professors from the Department of Construction Engineering at the UPC, three building engineers from Spanish design firms who are specialised in existing buildings, and one quality manager from a Spanish construction company who is specialised in residential buildings.

At the start of the workshop, the panel of experts defined three premises to take into consideration: (1) comprehensiveness, which refers to the extent to which the classification can cover all the main categories and issues associated with types of façades; (2) functionality, which refers to the extent to which the façade classification can be used by different technicians to obtain the same results; and (3) suitability, which refers to the extent to which the classification facilitates energy studies. Then, the classification proposal was presented. To improve the comprehensiveness of the classification, proposals were made to modify its levels, based on original existing buildings in the Spanish area, without taking into account any measures that had been implemented to upgrade façades. Firstly, the panel of experts proposed using the number of skins as the main level, given that they considered that this first level of classification has a great impact on façades' energy performance. The experts agreed on the levels referring to the existence of an air cavity and its position and type, and on the levels referring to the existence and position of insulation and to the type of external wall covering. These aspects also play an important role in the energy performance of the façades. In order to cover the typical types of façades in existing Spanish residential buildings, and to minimize the number of types, the experts agreed to take as variables the materials and the thickness of layers in the opaque part of façades. As a result, the classification was organised into four levels:

1. Number of skins of the façade. The main layer of façades is usually made of different types of ceramic or concrete bricks. The inner layer, in the case of double skin façades, is generally made of ceramic or concrete bricks, or laminated plasterboard.
2. Existence of air cavity. Façades may or may not have an air cavity. Air cavities can be ventilated (internally or externally) or non-ventilated.
3. Existence of insulation. Façades may or may not have insulation. Insulation can be placed on the outside of the main layer (external insulation) or inside the air cavity (internal insulation).
4. Type of external wall covering. Façades may be finished with a continuous covering, a non-continuous covering or faced (without a covering).

Table 1 presents the resulting façade classification for existing residential buildings in Spain.

| **Façades classification for existing residential buildings** | | | | | | | | **Maximum *U-values* for heavy façades according to NBE-CT-79 (Spain 1979)** | | | | | **Maximum *U-values* for façades according to the Spanish Technical Building Code (Spain 2006)** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Number of skins** | | **Air cavity** | | **Insulation** | | **Wall covering** | | **Zone V** | **Zone W** | **Zone X** | **Zone Y** | **Zone Z** | **Zone A** | **Zone B** | **Zone C** | **Zone D** | **Zone E** |
| F.1 | Single skin | AC.1 | Without air cavity | I.1 | Without insulation | WC.1 | Faced | | | | | | | | | | |
| | | | | | | WC.2 | Continuous covering | | | | | | | | | | |
| | | | | | | WC.3 | Non-continuous covering | | | | | | | | | | |
| | | | | I.3 | External | WC.2 | Continuous covering | | | | | | | | | | |
| | | AC.2 | With external ventilated air cavity | I.1 | Without insulation | WC.3 | Non-continuous covering | | | | | | | | | | |
| | | | | I.3 | External | WC.3 | Non-continuous covering | | | | | | | | | | |
| F.2 | Double skin | AC.1 | Without air cavity | I.2 | Internal | WC.1 | Faced | | | | | | | | | | |
| | | | | | | WC.2 | Continuous covering | | | | | | | | | | |
| | | | | | | WC.3 | Non-continuous covering | | | | | | | | | | |
| | | AC.2 | With external ventilated air cavity | I.1 | Without insulation | WC.3 | Non-continuous covering | | | | | | | | | | |
| | | | | I.2 | Internal | WC.3 | Non-continuous covering | | | | | | | | | | |
| | | AC.3 | With internal ventilated air cavity | I.1 | Without insulation | WC.1 | Faced | 1,80 | 1,80 | 1,60 | 1,40 | 1,40 | 0,94 | 0,82 | 0,73 | 0,66 | 0,57 |
| | | | | | | WC.2 | Continuous covering | | | | | | | | | | |
| | | | | | | WC.3 | Non-continuous covering | | | | | | | | | | |
| | | | | I.2 | Internal | WC.1 | Faced | | | | | | | | | | |
| | | | | | | WC.2 | Continuous covering | | | | | | | | | | |
| | | | | | | WC.3 | Non-continuous covering | | | | | | | | | | |
| | | AC.4 | With non-ventilated air cavity | I.1 | Without insulation | WC.1 | Faced | | | | | | | | | | |
| | | | | | | WC.2 | Continuous covering | | | | | | | | | | |
| | | | | | | WC.3 | Non-continuous covering | | | | | | | | | | |
| | | | | I.2 | Internal | WC.1 | Faced | | | | | | | | | | |
| | | | | | | WC.2 | Continuous covering | | | | | | | | | | |
| | | | | | | WC.3 | Non-continuous covering | | | | | | | | | | |

Table 1. Classification of façades in existing residential buildings in Spain and maximum U-values for façades according to national regulations

### 2.2 Classification of anomalies that affect the façades of existing residential buildings

Literature reviews were carried out to characterize all the anomalies that may occur in any type of façade and deteriorate its conservation state, in Spanish residential buildings.

Concerning external wall covering systems, Gaspar and Brito (2005) defined different levels of anomalies that can affect cementitious mortar renders such as staining, cracking, presence of fungi, efflorescence, dampness, damaged material, infiltrations, spalling of the surface, corrosion, ruptures, loss of adhesion between layers and detachments. Flores-Colen et al. (2008) characterised eleven types of stains in rendered walls as efflorescence / cryptoflorescence, carbonation, uniform dirt / non-uniform dirt, "ghost-like stains", moisture, fungi/moulds, parasitic vegetation, corrosion, chromatic changes/ decolouration, graffiti and bird droppings. Silva et al. (2013) and Gaspar and Brito (2008) characterised anomalies that affect cement-rendered façades as staining, cracking and detachment. Neto and Brito (2011) classed anomalies in natural stone cladding into seven groups: four groups are related to anomalies in the cladding element (colour change, fracture and cracking, presence of biological or other elements and loss, volume change or deterioration of the stone); and three groups are related to elements of the cladding system (loss of adherence or loosening of the stone slab, joint anomalies and anomalies in the fixing elements). Pires et al. (2013) classified fourteen types of anomalies in painted rendered façades in five groups that distinguish between the various forms of pathological manifestation: adherence to the substrate anomalies, film cohesion anomalies, colour anomalies, stains and texture anomalies. Amaro et al. (2013) classified eighteen types of anomalies in External Thermal Insulation Composite Systems (ETICS) in three groups: materials rupture anomalies, colour/ aesthetic anomalies, and flatness anomalies. Along the same line, Silvestre and Brito (2009, 2011) classified anomalies that affect adherent ceramic tiling systems on façades into four groups, namely: detachment of the adherent ceramic tiling outer layer, cracking of the adherent ceramic tiling outer layer, deterioration of the tiles, and aesthetic anomalies.

In relation to anomalies that affect façades as a construction element, Monjo (1988) classified nine types of damage in a statistical study of the construction pathology of urban façades in Madrid: dampness, cracks, fissures, detachments, erosion, efflorescence, corrosion, dirtiness and biological organisms. Chew and Silva (2004) defined types of anomalies in US traditional façade systems as cracking, blistering, corrosion, peeling and flaking, chipping, spalling, discoloration, delamination, staining, biological growth, sealant/joint failure, efflorescence and dampness. Finally, Rodrigues et al. (2011) identified the main anomalies in façades as discolouring and detachment, cracks, efflorescence spots and dark spots, and dampness. Likewise, the UNE 41805-10 IN: 2009 (AENOR 2009) report defines three groups of pathological processes that can affect façades: physical processes (dampness, dirtiness and physical erosion), mechanical processes (cracks, fissures, detachment and mechanical erosion) and chemical processes (efflorescence, biological organisms, corrosion and chemical erosion).

Regarding classifications of anomalies in building elements, Monjo (2007) grouped construction failures that damage construction materials and building elements into three families:

physical (dampness, dirtiness and erosion), mechanical (deformation, rupture, detachment and erosion) and chemical (efflorescence, corrosion, biological organisms and erosion). Craig et al. (2010) organised snagging-related items in the private house building sector under the three headings of technical quality, aesthetic issues and omissions, but they did not identify the construction element to which the anomalies referred. Ahzahar et al. (2011) ranked a relative index for common types of building anomalies and failures in construction projects in Malaysia as blemishes, corrosion of reinforced steel, damage of the exterior surface, dampness, peeling paint, roof anomalies, cracking, spalling or chipping, foundation failure and structure instability.

The literature review did not reveal a unified classification system. Therefore, a system for classifying anomalies was developed and codified on the basis of the review. The initial proposal was comprised of a one-level category with nineteen anomalies that covered all of the defects found in the review. During the workshop, the initial anomaly classification was analysed, enhanced and validated by the same panel of experts, using the same methodology as that applied in the façade classification for existing residential buildings. The anomaly classification was developed taking into account the abovementioned premises: (1) comprehensiveness, (2) functionality, and (3) suitability.

In the workshop, experts considered two ways to minimize the number of categories required to search functionality, in accordance with Mills et al. (2009). The first concerned differences in the levels of detail of the anomalies, which can be either specific or generic. Experts suggested grouping specific anomalies that have analogous consequences on the level of degradation of façades. This solution affected the degradation of materials category, which included the initial categories of chemical, physical and mechanical erosion, biological organisms, efflorescence, dirtiness and staining. The second concerned the elimination of anomalies that had no influence on the level of degradation of façades, as they were purely aesthetic and did not reduce the quality of façade elements or materials. As a result, aesthetic anomalies, graffiti and discoloration or brittleness were removed as a category. Furthermore, in accordance with Macarulla et al. (2013), the experts agreed to include only singular words to standardize the vocabulary.

The resulting anomaly classification has eight categories: (1) adhesion failure, (2) cracking, (3) dampness, (4) deformation, (5) degradation of material, (6) detachment, (7) oxidation and corrosion, and (8) rupture. These categories cover potential damage that can affect the state of conservation of elements or materials in the façades of existing residential buildings. Table 2 presents the anomaly classification for closures in residential buildings and its definition.

| Category | | Definition |
|---|---|---|
| D.1 | Adhesion failure | Lack of junction between a material that mainly serves as a coating and its support, without detachment. |
| D.2 | Cracking | Longitudinal division that affects the surface of a construction element, and can be continuous, non-continuous or involves the total thickness of the element. |
| D.3 | Dampness | Presence of water in higher proportions than expected in a material or a building element. |
| D.4 | Deformation | Loss of the original shape of the element. |
| D.5 | Degradation of material | Reduction in the quality of an element, without affecting its functionality. This may occur as a result of staining, erosion, dirtiness, etc. and is due mainly to a lack of maintenance. |
| D.6 | Detachment | Lack of continuity of a coating on the wall, as a result of either constant degradation of a material or adhesion failure. |
| D.7 | Oxidation and corrosion | Chemical reaction generally produced in metals by the presence of oxygen. The reaction is usually increased by moisture. In corrosion, the material is gradually destroyed. |
| D.8 | Rupture | Absence of material that is not caused by continuous degradation, and appears in bulky items. |

Table 2. Classification of anomalies damaging façades in existing residential buildings in Spain

### 2.3 Determination of the relationship between façades and the anomalies that affect their state of conservation in existing residential buildings

The relationship between façades and the anomalies that affect, or can affect, each type of façade were analysed, to facilitate an accurate, systematic analysis of the energy impact of closures' state of conservation on building thermal performance.

A second workshop was held with the same panel of experts to discuss an initial proposal. The results showed that cracking, dampness, deformation, degradation of material, and oxidation and corrosion anomalies can affect all types of façades. Adhesion failure and detachment anomalies can damage types of façades with continuous and non-continuous external covering, but do not affect faced façades. Rupture can affect types of façades with non-continuous external covering and faced façades, but does not affect façades with external continuous covering. Table 3 shows the types of anomalies that affect, or have the potential to affect, the state of conservation of each type of façade.

| Façade classification for existing residential buildings [a] | | | | Anomaly classification for façades in existing residential buildings [b] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Number of skins** | **Air cavity** | **Insulation** | **External wall covering** | **D.1** | **D.2** | **D.3** | **D.4** | **D.5** | **D.6** | **D.7** | **D.8** |
| F.1 | AC.1 | I.1 | WC.1 | | x | x | x | x | | x | x |
| | | | WC.2 | x | x | x | x | x | x | x | |
| | | | WC.3 | x | x | x | x | x | x | x | x |
| | | I.3 | WC.2 | x | x | x | x | x | x | x | |
| | AC.2 | I.1 | WC.3 | x | x | x | x | x | x | x | x |
| | | I.3 | WC.3 | x | x | x | x | x | x | x | x |
| F.2 | AC.1 | I.2 | WC.1 | | x | x | x | x | | x | x |
| | | | WC.2 | x | x | x | x | x | x | x | |
| | | | WC.3 | x | x | x | x | x | x | x | x |
| | AC.2 | I.1 | WC.3 | x | x | x | x | x | x | x | x |
| | | I.2 | WC.3 | x | x | x | x | x | x | x | x |
| | AC.3 | I.1 | WC.1 | | x | x | x | x | | x | x |
| | | | WC.2 | x | x | x | x | x | x | x | |
| | | | WC.3 | x | x | x | x | x | x | x | x |
| | | I.2 | WC.1 | | x | x | x | x | | x | x |
| | | | WC.2 | x | x | x | x | x | x | x | |
| | | | WC.3 | x | x | x | x | x | x | x | x |
| | AC.4 | I.1 | WC.1 | | x | x | x | x | | x | x |
| | | | WC.2 | x | x | x | x | x | x | x | |
| | | | WC.3 | x | x | x | x | x | x | x | x |
| | | I.2 | WC.1 | | x | x | x | x | | x | x |
| | | | WC.2 | x | x | x | x | x | x | x | |
| | | | WC.3 | x | x | x | x | x | x | x | x |

[a] Façade codes can be found in Table 1.
[b] Codification of anomalies for façades obtained from Table 2.

Table 3. Relationship between façades and anomalies that affect their state of conservation

## 3. Case study and discussion

A case study was performed to verify the aforementioned associations between types of façades and their anomalies.

As in Mills et al. (2009) and Macarulla et al. (2013), data were obtained from an organisation's database. In this case, the database contained a collection of technical reports generated by the UPC's Building Laboratory. The reports give textual descriptions of damage affecting buildings and a set of pictures illustrating the anomalies (Fig. 2). The case study included 154 public housing buildings located in Barcelona and erected between 1800 and 2005 (Table 4). Residential buildings erected after 2006 were not inspected, since they are relatively new and should not have any anomalies resulting from the passage of time. The buildings were grouped by year of construction (built before and after 1980). Residential buildings that were built before 1980 in Spain did not have to comply with any thermal requirements, and therefore most buildings from this period do not have any insulation. Residential buildings built between 1980 and 2006 fall under the thermal requirements established by NBE CT 79. The use of cavity walls with thermal insulation in the cavity was very common in this period. Façades are usually rendered and painted. Table 1 shows typical *U-values* for these buildings (Gangolells and Casals 2012). New residential buildings added to building stock between 2007 and 2010 were built under the new thermal requirements established by the TBC (Table 1). Construction techniques and systems used during the previous period are still very common. However, a thicker insulation layer and higher performance insulation materials are used to meet the higher requirements (Gangolells and Casals 2012). Table 4 describes the main characteristics of the analysed buildings.

A total of 216 types of façades were identified in the 154 public housing buildings, as some buildings were found to have more than one type of façade. The types of façades in residential buildings were identified through visual inspection and knowledge of traditional building techniques used in the construction period (City Council of Barcelona 2002). The sample of buildings analysed included all the types of façades that had been identified in the section "Classification of façades in existing residential buildings". Single-skin façades without an air cavity and with external insulation and continuous covering (code F.1-AC.1-I.3-WC.2), and single-skin façades with an external ventilated air cavity, external insulation and non-continuous covering (code F.1-AC.2-I.3-WC.3) were types of façades that resulted from the refurbishment of buildings' envelopes. By the end of the case study, all of the analysed façades had been classified.

| **Year of construction** | **Number of buildings** | **Number of dwellings** | **Floor area (m²)** [a] | **Number of storeys above ground** |
|---|---|---|---|---|
| < 1980 | 73 | 608 | 94,206.00 | From 3 to 7 |
| From 1980 to 2005 | 81 | 818 | 89,728.00 | From 4 to 7 |
| Total | 154 | 1,426 | 183,934.00 | - |

[a] Data obtained from the Spanish Cadastral Electronic Site (Spanish Ministry of Finances and Public Administration 2009).

Table 4. Characteristics of the Case Study

| Identification of facade | | |
|---|---|---|
|  | Location: | Main facade, Side facade1 and Side facade 2 |
| | Description: | External wall covering |
| | Typology: | Continuous |
| | Material: | Stucco |

**Identification of anomalies**

| | ELEMENT | State | T / Es P | T / Es L | T / Es G | F P | F L | F G | DM P | DM L | DM G | O P | O L | O G | B P | B L | B G |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COVERING SYSTEM | Non-continuous covering | 1 | | | | | | | | | | | | | | | |
| | Mortar render | X | | | | 3 | | | | | | | | | | | |
| | Faced | | | | | | | | | | | | | | | | |
| | Single layer coating | | | | | | | | | | | | | | | | |
| | Painted surface | X | 2 | | | | | | 2 | | | | | | | | |
| | Other: | | | | | | | | | | | | | | | | |

| Description of anomalies | | |
|---|---|---|
|  | Photographic reference: | _01 |
| | Location: | Main facade |
| | Element: | Mortar render |
| | Defect: | Detachment |
| | Magnitude: | Isolated |
| | Intervention: | 2 |

Fig. 2. Samples of technical reports provided for the case study (photographs by the UPC's building laboratory)

Once all of the façades had been classified, the anomalies were mapped using the data and pictures contained in the technical reports on the analysed buildings. As façades may have more than one type of anomaly, a total of 262 types of anomalies that damage the opaque part of façades were found. A total of 121 façades were found to be affected by degradation of materials (352 cases were found), 49 façades were affected by cracking (found in 582 cases), and 33 façades were affected by detachment (245 cases found). A total of 79 occurrences of oxidation and corrosion were found in 27 façades, and 59 cases of rupture were found in 11 façades. Adhesion failure was found in 71 cases distributed in 11 façades, 8 façades were affected by dampness (found in 18 cases) and 2 façades were affected by deformation (a total of 2 cases were found). Sixty façades had no anomalies related to the object of the study, which does not mean they do not have anomalies in other parts of the façade, such as balconies or windows. All the types of anomalies included in the section "Classification of anomalies that affect the façades of existing residential buildings" were found in the sample. Similarly, all the anomalies that affected closures in the sample of façades could be explained within the established classification. Thus, possible relationships between types of façades and the types of anomalies that can damage them were verified. Table 5 shows the number of façades of each type covered by the case study, the number of façades affected by each type of anomalies, and the number of façades that were not affected by any anomalies. A lack of relationship between types of façade and types of anomalies is marked with a cross.

| **Façade classification for existing residential buildings [a]** | | | | **Number of façades** | **Anomaly classification for façades in existing residential buildings [b]** | | | | | | | | **Number of façades without anomalies** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Number of skins** | **Air cavity** | **Insulation** | **External wall covering** | | **D.1** | **D.2** | **D.3** | **D.4** | **D.5** | **D.6** | **D.7** | **D.8** | |
| F.1 | AC.1 | I.1 | WC.1 | 2 | x | 0 | 0 | 0 | 2 | x | 1 | 0 | 0 |
| | | | WC.2 | 35 | 5 | 14 | 2 | 2 | 15 | 15 | 14 | x | 9 |
| | | | WC.3 | 2 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| | | I.3 | WC.2 | 3 | 0 | 2 | 0 | 0 | 3 | 1 | 0 | x | 0 |
| | AC.2 | I.1 | WC.3 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| | | I.3 | WC.3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| F.2 | AC.1 | I.2 | WC.1 | 20 | x | 3 | 2 | 0 | 5 | x | 0 | 2 | 12 |
| | | | WC.2 | 40 | 0 | 5 | 2 | 0 | 39 | 0 | 0 | x | 1 |
| | | | WC.3 | 7 | 1 | 1 | 0 | 0 | 7 | 0 | 0 | 0 | 0 |
| | AC.2 | I.1 | WC.3 | 2 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 |
| | | I.2 | WC.3 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| | AC.3 | I.1 | WC.1 | 2 | x | 0 | 0 | 0 | 1 | x | 0 | 0 | 1 |
| | | | WC.2 | 9 | 1 | 1 | 0 | 0 | 7 | 1 | 1 | x | 0 |
| | | | WC.3 | 7 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 5 | 0 |
| | | I.2 | WC.1 | 2 | x | 1 | 0 | 0 | 0 | x | 1 | 0 | 1 |
| | | | WC.2 | 7 | 0 | 4 | 0 | 0 | 4 | 1 | 0 | x | 2 |
| | | | WC.3 | 6 | 1 | 0 | 0 | 0 | 2 | 0 | 1 | 2 | 2 |
| | AC.4 | I.1 | WC.1 | 9 | x | 0 | 0 | 0 | 2 | x | 0 | 0 | 7 |
| | | | WC.2 | 19 | 3 | 7 | 1 | 0 | 12 | 8 | 1 | x | 2 |
| | | | WC.3 | 3 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 2 |
| | | I.2 | WC.1 | 11 | x | 0 | 0 | 0 | 1 | x | 0 | 0 | 10 |
| | | | WC.2 | 23 | 0 | 6 | 1 | 0 | 11 | 4 | 8 | x | 9 |
| | | | WC.3 | 4 | 0 | 1 | 0 | 0 | 2 | 1 | 0 | 1 | 0 |

Note: Anomalies refer only to the opaque part of façades. x = lack of relationship between type of façade and type of anomaly.
[a] Façade codes can be found in Table 1.
[b] Codification of anomalies for façades can be found in Table 2.

Table 5. Number of façades affected by types of anomalies

Within the sample, all types of closures were found to be affected by anomalies that had an impact on their state of conservation, except single-skin façades with an external ventilated air cavity, external insulation and non-continuous covering (code F.1-AC.2-I.3-WC.3). This type of façade was not affected by any anomaly, but the sample only included one recently refurbished façade, according to the pictures included in the technical report. During the mapping, all the existing relationships were verified for the type of single-skin façade without an air cavity or insulation, finished with continuous covering (code F.1-AC.1-I.1-WC.2).

Since coatings are the outermost part of façades and are thus very susceptible to damage, anomalies affecting closures were analysed by external coating type. It was observed that the three types of external wall covering were affected by all the types of anomalies established in the section "Classification of anomalies that affect the façades of existing residential buildings", except deformations (D.4), which were only observed in façades finished with continuous covering.

Deformations were the least frequent anomaly. This may be due to the fact that they are generated not only by the effects of the environment and lack of maintenance, but also by other situations involving risk, for instance, problems with material behaviour, movements of the building or structural issues.

## 4. Conclusions

In this study, a classification system for façades and the anomalies that affect the envelope's conservation status in existing Spanish residential buildings was developed for the first time. The findings will be a starting point for a future analysis on the gap between the predicted and actual energy performance of existing residential buildings due to façade conservation status.

The façade classification for existing residential buildings was based on the opaque part of closures and organised into four levels: number of skins, existence of an air cavity, existence of insulation and type of external wall covering. The research covered original buildings in the Spanish area and did not take into account any measures to upgrade the façades. Twenty-three types of façades were identified, depending on the type of material and thickness of the different layers comprising the building closures. The anomaly classification had eight categories: adhesion failure, cracking, dampness, deformation, degradation of material, detachment, oxidation and corrosion, and rupture. During a workshop with a panel of experts, both classifications were found to be comprehensive, functional and suitable.

To determine the types of anomalies that affect, or have the potential to affect, the state of conservation of each type of façade, a relationship between the classifications was established. This relationship was validated by the same panel of experts in a second workshop.

The classification system can be applied to most Spanish buildings. The comprehensiveness of the classification system was demonstrated with a case study, using real data on 154 public housing buildings. All the closures in the sample of buildings were covered by the classification system, and all the façades in the classification system were found in the sample of buildings. Furthermore, all the anomalies affecting façades in the sample of buildings were found in the classification system, and all the types of anomalies established in the classification system were identified in the sample of façades.

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## 4.2 Journal paper II. 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]:

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

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 [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:

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

where $d$ is the thickness of the layer in the element, and $\lambda$ 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/m²).
- 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:

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

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 ($\sigma U$) is obtained according to the following expression:

$$\sigma U^2 = \left(\frac{\delta U}{\delta q}\right)^2 \cdot \sigma q^2 + \left(\frac{\delta U}{\delta T_i}\right)^2 \cdot \sigma T_i^2 + \left(\frac{\delta U}{\delta T_e}\right)^2 \cdot \sigma T_e^2 = = \left(\frac{1}{T_i - T_e}\right)^2 \cdot \sigma q^2 + \left(\frac{-q}{(T_i-T_e)^2}\right)^2 \cdot \sigma T_i^2 + \left(\frac{q}{(T_i-T_e)^2}\right)^2 \cdot \sigma {T_e}^2 \quad (4)$$

where $\sigma q$ is the uncertainty associated with the heat flow rate measuring equipment, $\sigma T_i$ is the uncertainty associated with the environmental indoor temperature measuring equipment, and $\sigma T_e$ 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:

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

where $T_{Ii}$ and $T_{Ei}$ are the indoor and outdoor ambient temperatures taken at 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 $\tau_n$. The coefficients $\beta_n$ are exponential functions of the time constant $\tau_n$, where $\beta_n = \exp\left(-\frac{\Delta t}{\tau_n}\right)$, and the time constants $\tau_n$ 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:

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

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. 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.

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

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 $\tau_1$ 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 ($\tau_1$) 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]:

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

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.

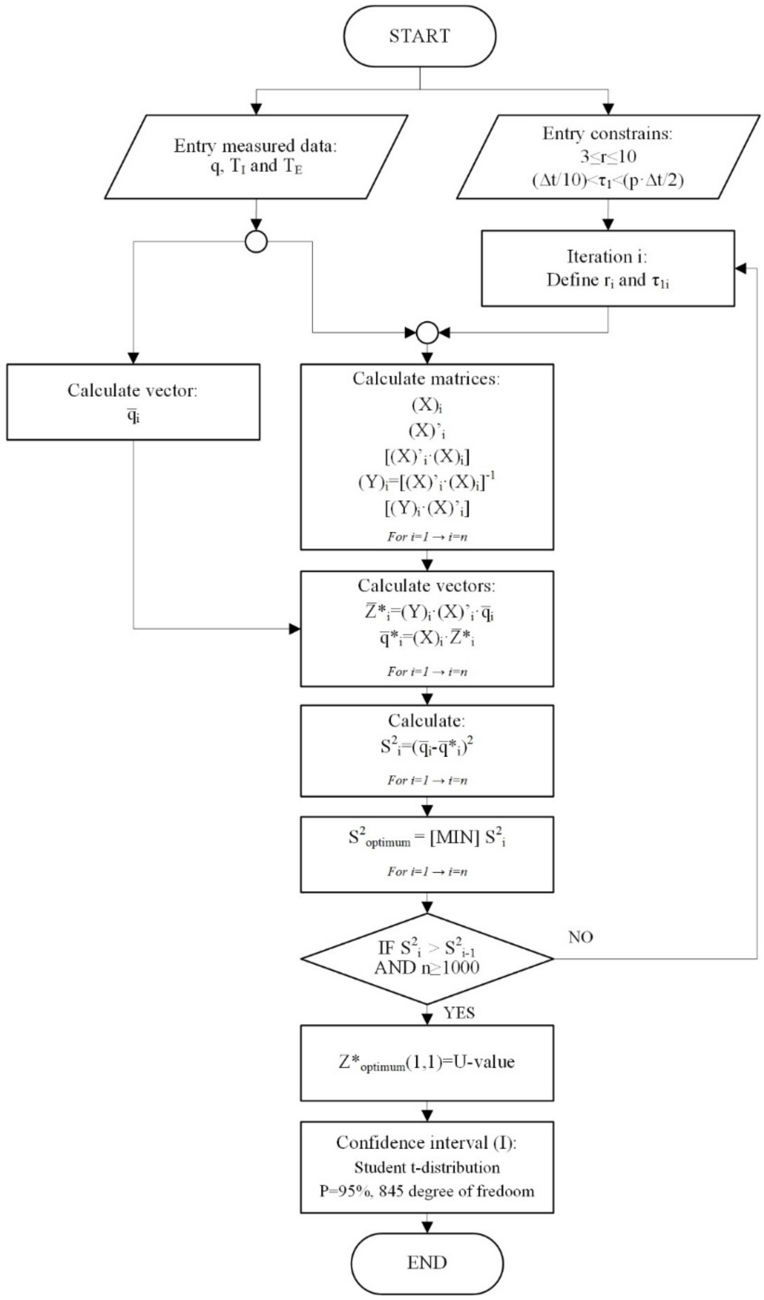


Figure 1. Flowchart of the programmed spreadsheet of the dynamic method, based on least squares adjustment

### 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:

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

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

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

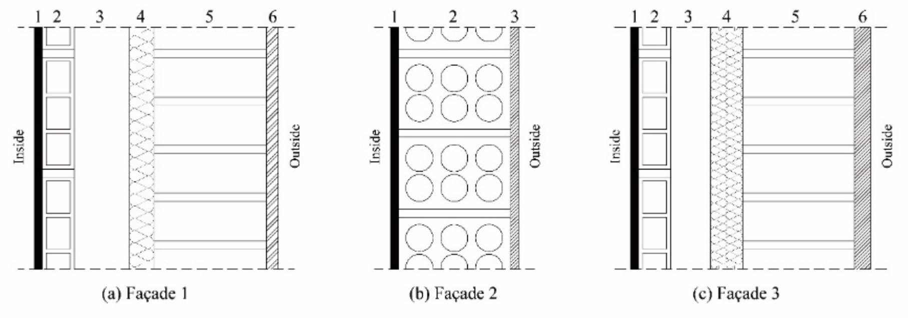


Figure 2. Schematic sections of the façades

| 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.

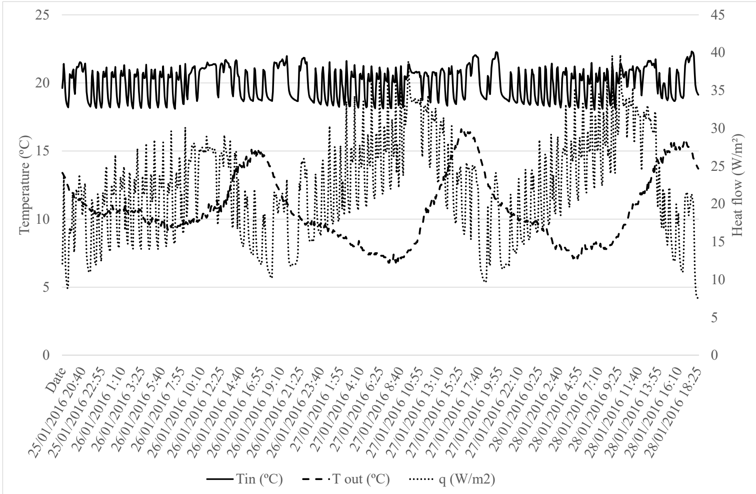


Figure 3. Data obtained from the process of monitoring Façade 2 for the period 25–28 January 2016

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 method 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)** | **$U_{M-Av}±σ_{95\%}$ (W/m²·K)** | **$U_{M-Dyn}±I_{95\%}$ (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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## 4.3 Journal paper III. In situ measurement of façades with a low U-value: avoiding deviations

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**Abstract**

In situ measurements of low thermal transmittance façades are required to ensure compliance with energy performance strategies for new nearly zero-energy buildings (nZEB) and with energy policies for the transition of existing building stock to nZEB. The aim of this paper was to enhance the accuracy of the in situ measurement of low U-value façades, employing the widely used ISO 9869-1:2014 HFM method and exploring the limits of its conditions. To refine the testing conditions, three variables were analysed and compared with indications of ISO 9869-1:2014 and the existing literature: the temperature difference, the test duration and the accuracy of equipment. A continuous experimental campaign was conducted in a building mock-up. The findings showed that to accurately measure in situ low U-value façades, the temperature differences must be greater than those indicated in the existing literature. Temperature differences above 19ºC required a test duration of 72 hours, while for lower temperature differences the test duration must be prolonged. The accuracy of temperature sensors had a greater impact on the accuracy of measurement in the initial cycles of the test. Likewise, the accuracy of ambient temperature sensors was found to have a considerable influence on the uncertainty of measurements.

**Keywords:** low thermal transmittance, in situ measurements, HFM method, temperature difference, test duration, equipment accuracy

## 1. Introduction

To meet the 2020 energy targets, the Directive on the energy performance of buildings establishes that all new buildings must be nearly zero-energy by 31 December 2020. New buildings that are publicly occupied or owned must be nearly zero-energy by 31 December 2018 [1]. The definition of nearly zero-energy buildings has been widely studied [2–6]. Most EU member states use a primary energy use indicator in kWh/(m²·y), but other parameters are also employed, such as net and final energy for heating and cooling, $CO_2$ emissions and the U-values of building envelope components [7].

Existing approaches in literature reviews on nearly zero-energy building technologies can be summarized in three categories: passive energy-saving technologies, energy-efficient building service systems, and renewable energy production technologies [8]. Focusing on passive energy saving technologies, Friess and Rakhshan [9], Omrany et al. [10] and Sadineni et al. [11] reviewed various advanced wall technologies to improve the energy efficiency and comfort levels in buildings. According to Sadineni et al. [11], the improvement of building envelopes primarily relies on reducing thermal transmittances, combined with passive heating or cooling [8].

Currently, there is great concern about the role of building envelopes in defining strategies for new nearly zero-energy buildings. There are numerous strategies available to design and construct building façades for low-energy or nearly zero-energy buildings. Several authors [12–19] have studied the optimization of building envelope design for nearly zero-energy buildings through models and simulations in different climate zones. Ascione et al. [12] focused on the optimization of the building envelope design for nearly zero-energy buildings in the Mediterranean climate through energy simulations. Berry and Davidson [13] explored the economic feasibility of the net zero-energy building policy in warm temperate climates based on energy monitoring evidence and construction economics. In order to achieve the NZEB goal, Buonomano et al. [14] developed a computer model for predicting the energy demand of buildings integrating new technologies such as phase change materials, photovoltaic-thermal collectors, adjacent sunspaces and innovative daylighting control. Charisi [15] conducted a study focusing on the potential reduction of energy demands in typical Greek residential building. The researcher modelled the effect of insulation, openings and shading devices of building envelopes on the energy demand. The model was examined in four climate zones using dynamic simulation software tools. In order to achieve nearly-zero energy buildings in the climate conditions of Cyprus, Loukaidou et al. [16] conducted a cost-optimal analysis of thermal features of the building envelope, including thermal insulation on wall, roof and ground floor and optimal window properties. Micono and Zanzottera [17] checked the results of the simulation of an office building in Northern Italy taking into consideration variations occurred during the construction phase to guarantee the energy performances forecasted. Moran et al. [18] conducted a study to determine the optimal strategy to design a nearly zero-energy building in a temperate oceanic climate, such as Ireland. Eight different versions of a modelled semi-detached house were investigated with two different building fabrics, airtightness and ventilation strategies employed. The analysis was focused on the life cycle cost and environmental analysis of nearly zero-energy buildings using various heat sources. To optimality design of eleven nearly zero-energy new buildings types in cold climate conditions, Zakis et al. [19] coupled evolutionary algorithms with a building dynamic simulation engine. The multi-objective computer model took into account life cycle cost and performance modulation.

Energy renovation measures for existing building stock to bring it up to the nearly zero-energy building level were also analysed by several authors [20–26] through energy simulation tools. Albadry at al. [20] proposed a validated guideline to achieve net zero-energy buildings through retrofitting existing residential buildings using photovoltaic panels in Egypt. Brandão De Vasconcelos et al. [21] identified cost-optimal packages of energy efficient solutions from among a set of possible refurbishment measures taking into consideration different discount rates and building orientations. The research was applied to a Portuguese reference building. Corrado et al. [22] showed the approach and the methodology adopted in the European Project, RePublic_ZEB, for the assessment of retrofit measures suitable to reach nearly zero-energy buildings. In order to reach the nearly zero-energy target for buildings that represent the national residential building stock in Italy, Corrado et al. [23] identified packages of energy efficiency measures to apply. Ferreira et al. [24] compared cost-optimal renovation packages with nearly zero-energy building levels of energy performance in building renovation of modelled representative buildings of Portuguese residential building stock. Based on site surveys and expert interviews, Hou et al. [25] conducted a comparative analysis on incentive policies to implement commercial building energy efficiency retrofit programs in China. Kuusk et al. [26] discussed energy renovation scenarios from major renovation to nearly zero-energy building level for apartment buildings in a cold climate (Estonia).

Due to deviations between predicted and actual energy consumption in nearly zero-energy buildings, energy performance strategies for both new and existing buildings need to be checked. Some authors [27–32] have modelled differences between forecasted and actual energy consumption. Ascione et al. [27] created a numerical model to investigate deviations between the expected and the measured electric usage in the areas of heating and domestic hot water, ventilation, lighting, equipment and auxiliaries, yield of the photovoltaic system. The modelled building was a two-storey NZEB situated in Berlin. Kampelis et al. [28] investigated the operational performance of industrial, residential and research/educational buildings with the use of simulation tools. Researchers evaluated the significance for smart near-zero energy buildings energy efficient technologies, renewable energy technologies, storage and smart monitoring and controls. In order to determine if building designs reach target energy efficiency improvements, Kneifel and Webb [29] developed a statistically derived regression model to predict energy performance of a net-zero energy building. Ulpiani et al. [30] conducted an experimental study focused on the energy benefits achieved by coupling an energy efficient building with a sunspace in winter season and Mediterranean climate. The monitoring phase was used to calibrate the simulation model and provide on-site validated data for subsequent assessments and comparisons. Zavrl and Stegnar [31] investigated the calculated and metered energy use of monitored apartments in a highly energy efficient apartment building Eco Silver House committed to meet the national nearly zero energy buildings requirements. Zhou et al. [32] investigated the operational performance of an occupied net zero energy office building in Tianjin, China, during a year. Results showed that energy consumption of the case building was much higher than the energy generated from the solar photovoltaic system selected according to the simulated energy consumption of the building at design phase. The researchers highlighted that during the design process of net zero energy buildings, it was imperative to ensure that the energy simulation accurately reflects how the building will actually operate once occupied.

Deviations between a building's overall energy efficiency target and its actual operating performance are associated with factors in the design and construction of the building envelope and systems or in the management procedures affecting the operational phase of the building [28]. Therefore, in situ measurements are needed to assess the actual performance of building envelopes and ensure that they reach the nearly zero-energy building level. In 1994, the International Organization for Standardization published the first edition of the standard for in situ measurement of the thermal resistance and thermal transmittance, ISO 9869:1994, by the Technical Committee ISO/TC 163/SC 1 *Test and measurement methods*. This standard was revised and replaced by a new version in 2014 [33].

The literature review revealed that only a few researchers [34–39] have measured in situ the actual thermal transmittance of façades with low U-values. As shown in Table 1, these researchers encountered difficulties in the measurements, as they frequently obtained high deviations from theoretical U-values. Albatici et al. [34] validated quantitative infrared thermography for the evaluation of building thermal transmittance by assessing two walls with low U-values (0.17 $W/m^2{\cdot}K$ and 0.18 $W/m^2{\cdot}K$), using the standardized average calculation method [33] to obtain the HFM measured U-value. Asdrubali et al. [35] presented the results of in situ thermal transmittance measurements performed on six energy efficient buildings funded by the Umbria Region in Italy. The buildings were constructed between 2007 and 2008, and their calculated thermal transmittance using the standardized average calculation method [33] ranged from 0.23 $W/m^2{\cdot}K$ to 0.33 $W/m^2{\cdot}K$. For the energy performance analysis of two houses, Bros-Williamson et al. [36] monitored over two periods the corresponding façades, which had theoretical U-values of 0.10 $W/m^2{\cdot}K$ and 0.23 $W/m^2{\cdot}K$. In a study about the thermal behaviour of a building envelope with varying insulation conducted by Mandilaras et al. [37], the authors analysed performance with a vacuum insulation panel and compared it with a theoretical estimation of R-value of 4.98 $m^2{\cdot}K/W$, which is equal to thermal transmittance of 0.20 $W/m^2{\cdot}K$. The experimental determination of R-value was calculated using the dynamic method of ISO 9869:1994 [33]. In a comparison of experimental measurements of thermal transmittance using infrared technology, the heat flow meter method and the calculated U-value [40], Nardi el al. [38] analysed a wall with a theoretical U-value of 0.23 $W/m^2{\cdot}K$. Authors used the standardized average calculation method [33] to obtain the measured U-value. Finally, Samardzioska and Apostolska [39] conducted a study on façades with a new construction system. The thermal transmittance of the wall with the new construction system was 0.22 $W/m^2{\cdot}K$, according to calculations using analytical software. Authors performed measurements on the walls of three buildings whose façades had been constructed using the new system. To obtain the calculated thermal transmittances, they used the standardized average calculation method [33], but excluded results obtained on one day on the first and third building.

Absolute values of relative differences between the design and measured thermal transmittance obtained by the existing literature approaches are summarized in Table 1.

| Authors in the literature review | Design thermal transmittance (W/m²·K) | HFM-measured thermal transmittance (W/m²·K) | Absolute value of relative deviation (%) |
|---|---|---|---|
| Albatici et al. [34] | 0.17 | 0.18 | 6% |
| | 0.18 | 0.18 | 1% |
| Asdrubali et al. [35] | 0.23 | 0.22 | 4% |
| | 0.25 | 0.34 | 36% |
| | 0.27 | 0.34 | 26% |
| | 0.30 | 0.37 | 23% |
| | 0.32 | 0.56 | 75% |
| | 0.33 | 0.39 | 18% |
| Bros-Williamson et al. [36] | 0.10 | 0.12 | 20% |
| | 0.10 | 0.11 | 10% |
| | 0.23 | 0.26 | 13% |
| | 0.23 | 0.38 | 65% |
| Mandilaras et al. [37] | 0.20 | 0.26 | 28% |
| Nardi el al. [38] | 0.23 | 0.42 | 83% |
| Samardzioska and Apostolska [39] | 0.22 | 0.23 | 3% |
| | 0.22 | 0.35 | 59% |
| | 0.22 | 0.23 | 4% |

Table 1. Calculated and measured low thermal transmittance walls in a literature review

In addition, and as shown in the literature review, due to Directive 2010/31/EC targets [1] the actual energy performance of building envelopes with low U-values must be checked to ensure compliance with policies to transition the existing building stock to nearly zero-energy buildings, and to confirm energy performance strategies for new nearly zero-energy buildings. As shown in the literature review, the in situ measurement of low thermal transmittance façades is a challenging task.

Standard ISO 9869-1:2014 [33] is used extensively for the in situ measurement of thermal transmittance. Although this standard describes the apparatus to be used, the calibration procedure for the apparatus, the installation and measurement procedures, and the analysis of the data, some testing parameters for the measurement process are not fully specified. Standard ISO 9869-1:2014 does not establish any minimum value of temperature difference between the indoor and outdoor environment to obtain accurate measurements. In the literature review, authors such as Asdrubali et al. [35], Desogus et al. [41] and Li et al. [42] found that when the temperature difference between the indoor and outdoor ambient was above 10ºC and the temperature of the internal surface was kept as constant as possible, the measurement uncertainty was reduced. Tadeu et al. [43] emphasized that a temperature difference between the indoor and outdoor environment of less than 10ºC may not be enough to obtain accurate measurements. Nevertheless, the temperature difference between the indoor and outdoor environment for measuring façades with low thermal transmittance has not been analysed in depth. Standard ISO

9869-1:2014 establishes a minimum test duration of 72 hours when the temperature is stable around the heat flux meter plate, regardless of the magnitude of the thermal transmittance of façades. However, the actual duration depends on the values obtained during the course of the test. The 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. 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. The last condition is that the U-value obtained by analysing data from the first time period over $INT(2 \cdot D_T/3)$ days must not deviate more than 5% from the value obtained from the data for the last period of the same duration, where $D_T$ is the test duration in days and *INT* is the integer part. No studies in the existing literature provide guidance on the duration of tests on façades with low thermal transmittance. In addition, standard ISO 9869-1:2014 describes several factors that can affect the accuracy of the measurement: the accuracy of the calibration of the HFM and the temperature sensors, the accuracy of the data logging system, random variations caused by slight differences in the thermal contact between the sensors and the surface, operational error of the HFM due to modifications of the isotherms caused by the presence of the HFM, errors caused by variations over time of the temperature and heat flow, temperature variations within the space, and differences between air and radiant temperatures. When the above factors are taken into consideration, the total uncertainty that can be expected is between 14% and 28%. To assess the influence of equipment accuracy on the accuracy of results, Ficco et al. [44] evaluated metrological performance by focusing on heat flux meter sensors with the same expected accuracy, without analysing the impact of the temperature sensors. They found that the shape and dimensions of HFM do not seem to affect the measurements significantly.

In this context, the aim of this study was to improve the accuracy of the in situ measurement of façades with low thermal transmittance using the ISO 9869-1:2014 standardised heat flow meter method, through exploration of the boundaries of the requirements for using the method. To refine the testing conditions of the method in low U-value façades, three variables were analysed: the temperature difference, the test duration and the accuracy of equipment. The results obtained were contrasted with standard ISO 9869-1:2014 and indications from the literature review. To perform this analysis, authors conducted a continuous experimental campaign in a façade constructed with a new system that has a low U-value.

This research will contribute to the verification of compliance with energy performance policies in façades retrofitted to attain nearly zero-energy buildings and corroborate the energy performance of façade strategies for nearly zero-energy buildings.

The paper is organized as follows. After the introduction, the second section specifies the method used in the research and describes the experimental mock-up, the third section discusses the results, the fourth section discusses the impact of findings on standard ISO 9869-1:2014, and the fifth section presents conclusions.

## 2. Method

A five-step method was devised to determine the test condition limits that would enhance the accuracy of in situ measurement of low thermal transmittance façades using the HFM method, which is used to verify the actual energy performance of new or refurbished building façades (Fig. 1):

- First, a building mock-up was constructed with panels designed to be incorporated in nearly zero-energy buildings.
- Second, the façade's U-value was measured in situ, taking into consideration guidelines associated with equipment and environmental conditions, according to ISO 9869-1:2014. Data were analysed in periods of complete days, using the average method.
- Third, test conditions were evaluated through three variables: the temperature difference, the test duration and the accuracy related to equipment.
- Fourth, the impact of the three variables on the accuracy of results were presented and discussed.
- Fifth, findings obtained during the analysis of the impact of the three variables on the accuracy of results were compared with the indications of standard ISO 9869-1:2014 and the literature review.

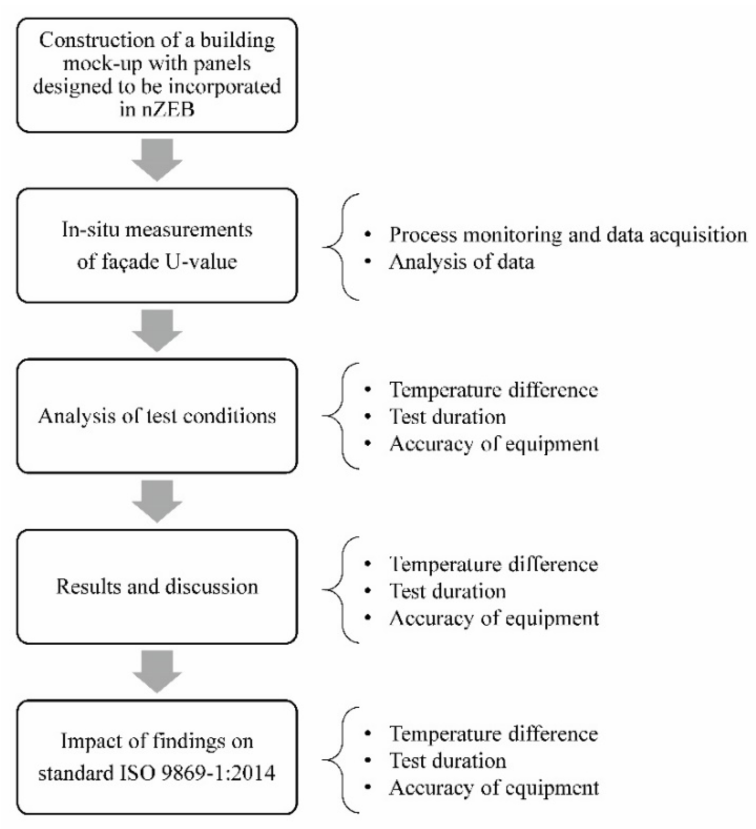



Fig 1. Research methodology

### 2.1. Construction of a building mock-up with panels designed to be incorporated in nZEB

A building mock-up with an area of 12 m² was constructed to investigate the limits of application of the HFM method for the in situ measurement of low thermal transmittance façades, to verify the actual energy performance of new or refurbished building façades. The façade construction system was based on prefabricated panels, which have structural and insulation functions and incorporate installations and finishes. The panel was monitored in a building mock-up, equipped with a heating system to adjust environmental indoor temperature conditions (Fig. 2). The experimental campaign was performed continuously under real weather conditions from December 2016 to April 2017, covering a range of average temperature differences from 11ºC to 21ºC.

Fig. 2. Building mock-up

The panel consisted of a four-layer wall incorporating a galvanized steel structure. Its total thickness was 0.30 m. Table 2 summarizes the specific heat capacity per unit area of each layer, the total specific heat capacity per unit area of the panel, and the theoretical U-value of the panel. From inside to outside, it was composed of a 0.015 m layer of gypsum plaster (A), a 0.07 m layer of lightweight concrete (B), a 0.06 m non-ventilated air cavity (C), a 0.08 m layer of thermal insulation consisting of polyisocyanurate (PIR) (D), a 0.06 m layer of lightweight concrete (E), and a 0.015 m layer of mortar plaster (F). The monitored panel does not have openings. A scheme of the monitored panel is shown in Fig. 4 and a detailed view of section A-A' is shown in Fig. 3.

| Wall | Material layer (inside-outside) | Thickness (m) | Specific heat capacity per unit area (KJ/m²·K) | Total specific heat capacity per unit area (KJ/m²·K) | Theoretical U-value (W/m²·K) |
|---|---|---|---|---|---|
| Prefabricated panel | Mortar plaster | 0.015 | 30.0 | 243.8 | 0.27 |
| | Lightweight concrete | 0.060 | 85.8 | | |
| | PIR polyisocyanurate insulation | 0.080 | 8.4 | | |
| | Non ventilated air cavity | 0.060 | 0.0 | | |
| | Lightweight concrete | 0.070 | 100.1 | | |
| | Gypsum plaster | 0.015 | 19.5 | | |

Table 2. Properties of the prefabricated panel

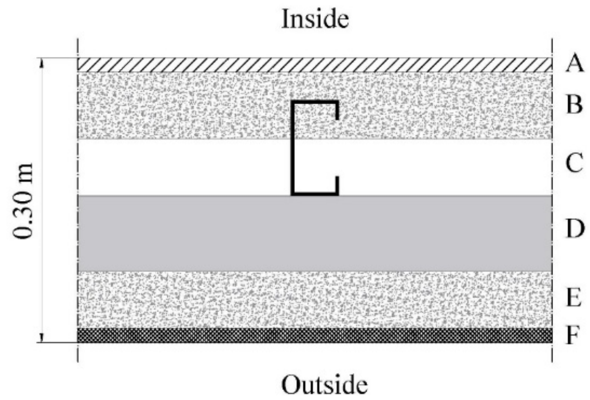



Fig. 3. Schematic section of the prefabricated panel

## 2.2. In situ measurement of the façade's U-value

### *2.2.1. Process monitoring and data acquisition*

The instrumentation was carefully selected to obtain the actual thermal transmittance in the building mock-up. The main specifications and a priori accuracy of the calibrated 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 certified sensitivity of 61.68 µV/(W/m2).
- The inside air temperature sensor (107, Campbell Scientific, Inc.) consists of a thermistor encapsulated in epoxy-filled aluminium housing. It has a resolution of 0.1ºC, accuracy of ±0.5°C and a temperature measurement range from -35° to +50°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 voltage 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 and its acquisition system (175T1, Instrumentos Testo, SA). It has a resolution of 0.1ºC, accuracy of ±0.5°C and a temperature measurement range from -35° to +55°C.

The location of sensors was investigated by thermography with an infrared thermographic camera (FLIR E60bx Infrared Camera), as recommended by Ahmad et al. [45], Asdrubali et al. [35], Evangelisti et al. [46], ISO [33], and Tejedor et al. [47]. Sensors were placed in a representative part of the panels, avoiding corners, the vicinity of junctions, direct solar radiation and the direct influence of a heating or cooling device [48] (Fig. 4). The heat flux meter plates were installed on the internal side of the panels, taking into consideration that the inner temperature was the most stable before and during the test. To assure proper thermal contact between the entire area of each sensor and the corresponding panel surfaces, a thin layer of thermal interface material was carefully applied. Indoor temperature was kept constant by a heating system, and was always higher than outdoor temperature. Weather conditions were observed during the testing process (Fig. 5). Dataloggers were configured to sample data every 1 second and store the 30-minute averaged data in their memories.

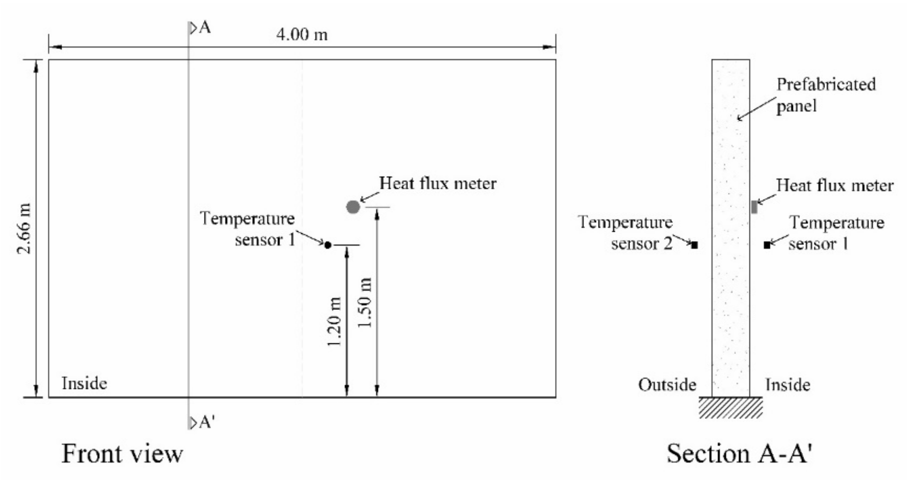
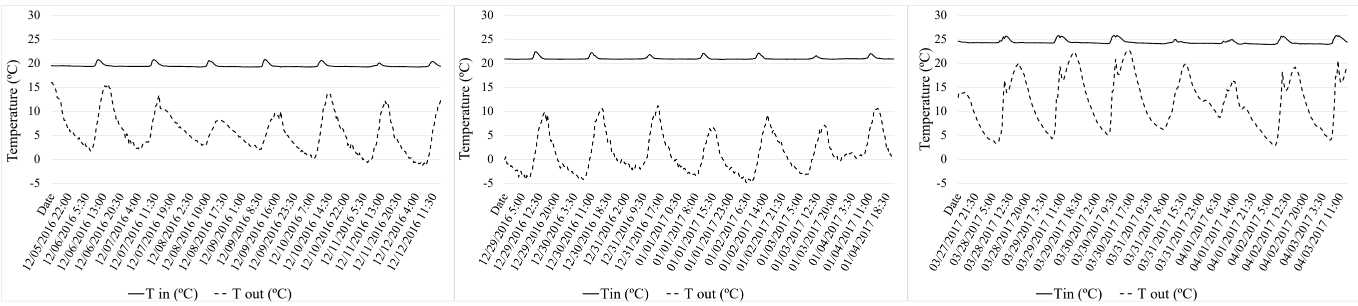



Fig. 4. Scheme of the monitored panel




**a)** **b)** **c)**

Fig. 5. Temperature data obtained from the process of monitoring for the periods a) 05-12 December 2016, b) 29 December 2016 – 04 January 2017, and c) 27 March – 03 April 2017

### *2.2.2. Analysis of data*

Data were analysed using the standardized average method described by ISO 9869-1:2014 and following the guidelines of Gaspar et al. [49]. The average method assumes that transmittance (*Um*) can be obtained by dividing the mean density of the heat flow rate by the mean temperature difference, assuming a steady state heat flow where thermal mass is neglected, as in the following equation:

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

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 was calculated according to the Guide to the expression of uncertainty in measurement [50], considering the accuracy of the equipment (sensors and acquisition systems). The uncertainty ($u_c(U)$) is obtained according to the following expression:

$$u_c{}^2(U) = \left(\frac{\delta U}{\delta q}\right)^2 \cdot u_c{}^2(q) + \left(\frac{\delta U}{\delta T_i}\right)^2 \cdot u_c{}^2(T_i) + \left(\frac{\delta U}{\delta T_e}\right)^2 \cdot u_c{}^2(T_e) =$$

$$= \left(\frac{1}{T_i - T_e}\right)^2 \cdot u_c{}^2(q) + \left(\frac{-q}{(T_i-T_e)^2}\right)^2 \cdot u_c{}^2(T_i) + \left(\frac{q}{(T_i-T_e)^2}\right)^2 \cdot u_c{}^2(T_e) \quad (2)$$

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.

### 2.3. Analysis of test conditions

Three variables were assessed to refine the test conditions in façades with low thermal transmittance: the temperature difference, the test duration and the accuracy related to the equipment.

#### *2.3.1. Temperature difference*

To analyse the influence of the temperature difference on the accuracy of the results, three periods of measurements with a duration of 168 hours and a range of temperature differences were selected. The thermal transmittance of the wall was determined in the seven consecutive cycles of complete days, using cumulative values. Therefore, the first cycle contained data on the 24 hours tested, the second cycle contained data on the 48 hours tested, and successively for each cycle until the seventh day. The analysis was performed by observing the accuracy of results between theoretical and measured thermal transmittance for different intervals of temperature difference. To check the adjustment between the theoretical and the measured values, absolute values of the relative difference between theoretical and measured thermal transmittances were calculated according to the expression:

$$Absolute\ value\ of\ the\ relative\ difference\ U_t - U_m(\%) \quad = \left|\frac{(U_t - U_m)}{U_t} \times 100\right| \tag{3}$$

where $U_t$ is the theoretical thermal transmittance of the façade and $U_m$ is the measured thermal transmittance of the façade.

### *2.3.2. Test duration*

The impact of the test duration was analysed to determine how the accuracy of theoretical and measured thermal transmittance varied as the test evolved. The variability of results was analysed by calculating the relative standard deviation (the coefficient of variation) of the resulting U-values, as proposed in ASTM standard C1155 [51] and by Atsonios et al. [52]. In this study, the condition for ending the test was that the coefficient of variation of the U-value obtained at the end of the test must not deviate more than 1% from the value obtained 48 hours earlier. The reason was that the coefficient of variation had a greater impact on walls with low U-values than on walls with high thermal transmittances. Likewise, the coefficient of variation was calculated using the previous 48 hours' values. The coefficient of variation was calculated following the expression:

$$Coefficient\ of\ variation\ (cv)(\%) \quad = \sqrt{\frac{\sum_i^{i+(n-1)}(Um_i - \overline{Um})^2}{n-1}} \times \frac{1}{\overline{Um}} \times 100 \tag{4}$$

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

### *2.3.3. Accuracy of equipment*

To assess the influence of equipment accuracy on the accuracy of results, the authors simulated the measurement uncertainty following Eq. 2 in two situations. Since it was a simulation, the duration of the test was extended to 504 hours to assess the long-term impact of the accuracy of equipment. In the first situation, the original accuracy of the heat flow meter was kept constant in three scenarios for the indoor and outdoor environmental temperature sensors' accuracy, taking into account the specifications of equipment that is commonly used in studies of the in situ measurement of thermal transmittance [35,37,44,45], scenario 1 corresponded to specifications of the apparatus used for the experimental campaign. In the second situation, the original accuracy of the temperature sensors was kept constant in three scenarios for heat flow meter accuracy, taking into account the specifications of equipment commonly used in studies of the in situ measurement of thermal transmittance [53,54], scenario 2 corresponded to specifications of the apparatus used for the experimental campaign. Table 3 summarizes the accuracy of the selected equipment for the two situations and the three scenarios.

| Situation | Type of equipment | Equipment accuracy scenario 1 | Equipment accuracy scenario 2 | Equipment accuracy scenario 3 |
|---|---|---|---|---|
| 1 | Heat flux meter plate | ±5% * | ±5% | ±5% |
| | Inside and outside air temperature sensor | ±0.5°C * | ±0.2°C | ±0.1°C |
| 2 | Heat flux meter plate | ±6% | ±5% * | ±3% |
| | Inside and outside air temperature sensor | ±0.5°C | ±0.5°C * | ±0.5°C |

* Specifications of apparatus used for the experimental campaign.

Table 3. Accuracy of equipment in the two situations for the three scenarios

## 3. Results and discussion

### 3.1. Temperature difference

To analyse the impact of the temperature difference on the accuracy of the U-value measurement, three periods of 168 hours with favourable weather conditions (no rain and no strong wind) and varying average temperature differences were selected. Measurements were classified into three intervals of temperature difference: less than 13ºC, from 13ºC to 19ºC, and higher than 19ºC. The thermal transmittance of the wall was determined in consecutive cycles of complete days, using cumulative values. Thermal transmittances and their associated combined uncertainty were calculated for each of the seven cycles of test duration following Eq.1 and Eq. 2, respectively. Then, absolute values of the relative difference between theoretical and measured thermal transmittances were calculated in each cycle according to Eq. 3.

Measured U-values and their corresponding uncertainties obtained in each cycle for the intervals of temperature difference are depicted in Fig. 6 and summarized in Table 4. The higher the temperature difference, the lower the deviation obtained between theoretical and measured U-values. A temperature difference ranging from 11ºC to 13ºC led to high deviations between theoretical and measured U-values in initial cycles of the test and they were reduced below 5% in the seventh cycle. When the temperature difference ranged from 13ºC to 19ºC, relative differences between U-values remained below 5% from the third cycle onwards. With a temperature difference above 19ºC, deviations between theoretical and measured U-value were kept below 2% from the third cycle onwards.

Uncertainties of measurements decreased as the test was extended and when temperature difference increased. In the interval of temperature difference ranging from 11ºC to 13ºC, the uncertainty of measurements decreased when the duration of the test was extended, from ±0.032 $W/m^2 \cdot K$ in the first cycle to ±0.018 $W/m^2 \cdot K$ in the seventh cycle. In the interval ranging from 13ºC to 19ºC, results obtained in the third cycle were acceptable but uncertainty associated with the measurement was very high (±0.030 W/m²·K). However, when the test was extended 24 hours, the uncertainty was significantly reduced (±0.016 W/m²·K). In the range of temperature difference above 19ºC, the improvement neither in the result nor in the uncertainty of measurements would justify extending the test beyond 72 hours.

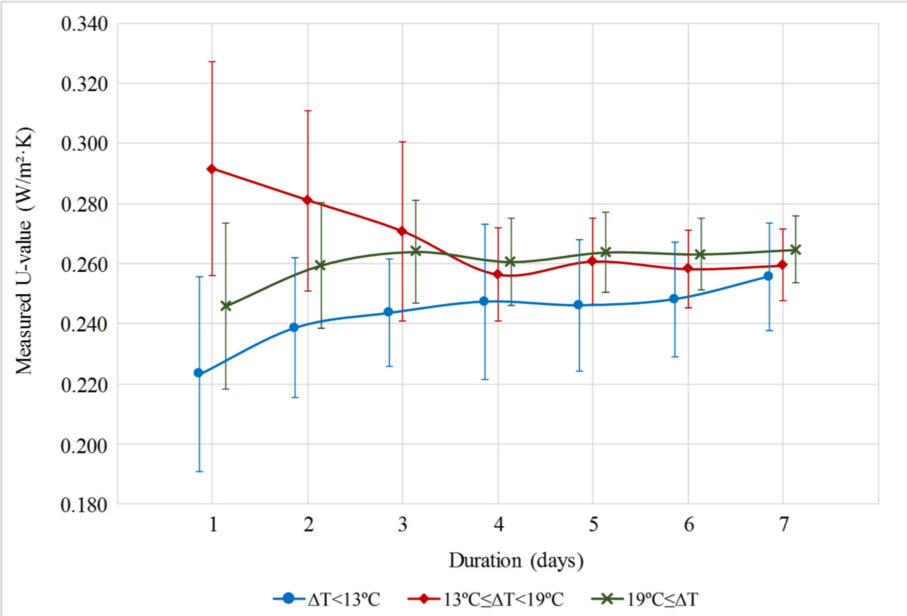



Fig. 6. Measured U-values and their associated combined uncertainties in each interval of temperature difference for the seven cycles of test duration

### 3.2. Test duration

The thermal transmittance of the wall was determined in consecutive cycles of complete days, using cumulative values, for the three ranges of temperature. Thermal transmittances and their associated combined uncertainties, and relative differences between theoretical and measured U-values were calculated for each of the seven cycles of test duration following Eq. 1, Eq. 2 and Eq. 3, respectively. Then, the coefficient of variation of the measured thermal transmittance was calculated for each cycle according to Eq. 4. In Table 4, the measured thermal transmittances and their associated uncertainties, the absolute values of the relative difference between theoretical and measured U-value, and the coefficient of variation are summarized for the results obtained in each cycle. For the interval of temperature difference above 19ºC, the test could be stopped at the fourth cycle, since the coefficient of variation of the results was lower than 1%, with a deviation between theoretical and measured U-values of 1.9%. In the interval of temperature difference ranging from 13ºC to 19ºC the test could be finished at the sixth cycle, with a deviation between theoretical and measured U-value of 2.8%. For the interval ranging from 11ºC to 13ºC, the test could be ended at the fifth cycle, obtaining a deviation between theoretical and measured U-value of 7.3%.

| | ΔT<13ºC | | | 13ºC≤ΔT<19ºC | | | 19ºC≤ΔT | | |
|---|---|---|---|---|---|---|---|---|---|
| **Number of cycles (duration)** | **Um±$u_c(U)$ (W/m²·K)** | $\left\lvert\frac{(U_t-U_m)}{U_t}\right\rvert$ **(%)** | **Cv (%)** | **Um±$u_c(U)$ (W/m²·K)** | $\left\lvert\frac{(U_t-U_m)}{U_t}\right\rvert$ **(%)** | **Cv (%)** | **Um±$u_c(U)$ (W/m²·K)** | $\left\lvert\frac{(U_t-U_m)}{U_t}\right\rvert$ **(%)** | **Cv (%)** |
| 1 (24h) | 0.223±0.032 | 15.9% | -- | 0.292±0.036 | 9.8% | -- | 0.246±0.028 | 7.4% | -- |
| 2 (48h) | 0.239±0.023 | 10.1% | -- | 0.281±0.030 | 5.8% | -- | 0.259±0.021 | 2.3% | -- |
| 3 (72h) | 0.244±0.018 | 8.3% | 4.4% | 0.271±0.030 | 1.9% | 3.9% | 0.264±0.017 | 0.6% | 3.6% |
| 4 (96h) | 0.247±0.026 | 6.9% | 1.8% | 0.256±0.016 | 3.4% | 4.7% | 0.261±0.015 | 1.9% | 0.9% |
| 5 (120h) | 0.246±0.022 | 7.3% | 0.8% | 0.261±0.014 | 1.8% | 2.8% | 0.264±0.013 | 0.7% | 0.7% |
| 6 (144h) | 0.248±0.019 | 6.6% | 0.4% | 0.258±0.013 | 2.8% | 0.8% | 0.263±0.012 | 0.9% | 0.6% |
| 7 (168h) | 0.256±0.018 | 3.7% | 1.9% | 0.259±0.012 | 2.3% | 0.5% | 0.265±0.011 | 0.3% | 0.3% |

Table 4. Measured U-values and their associated combined uncertainties, deviation between theoretical and measured U-value, and coefficient of variation of the measured thermal transmittance in the three intervals of temperature difference

### 3.3. Accuracy of equipment

In the assessment of the impact of the accuracy of equipment on the measurement, an interval of temperature difference above 19ºC was selected, since it led to more accurate results. Temperature data from the monitoring process for the period 29 December 2016 – 18 January 2017 is depicted in Fig. 7. Authors simulated the measurement uncertainty in two situations. In the first situation, the original accuracy of the heat flow meter was kept constant and three scenarios for the temperature sensors' accuracy were considered. The measured thermal transmittance and its associated uncertainty in the three scenarios for each cycle is depicted in Fig. 8, where $u_c(U)$ *Temp. sensor 1* is the uncertainty of measurements using equipment of scenario 1, $u_c(U)$ *Temp. sensor 2* is the uncertainty of measurements using equipment of scenario 2, and $u_c(U)$ *Temp. sensor 3* is the uncertainty of measurements using equipment of scenario 3 (Table 3). Temperature sensors that were more accurate resulted in lower uncertainty of measurements. However, the relation was not linear. The impact of equipment accuracy on the trueness of results was high in the first cycle of tests, and decreased when the test was extended (Fig. 8). The selection of ambient temperature sensors had a considerable impact on the uncertainty of measurements, especially in the initial cycles of the test.

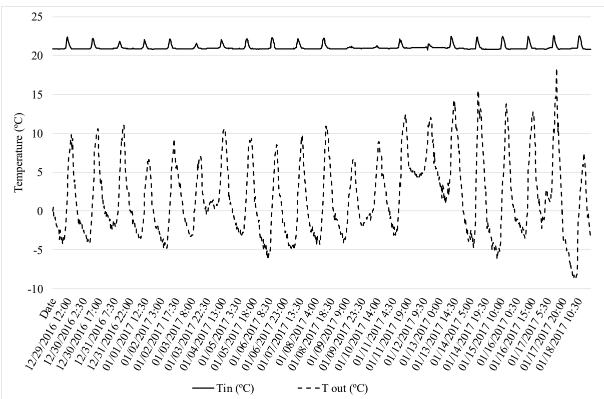



Fig. 7. Temperature data obtained from the process of monitoring for the period 29 December 2016 – 18 January 2017

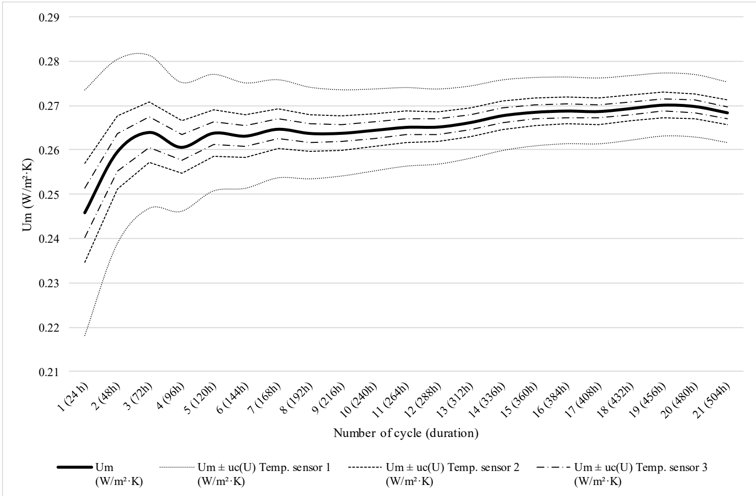



Fig. 8. Results of thermal transmittance and its associated combined uncertainty in situation 1, with a constant heat flux meter and the three scenarios of inside and outside temperature sensors' accuracy for each test cycle

In the second situation, the original accuracy of the inside and outside temperature sensors was kept constant and three scenarios for the heat flux meter accuracy were considered. The measured thermal transmittance and its associated uncertainty in the three scenarios for each cycle is depicted in Fig. 9, where *$u_c(U)$ HFM 1* is the uncertainty of measurements using equipment of scenario 1, *$u_c(U)$ HFM 2* is the uncertainty of measurements using equipment of scenario 2, and *$u_c(U)$ HFM 3* is the uncertainty of measurements using equipment of scenario 3 (Table 3). The most widely used heat flux meters by researchers for in situ measurements of façade U-value are highly accurate. Consequently, the change of scenario does not have a significant impact on the uncertainty of measurements, as shown in Fig. 9, where lines corresponding to the three scenarios overlapped.

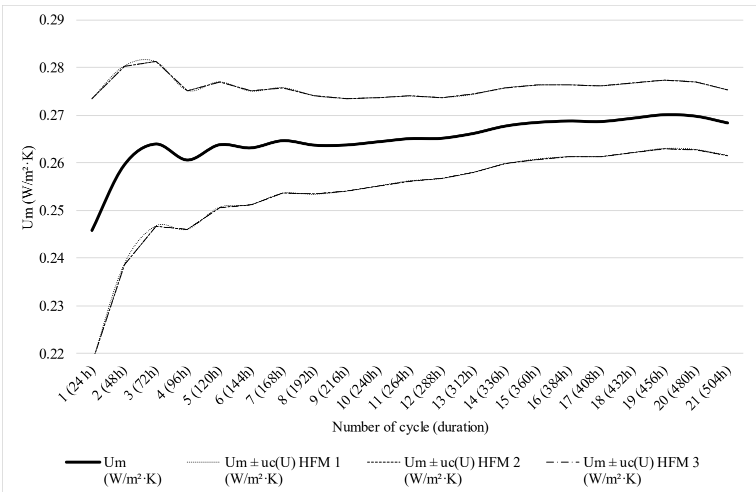



Fig. 9. Results of thermal transmittance and its associated combined uncertainty in situation 2, with constant inside and outside temperature sensors and the three scenarios of heat flux meter accuracy for each test cycle

## 4. Impact of findings on standard ISO 9869-1:2014

### 4.1. Temperature difference

Regarding the temperature difference between indoor and outdoor environment when low U-values are measured, the authors found that a temperature difference between 11ºC and 13ºC led to high deviations of 10% and above between theoretical and measured U-value in initial cycles. Based on the results of U-value measurements, and their associated uncertainty, the test should have a minimum duration of 7 days. With a temperature difference ranging from 13ºC to 19ºC, relative differences between U-values were above 5% in initial cycles. It was found that the test should have a minimum duration of 4 days to minimize deviations and uncertainties associated to the measurement. When the temperature difference was above 19ºC, deviations between theoretical and measured U-value were above 5% in initial cycles. The minimum duration of the test was found to be 3 days to obtain reasonable deviations and uncertainties associated to the measurement. Accordingly, to accurately measure in situ low U-value façades, temperature differences must be much higher than 10ºC.

### 4.2. Test duration

For the interval of temperature difference above 19ºC, the test could be finished after 72 hours according to the standard and after 96 hours considering the variability of results, with a deviation between theoretical and measured U-value of 1.9%. For the interval of temperature difference ranging from 13ºC to 19ºC, the test could be finished after 144 hours and meet the conditions for ending the test established in the standard, obtaining a deviation between theoretical and measured U-value of 2.8%. For the interval of temperature difference ranging from 11ºC to 13ºC, the test could be finished after 120 hours and meet the conditions for ending the test established in the standard, obtaining a deviation between theoretical and measured U-value of 7.3%. As observed, when the interval of temperature difference was above 19ºC, results obtained by the authors considering the variability of results were more restrictive than indications of the standard, requiring the test to last 24 hours more.

Standard ISO [33] establishes a minimum test duration of 72 hours. The results obtained in the experimental campaign showed that the test could not be stopped before 72 hours, since neither measurements nor its associated uncertainty would be acceptable. The duration of the test should be consistent with the temperature difference.

### 4.3. Accuracy of equipment

This paper demonstrates that, when low thermal transmittance façades (around 0.27 W/m²·K) are measured for the interval of temperature difference above 19ºC and using an accurate heat flux meter [44], the accuracy of the temperature sensors play a very important role in the total uncertainty of the measurement. When the accuracy of the heat flux meter was kept constant at ±5%, with temperature sensors that had an accuracy of ±0.5ºC, the simulated uncertainty of measurements was ±0.017 W/m²·K at 72 hours of test duration and meeting the conditions for ending the test according to the standard. When the accuracy of temperature sensors was ±0.2ºC, the simulated uncertainty was reduced to ±0.007 W/m²·K, and with temperature sensors with an accuracy of ±0.1ºC the simulated uncertainty was reduced to ±0.003 W/m²·K (Fig. 10). Selecting a heat flux meter with high performance is essential to obtain accurate results. When the accuracy of the temperature sensors was kept constant at ±0.5ºC, with a heat flux meter that had an accuracy of ±6%, the simulated uncertainty of measurements was ±0.017 W/m²·K at 72 hours of test duration and meeting the conditions for ending the test according to the standard. The simulated uncertainty of measurements did not differ significantly when accurate heat flux meters were used (with accuracies ranging from ±5% and ±3%) (Fig. 11). The selected heat flux meters, commonly used by researchers, were already very accurate (ranging from ±3% to ±6%), and the improvement of the measurement uncertainty by changing the sensor was not significant. Whereas the uncertainty of the U-value measurements can be significantly reduced by using temperature sensors with high accuracies (±0.1ºC or ±0.2ºC).

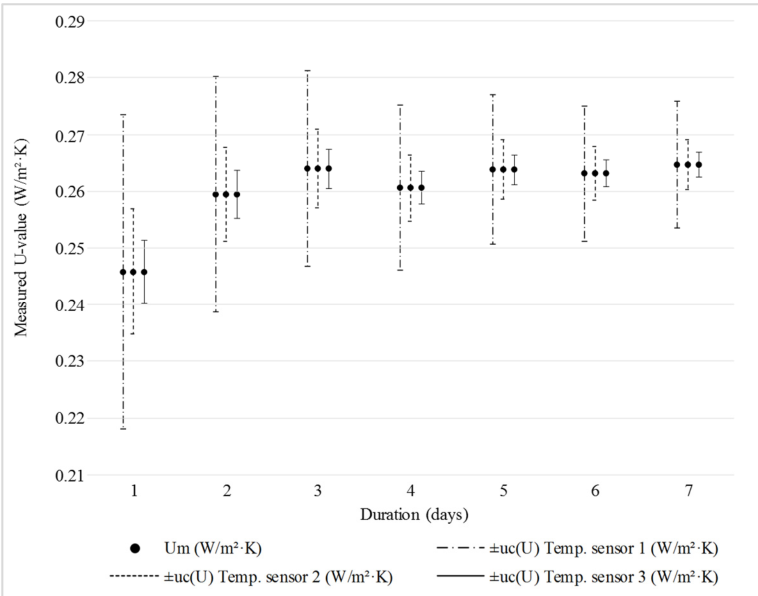



Fig. 10. Uncertainty related to equipment in situation 1, with a constant heat flux meter and the three scenarios of inside and outside temperature sensors' accuracy for the seven initial cycles

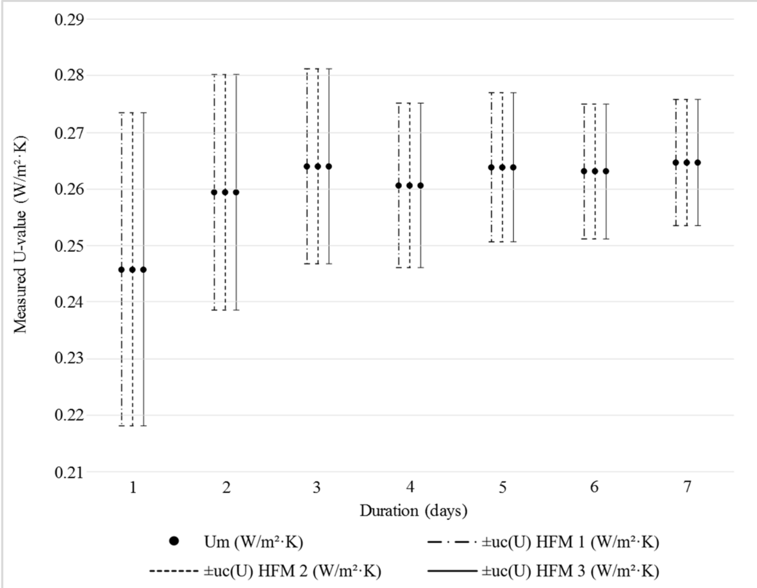



Fig. 11. Uncertainty related to equipment in situation 2, with constant inside and outside temperature sensors and the three scenarios of heat flux meter accuracy for the seven initial cycles

## 5. Conclusions

This study refined the appropriate conditions for applying the ISO 9869-1:2014 standardised HFM method for in situ measurement of low thermal transmittance façades. The research focused on the study of test variables that are not fully specified in the standard: temperature difference, test duration, and accuracy of equipment. A continuous experimental campaign was conducted in a building mock-up equipped with a heating system. The mock-up was constructed with a system of façades based on prefabricated panels with low U-values designed for nearly zero-energy buildings. Findings of the analysis of the three variables were compared with indications of standard ISO 9869-1:2014 and the existing literature.

In the in situ measurement of low U-value façades, low thermal flux is obtained, decreasing the accuracy of the measurement. To reduce this deviation, temperature differences should be increased. However, achieve temperature differences equal or greater than 19ºC may be a limitation in real conditions. Possibly, for low U-value façades greater deviations have to be assumed. Specifically, in the conducted experiment, deviations of 1.9% were obtained with temperature differences above 19ºC, and they increased to 7.3% with temperature differences ranging from 11ºC to 13ºC.

The analysis of in situ measurements of façades' U-values in the existing literature revealed that specific heat flow meters were used, with good technical performance and relatively high costs. However, the accuracy of the temperature sensors varied widely. Therefore, to reduce the uncertainty of measurements, practitioners could save on the acquisition of heat flow meters with accuracies of ±5% to ±6%, and invest in the acquisition of temperature sensors with accuracies between ±0.1 ºC and ±0.2ºC.

Since the heat flux meter method is a widely used technique for in situ measurement of the thermal transmittance of façades, this research aims to help avoid errors in its use when façades with a low U-value are measured. The findings complement those stated in ISO 9869-1:2014 and in the existing literature.

Based on the results obtained in this research, practitioners will be able to improve the design of the experimental campaigns required in energy audits of low U-value façades when they verify compliance with energy performance policies in façades retrofitted to attain nearly zero-energy buildings, and corroborate energy performance of façade strategies for new nearly zero-energy buildings.

Further research should consider the assessment of façades with very low thermal transmittance, since their use is increasing worldwide. Further research should also analyse the impact of convective motions in non-ventilated air cavities on the in situ U-value measurement using the heat flux meter method, for different thicknesses of air cavity. In addition, due to the estimated uncertainties of measurements in the research were very low, it would be interesting to compare the estimated uncertainties of measurements with experimental data.

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# Chapter 5. Annex: Submitted papers

This chapter reproduces a journal paper derived from this thesis that is currently under revision. Since this is still not published, the paper presented in this chapter cannot be considered as part of the official compendium of publications. However, the outcomes of this work answer important aspects discussed in the previous chapters. The paper follows its own numbering of sections, figures, tables, equations and references.

Journal paper IV:

Gaspar K., Casals M., Gangolells M. Review of criteria for determining HFM minimum test duration. Submitted to *Energy and Buildings* in April 2018.

## 5.1 Journal paper IV. Review of criteria for determining HFM minimum test duration

*Submitted to Energy and Buildings in April 2018.*

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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 required in 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. 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 ensure a successful decision-making process during energy efficiency improvements to buildings [14,15]. Several approaches are used to determine the thermal transmittance of existing buildings' façades:

- Methods based on classifying buildings by types or by historical analysis [9,16]. These methods are general, and usually lead to imprecise values for 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 [17], 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 according to ISO 6946:2007 [7,9,17], or non-destructive procedures, such as the use of the heat flow meter, quantitative thermography [13,18-21], or other methods developed by researchers. 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 [22]. The ISO 9869-1:2014 standard [22] defines two methods for data analysis: the average method and the dynamic method.

In the heat flow meter method, the standard [22] 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 [23], 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 [6,7,24-26]. In fact, ISO 9869-1:2014 [22] indicates that the actual test duration should be determined by applying criteria to the values obtained during the test.

## 2. Background

Some authors have used experimental campaigns of varying durations, from three days to one month, in comparisons of theoretical and measured U-value [22]. Asdrubali et al. [6] measured in situ thermal transmittance in buildings designed using bio-architecture principles, with calculated thermal transmittance ranging from 0.23 $W/m^2 \cdot K$ to 0.33 $W/m^2 \cdot K$. 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 [24] 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 $W/m^2 \cdot K$ to 2.65 $W/m^2 \cdot K$. 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. [27] monitored in two periods of between 14 and 21 days the corresponding façades, which had theoretical U-values of 0.10 $W/m^2 \cdot K$ and 0.23 $W/m^2 \cdot K$. Results showed relative differences between 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 $m^2 \cdot K/W$. 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. [28] on three conventional façades with calculated U-values ranging from 0.504 to 1.897 $W/m^2 \cdot K$, 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 $W/m^2 \cdot K$. 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. [25] 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 $W/m^2 \cdot K$ for walls that appeared to be of solid brick construction, and 1.34 $W/m^2 \cdot K$ for stone, with standard deviations of about 0.35 and 0.38 $W/m^2 \cdot K$, respectively. The authors found that the transient analysis methodology developed by Biddulph et al. [29] 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 [22].

Mandilaras et al. [30] 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 $m^2 \cdot K/W$, respectively. The measuring 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 [22] and other techniques. Ahmad et al. [31] 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 [32] and ISO 9869:1994 [22]. The results showed that the U-values were in a range of 1.402-1.490 $W/m^2 \cdot K$ with a mean of 1.456 $W/m^2 \cdot K$, 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. [29] performed measurements in 93 walls with calculated U-values ranging from 1.598 to 2.392 $W/m^2 \cdot K$, 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 [33] 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 $W/m^2 \cdot K$. For new or refurbished buildings, the measured conductance value was found to be about 20% higher than the reference value.

Nardi et al. [20] 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 $W/m^2 \cdot K$, and 72 hours for walls with a theoretical U-value of 0.23 $W/m^2 \cdot K$ and 0.51 $W/m^2 \cdot K$. 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 $W/m^2 \cdot K$, 82.6% for the wall with a theoretical U-value of 0.23 $W/m^2 \cdot K$, and 44.2% for the wall with a theoretical U-value of 0.51 $W/m^2 \cdot K$.

Deconinck and Roels [34] 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 $m^2 \cdot K/W$. 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. The minimum test durations using the three criteria were compared. The average and dynamic calculation methods were used for the analysis. The results 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 in 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. [35], 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 [17]:

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

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 [17], 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:

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

where $d$ is the thickness of the layer in the element, and $\lambda$ 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 [17] and the Spanish Technical Building Code's Catalogue of Building Elements [36] 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 [22], Ahmad et al. [31], Asdrubali et al. [6], Evangelisti et al. [28], and Tejedor et al. [37], with an infrared thermographic camera (FLIR E60bx Infrared Camera). Sensors were mounted on a representative part of the wall, and corners in the opaque part, the vicinity of defects, and the direct influence of a heating or cooling device were avoided [38]. 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). Indoor temperature was always higher than outdoor temperature, so the heat flow direction was stable. 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.

a)
b)
c)

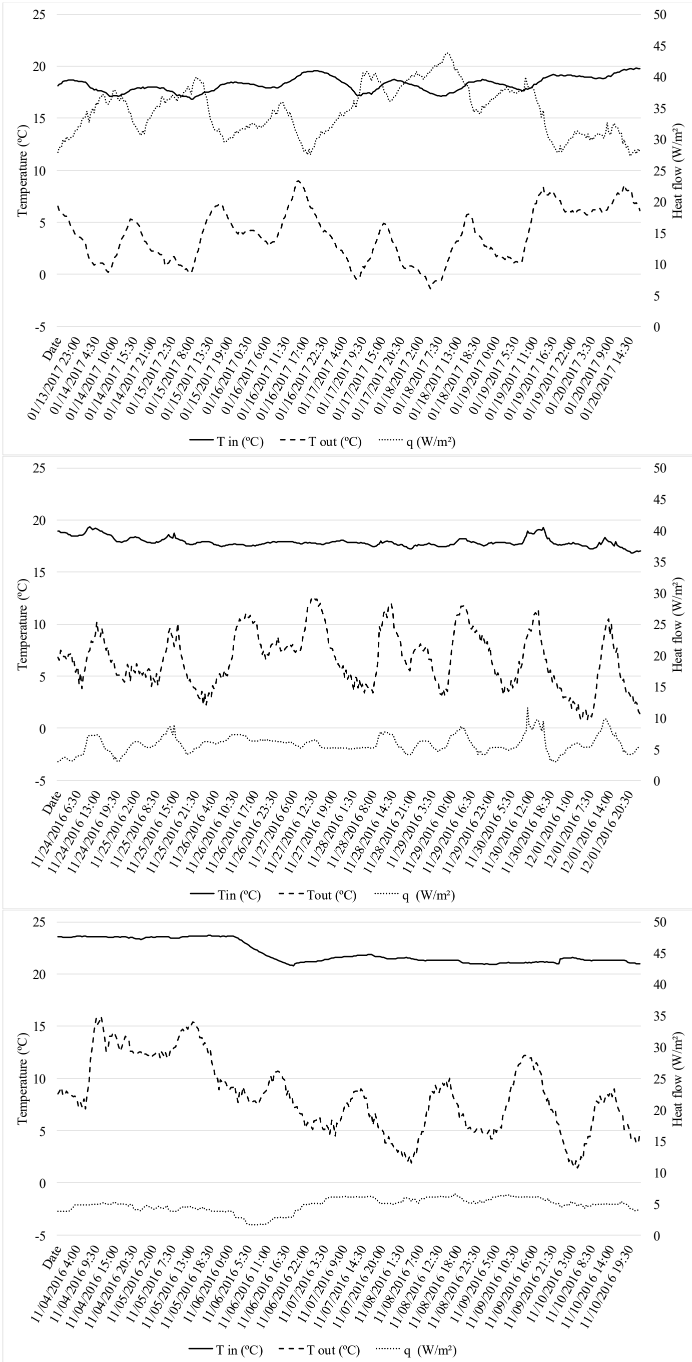



Fig. 2. Data obtained from the process of monitoring for a) Case study 1 for the period 13–20 January 2017, b) Case study 2 for the period 24 November to 01 December 2016, and c) Case study 3 for the period 03–10 November 2016

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 [22]. Following Flanders [39] indications for analysing data quality in the measurement of a façade's U-value, the thermal behaviour of the façades were 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 [22], assuming a steady state heat flow in which thermal mass is neglected [29], 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 [40], and following the guidelines established in Gaspar et al. [41], 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:

$$u_c{}^2(U) = \left(\frac{\delta U}{\delta q}\right)^2 \cdot u_c{}^2(q) + \left(\frac{\delta U}{\delta T_i}\right)^2 \cdot u_c{}^2(T_i) + \left(\frac{\delta U}{\delta T_e}\right)^2 \cdot u_c{}^2(T_e) =$$

$$= \left(\frac{1}{T_i-T_e}\right)^2 \cdot u_c{}^2(q) + \left(\frac{-q}{(T_i-T_e)^2}\right)^2 \cdot u_c{}^2(T_i) + \left(\frac{q}{(T_i-T_e)^2}\right)^2 \cdot u_c{}^2(T_e) \tag{4}$$

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 [22], 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:

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

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 dynamic characteristics of the wall without any particular significance, and depend on the time constant $\tau_n$. The coefficients $\beta_n$ are exponential functions of the time constant $\tau_n$, where $\beta_n = \exp\left(-\frac{\Delta t}{\tau_n}\right)$, and the time constants $\tau_n$ 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 data sets (more than $2m+3$) at various times, an overdetermined system of linear equations is created as follows:

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

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.

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

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. [41] 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 [32,39]:

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

In the dynamic method, quality criteria to indicate confidence in the U-value estimation results is calculated according to the following equation [22,42]:

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

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 $M$-$2m$-$5$ 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 [39].

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 [42].

### 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 [32] and by Atsonios et al. [43]. The coefficient of variation was calculated following the expression:

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

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:

$$e(\%) = 2 \times CV(\%) \quad (11)$$

In this study, the coefficient of variation is expected to be 10% for the average method and 6% for the dynamic method [43], for a confidence level of 95.4%.

### 3.2.3 ISO criteria

The ISO 9869-1:2014 standard [22] 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 in order 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).

$$D_T\ (days) \geq 3 \quad (12)$$

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

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

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 study 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 summarized in Table 3, and are depicted in Fig. 3.

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 [6,20].

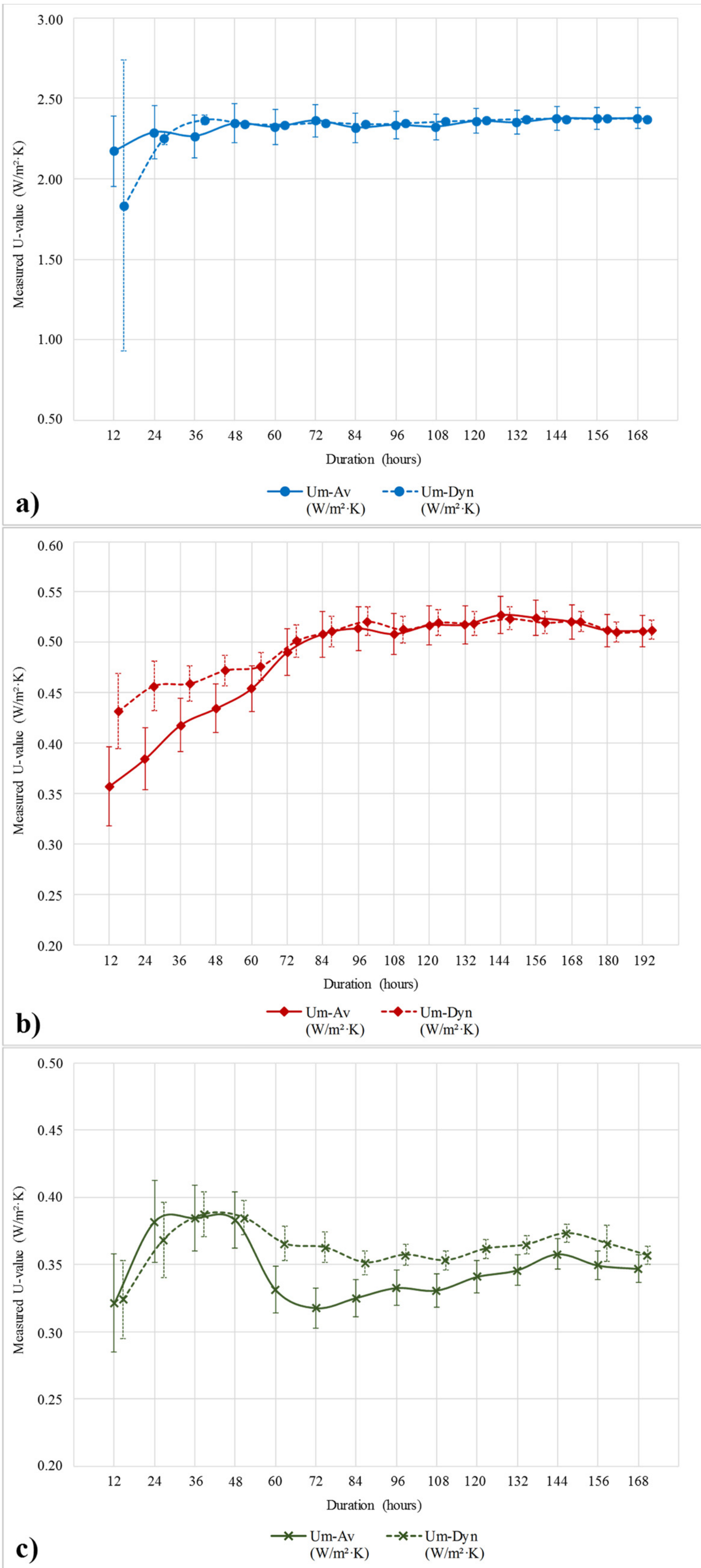



Fig. 3. Measured U-values and their associated uncertainties in a) Case study 1, b) Case study 2, and c) Case study 3

| | | Case study 1 | | Case study 2 | | Case study 3 | |
|---|---|---|---|---|---|---|---|
| | | $U_{m-Av}$ ±$U_{(C)}$ (W/m²·K) | $U_{m-Dyn}$ ±I95% (W/m²·K) | $U_{m-Av}$ ±$U_{(C)}$ (W/m²·K) | $U_{m-Dyn}$ ±I95% (W/m²·K) | $U_{m-Av}$ ±$U_{(C)}$ (W/m²·K) | $U_{m-Dyn}$ ±I95% (W/m²·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 | |
| ∆T average (K) | | 14.5 | | 11.3 | | 13.4 | |
| Ut (W/m²K) | | 2.35 | | 0.52 | | 0.36 | |

Table 3. Estimated theoretical thermal transmittance and measured thermal transmittance using the average and dynamic methods calculated by 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.

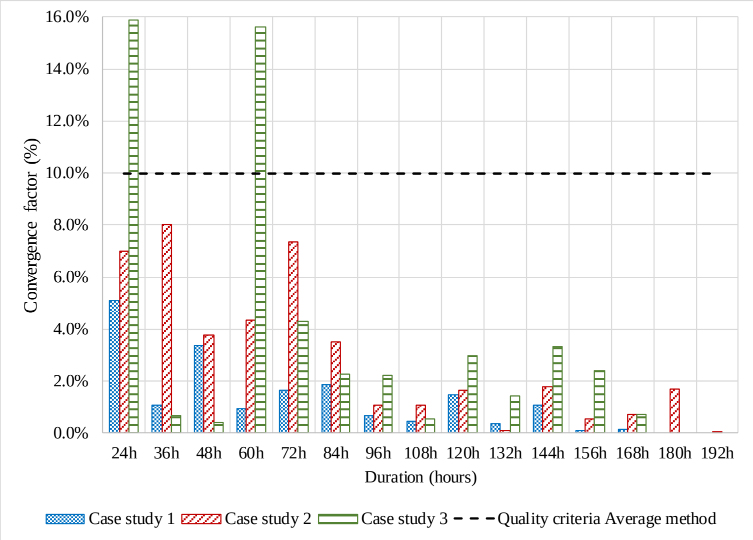



Fig. 4. Data quality criteria in Case study 1, Case study 2 and Case study 3 using the Average method

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.

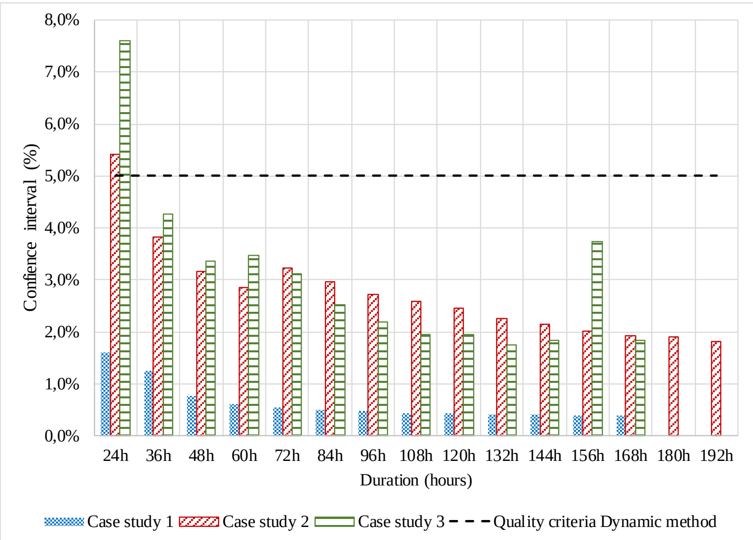
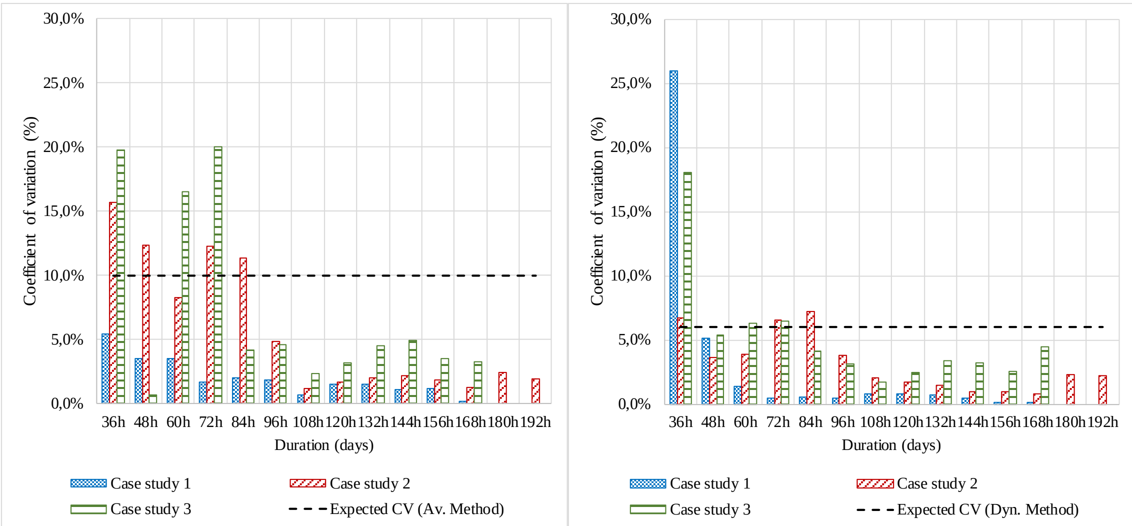



Fig. 5. Data quality criteria in Case study 1, Case study 2 and Case study 3 using the Dynamic method

### 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 the 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 [22] 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 [22] 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 $U_{m\text{-}Av}$ (%) | Deviation in $U_{m\text{-}Dyn}$ (%) | Deviation in $U_{m\text{-}Av}$ (%) | Deviation in $U_{m\text{-}Dyn}$ (%) | Deviation in $U_{m\text{-}Av}$ (%) | Deviation in $U_{m\text{-}Dyn}$ (%) |
| 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.

| 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/m²K)** | 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), 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, applying ISO criteria 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, to greater sensitivity of the ISO criteria, and to 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 the 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 showed that 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, but it would be reasonable to conduct further research to readjust the criteria.

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