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# Managing the uncertainty of the U-value measurement using an auxiliary set along with a thermal camera

Georgios Papadakos [a], Vangelis Marinakis [a,*], Christos Konstas [a], Haris Doukas [a], Agis Papadopoulos [b]

[a] Decision Support Systems Laboratory, School of Electrical and Computer Engineering, National Technical University of Athens, 15780 Zografou, Greece
[b] Process Equipment Design Laboratory, Department of Mechanical Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

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A B S T R A C T

The building elements' thermal transmittance index (known as U value) is the most essential parameter for the estimation of its thermal losses, and subsequently its energy performance. Laboratory measurements of the U value are practically of interest only for pre-fabricated or standardised building elements; hence, the commonly acceptable practice is to use theoretical estimations, taking into account the thermal resistance indexes of the building elements' layers. In this context, this paper aims at the assessment of the uncertainty budget of one of the already used in-situ building elements' thermal transmittance measurement, as long as this is applied using a thermal camera instead of contact thermometers. A specially designed and easily constructed auxiliary measurement set-up is presented and is used in comparison with simultaneous thermocouple measurements, to verify the adequacy of the auxiliary set up response time. This study concludes with the analysis of the uncertainty that affects the proposed procedure, along with an assessment of the impact in the final result. The uncertainty of these measurements is strongly related with the respective decisions on building upgrade and renovation. Therefore, managing it with a simplified procedure will be rather profitable both for those seeking to perform an in-situ U value measurement and for those who are engaged into a decision process upon renovating or not an existing building.



## 1. Introduction

Thermal insulation level is one of the most significant factors contributing to the building's energy consumption [1]. It is an essential factor influencing the decision-making process on building upgrade and renovation projects. Moreover, it is one of the building's characteristics that is significant even for the design and operation of the Building Energy Management Systems (BEMS) [2–3] and other advanced systems [4–5].

The building elements' thermal transmittance index (known as U value) is the most used parameter for the estimation of its thermal losses, and subsequently its energy performance. A number of studies on the thermal transmittance index have been presented in the literature, including U-value measurement of a whole dwelling [6], modelling of facade elements with switchable U-value [7], U-value assessment of argon-filled double glazed windows [8] and load bearing walls [9], as well as U-value time series analyses [10] and comparison of quantitative infrared thermography [11].

Given the tightening regulatory requirements, measuring in-situ the thermal transmittance in occupied buildings is often needed to face complaints over thermal discomfort or disputes on the quality of construction [1,12–13]. Many methods for in-situ measurement of the building element's thermal transmittance have been proposed in the literature [14]. Accordingly, consideration on the limitations of these methods due to the level of the result's uncertainty have been stated [15–16], especially in the energy performance class [17], energy performance certificates [18], energy performance contracting [19], sustainable retrofits [20–21], building energy management [22] and building simulation [23], as well as uncertainty in temperature measurements by infrared thermography [24], building operations, weather, occupancy and other parameters [25–26]. The estimation of uncertainty can improve energy measurement and verification procedures [27].

Nowadays, ISO requires that any decision upon a conformity assessment issue should be based on the level of risk of the measurement result provided by a laboratory [28], while ISO also defines risk as "the effect of uncertainty on objectives" [29]. Usually, decisions on the extent of upgrade and renovation projects for the building envelope's thermal insulation level are based on

* Corresponding author.
*E-mail address:* vmarinakis@epu.ntua.gr (V. Marinakis).

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calculations, such as ISO 6946 [30]. The uncertainty of these calculation's result strongly relies on: (a) the building's elements ageing process and the lack of information on the exact geometrical characteristics of the construction; (b) the degree of moisture content inside these materials [31]; (c) other factors [32] which in any case are expected to be in strong relation with the age of the construction. The uncertainty of these calculations is expected to be low, but significant for the interpretation of the result (ISO 13,790 [33]), for time intervals not far apart from the end of the construction of the building. The uncertainty, by time passing, is expected to be increasing (Fig. 1). In this respect, any in situ thermal transmittance measurement process is characterized by a corresponding uncertainty that has been investigated and analysed in the past [34–36]. Whenever this measurement is conducted at time not long after the end of the construction of the measured building element, the uncertainty is expected to be significantly larger than the uncertainty of a calculation of the element's thermal transmittance.

The measurement's result uncertainty is expected to vary according to the measurement conditions, the technical specifications of measurement equipment used and the level of expertise of the person performing the measurement. Thus, it is not expected to change significantly by the factor of the time that has elapsed since the initial construction (i.e. the age of the construction), unless there are issues with long term moisture absorption in the building elements, in which case the U value of the wall is increasing over time; although, the possibility of structural damages is clearly the main problem to face, especially in historical buildings [37]. Consequently, if the in-situ measurement process is conducted following a standardised procedure, assuring relatively acceptable uncertainty levels for the result, it is possible this kind of thermal transmittance index estimation to have a significantly prevailing accuracy compared to the results by corresponding calculations [38–40].

The only existing standardised thermal transmittance index measurement procedure for building envelope elements is the one described in ISO 9869–1 [41]. This standard describes the procedure based on the use of a Heat Flow Meter (HFM). The principle calculation uses:

$$U = \frac{Q}{\Delta T} \quad (1)$$

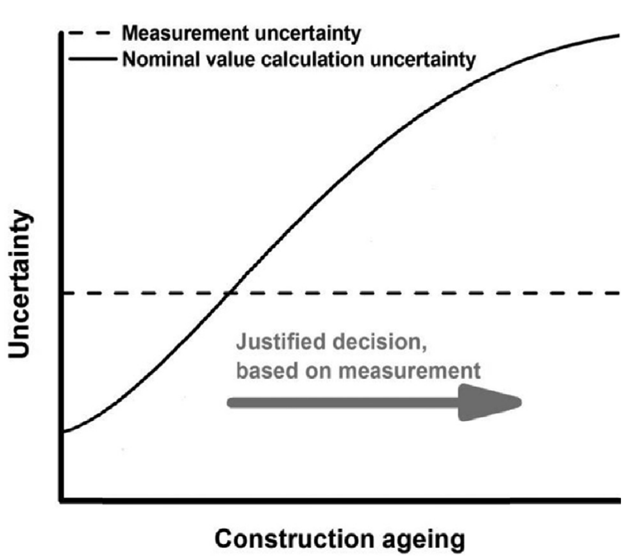


**Fig. 1.** Thermal transmittance index measurement uncertainty and nominal value calculation uncertainty as a function of building construction ageing.

were $Q$ is the heat flow rate due to the building envelope element being measured and $\Delta T$ is the air temperature difference between points that are located close to the interior ($T_{IN}$) and the exterior ($T_{OUT}$) surface of the building envelope elements. The numerator value is directly retrieved by a properly calibrated measurement using an HFM. The denominator temperature difference is estimated by the measurement results using any kind of contact thermometers.

An alternative measurement procedure [42–43] provides the same result using an approximation of the value in the numerator of equation (1) using the results of temperature measurements, i.e.:

$$U = \frac{\varepsilon \cdot \sigma \cdot \left(\mathrm{T_{IN}}^4 - \mathrm{T_W}^4\right) + a_c \cdot (\mathrm{T_{IN}} - \mathrm{T_W})}{\mathrm{T_{IN}} - \mathrm{T_{OUT}}} \quad (2)$$

where $T_W$ (expressed in Kelvin degrees, K) is the temperature of the internal surface of the measured building envelope elements, $T_{IN}$ & $T_{OUT}$ (also expressed in Kelvin degrees, K) are the internal and external air temperatures, respectively, and $\varepsilon$, $\sigma$, $\alpha_c$, are well-known constants based on the literature. In this procedure, the approximating numerator estimates the heat flow through a perpendicular building envelope element by adding: (a) its part which is transferred due to convection; (b) its part which is transferred due to thermal radiation. In this way, it is possible to conduct the same measurement by using only temperature measurement equipment.

In its most simplified implementation, this alternative procedure uses only contact thermometers.

According to the technical data sheets provided by thermal cameras manufacturer [44], the measurement of the temperature on the internal surface of the building envelope is possible to be conducted remotely and non-destructively by the use of such a non-contact measurement equipment, like a thermal camera. This attribute was the root cause for the evolution of a measurement method that has not been yet standardised [42,43,45,46].

Using a thermal camera for measuring the temperature of objects' surfaces is a procedure with a well-known uncertainty budget [47,48]. The case of a comparison of two surface temperature measurements using thermocouples and an infrared camera has been studied by Michalski et al. [49]. An attempt to capture all the needed temperature values in order to estimate the numerator of equation (2), with a single thermal image, has been already proposed and basically analysed as per the contribution of various parameters to the uncertainty of the result [50]. Although, there are still issues to be analysed, like the cross correlation of the different temperature measurement results, that are discussed and analysed in this paper.

The main principle in order that the above mentioned measurement procedure is representative for the measurand is that the ratio of the temperature values used in equation (2) to be constantly proportional of the true value of the thermal transmittance index, even if, during the measurement procedure, the thermal balance condition of the measured construction element is under slight and smooth variations (Fig. 2).

Earlier study by Tzifa et al (2017) [43] showed that the measurement method which is based on the use of a thermal camera could be performed with the levels of relative uncertainty close to a value of 20% (coverage factor $k$ = 2). Within the conclusions of this study it is mentioned that one of the most influencing uncertainty parameters of the corresponding method is the use of different measuring devices for the estimation of temperature differences used on the numerator of equation (2).

In this context, this paper aims at the assessment of the uncertainty budget of one of the already used in-situ building elements' thermal transmittance measurement, as long as this is applied along with an auxiliary set-up being proposed and tested within

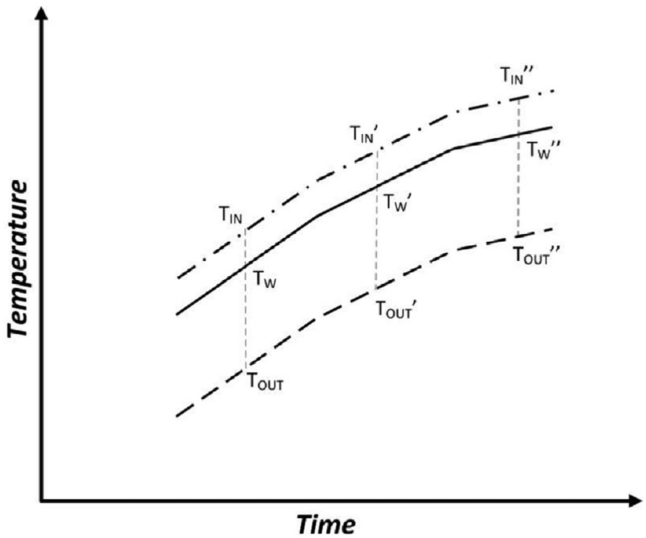


**Fig. 2.** Theoretical diagram of a possible fluctuation in the temperature measured values that contribute to the final thermal transmittance index calculation.

this study. Any optimization of such a decision support processing is profitable when this relies on measurements with proper reliability using easily portable equipment and a short-time series of measurements. Optimization of the procedure could be considered to refer either to the uncertainty levels, or even to the feasibility and simplicity of the procedure.

An experiment was conducted in this paper due to which the possibility for maintaining the performance of such a measurement was assessed, in the case where the procedure is simplified as proposed. More specifically, a procedure of simultaneously measuring the air temperature and the temperature of the adjacent internal wall surface, using the same thermal camera and an auxiliary target set-up, instead of using both a thermal camera and contact thermometers for measuring the air temperature, was designed and constructed, based on a combination of proposals stated by Albatici & Tonelli (2010) [42]. The uncertainty of these measurements is strongly related with the respective decisions on building upgrade and renovation. Therefore, maintaining it to the same level will be interesting for those seeking to perform an in-situ U value measurement and for those who are engaged into a decision process upon renovating or not an existing building.

The rest of the paper is organised as follows. In Section 2, the theoretical background of the proposed method for measuring thermal transmittance on a practically flat building element, using the technology of a thermal camera is analysed, along with the basic components for its application. Section 3 presents an experimental investigation aiming at the definition of the proposed measurement procedure. A specially designed and easily constructed auxiliary measurement set-up is presented and is used for verification reasons. Section 4 is devoted to the analysis of the uncertainty that affects this measuring method, along with an assessment of their impact in the final result. The uncertainty of these measurements is strongly related with the respective decisions on building upgrade and renovation. Finally, the last section summarises the key issues that have arisen in this paper.

## 2. The proposed approach

### 2.1. The measured building element and reference values of thermal transmittance

The experiment was realised on the envelope of an existing building. The nominal value of thermal transmittance index was calculated according to ISO 6946:2017 [30]. Table 1 presents the layers of the building elements and their thermal transmittance, integrating also the lack of accuracy of the result due to the inexactness of the assumptions on the construction characteristics.

The above lead to an estimation of U = 1.5 W/ ($m^2$·K) with minimum to maximum values of 1.0 to 2.0 W/($m^2$·K).

Moreover, the U value was measured in November 2016 with the standard procedure of using a Heat Flowmeter (HFM, model GreenTEG U-value measurement kit), according to ISO 9869–1:2014 [38]. The measurement lasted for 72.27 h (from 12:46 of 25th of November 2016 until 13:02 of 28th of November 2016). The result was U = 1.6 W/$m^2$K with a fluctuation of the estimated result to be 3.14% in the last 24 h of a 3-day time series of measurements. It should be noted that this fluctuation statistic does not correspond to the actual uncertainty of the estimation. Many parameters (i.e. the trueness of the HFM measurement as this is declared by the equipment's calibration procedure) should be analysed in detail in order to retrieve a complete uncertainty budget.

The above results are statistically compatible to each other and it could be assumed that they provide a trustworthy reference for the estimations according to the proposed procedure of this study.

Further referencing was gained by measurement results using type K thermocouples along with a high accuracy Agilent 34972A Data Acquisition/Switch Unit (i.e. a data logger) calibrated against the ITS-90 conversion factors. The aim of the use of the thermocouples was not essentially to retrieve the differences between measuring with thermocouples and with the thermal. Mainly, thermocouples provided a figure of the time response of the temperatures involved in the method. Thermocouples have an adequately short response time when they are used without any kind of time integration on the logged time series of measurements.

### 2.2. The measurement set up

For the procedure examined in this study, two different thermal cameras where used (FLIR, type InfraCAM and type b40) simultaneously for the same measurements, aiming at the verification of the results. A number of contact thermometers (type K thermocouples) were also used for the verification and check of these results. These were placed at: (a) a distance of 1 cm from the internal surface of the measured construction element (2 thermocouples); (b) within a limited distance from the adjacent outer surface of the same construction element (2 thermocouples); (c) inside the auxiliary target set-up (3 thermocouples).

The auxiliary (passive) target set-up combines the use of a hollow target (Figs. 3 and 4) with the use of a black coloured piece of textile which is used as the target on which the thermal camera is targeting. These two elements of the set up were proposed by Albatici & Tonelli since 2010 [42], as alternative methods for measuring the air temperature using only an infrared camera and not any kind of contact thermometer. The three verifying thermocouples were placed between the textile and the bottom of the card box. The final measuring position was such that the target side to be at 1 m distance away from the internal wall surface.

Completing the construction of the auxiliary target set-up, the card box cover was covered by a reflecting material (simple aluminium foil for domestic use) and a square opening of dimension 8 cm by 8 cm was made in the middle of it. In such a way, the auxiliary target set-up was made as a cheap, easy to make black body reference material.

Respectively, for the measurements on the external air temperature, adjacent to the measured part of the building's envelope, both thermocouples were positioned very close to the external surface of the wall, adjacent to the point where temperatures were measured internally by the use of the thermal camera (Fig. 3). A

**Table 1**
Building element's layers of materials, their thickness *d* and corresponding thermal resistance values λ for calculation of U according to ISO 6946:2017 (*R* is the thermal resistance introduced by each layer).

| Wall Component | *d* [cm] | | λ [ W/(m·K) ] | | *R* [(m$^2$·K)/W ] | |
|---|---|---|---|---|---|---|
| | min | max | min | max | min | max |
| Standard acrylic base paint (internal) | 0.1 | 0.2 | 0.500 | 0.500 | 0.002 | 0.004 |
| lime cement mortar or cement mortar (internal) | 1.5 | 2.5 | 0.870 | 1.400 | 0.011 | 0.029 |
| Porous clay brick or Perforated bricks | 17.5 | 18.5 | 0.260 | 0.580 | 0.302 | 0.712 |
| lime cement mortar or cement mortar (external) | 0.0150 | 0.0250 | 0.870 | 1.400 | 0.017 | 0.018 |
| Standard acrylic base paint (external) | 0.0010 | 0.0020 | 0.500 | 0.500 | 0.002 | 0.004 |
| Ri - thermal resistance of inner air film | | | | | 0.13 | 0.13 |
| Ra - thermal resistance of outer air film | | | | | 0.04 | 0.04 |
| **Total thermal Resistance** | | | | | **0.504** | **0.936** |

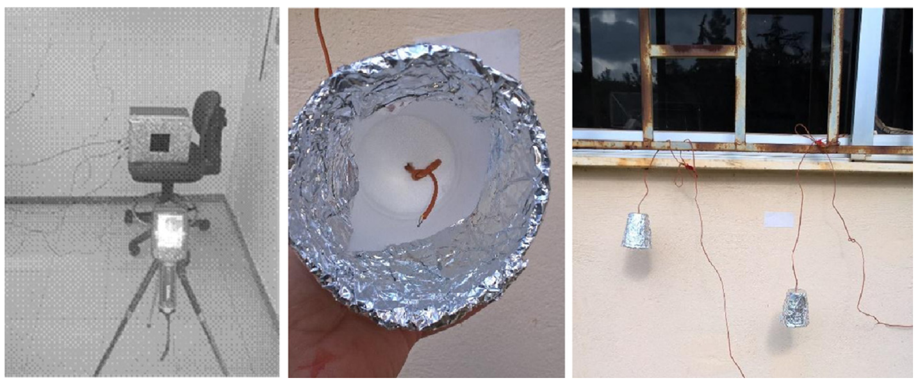

**Fig. 3.** Internal (left picture) and external (centre and right picture) part of the measurement set-up.

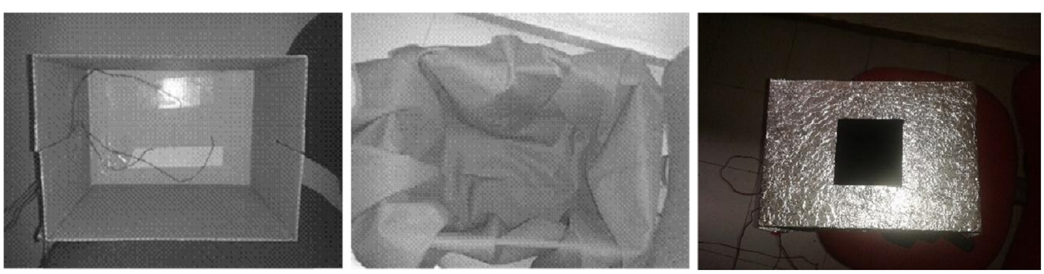

**Fig. 4.** Left: The hollow target (a simple card box for a commercial product; the three placed thermocouples are also shown), Centre: the black coloured textile covering the internal surface of the hollow target and Right: the reflective surface on the box cover as the auxiliary set up is assembled and ready for use.

way to protect the thermocouple sensors was proposed in order to minimise the influence of solar radiation to the corresponding measurements by applying a reflecting cover around the thermocouple endings.

It was concluded that this protection is a major point for maintaining acceptable levels of the measurement procedure uncertainty. The experimental conditions during the present study were rather unfavourable: (a) The sunshine conditions were alternating frequently between situations of medium cloudy conditions and fully sunshine; (b) the wall where the measurements took place is facing the South and the measurement hours were around midday; (c) moderate velocity, continuously alternating direction wind was blowing.

### 2.3. The measurement procedure

For a given time point, a single thermal image was taken, giving simultaneously (Fig. 5):

- A temperature measurement on the internal wall surface ($T_w$).

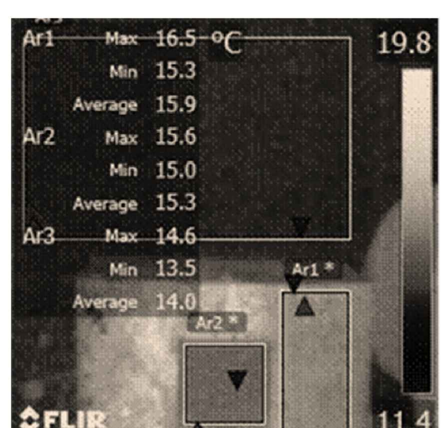


**Fig. 5.** Combined temperature measurement using thermal camera.

- A temperature measurement on the textile positioned in the bottom of the auxiliary set-up through the opening on the cover ($T_{AUX}$).
- A temperature measurement on the reflecting material covering the face of the auxiliary set-up in order to be used to estimate the reflected temperature (according to FLIR manual and ASTM E1862-14(2018) [51]).

At the same time, a data logger was acquiring temperature measurements from the 8 thermocouples by 1 min intervals. This way, for any time point that a thermal camera measurement was taken, an adjacent thermocouple measurements set was also retrieved corresponding to: (a) the air temperature inside the cavity of the auxiliary set-up ($T_{IN,TC,insideAUX}$: the mean from using the three thermocouples placed on the bottom of the auxiliary set-up cavity), (b) the air temperature at a point about 1 m away from the auxiliary set-up ($T_{IN,TC}$: the mean from using three thermocouples) and (c) the air temperature just outside the tested wall ($T_{OUT,TC}$: the mean from using two thermocouples).

As shown in Fig. 5, all of the thermal cameras' images contained both the face of the auxiliary set-up and a part of the internal surface of the tested wall. Using the manufacturer's software for thermal image analysis, in each thermal image, three measurements were gained using the "area" tool. This retrieves all the temperature measurements corresponding to pixels within a specified by the cursor area of the thermal image:

- Area 1 ("Ar1" in Fig. 5) corresponds to pixels of the thermal image on the reflecting surface of the auxiliary set-up. The mean of these measurement results was used in order to estimate the "reflected temperature" of the surfaces, according to a standardised method [51]. This result was then used for a correction on all other measurements gained by the same thermal image.
- Area 2 ("Ar2" in Fig. 5) corresponds to pixels of the thermal image inside the cavity of the auxiliary set-up, through the face opening (the hole on the cover of the box). The mean of these measurement results was used as an estimation of the air temperature ($T_{IN,AUX}$) at a point right in front of the tested wall.
- Area 3 corresponds to pixels of the thermal image on the tested wall. The mean of these measurement results was used as an estimation of the walls internal surface temperature ($T_{W,InfraCAM}$). It is of great importance that the accuracy of the mean retrieved this way is a subject of spatial fluctuation due to many sources of uncertainty [47,48].

By the above procedure, a time series of simultaneous measurements with the thermal camera along with the auxiliary set up and with the eight thermocouples was created at 6th of February 2016 starting from 12:20 (local time in Athens) until 15:50 the same day.

It should be noticed that the conditions under which the experiment took place were chosen to be not favourable for the proposed procedure. More specifically, as described in section 2.1, the tested wall was chosen to be:

- an old construction (constructed earlier than the 80′s), so that many factors related to the ageing of the construction have affected its thermal status and
- not insulated, in order to be sensitive to the changes of thermal conditions in the inside and outside environment.

Moreover, the day of the measurements time series was selected to be a winter day with alternating solar irradiation effect (conditions were alternating continuously between sunshine and light cloudy), something that was depicted in the results of temperature measurements in the outer air (see Fig. 6 in the results section below).

As for the experimental procedure to be complete and the conclusions to be rather representative as for the modification of the usually applied procedure, the experiment was not conducted only under near stable internal air temperature conditions. The experiment was divided into three stages, for which the measurements were performed:

(1) Without stimulating any change in the internal air temperature conditions (duration 1.5 h).
(2) Causing an increase on the internal air temperature by the use of an air heater which was placed far enough away from the tested wall so as that the produced hot air stream could not affect the wall by increasing the conductivity phenomena on the internal wall surface (duration 1.5 h).
(3) During the warming period of the internal air, right after switching off the air heater (duration 0.5 h).

Stages (2) and (3) described above was a robustness test on the validity of the proposed procedure. Robustness was tested against the parameter of changing the heat sources status in the interior space of the measurement set up. The investigated hypothesis was whether the thermal camera measurement on the auxiliary set up will introduce hysteresis parameter to the uncertainty budget of the proposed procedure due to a delay of response of the time series of the results of these measurements.

### 2.4. The proposed procedure

The simplest procedure in which to realize the proposed approach consists of the following steps:

1. Measurement of ambient air temperature before entering the building under study ($T_{OUT}$ in equation (2)) using a simple contact thermometer.
2. As long as keeping the building tightly closed, selection of the proper spot on the internal surface of the building envelope and taking of a series of thermal images by using the auxiliary set-up (10 images taken at 2–3 min time distances could be considered enough, providing all the data for estimating the numerator of equation (2)). The auxiliary set-up could be carried easily to the place of measurement, inside a simple handheld plastic bag. Placing of the auxiliary set-up for the measurements time series would require the use of a desk, a chair (e.g. see Fig. 3) or even of a stool that could be found among the furniture in the measurement place.
3. At the same time with step 2, taking a couple of ambient air temperature measurements ($T_{IN}$ in the denominator of equation (2)) close to the measured spot of the building envelope using the same equipment as in step 1.
4. Optionally, measurement of ambient air temperature outside the building, wright after the auditor / inspector exits the building. In the latter case where step 4 is realized, $T_{OUT}$ could be estimated as the mean of the measurements performed during the 1st and the 4th step of the procedure.

This procedure description also provides a thought on how an external air temperature measurement could be deployed in the total procedure in such a way that it could be kept simplified.

This procedure is not cost effective for a professional that already performs auditing and / or inspection in buildings using a thermal camera of his own. Considering that the number of professionals owing a thermal camera for such activities [52], the assumption that the proposed approach is not cost effective could be generalised.

## 3. Results and discussion

Results based only on measurements by thermocouples are shown in Fig. 6, where $T_{AUX}$ is the value taken on the auxiliary target set up:

In Fig. 6, the time interval following the heater switching on is clearly shown, during which the balance among temperature values was disturbed, despite the fact that such a balance was kept during the entire first stage period. The external air temperature presented a significant variation during the measurement period. This happened despite the fact that the corresponding thermocouples were elementary protected from solar irradiation.

Fig. 7 shows a comparison between the measurements that were conducted within this study (where values were taken upon setting $\varepsilon$ equal to 1), to those taken respectively by the use of the thermocouples that were placed at the bottom of the auxiliary set up. The matching of these values indicates that, even during the transition period, when the heater was started, the auxiliary set-up provided a time series of results that follow the temperature changes retrieved by the thermocouples without any time lag. As explained in the following section of this study, the most essential feature of the proposed procedure is the response of the measuring set-up, as any other uncertainty source in the form of bias may be corrected and its contribution to the results be minimized.

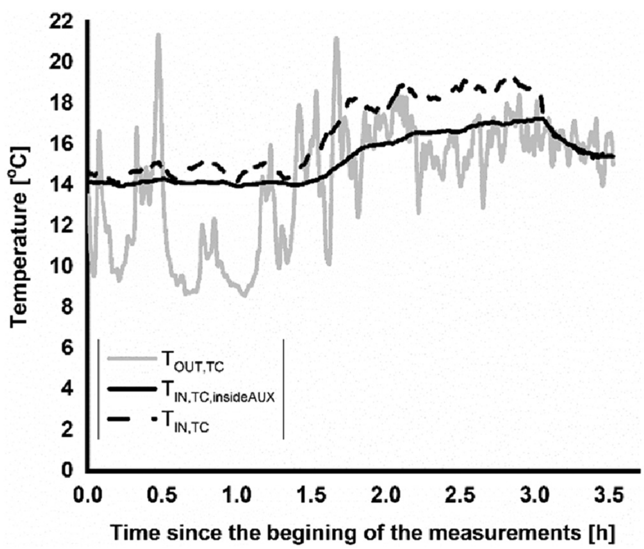


**Fig. 6.** Temperature measurement results using only Thermocouples.

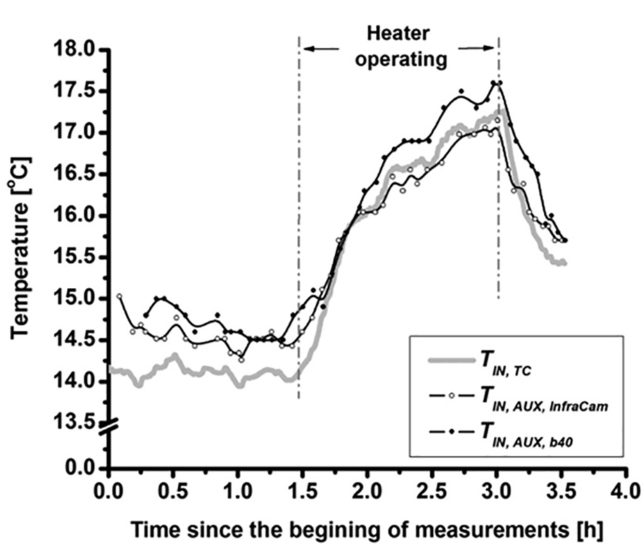


**Fig. 7.** Comparison on the results of temperature measurement inside the auxiliary target set up.

By applying equation (2) on the measurement results taken by the proposed procedure (i.e. using $T_{IN,AUX}$, $T_{W,InfraCAM}$ and $T_{OUT,TC}$), the U-value of the wall was estimated 1.87 W/m$^2$K. The uncertainty of this estimation is analysed in the following section.

Moreover, as explained in paragraph 4.2.6 below, this estimation could be considered to be in line with the reference values as per the calculation method and the HFM measurement, taking into account the corresponding uncertainties.

The variables $T_{IN,TC,insideAUX}$ and $T_{IN,AUX,InfraCAM}$ (or $_{b40}$) correspond to different measurements. The first provides the result of temperature measurement based on the thermocouples that were placed in the bottom of the card box of the auxiliary set-up, while $T_{IN,AUX,InfraCAM}$ (or $_{b40}$) is the result of the measurement using either the InfraCAM or the b40 model infrared camera aiming at the depth of the hollow auxiliary set-up (on the surface of the black textile). The reason for $T_{IN,TC,insideAUX}$ measurement was to monitor, using thermocouples, the increase of air temperature in the depth of the auxiliary set-up, even below the textile that is the target when performing the proposed approach.

## 4. Uncertainty analysis

### 4.1. The full Ishikawa diagram

A complete analyses of all contributing uncertainty sources when equation (2) is used upon IR measurement results, is given in Fig. 8.

#### 4.1.1. Definitional uncertainty

The calculation of the U-value according to equation (2) requires a one-dimensional heat flow transfer through the wall. Inhomogeneities in the wall structure, such as geometrical inconsistencies, can lead to deviations from the one-dimensional heat flow and, consequently, to definitional uncertainty.

By analysing the phenomenology of the thermal transmittance index of building elements it is clear that U-value is not a constant. A multitude of environmental conditions contribute to time variability (short time and long-time effects) of its values.

#### 4.1.2. Measurement significant parameters

The most significant parameter in the building elements' thermal transmittance index measurement is moisture contained in building materials. The presence of moisture adversely affects the thermal conductivity of any building material, especially those used as thermal insulating materials, significantly affecting the U-value of building elements. Budaiwi and Abdou (2013) show in their experiments a thermal conductivity's increase up to 98% for a corresponding moisture increase of 10%, depending on the type of thermal insulation materials being used [31].

Another significant parameter is the operational temperature of the building elements corresponding to the exact time spot when the measurement takes place. As well known, the thermal conductivity value of materials depends on temperature [30]. A more than 8% deviation of the thermal transmittance coefficient value, for an expected 30 K temperature seasonal variation, has been estimated, referring to a typical building element which is part of a wall in a construction in South Europe.

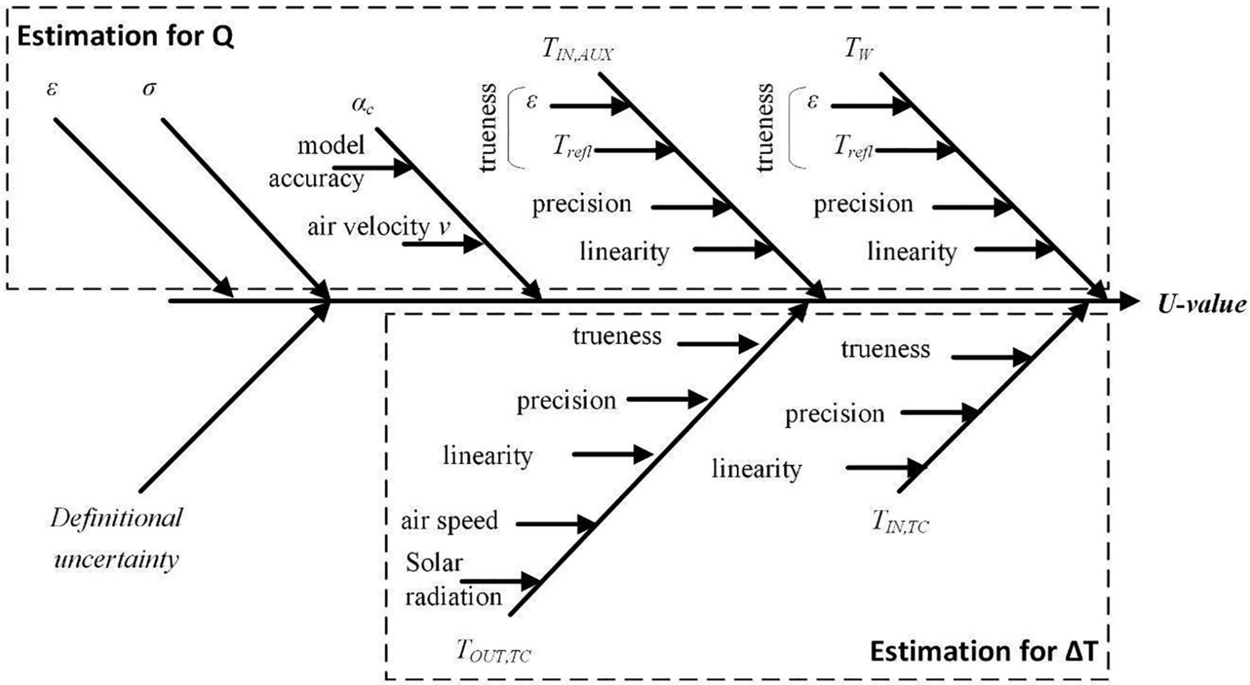


**Fig. 8.** The complete initial Ishikawa diagram for the uncertainty analyses.

Direct solar radiation absorbed by the external building element surface or the low radiant temperature under clear sky conditions, also affect the one-dimensional heat flow transfer. The extent of the effect on the thermal transmittance coefficient measurement increases as building elements' thermal capacity decreases. According to ISO 9869–1, this effect may be avoided significantly by shading the external building element's surface.

### 4.2. Procedure elements under discussion

An analysis on the possibilities for simplification of the measurement procedure and of the corresponding uncertainty estimation follows, according to the results from the experiment within this study.

#### 4.2.1. Systematic deviations during measurements using thermal camera

As it has been investigated within an earlier study [43], a very significant parameter for the reliability of the method is the trueness of the wall surface temperature measurement using the thermal camera. Fig. 9 presents an update of that finding by adding the results from this study. A regression line on these data provides an estimation of a systematic deviation among calibration curves of different thermal cameras provided by the same manufacturer. Probably this is because the type b40 and b50 devices operate on a calibrated range between 0 and 100 °C, while the type InfraCAM has a range from −20 to 350 °C.

Based on that, all measurements performed with the InfraCAM have been corrected according to the results from regression line shown in Fig. 9. The regression line was estimated using 98 pairs of measurements, the line intercept was calculated as 2.7 ± 0.1 °C and the slope factor as 0.850 ± 0.008 (dimensionless). The corresponding Pearson r correlation coefficient was 0.999.

When a difference between two different estimations of the same measurand (i.e. a difference between two temperature measurements as in the present study) are used in order to achieve a final measurement result, there is a great opportunity to maintain

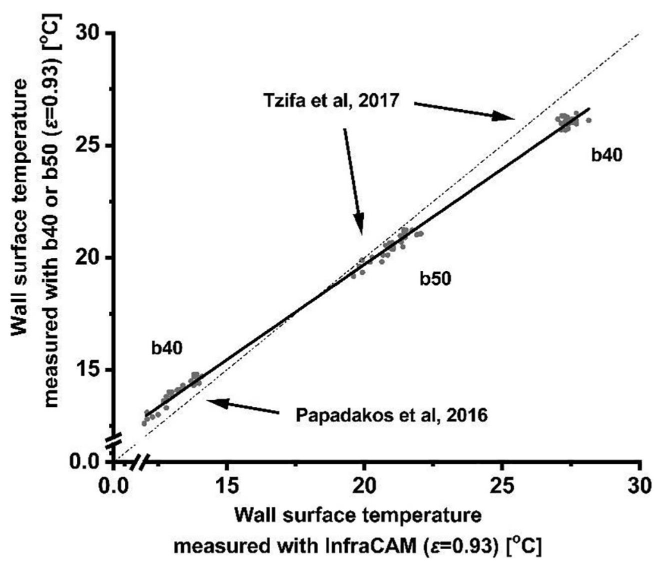


**Fig. 9.** Systematic deviations between measurement results using different thermal cameras.

low levels of uncertainty of the result by performing both contributing measurements using the same or strongly reproducible equipment. As shown in Fig. 9, measurements of a surface temperature using even two different thermal cameras could provide strongly reproducible results. This is of great interest if there is a consideration for further applying the proposed auxiliary set up for measuring, also, the external air temperature. This way, not only the nominator, but the whole ratio of equation (2) would be estimated using only results from thermal cameras.

The difference between the measurement results using any of the two infrared cameras (either InfraCAM or b40) and the measurement results using thermocouples is something that is totally normal when different measuring apparatus are used even for exactly the same measurement. The reasons for that lie among parameters that could lead to different behaviour of the calibration of any separate measuring apparatus (e.g. the case shown in Fig. 9 depicting the systematic deviation between the calibrations of the two infrared cameras).

When using the subtraction of two measurement results inside a model that provides a final result, the above systematic deviations are inevitable if we use different apparatus for each of the measurement results being subtracted. The aim of this study and of the corresponding proposed approach is to diminish the effect of those systematic deviations, as using exactly the same apparatus to estimate both measurement results being subtracted leads to a mutual deletion of the same effect on both measurement results being subtracted.

Using a single thermal image in the proposed approach in order to estimate both the wall surface temperature and the ambient air temperature leads to a procedure where, practically, the calibration quality of the measuring equipment (the thermal camera) is nearly obsolete. This means that a thermal camera user could perform the proposed procedure even if using a thermal camera that is not calibrated at an accredited laboratory.

#### *4.2.2. Auxiliary set up calibration for air temperature measurements*

An essential factor related to the proper use of the auxiliary target set up is the estimation of a representative setting value for the parameter of emissivity $\varepsilon$ on the thermal camera so as to achieve measurement results that correspond accurately to the value of air temperature.

#### *4.2.3. Surface temperature measurement using a thermal camera*

Semi-variogram has been used to exploit the information from the thermal camera. A semivariogram is a graphical representation of the spatial variability in a given set of data [53,54]. Analysis using a semivariogram could even provide a complete uncertainty budget, based on a type A estimation, for measurements where the spatial variation of the results is the prevailing parameter [55].

Fig. 10 shows the semi-variogram for one of the measurements using the InfraCAM on the surface of the wall. It is evident that due to any uncertainty parameter attributed to the use of a thermal image, including the factor of the spatial variation of the measurement itself, an uncertainty of the order of 0.12 °C cannot be avoided for a measurement of surface temperature at about 14 °C. This is in line with the technical specifications referred by the manufacturer of the equipment and this could be mostly attributed to the electronic noise produced by the circuits of the device itself and all kinds of resolution, also referred by the manufacturer of the device. In any case, a similar estimation could be performed for verification of spatial uncertainty level, every time such a measurement is conducted.

#### *4.2.4. Sensitivity analysis*

Equation (2) consists of many elements, three of which are measurement results ($T_{IN}$, $T_{OUT}$ & $T_W$). Sensitivity analysis on the effect of each element's uncertainty to the combined uncertainty of the U-value estimation reveals the different impact of the corresponding quantities. The following equations refer to the sensitivity coefficient $C_x = \frac{\partial U}{\partial x}$ of each of the equation (2) elements, in the case where $T_{IN}$, $T_{OUT}$ and $T_W$ are estimated with three measuring devices (i.e. two contact thermometers for $T_{IN}$ and $T_{OUT}$ and a thermal camera for $T_W$, as in the procedure proposed by the manufacturer of the thermal camera):

$$C_{T_{IN}} = \frac{\varepsilon \cdot \sigma \cdot \left(3 \cdot \mathrm{T_{IN}}^4 - 4 \cdot \mathrm{T_{IN}}^3 \cdot \mathrm{T}_{OUT} + \mathrm{T}_W{}^4\right) + a_c \cdot (\mathrm{T}_W - \mathrm{T}_{OUT})}{(\mathrm{T_{IN}} - \mathrm{T}_{OUT})^2} \tag{3}$$

$$C_{T_{OUT}} = \frac{\varepsilon \cdot \sigma \cdot \left(\mathrm{T_{IN}}^4 - \mathrm{T}_W{}^4\right) + a_c \cdot (\mathrm{T_{IN}} - \mathrm{T}_W)}{(\mathrm{T_{IN}} - \mathrm{T}_{OUT})^2} \tag{4}$$

$$C_{T_W} = -\frac{4 \cdot \varepsilon \cdot \sigma \cdot \mathrm{T}_W{}^3 + a_c}{\mathrm{T_{IN}} - \mathrm{T}_{OUT}} \tag{5}$$

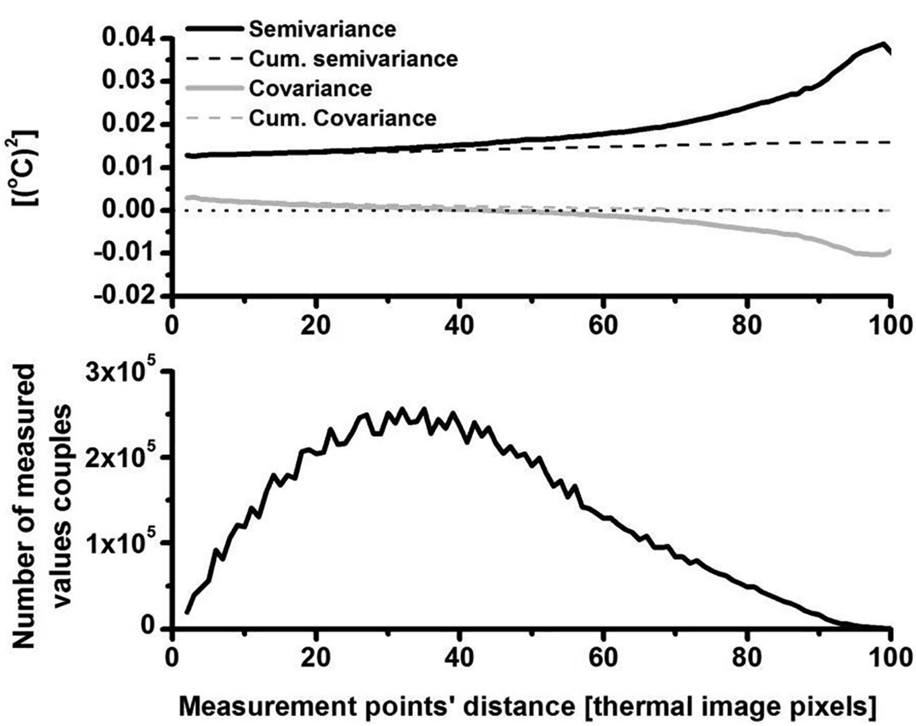


**Fig. 10.** Surface temperature measurements semi-variogram per pixel of thermal image (for a given distance between the camera lens and the target, one pixel is approximately equal to a distance interval one the measured surface).

$$C_{\varepsilon} = \sigma \cdot \frac{T_{IN}{}^{4} - T_{W}{}^{4}}{T_{IN} - T_{OUT}} \tag{6}$$

$$C_{\sigma} = \varepsilon \cdot \frac{T_{IN}{}^{4} - T_{W}{}^{4}}{T_{IN} - T_{OUT}} \tag{7}$$

$$C_{\alpha_c} = \frac{T_{IN} - T_{W}}{T_{IN} - T_{OUT}} \tag{8}$$

The above sensitivity coefficients were used to estimate the uncertainty budget of the result, according to the law of error propagation, according to equation (9) proposed by ISO [40]:

$$u_c(y) = \sum \left(c_i^2 \cdot u^2(x_i)\right) + 2 \cdot \sum \sum c_i \cdot c_j \cdot u(x_i, x_j) \tag{9}$$

where $u_c(y)$ is the combined standard uncertainty of the final measurand $y$, which in the case of this study is the U-value of the wall.

The calculation according to equation (9) was performed both in the case were the result was taken if using the proposed procedure and if using the thermocouples measurement results for the inside air temperature. Measurement results only from the 1st phase of the experiment (steady-state conditions) were used in both cases.

#### 4.2.5. Uncertainty budget

Table 2 shows the uncertainty budget in the above-mentioned case. According to the JCGM 200: 2008 [41], the definition of the term "uncertainty budget" is the following:

"2.33 uncertainty budget: statement of a measurement uncertainty, of the components of that measurement uncertainty, and of their calculation and combination

*NOTE* (as in the reference) *An uncertainty budget should include the measurement model, estimates, and measurement uncertainties associated with the quantities in the measurement model, covariances, type of applied probability density functions, degrees of freedom, type of evaluation of measurement uncertainty, and any coverage factor.*"

The contribution of the cross – correlation between temperature measurements been used in each case was estimated upon the Pearson correlation coefficient ($r_s$) which was estimated by the time series of simultaneous measurement results along the entire duration of the experiment (including the stages of the robustness investigation). Specifically, covariance factors for any pair of variables $x_i$ and $x_j$ was estimated as $u(xi,xj) = r_s(x_i,x_j) \cdot u(x_i) \cdot u(x_j)$, where $u(xi)$ and $u(xj)$ are the standard uncertainty characterising the estimation of $x_i$ and $x_j$.

The measurement result for $x_i$ (or $x_j$) reported in table 2 refers to the mean of the analysed variable during the 1st phase of the experiment. The uncertainty for each temperature measurement was estimated also by applying equation (9), taking into account the standard deviation of the time series of results of each variable during the 1st phase of the experiment (a type evaluation of uncertainty) and the contribution of the accuracy of the calibration procedure for the TC's apparatus (a type B evaluation of uncertainty, having a triangular distribution, based on a reasonable assumption). Standard uncertainty for emissivity $\varepsilon$ was assumed safely as having bonds of ± 0.05 (due to the fact that the exact characteristics of the wall surface material – the paint – are unknown) and a type B evaluation was performed with a triangular distribution. Stephan – Boltzman's constant σ was assumed as having zero uncertainty. Air convection coefficient's value was assumed to have bonds of ± 0.01 W·m$^{-2}$, due to a slight variation in the status of air velocity, so a type B evaluation with a triangular distribution was performed.

Systematic error in estimating the emissivity of the wall surface can be dealt by using the ASTM E1933 – 14(2018), "Standard Practice for Measuring and Compensating for Emissivity Using Infrared Imaging Radiometers" [56]. But this would make the proposed approach more complicated and would deteriorate scope of the proposed procedure.

The uncertainty budgets shown in Tables 2 & 3 explain how the cross-correlation between the three temperature measurement results affects the accuracy of the final result. It is evident that these three measurements must be dealt with as a set, i.e. as

**Table 2**
Uncertainty budget for the already been used procedure (using thermocouple for estimating $T_{IN}$).

| Variable(s) $x_i$ (, $x_j$) | Mean value of $x_i$ | $u(x_i)$ or $u(x_i,x_j)$ | Sensitivity coefficient(s) $c_i$ (, $c_j$) | $(c_i \cdot u(x_i))^2$ or $2 \cdot c_i \cdot c_j \cdot u(x_i,x_j)$ |
|---|---|---|---|---|
| *mean* $T_{IN,TC}$ [K] | 286.85 | 0.12 | 0.98 | 0.014 |
| *mean* $T_{W,infraCAM}$ [K] | 283.65 | 0.17 | −1.55 | 0.073 |
| *mean* $T_{OUT,TC}$ [K] | 285.65 | 0.22 | 0.58 | 0.016 |
| $T_{IN,TC}$, $T_{W,InfraCAM}$ [K] | see above | 0.039 | see above | −0.048 |
| $T_{IN,TC}$, $T_{OUT,TC}$ [K] | see above | 0,031 | see above | 0.023 |
| $T_{OUT,TC}$ , $T_{W,InfraCAM}$ [K] | see above | 0,051 | see above | −0.052 |
| ε [-] | 0.93 | 0.020 | 1.99 | 0,002 |
| $\sigma$ [W·m$^{-2}$·K$^{-4}$] | 5.67 × 10$^{-8}$ | 0 (const.) | 3.3 × 10$^{8}$ | 0 |
| $\alpha_c$ [W·m$^{-2}$] | 0.04 | 0.0029 | 0.38 | 1.2 × 10$^{-6}$ |
| $u_c^2(y)$ | | | | 0,027 |
| Combined standard uncertainty $u_c(y)$ (coverage factor $k$ = 1) (y is U-value) | | | | 0.16 |

**Table 3**
Uncertainty budget for the proposed procedure (using thermal camera, model FLIR InfraCAM, for estimating $T_{IN}$).

| Variable(s) $x_i$ (, $x_j$) | Mean value of $x_i$ | $u(x_i)$ or $u(x_i,x_j)$ | Sensitivity coefficient(s) $c_i$ (, $c_j$) | $(c_i \cdot u(x_i))^2$ or $c_i \cdot c_j \cdot u(x_i,x_j)$ |
|---|---|---|---|---|
| *mean* $T_{IN,AUX}$ [K] | 286.85 | 0.17 | 0.98 | 0.029 |
| *mean* $T_{W,InfraCAM}$ [K] | 283.65 | 0.17 | −1.55 | 0.073 |
| *mean* $T_{OUT,TC}$ [K] | 285.65 | 0.22 | 0.58 | 0.016 |
| $T_{IN,AUX}$, $T_{W,InfraCAM}$ [K] | see above | 0.056 | see above | −0.067 |
| $T_{IN,AUX}$ , $T_{OUT,TC}$ [K] | see above | 0.056 | see above | 0.032 |
| $T_{OUT,TC}$ , $T_{W,InfraCAM}$ [K] | see above | 0.051 | see above | −0.050 |
| ε [-] | 0.93 | 0.020 | 1.99 | 0.002 |
| $\sigma$ [W·m$^{-2}$·K$^{-4}$] | 5.67 × 10$^{-8}$ | 0 (const.) | 3.3 × 10$^{7}$ | 0 |
| $\alpha_c$ [W·m$^{-2}$] | 0.04 | 0.0029 | 0.38 | 1.2 × 10$^{-6}$ |
| $u_c^2(y)$ | | | | 0.035 |
| Combined standard uncertainty $u_c(y)$ (coverage factor $k$ = 1) (y is U-value) | | | | 0.19 |

differences of temperatures and not as isolated figures. It is also shown that the proposed management of the U-value measurement procedure, using the auxiliary set-up, provides uncertainty levels comparable to those provided by a realization of equation (2) under conditions where high accuracy equipment is used.

The analogue to digital transformer and data logger that was used is a quite expensive one. It is not expected to be available to many professionals performing such a kind of audits or inspections in existing buildings.

The uncertainty of the existing method shown in table 2 could be characterized as the ideal case. Table 3 shows that the simplified approach, using only one thermal camera and a simple commercial thermometer, provides the same uncertainty with the reference procedure.

#### 4.2.6. Verification of the proposed measurement procedure

The uncertainty budget for the proposed approach, as analysed in table 3, is almost 0.4 $W/m^2K$ for an expanded uncertainty with $k = 2$ (approximately a 95% confidence interval). This leads to a final estimation in the interval (1.5, 2.3) for the U-value of the tested wall. This interval already includes the value of 1.6 obtained by the HeatFlowMeter procedure (ISO 9869–1:2014) and is also compatible with the value of 1.5 estimated by the calculation method (ISO 6946:2017) which, as shown in table 1, corresponds to a quiet wide interval (almost 1.0 to 2.0).

By the above results, the result of the proposed procedure is verified even though the two measurements (the ISO 9869–1:2014 HFM method and the proposed) were performed in different days, so even the true U-value could be slightly different between these two experiment periods.

### 4.3. Reduced final Ishikawa diagram

Upon the above analysis, the cause and effect diagram on the analysis of uncertainty parameters that final contribute significantly to the result that should be taken into account are shown in Fig. 11.

According to this reduced form, the variables that influence the most the final result are (a) the temperature difference between the internal air and the corresponding wall surface, measured by a single thermal image as analysed in a previous paragraph and (b) the temperature difference between internal and external air, measured even with the use of simple contact thermometers. As shown in Fig. 12, no matter which between the contact thermometers and the thermal image method has the best trueness, it seems that the latter exhibits the smallest variation in relation to time dimension, probably because of the smaller sensitivity to the environmental factors.

Referring to "smaller sensitivity to environmental factors" aims at the conclusion derived by the robustness test which was per-

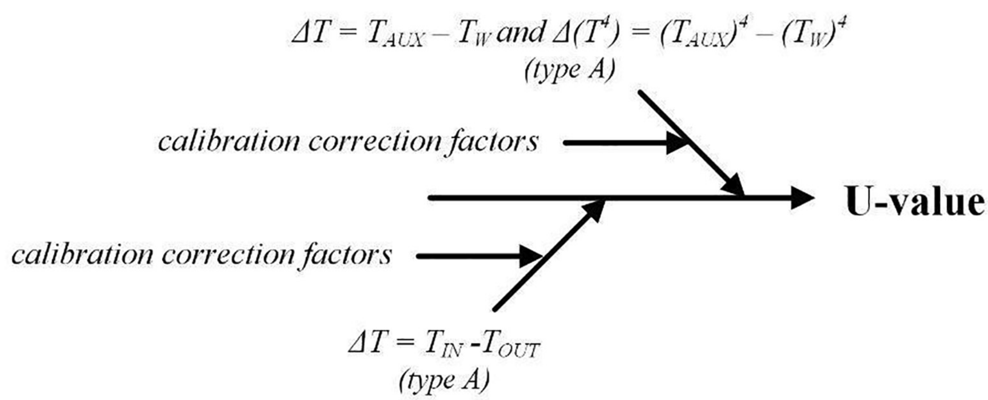


**Fig. 11.** Final, reduced Ishikawa (cause and effect) diagram for uncertainty parameters analysis.

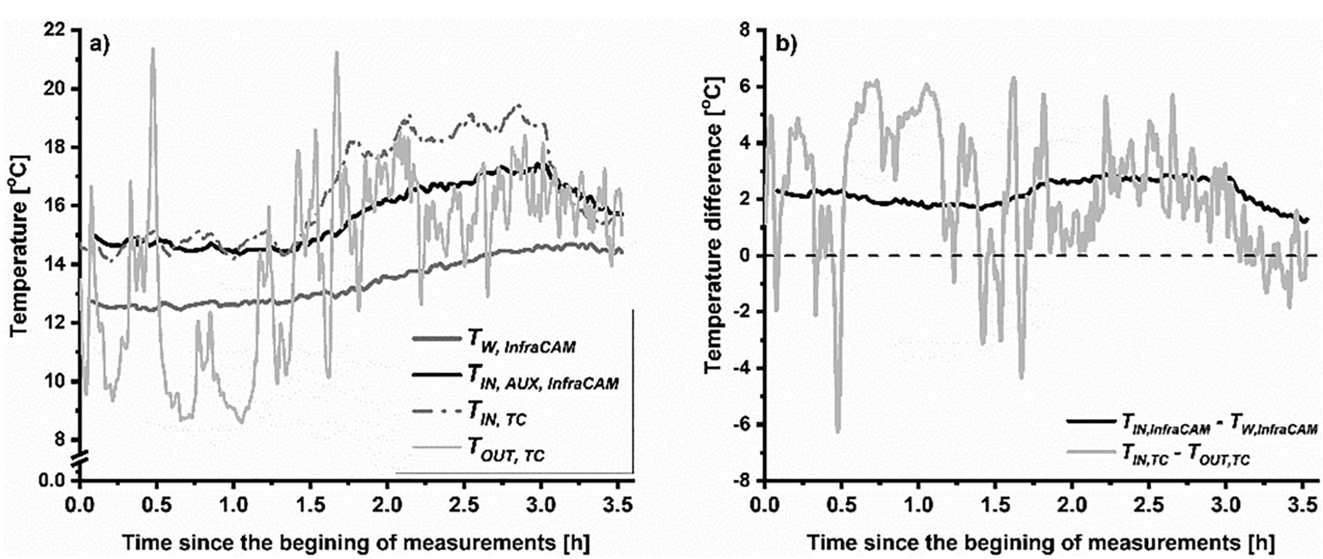


**Fig. 12.** Temperature measurement results used for estimating equation (2) values, due to the proposed procedure: a) all temperature measurement results separately, b) as differences of measurement results as presented in the numerator and the denominator of equation (2).

formed due to changing the air temperature (and, subsequently, due to slightly changing the air velocity) status in the region of the experiment. Fig. 6 and Fig. 7 show that thermocouples exhibit a more steeple increase in the air temperature measurement results than those provided by the infrared camera proposed approach.

## 5. Conclusions

Thermal transmittance index measurement with the use of a thermal camera is a simple and fast procedure that does not need massive equipment nor prolonged periods of measurements, as in the case of heat flux measurements conducted in a laboratory in order to determine the thermal characteristics of materials. The reliability of its results, expressed by the criterion of the corresponding uncertainty, could be maintained into manageable levels and it could be also a subject for optimisation within future efforts.

The use of the auxiliary target set up that is described and analysed within this study is assessed as successful. Under the proposed procedure, the U-value of the wall was estimated 1.87 W/m$^2$K, in line with the reference values, taking into account the estimated uncertainty of 0.37 W/m$^2$K at a 95 percent level of confidence (coverage factor $k$ = 2). Even during the transition period, when the heater was started, the auxiliary set-up provided a time series of results that follow the temperature changes retrieved by the thermocouples without any time lag. The most essential feature of the proposed procedure is the response time of the measuring set-up, as any other uncertainty source in the form of bias may be corrected and its contribution to the results be minimized.

Moreover, the design of this set-up could be a subject of further optimisation. It is of critical importance to create a similar auxiliary set-up that could serve the same way to the simplification of the internal to external air temperature difference measurement, which could be conducted either by means of contact thermometers, to determine heat fluxes, or by the use of thermal camera, i.e. based on the infrared radiation. The above-mentioned auxiliary set-up, as it can be concluded based on this study's measurement results, should be carefully selected in order to reduce the contribution to the distortion caused by the external environment conditions.

Upon managing all these partial parameters and their integration to the proposed procedure, this could eventually become a useful tool for supporting the decisions that have to be made during the refurbishment of buildings, emphasising on the improvement of their thermal performance and thermal comfort.

Furthermore, this study can be expanded to provide answers to some equally interesting research questions, including the upscaling of the process with a sufficient number of existing buildings so as to be able to verify the validity also for other types of constructions and the simultaneous use, for some of these repetitions, of a heat flow meter apparatus for further verification or not of the nominal values for the thermal transmittance index values that correspond to the measured specimens. Finally, if the ambitious European goal of having the entire building stock upgraded to Nearly Zero Energy Building levels by 2050 is to be achieved, a Herculean auditing work will be needed; fast and reliable U value determinations are an integral part of this work.

## CRediT authorship contribution statement

**Georgios Papadakos:** Conceptualization, Methodology, Investigation, Writing - original draft. **Vangelis Marinakis:** Visualization, Writing - review & editing. **Christos Konstas:** Data curation. **Haris Doukas:** Project administration. **Agis Papadopoulos:** Supervision.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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