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# In situ thermal characterization of existing buildings aiming at NZEB standard: A methodological approach

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ABSTRACT

Building performance is strongly influenced by the performance of their structural parts, consequently affecting annual energy demands. The thermal characterization of building components can be achieved thanks to the knowledge of their internal layers and the thermal properties of each material. Considering existing buildings, technical data may be unidentified and heat transfer phenomena between walls and environments can be influenced by air-conditioning systems and local thermo-fluid dynamic conditions. Moreover, the conversion of an existing building into a Nearly Zero Energy Building (NZEB) requires accurate measurements and simulations compared with Standards suggestions, based on simplified procedures. Therefore, on-site surveys become fundamental. Standards suggestions can help engineers or technicians to define some unknown information related to heat transfer coefficients and thermo-physical properties. Nevertheless, can Standards' suggestions be considered reliable in every situation? This paper tries to answer this question, debating some investigations conducted in the last years and proposing a methodological approach.

## 1. Introduction

Energy efficiency in the building sector is considered a key issue in order to reach sustainable development goals, also reducing greenhouse gas emissions (European Directive, 2002/9, 2002). Buildings energy performance can be enhanced through several measures, also considering local conditions in addition to the features of the built environment. In certain countries, historical heritage requires specific retrofit assessments due to legal restrictions (Costanzo et al., 2006). Considering thermal characterization of buildings, it is fundamental to distinguish new and old structures. In new constructions, the design phase makes it possible to exploit a complete set of information commonly deriving from the technical data sheets of the products and materials. On the other hand, in existing buildings it may not be possible to trace the technical data of the used materials because the documentation may have been lost or structural interventions could have altered the internal composition of the walls (Desogus et al., 2011). Moreover, heat transfer phenomena between walls and environment can be influenced by air-conditioning systems and local thermo-fluid dynamic conditions. In these cases, on-site measurements become crucial (Evangelisti et al., 2018a). In addition, it is worthy to notice that Standards can help engineers or operators to define some unidentified information related to heat transfer coefficients and thermo-physical properties. However, the question is: "*can Standards' suggestions be considered reliable in every situation?*".

In addition, this question is fundamental when the aim of an energy retrofit is the conversion of an existing building into a Nearly Zero Energy Building (NZEB) (Kelly, 1920; Foley, 2012; Menassa, 2011).

The Energy Performance of Buildings Directive (EPBD, 2010/31/EC) (European Commission and Commission delegated regulation (EU), 2012) instituted the NZEB meaning as a building characterized by high-ranking energy performance, where the remaining energy demand should be for most covered by renewable energy generated on-site or nearby. Therefore, the NZEB concept is very flexible with no single, standardized classification in Europe. In Italy, a NZEB is defined according to the Ministerial Decree 26 June 2015 (DM, 2015) as a building characterized by a higher performance than a virtual building, considered as reference. This virtual structure has the same shape, location, orientation and function as the actual one, and its physical properties are those fixed by law in the definition of the reference building. Different strategies were promoted by member states for increasing the number of NZEBs and for simplifying the requalification of old buildings. Taking into account existing buildings, cost-benefits analyses have been proposed to assess the financial efficiency of energy requalification interventions. The economic investigation can be extended to the energy and environmental fields introducing indicators, such as energy and

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**Nomenclature**

| | |
|---|---|
| $H$ | Vertical surface height [m] |
| $h_{c,ext}$ | External convective coefficient [W/m$^2$K] |
| $h_{c,int}$ | Internal convective coefficient [W/m$^2$K] |
| $h_{e,tot}$ | External total coefficient [W/m$^2$K] |
| $h_{i,tot}$ | Internal total coefficient [W/m$^2$K] |
| $h_{r,ext}$ | External radiative coefficient [W/m$^2$K] |
| $h_{r,int}$ | Internal radiative coefficient [W/m$^2$K] |
| $q$ | heat flux density [W/m$^2$] |
| $R_i$ | Thermal resistance of the i-th layer [m$^2$K/W] |
| $R_{se}$ | External surface thermal resistance [m$^2$K/W] |
| $R_{si}$ | Internal surface thermal resistance [m$^2$K/W] |
| $R_{wall}$ | Wall thermal resistance [m$^2$K/W] |
| $T_e$ | Outdoor air temperature [°C] |
| $T_i$ | Indoor air temperature [°C] |
| $T_s$ | Surface temperature [°C] |
| $U$ | Wall thermal transmittance [W/m$^2$K] |
| $v$ | Wind velocity [m/s] |
| $V_{loc}$ | Wind velocity near wall [m/s] |
| $\Delta T$ | Surface-air temperature difference [°C] |

environmental payback times, to describe the effectiveness of the retrofit intervention from a more extensive point of view (Asdrubali et al., 2019). When proposing a retrofit aiming at the NZEB standard, it is important to perform a cost-benefit analysis also from the environmental point of view, so the modeling and the design need to be very accurate (Asdrubali et al., 2020; Ballarini et al., 2017; Becchio et al., 2015).

Aiming at assessing NZEBs energy performance requirements, European Community countries applied a cost-optimal methodology framework to assess cost-optimal levels of buildings minimum energy performance requirements (Saglam et al., 2017). This methodology framework assesses the buildings costs and effects on primary operational energy demand for heating, cooling, ventilation, domestic hot water and lighting systems. Several researches were carried out in different countries with the aim of defining cost-optimal retrofit solutions for different buildings category (Ferreira et al., 2016; De Lieto Vollaro et al., 2015; Ascione et al., 2015; Foucquier et al., 2013).

New constructions are based on efficient and sustainable principles, thus, for achieving a significant energy saving level and reducing the environmental impacts, the real challenge deals with the retrofit interventions on existing constructions. The conversion of an existing building into a nearly Zero Energy Building requires accurate measurements and simulations compared with Standards suggestions, based on simplified procedures (Fumo, 2014). Buildings are often characterized by complex components, characterized by specific stratigraphy not always known. For this reason, it is important to understand buildings energy behavior through accurate energy analysis (Pisello et al., 2014; Friedman et al., 2014; Evangelisti et al., 2014). Moreover, nowadays many software tools can be applied, characterized by advanced calculation codes, and different instrumental diagnosis can be performed. Of course, the performances of the building's component are crucial in order to assess the annual energy needs (UNI TS 11300, 1130; UNI 10351, 1035; UNI 10355, 1035). The energy retrofit of a building is often addressed by using a simulation software (Fumo, 2014). In new buildings (or recently built), predictive models can be realized through dynamic codes, using technical data from product data sheets. Conversely, when buildings need requalification for enhancing energy performance, in situ experimental evaluation may be essential.

The knowledge of the actual building performance is strictly related to understanding the real behavior of its components. In Italy, when reliable information about walls stratigraphy cannot be obtained, the categorization indicated by the Standard UNI TS 11300 (Evangelisti et al., 2016) can be used. Starting from the building construction year, a conventional stratigraphy of that historical period is indicated by the Standard, providing information about its thermal transmittance in function of the wall thickness.

On the other hand, if the wall stratigraphy is known but reliable information about the material's thermal properties are not available, the Standards UNI 10351 (Özisik and Orlande, 2000) and UNI 10355 (Kim et al., 2002) can be consulted. These Standards suggest reference values for the thermophysical properties of commonly used building materials. Therefore, achieving consistent information regarding each layer of a wall is rather difficult.

Considering on-site surveys, the elaboration of the acquired data allows to characterize the behavior of the wall in steady state regime (Antonopoulos et al., 1997). Dynamic characterization needs parameters that take into account the thermal inertia of the wall. The inertial properties are not computed by a sole parameter and different methods have been studied for evaluating it. The evaluation of thermo-physical properties is an example of assessing parameters as a reverse problem (Chaffar et al., 2014), a topic considered by numerous researchers (Faye et al., 2015).

An analytical approach was proposed by Antonopoulos et al. (Orosa and Oliveira, 2012) for the on-site evaluation of walls thermal properties characterized by different layers. The authors validated their method relating theoretical and experimental data, discovering a correspondence with the a priori identified values.

Aiming at defining the thermo-physical properties of a homogeneous wall, thermal stresses combined with infrared thermal imaging, were used by Chaffar et al. (Gori and Bisegna, 2010) in an experimental set-up. An iterative procedure was applied for achieving the error minimization between the simulated and the experimental temperatures registered by the thermal imaging camera.

A procedure for estimating the actual heat capacity of a symmetric wall was presented by Faye et al. (Maillet et al., 2000). A model based on the thermal quadrupole approach was validated by using a climatic chamber, imposing sinusoidal boundary conditions.

The thermal inertia of a wall was characterized by Orosa and Oliveira (O 6946 Building compone), using the time constant. They investigated the inertial behavior of two walls using the linear regressions of the logarithmic temperature differences with respect to the outdoor conditions.

The parameter assessment can also be done applying stochastic methods, which allow to overcome a few of the restrictions of deterministic approaches, especially the multiple-minima nature of the function to be minimized (Evangelisti et al., 2017).

Starting from what has been stated, a multilayer wall can be studied as a single homogeneous layer characterized by equivalent thermophysical properties. To reach this goal, an equivalent model needs to be defined. In literature, the equivalence between a homogenous medium and a two-layer slab exposed to a thermal flux that is uniformly distributed on one face was analyzed (O 9869-1 - Thermal Insu), concluding that there is no equivalent homogenous medium. The exception is represented by the case where the thermal effusivities of the two original layers are equal. Beyond this limitation, it is interesting to ask whether an approximate similarity is still possible and to what extent an equivalent wall can reproduce the dynamic thermal behavior of different multilayer walls. This is one of the subjects of this work.

Moreover, considering the heat transfers between air and walls, the standard ISO 6946 (Evangelisti et al., 2015) allows to obtain useful information about the heat transfer coefficient. Standardized coefficients values are provided in function of the heat flux direction. Currently, these coefficients are widely used for calculating thermal transmittance values and for running simulation models. Nevertheless, Standards' suggestions cannot be considered reliable in every situation (Evangelisti et al., 2019).

Understanding the real performance of buildings allows to realize an improved building-plant coupling, preventing both the oversizing of air-conditioning systems and cutting harmful emissions and environmental

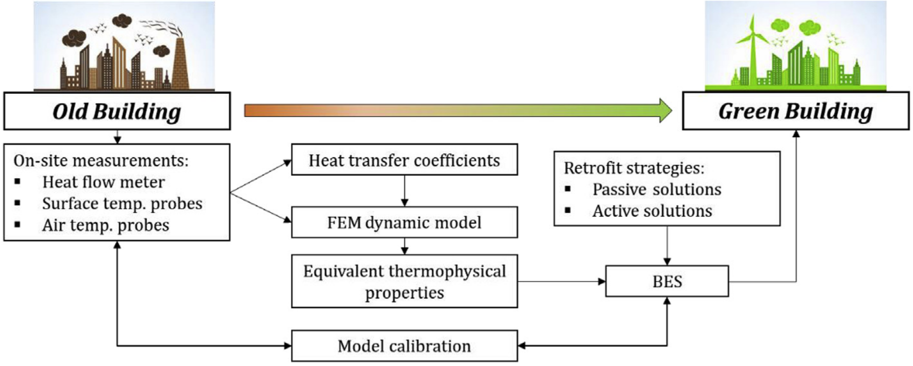

**Fig. 1.** From inefficient to green buildings: the whole methodological approach. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

effects. The novelty of the work regards the assessment of a methodology able to define the equivalent thermal properties of a multilayer wall when the stratigraphy is unknown (common condition for old buildings) or when, even if the stratigraphy is known, it is not possible to accurately identify the actual thermal properties of each specific layer. Moreover, another aspect that is quite innovative in this paper is the analysis of the reliability of the internal and external convective/radiative coefficient values calculating them through different correlations, experimental data and applying the Standards suggestions.

Thus, some methodological approaches are presented, providing possible interactions among them, in order to obtain additional useful information to generate reliable energy simulation models. Moreover, on-site thermal characterization can help practitioners to generate reliable models in order to lead old and inefficient buildings towards efficient and sustainable solutions.

## 2. Materials and methods

### 2.1. Methodological approach

In this section some methodological approaches, based on experimental investigations, will be discussed. The proposed methods allow to obtain information about the internal and external heat transfer coefficients, thermal transmittance and dynamic thermal properties of building components. All this can be achieved using specific measurement instruments and processing data for obtaining additional information, also considering simulation codes to solve inverse engineering problems.

All these methodological approaches represent fundamental elements of a whole operational approach useful for analyzing old buildings and leading them to green buildings. This global approach is schematized in Fig. 1. The first step is based on in situ surveys for acquiring data about heat fluxes, surface and air temperatures inside and outside the building. As will be discussed in the next sections, these data can be processed for obtaining total heat transfer coefficient. Moreover, it is possible to carry out a more detailed analysis, also highlighting the radiative and convective contributions.

The obtained data can be also used to set the actual boundary conditions in a simulation software for solving reverse engineering problems related to the equivalent thermophysical properties identification of multilayer walls, characterized by unknown stratigraphy (as often happens in old buildings).

As it is known, experimental data are fundamental for calibrating Building Energy Simulation (BES) models. Consequently, passive and active solutions can be tested for reducing annual energy needs, thus reaching the green building concept.

#### 2.1.1. Thermal transmittance measurements

Heat fluxes and air temperatures can be acquired through thermal transmittance (generally identified as *U-value*) measurements. These surveys are performed applying the Heat-Flow Meter (*HFM*) method, following the ISO 9869–1 (Meng et al., 2015). The *HFM* method is based on heat fluxes and indoor/outdoor air temperature measurements. Heat fluxes are acquired by means of a sensor (called heat-flow plate) which needs to be attached on the inner side of the building envelope. It is essential to fasten the heat-flow sensor in a representative part of the wall, avoiding effects related to cold bridges. Therefore, areas near corners and zones influenced by irregularities must be avoided for avoiding errors during measurements. The infrared thermography can be used as preliminary investigation for the cold bridges' identification (Ito et al., 1972a).

As mentioned before, for obtaining the thermal transmittance, outdoor and indoor air temperatures need to be recorded. Heat fluxes and air temperatures can be employed for calculating the U-value applying the next formula:

$$q = U(T_i - T_e) \tag{1}$$

where $q$ is the heat flux density, and $T_i$ and $T_e$ are the temperatures of the air inside and outside the building. The measuring device saves thermal transmittance values for each data acquisition step. Then, the progressive average method needs to be applied for determining the stationary U-value:

$$U = \frac{\sum_{j=1}^{N} q_j}{\sum_{j=1}^{N} \left(T_{ij} - T_{ej}\right)} \tag{2}$$

where $N$ represents the overall recorded samples.

A minimum time of 72 h is necessary for finding a steady thermal transmittance value. When measurement conditions are not stable, a longer measurement time is required, commonly more than 7 days (Loveday and Taki, 1996a). However, the measurements accuracy can be influenced by the effect of wind velocity, place of the sensors, radiative influences and solar radiation impacts. Accordingly, measurements on walls facing north are preferred (Hagishima and Tanimoto, 2003a).

The measured U-value may be compared with the theoretical thermal transmittance calculated using ISO 6946. If the percentage difference between *HFM* and the theoretical values is greater than 20%, the ISO 9869–1 criterion are not satisfied.

#### 2.1.2. Heat transfer coefficients evaluation

The ISO 6946 standard is currently used for calculating the thermal resistances of the walls. The total thermal resistance can be defined as the sum of the thermal resistances of the single layers of a wall, also

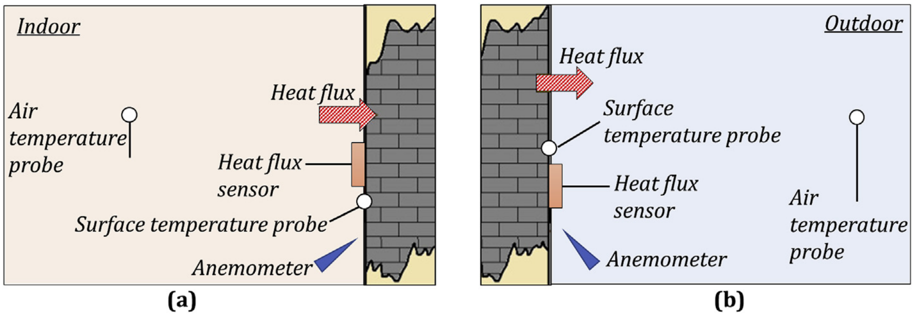

**Fig. 2.** Schema of the measuring system for investigating internal (a) and external (b) heat transfer coefficients.

considering the surface thermal resistances. These last resistances are defined in function of the convective ($h_c$) and radiative ($h_r$) heat transfer coefficient. $h_c$ and $h_r$ are identified for the inner and outer surfaces of the wall. Considering the inner part of the building envelope (horizontal heat fluxes), the Standard suggests a surface thermal resistance equal to 0.13 m$^2$K/W. The $h_c$ coefficient is equal to 2.5 W/m$^2$K. The $h_r$ coefficient can be calculated subtracting these values and obtaining 5.19 W/m$^2$K. The radiative coefficient can also be evaluated in function of the wall characteristics, applying the equation:

$$h_r = 4\varepsilon\sigma T_m^3 \tag{3}$$

where $\varepsilon$ is the emissivity of the building exposed surface, σ is the Stefan-Boltzmann constant and $T_m$ is the average thermodynamic temperature of the surface and the surrounding surfaces.

Following Eq. (3), $h_r$ can be evaluated using an experimental approach based on $\varepsilon$ and $T_m$ measurements. Even if ISO 6946 specifies that $T_m$ is the average thermodynamic temperature of the surface and the surrounding surfaces, it was demonstrated in (Evangelisti et al., 2016) that $h_r$ can be calculated only using the surface temperature of the investigated wall. This procedure does not introduce significant errors (UNI 10355, 1035).

In order to obtain information about convective and radiative heat transfer, an experimental approach based on heat flows and temperatures measurements can be employed. A heat-flow meter sensor can be installed on the inner (or the outer) surface of the investigated wall. Surface and air temperatures can be registered by means of contact temperature sensors and air temperature probes. Air temperatures are acquired in the indoor and outdoor environment. Surface temperature probes can be installed on the inner or the outer surface, in function of an internal or external analysis. In addition, an anemometer can be used for measuring the air velocity near the wall. Starting from the measurements of the heat flow through the wall and the temperature differences between the wall surface and the air, the total heat transfer coefficients are obtained by applying the following formula:

$$h_{tot} = \frac{q_{HFM}}{(T_s - T_{air})} \tag{4}$$

where $q_{HFM}$ is the heat flux density, $T_s$ is the temperature of the wall's surface (inner or outer) and $T_{air}$ is the temperature of the air (inside or outside the building).

Subtracting the heat transfer coefficients achieved by applying Eq. (3) to those obtained from Eq. (4), the convective heat transfer coefficient can be assessed.

When heat transfer phenomena are analyzed on the outer side of a wall, air velocity data can be useful for calculating $h_c$ following simplified equations, such as that reported in the ISO 6946:

$$h_c = 4 + 4v \tag{5}$$

where $v$ is the wind velocity.

Other equations defined in function of the wind velocity can be found in literature. Specifically, three equations can be applied:

- ASHRAE task group model (Ito et al., 1972b).

$$h_{c,ext} = 18.6 \cdot V_{loc}^{0.605} \tag{6}$$

- Loveday & Taki model (Loveday and Taki, 1996b).

$$\text{Windward:}\ \ h_{c,ext} = 16.15 \cdot V_{loc}^{0.397} \tag{7}$$

$$\text{Leeward:}\ \ h_{c,ext} = 16.25 \cdot V_{loc}^{0.503} \tag{8}$$

- Hagishima & Tanimoto model (Hagishima and Tanimoto, 2003b).

$$\text{Vertical surfaces:}\ \ h_{c,ext} = 10.21 \cdot V_{loc} + 4.47 \tag{9}$$

where $V_{loc}$ is the air velocity near the wall.

It is worthy to notice that an anemometer can be also used on the inner side of the wall. This can be useful for comprehending if convection is natural or forced, under an empirical approach point of view. To do this, the correlation between two known dimensionless numbers, the numbers of Grashof ($Gr$) and Reynolds ($Re$), can be computed. When potentially mixed convection is examined, the Archimedes number ($Ar$) parametrizes the relative strength of natural and forced convection. More in detail, $Ar$ number is defined as the ratio between $Gr$ number and $Re^2$ number. If $Ar$ is much greater than 1, natural convection dominates and when $Ar$ is much less than 1, forced convection prevails (Song et al., 2018). Under natural convection conditions, convective coefficients can be correlated to the Nusselt ($Nu$) number. This approach is related to the available correlations in literature, able to calculate $h_c$ as a function of the temperature difference between wall and air (Peeters et al., 2011). When natural convection prevails ($Ar >> 1$), the following correlations can be applied:

- The Alamdari and Hammond correlation (Alamdari and Hammond, 1983).

$$h_{c,int} = \left\{ \left[ 1.5 \left( \frac{\Delta T}{H} \right)^{1/4} \right]^6 + \left[ 1.23 \Delta T^{1/3} \right]^6 \right\}^{1/6} \tag{10}$$

- The Khalifa and Marshall correlation (Khalifa and Marshall, 1990).

$$h_{c,int} = 2.3 \Delta T^{0.24} \tag{11}$$

- The Churchill and Chu correlation (Churchill and Chu, 1975).

$$h_{c,int} = \frac{0.0257}{H} \left( 0.825 + 7.01 \Delta T^{1/6}\ H^{3/6} \right)^2 \tag{12}$$

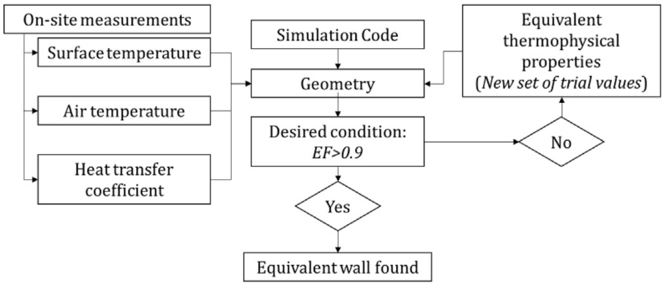

**Fig. 3.** Flow-chart of the applied method used for finding the equivalent thermophysical properties.

- The Fohanno and Polidori correlation (Fohanno and Polidori, 2006).

$$h_{c,int} = 1.332\left(\frac{\Delta T}{H}\right)^{1/4} \rightarrow Ra < 6.3 \cdot 10^9 \tag{13}$$

Fig. 2 shows a schematic representation of the measuring system, both for the internal and external environments.

### 2.1.3. Equivalent thermophysical properties

Data obtained from the on-site measurement campaign can be employed for generating a model through FEM software (Evangelisti et al., 2018b). The measuring apparatus described above allowed to acquire data useful to set the boundary conditions in the model. A thermal solicitation, equal to the surface temperature trend registered by the surface sensor positioned on the inner/outer side of the wall, can be set in the model. This agrees to the heat flow direction produced by the temperature difference between the two sides of the wall. The internal/-external measured air temperature values and the heat fluxes were employed to calculate proper internal convective heat transfer coefficients.

The stratigraphy of the actual wall can be reproduced in the software as a single homogeneous layer, characterized by equivalent thermophysical properties.

The methodological approach applied for finding the equivalent thermophysical properties of a wall is reported in Fig. 3.

On-site measurements are used as boundary conditions in the model: external/internal surface temperature values can be used as an external forcing function; on the other side of the equivalent layer, a heat transfer based on the equation $q = h(T - T_{env})$ is set, where $T$ is the internal surface temperature and $T_{env}$ is the temperature of the environment, outside the simulated domain. From the experimental measurements, the heat transfer coefficient values along time are calculated and used in the simulation code. Thus, different equivalent thermophysical properties can be tested and the internal/external surface temperatures are simulated. The search for equivalent thermophysical properties aims to obtain the finest reproduction of the behavior of the wall, aiming to achieve the finest match between measured and simulated surface temperatures. The desired condition to stop searching for the best parameters is represented by the value of the Model Efficiency (*EF*) (Loague and Green, 1991), expressed as follows:

$$EF = \frac{\sum_{i=1}^{N}(m_i - \overline{m})^2 - \sum_{i=1}^{N}(s_i - m_i)^2}{\sum_{i=1}^{N}(m_i - \overline{m})^2} \tag{14}$$

where $mi$ is the measured value at time $ti$, $si$ is the simulated value for each time $ti$, $\overline{m}$ is the average of the measured values and $N$ is the total number of samples. *EF* allows to understand the capability of the equivalent structure to reproduce the original one behavior, showing values between 0 and 1 (the value 1 reveals that measured and simulated data are equal). As shown in Fig. 3, the desired condition is represented by $EF > 0.9$ (Evangelisti et al., 2018b).

**Fig. 4.** Case studies selected for thermal transmittance and the internal heat transfer coefficient analyses: the early-50s building (a); the house built in 2000 (b); the early-60s building (c).

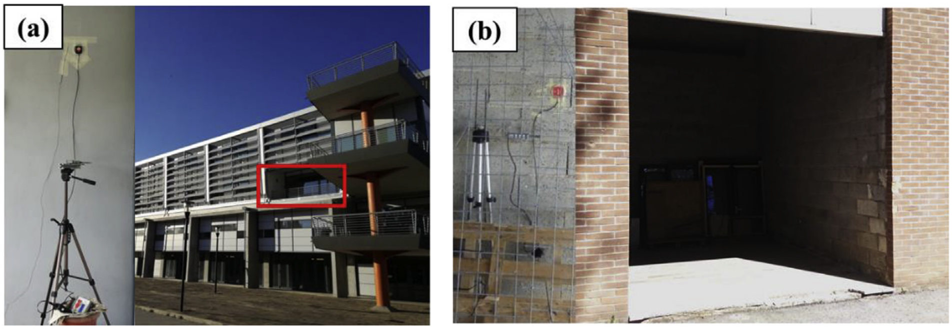

**Fig. 5.** Case studies for the analysis of the external heat transfer coefficients: the new insulated building (a); the older structure (b).

**Table 1**
Real wall stratigraphy (*Case 1*).

| Wall layer | 1 | 2 | 3 |
|---|---|---|---|
| Material | Drywall | Rockwool | Drywall |
| Thermal conductivity [W/mK] | 0.210 | 0.045 | 0.210 |
| Specific heat capacity [J/kgK] | 800 | 1030 | 800 |
| Mass density [kg/m$^3$] | 750 | 20 | 750 |
| Thickness [m] | 0.015 | 0.07 | 0.015 |

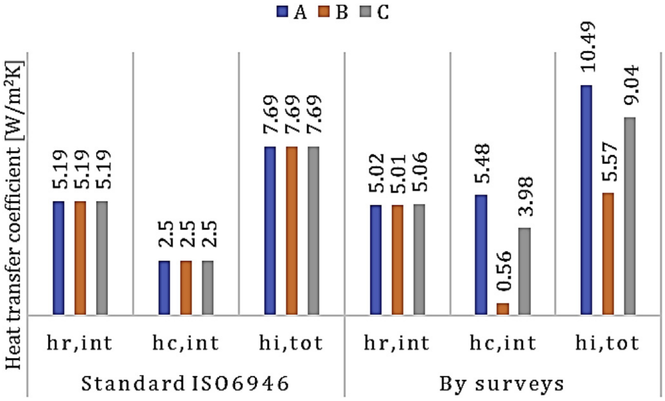

**Fig. 6.** Internal heat transfer coefficients considering ISO 6946 and experimental surveys.

### 2.2. Case studies

Seven case studies were investigated, applying the methodological approaches mentioned before. The analyzed case studies can be grouped in the following manner:

- Taking into account the analysis of the thermal transmittance and the internal heat transfer coefficient evaluations, on-site U-value measurements were carried out in an early-50s building (called in the following section "*A*"), a house built in 2000 (called in the following section "*B*") and an early-60s building (called in the following section "*C*"),(Fig. 4). Heat flow meter and surface temperature sensors were applied for obtaining data useful for employing the appropriate correlations. A comparison among Standard recommendations, correlations and experimental investigations was carried out. All the mentioned case studies are characterized by heating systems with radiators, with an *Ar* number much greater than 1 (natural convection prevails);

- Considering the analysis of the external heat transfer coefficient, two case studies were analyzed: a new structure characterized by an insulated wall (called in the following section "*Case A*″) and an older wall, not insulated (called in the following section "*Case B*″) (Fig. 4). In particular, these case studies are characterized by particular geometries (balcony and portico). For these geometries there are no specific correlations and the formulas mentioned in section 3.1.2 were tested. Fig. 5 shows the two case studies.

- Considering the determination of the equivalent thermophysical properties, two actual walls were assessed. The first is a plasterboard wall (called in the following section "*Case 1*") whose stratigraphy is known and listed in Table 1. On the contrary, for the second real wall (called in the following section "*Case 2*") the internal composition is unknown, and the thickness equal to 0.35 m is the only available information.

## 3. Results and discussion

The analyses of the radiative and convective heat transfer coefficients were performed in the first phase of the methodological approach. The results reported in Fig. 6 allow to highlight small differences among radiative coefficients: comparing the value suggested by the standard and the actual ones, it is possible to observe differences ranging between −2.5 and −3.5%. On the other hand, taking into account convective coefficients, both higher and lower values can be observed. This can be related to local fluid-dynamic phenomena which influenced the convective heat transfer coefficient values, thus affecting the total coefficients. According to this, ISO 6946 values are higher and lower than those obtained by surveys.

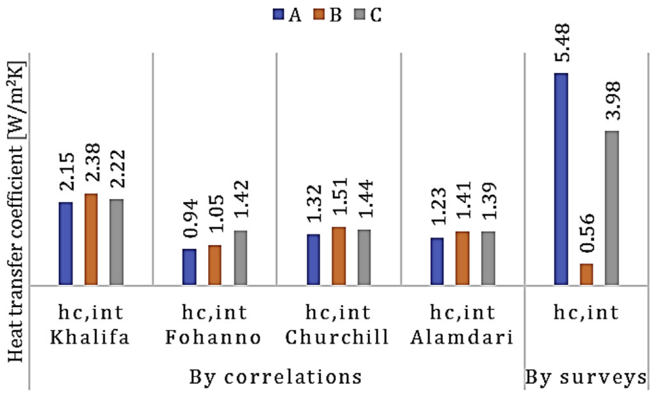

**Fig. 7.** Convective heat transfer coefficient considering correlations and experimental surveys.

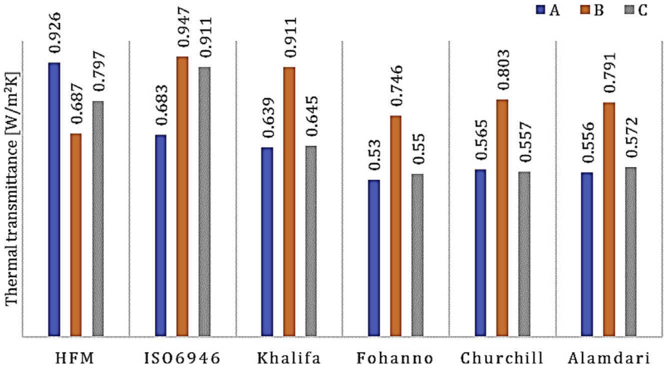

**Fig. 8.** Thermal transmittance values found by applying heat flow sensor (*HFM*), Standard and correlations.

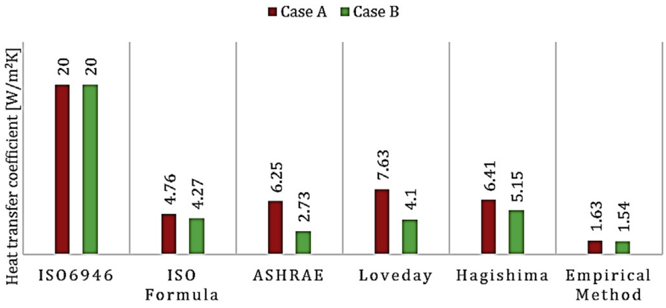

**Fig. 9.** Mean values of the external total heat transfer coefficients.

Applying the equations described in Section 2.1.2 (related to the internal heat transfer coefficients), the differences shown in Fig. 7 can be observed. The adopted correlations allowed to obtain similar convective coefficients, much lower than those obtained by surveys. Using the correlation proposed by Khalifa and Marshall, values comparable with those suggested by the Standard can be observed, with negligible percentage differences. On the contrary, the coefficients obtained by other three correlations are lower than that proposed by ISO 6946. The differences between surveys and correlations can be related to the indoor air movements, able to vary the heat flows measured near the walls, thus influencing the heat transfer coefficients. On the other hand, the calculation of the $h_{c,int}$ by means of the correlations is a function of the only air-wall temperature difference.

Using different convective heat transfer coefficients leads to different total coefficients, thus influencing the thermal transmittance. The analysis conducted using different formulas for the calculation of the $h_{c,int}$ can be useful when heat flow sensors are not available and heat fluxes are computed multiplying $h_{c,int}$ and the air-wall temperature differences. Following the mentioned approach, the achievable thermal transmittances are reported in Fig. 8. It is possible to observe that ISO 6946 allows to obtain higher values than those achieved by the *HFM* method, except for case *A*.

Taking into account the external heat transfer phenomena, Fig. 9 shows the mean values of the external heat transfer coefficients. Comparing the Standard and the applied correlations, it is possible to observe discrepancies. ISO 6946 provides $h_{c,ext}$ characterized by the highest values, provided considering a wind speed equal to 4 m/s. This wind velocity is typical of specific environmental conditions, such as those in airports where wind speeds are measured at an elevation of 10 m, without nearby structures. Within the cities (when balconies or porticos are accounted) 4 m/s is a too high and not very representative velocity. In *Case A*, the wind speed average value is equal to 0.19 m/s, and in *Case B* is 0.07 m/s. Starting from the wind velocities near the investigated walls and applying the Eq. (5), the average $h_{c,ext}$ values reported in Fig. 9 were obtained (labeled as ISO Formula in the bar chart). The external coefficient suggested by the Standard cannot be considered representative of complex urban fabric and geometries. All the $h_{c,ext}$ values reported in Fig. 9 are much less than 20 W/m$^2$K suggested by ISO 6946.

The last phase of the research was related to the equivalent thermophysical properties identification, investigating two actual walls, also using on-site surveys. As already mentioned, the first wall is a plasterboard wall whose stratigraphy is known. It was named *Case 1*. On the contrary, for the second wall (named *Case 2*) the internal composition is unknown, and the thickness equal to 0.35 m is the only available information. The heat flow plate and the surface temperature sensors were applied for obtaining the wall thermal resistance. Therefore, aiming to obtain a similar behavior in both stationary and dynamic conditions, the equivalent thermal resistance was found by applying the progressive average method, relating the differences in surface temperatures (internal and external) and heat flows, both derived from the in-situ measurements. Fig. 10 shows the trends and the overlaps among the measured surface temperatures (internal and external) and those simulated with the calculation code (using the information listed in Table 1). The obtained *EF* index was equal to 0.91. For *Case 1* the equivalent properties were: thermal conductivity, mass density and specific heat capacity equal to 0.057 W/mK, 650 kg/m$^3$ and 500 J/kgK, respectively.

Considering *Case 2*, characterized by a completely unknown stratigraphy, Fig. 11 shows the outcomes in terms of surface temperatures. In this case, the *EF* index was equal to 0.93. The set of thermal properties employed for the equivalent wall are: thermal conductivity, mass density and specific heat capacity equal to 0.236 W/mK, 50 kg/m$^3$ and 250 J/kgK, respectively. Considering the preliminary visual survey and the date of construction of the building, it is possible to state that the examined structure is a non-massive wall, characterized by high insulation, whose equivalent model can be considered representative.

## 4. Conclusions

The starting question was: "*can Standards' suggestions be considered reliable in every situation?*". The answer needs to be related to the complexity of reality and it could be answered by stating that every case study is specific and, for this reason, needs specific reflections. It is evident that using Standard suggestions is certainly convenient, but these suggestions need to be carefully considered by engineers and technicians, understanding that every choice can influence the results. It is fundamental to underline that engineers and technicians are dealing with complexity and it is necessary to learn how to manage it. From this point of view, experimental measurements become fundamental for investigating reality and on-site surveys should be considered essential for acquiring reliable data or for performing reliable simulations, with the aim of reproducing actual heat transfer conditions and phenomena, also reducing uncertainties. For these reasons, the renovation of an existing building towards a NZEB needs accurate investigations and reliable simulation models.

The cases studies taken into account in this research were chosen as representative of typical and most diffused Italian construction typologies from the 50s to today. Because of the high percentage of this kind buildings in Italy, the renovation of an existing one towards a NZEB needs accurate investigations and reliable simulation models. Due to this, the final aim of our work was to propose and verify different methods

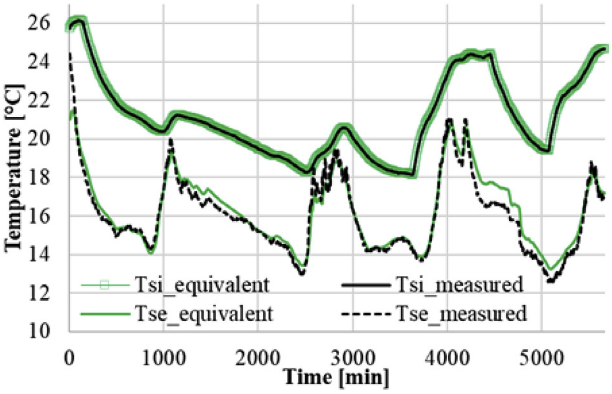

**Fig. 11.** *Case 2*: surface temperatures obtained through measurements and equivalent model.

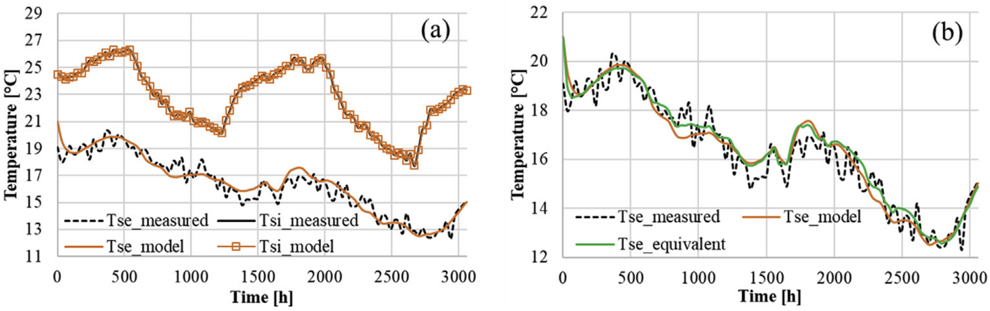

**Fig. 10.** *Case 1*: inner and outer measured surface temperatures compared with those measured through the FEM code (a); external surface temperatures obtained by on-site surveys and by the model of the real wall and the equivalent one (b).

able to help practitioners to generate reliable models in order to identify efficient and sustainable solutions for old and inefficient buildings. This approach can also provide quantitative indications about the possible differences between experimental data and values derived by Standards.

Starting from the obtained results, the proposed methodological approach can represent a viable solution to quantify both heat transfer phenomena and equivalent thermophysical properties, not following Standards suggestions. Moreover, the model calibration procedure can be also speeded up passing through the equivalent thermophysical properties concept. This allows to obtain information about the dynamic performance of building envelopes, not requiring model calibrations based on air or surface temperature registrations for long periods of time.

Future developments will concern the applicability of the analyzed methodological approach to inefficient buildings. Furthermore, it will be pursued the design of a user-friendly code able to find equivalent thermophysical properties from on-site measured data.

## Declaration of competing interest

The Authors declare no conflict of interest.

## References

Alamdari, F., Hammond, G., 1983. Improved data correlations for buoyancy-driven convection in rooms. Build. Serv. Eng. Technol. 4, 106–111.

Antonopoulos, K.A., Tzivanidis, C., Vrachopoulos, M., 1997. Using orthogonal expansion of functions over multilayer walls for calculating the layer thermal properties. Appl. Therm. Eng. 17, 193–201.

Ascione, F., Bianco, N., de Masi, R.F., de'Rossi, F., Vanoli, G.P., 2015. Energy retrofit of an educational building in the ancient center of Benevento. Feasibility study of energy savings and respect of the historical value. Energy Build. 95, 172–183.

Asdrubali, F., Baggio, P., Prada, A., Grazieschi, G., Guattari, C., 2020. Dynamic life cycle assessment modelling of a NZEB building. Energy 191, 116489. https://doi.org/10.1016/j.energy.2019.116489.

Asdrubali, F., Ballarini, I., Corrado, V., Evangelisti, L., Grazieschi, G., Guattari, C., 2019. Energy and environmental payback times for an NZEB retrofit. Build. Environ. 147, 461–472.

Ballarini, I., Corrado, V., Madonna, F., Paduos, S., Ravasio, F., 2017. Energy refurbishment of the Italian residential building stock: energy and cost analysis through the application of the building typology. Energy Pol. 105, 148–160.

Becchio, C., Dabbene, P., Fabrizio, E., Monetti, V., Filippi, M., 2015. Cost optimality assessment of a single family house: building and technical systems solutions for the nZEB target. Energy Build. 90, 173–187.

Chaffar, K., Chauchois, A., Defer, D., Zalewski, L., 2014. Thermal characterization of homogeneous walls using inverse method. Energy Build. 78, 248–255.

Churchill, S., Chu, H., 1975. Correlating equations for laminar and turbulent free convection from a vertical plate. Int. J. Heat Mass Tran. 18, 1323–1329.

Costanzo, S., Cusumano, A., Giaconia, C., Giaconia, G., 2006. Preservation of the artistic heritage within the seat of the Chancellorship of the University of Palermo A proposal on a methodology regarding an environmental investigation according to Italian Standards. Build. Environ. 41, 1847–1859.

De Lieto Vollaro, R., Guattari, C., Evangelisti, L., Battista, G., Carnielo, E., Gori, P., 2015. Building energy performance analysis: a case study. Energy Build. 87, 87–94.

Desogus, G., Mura, S., Ricciu, R., 2011. Comparing different approaches to in situ measurement of building components thermal resistance. Energy Build. 43, 2613–2620.

DM, June 26, 2015. Application of Energy Performance Calculation Methods and Definition of the Requirements and Minimum Requirements of Buildings.

European Commission, Commission delegated regulation (Eu), 2012. No of 16.1.2012 Supplementing Directive 2010/31/EU of the European Parliament and of the Council on the Energy Performance of Buildings (Recast) by Establishing a Com- Parative Methodology Framework for Calculating Cost-. Brussels.

European Directive 2002/91/CE 16 December 2002 Regarding Buildings Energy Performance.

Evangelisti, L., Battista, G., Guattari, C., Basilicata, C., de Lieto Vollaro, R., 2014. Influence of the thermal inertia in the European simplified procedures for the assessment of buildings' energy performance. Sustainability 6, 4514–4524.

Evangelisti, L., Guattari, C., Gori, P., De Lieto Vollaro, R., 2015. In situ thermal transmittance measurements for investigating differences between wall models and actual building performance. Sustainability 7, 10388–10398.

Evangelisti, L., Guattari, C., Gori, P., De Lieto Vollaro, R., Asdrubali, F., 2016. Experimental investigation of the influence of convective and radiative heat transfers on thermal transmittance measurements. Int. Commun. Heat Mass Tran. 78, 214–223.

Evangelisti, L., Guattari, C., Gori, P., Bianchi, F., 2017. Heat transfer study of external convective and radiative coefficients for building applications. Energy Build. 151, 429–438.

Evangelisti, L., Guattari, C., Asdrubali, F., 2018a. Influence of heating systems on thermal transmittance evaluations: simulations, experimental measurements and data post-processing. Energy Build. 168, 180–190.

Evangelisti, L., Guattari, C., Gori, P., Asdrubali, F., 2018b. Assessment of equivalent thermal properties of multilayer building walls coupling simulations and experimental measurements. Build. Environ. 127, 77–85.

Evangelisti, L., Guattari, C., Asdrubali, F., 2019. Comparison between heat-flow meter and Air-Surface Temperature Ratio techniques for assembled panels thermal characterization. Energy Build. 203, 109441.

Faye, M., Lartigue, B., Sambou, V., 2015. A new procedure for the experimental measurement of the effective heat capacity of wall elements. Energy Build. 103, 62–69.

Ferreira, M., Almeida, M., Rodrigues, A., Silva, S.M., 2016. Comparing cost-optimal and net-zero energy targets in building retrofit. Build. Res. Inf. 44, 188–201.

Fohanno, S., Polidori, G., 2006. Modelling of natural convective heat transfer at an internal surface. Energy Build. 38, 548–553.

Foley, H.C., 2012. Challenges and opportunities in engineered retrofits of buildings for improved energy efficiency and habitability. AIChE J. 58 (3), 658–667.

Foucquier, A., Robert, S., Suard, F., Stéphan, L., Jay, A., 2013. State of the art in building modelling and energy performances prediction: a review. Renew. Sustain. Energy Rev. 23, 272–288.

Friedman, C., Becker, N., Erell, E., 2014. Energy retrofit of residential building envelopes in Israel: a cost benefit analysis. Energy 77, 183–193.

Fumo, N., 2014. A review on the basics of building energy estimation. Renew. Sustain. Energy Rev. 31, 53–60.

Gori, P., Bisegna, F., 2010. Thermophysical parameter estimation of multi-layer walls with stochastic optimization methods. Int. J. Heat. Technol 28, 109–116.

Hagishima, A., Tanimoto, J., 2003a. Field measurements for estimating the convective heat transfer coefficient at building surfaces. Build. Environ. 38, 873–881.

Hagishima, A., Tanimoto, J., 2003b. Field measurements for estimating the convective heat transfer coefficient at building surfaces. Build. Environ. 38, 873–881.

Ito, N., Kimura, K., Oka, J., 1972a. A field experiment study on the convective heat transfer coefficient on the exterior surface of a building. ASHRAE Trans 78 (Part 2), 184.

Ito, N., Kimura, K., Oka, J., 1972b. A field experiment study on the convective heat transfer coefficient on the exterior surface of a building. ASHRAE Trans 78 (Part 2), 184.

M.J. Kelly, Retrofitting the existing UK building stock, Build. Res. Inf. 37 (2) (20 09) 196-1920 0.

Khalifa, A., Marshall, R., 1990. Validation of heat transfer coefficients on interior building surfaces using real-sized indoor test cell. Int. J. Heat Mass Tran. 33, 2219–2236.

Kim, S., Kim, M.C., Kim, K.Y., 2002. An integral approach to the inverse estimation of temperature dependent thermal conductivity without internal measurements. Int. Commun. Heat. Mass 29, 107–113.

Loague, K., Green, R.E., 1991. Statistical and graphical methods for evaluating solute transport models: overview and application. J. Contam. Hydrol. 7, 51–73.

Loveday, D.L., Taki, A.H., 1996a. Convective heat transfer coefficients at a plane surface on a full-scale building facade. Int. J. Heat Mass Tran. 39, 1729–1742.

Loveday, D.L., Taki, A.H., 1996b. Convective heat transfer coefficients at a plane surface on a full-scale building facade. Int. J. Heat Mass Tran. 39, 1729–1742.

Maillet, D., André, S., Batsale, J.C., Degiovanni, A., Moyne, C., October 2000. Thermal Quadrupoles: Solving the Heat Equation through Integral Transforms, ISBN 978-0-471-98320-0.

Menassa, C.C., 2011. Evaluating sustainable retrofits in existing buildings under uncertainty. Energy Build. 43 (12), 3576–3583.

Meng, X., Yan, B., Gao, Y., Wang, J., Zhang, W., Long, E., 2015. Factors affecting the in situ measurement accuracy of the wall heat transfer coefficient using the heat flow meter method. Energy Build. 86, 754–765.

ISO 6946 Building Components and Building Elements – Thermal Resistance and Thermal Transmittance – Calculation Method.

ISO 9869-1 - Thermal Insulation –Building Elements –In Situ Measurement of Thermal Resistance and Thermal Transmittance.

Orosa, J.A., Oliveira, A.C., 2012. A field study on building inertia and its effects on indoor thermal environment. Renew. Energy 37, 89–96.

Özisik, M.N., Orlande, H.R.B., 2000. Inverse Heat Transfer: Fundamentals and Applications. Taylor and Francis, New York.

Peeters, L., Beausoleil-Morrison, I., Novoselac, A., 2011. Internal convective heat transfer modeling: critical review and discussion of experimentally derived correlations. Energy Build. 43, 2227–2239.

Pisello, A.L., Rossi, F., Cotana, F., 2014. Summer and winter effect of innovative cool roof tiles on the dynamic thermal behavior of buildings. Energies 7, 2343–2361.

Saglam, N.G., Yılmaz, A.Z., Becchio, C., Corgnati, S.P., 2017. A comprehensive costoptimal approach for energy retrofit of existing multi-family buildings: application to apartment blocks in Turkey. Energy Build. 150, 224–238.

Song, Y., Cheng, D., Zhao, L., 2018. Microfluidics: Fundamental, Devices and Applications: Fundamentals and Applications. Wiley Online Library, ISBN 9783527800643. https://doi.org/10.1002/9783527800643. Online.

UNI 10351 - Building Materials. Thermal Conductivity and Vapor Permeability.

UNI 10355 - Walls and Floors. Thermal Resistance Values and Calculation Method.

UNI TS 11300 - Energy Performance of Buildings.