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In Situ Thermal Transmittance Assessment of the Building Envelope: Practical Advice and Outlooks for Standard and Innovative Procedures

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Abstract: Different standard methods for the assessment of the thermal performance of the building envelope are used: analogy with coeval building, theoretical method, heat flow meter measurement, simple hot box, infrared thermography, and thermometric method. Review papers on these methods, applied in situ and in laboratory, have been published, focusing on theory, equipment, metrological performance, test conditions and data acquisition, data analysis, benefits, and limitations. However, steps forward have been done and not been deepened in previous works: in fact, the representative points method and the weighted area method have been proposed, too, whilst artificial intelligence and data-driven methods have begun to prove the reliability also in the U-value prevision using available datasets. Considering this context, this work aims at updating the literature background considering exclusively in situ methods. The work starts from bibliometric and scientometric analysis not previously conducted: this helped to group the methods and to sketch the innovations and the future perspectives. Indeed, from the bibliometric and scientometric literature analysis what emerged was (i) the richness of the background on this topic, especially in the recent years, (ii) two macro-groups (methods with and without measurements), and (iii) the importance of paper keywords (otherwise, interesting papers are eluded by the output of simple database queries). The method study that followed aims at providing (i) a broader view of the thermal transmittance (U-value) assessment procedures, including the utmost recent applications, proposal, and outlooks in this field, (ii) the understanding on the fundamental theories of the techniques, (iii) practical advice for building-envelope assessment, focusing on the advantages and limitations useful for professionals and researchers involved in the energy audit, conservation, or refurbishment of building stock, (iv) the identification of the interconnection between the techniques that often rely on one another, and (v) final remarks and future perspective of the procedures, which embrace the use of artificial intelligence (AI). From the topic analysis, as a result, it emerged that this is an open field for future research, especially with the implementation of AI, which requires good datasets and trials on the models' architectures, in terms of input layer, number of hidden layer and neurons, and percentage of data to be employed for model training and testing.

Keywords: thermal transmittance (U-value); building envelope; inverse method; heat flow meter measurement (HFM); quantitative infrared thermography (QIRT); thermometric method (THM); representative point method (RPM); weighted area method (WAM); artificial intelligence (AI); artificial neural network (ANN); bibliometric analysis; scientometric analysis

Citation: Nardi, I.; Lucchi, E. In Situ Thermal Transmittance Assessment of the Building Envelope: Practical Advice and Outlooks for Standard and Innovative Procedures. *Energies* **2023**, *16*, 3319. https://doi.org/10.3390/en16083319

Academic Editors: Anastasios Dounis and Paulo Santos

Received: 17 March 2023
Revised: 5 April 2023
Accepted: 6 April 2023
Published: 7 April 2023

1. Introduction

The building sector needs to promote and accelerate the reduction in emissions and energy consumption. In fact, in 2021, the operation of buildings has been responsible for 27% of total energy-sector emissions (which include buildings, energy combustion, and industrial processes) and for 30% of global final energy consumption [1]. Big efforts are needed to accomplish the objectives agreed to around international tables. Attention is now devoted to zero-carbon-ready buildings that are characterized by high energy efficiency and that «(. . .) *either use renewable energy directly, or rely on a source of energy supply that can be fully decarbonized, such as electricity or district energy. The zero-carbon-ready concept include both operational and embodied emissions*» [1].

In parallel, it is possible to configure the net-zero scenario, which settles some ambitious goals for 2030 [1]: energy consumption reduction (by 25% compared to today), fossil fuel use reduction (by more than 40%), and the phase-out of traditional biomass use. This can be pursued by acting on different sides: (i) improving building envelopes to reduce thermal energy need; (ii) choosing efficient appliances, lamps, and air conditioners; (iii) preferring efficient and clean technologies, such as heat pumps or district energy; and (iv) increasing building flexibility. These aspects are based on the knowledge, characterization, and quantification of the building energy losses. This can be achieved with a building energy audit, a procedure for assessing the energy-related inefficiencies of the envelope and heating systems [2]. This procedure aims at identifying and quantifying possible energy savings by hypothesizing suitable interventions that are analyzed under the cost–benefit light, also considering their payback time. This is a key point for the estimation of energy consumption and, then, of energy retrofitting measures and, in turn, of the energy and money savings. Toward this aim, the proper knowledge of the building features and characteristics is crucial. These can be briefly defined by the thermal transmittance (also called U-value) that expresses the ability of a component to transmit heat under steady-state conditions [3]. Specifically, the U-value (W/m^2 K) defines the quantity of heat that flows in a unit time through a unit area of the component per unit difference in temperature occurring between the two sides [4]. The assessment of U-values (or its reciprocal, the thermal resistance, also called R-value) in building elements can be carried out with different calculation or measurement procedures, and it is fundamental for having a reliable evaluation of the thermal behavior of a building.

An extensive study of widely used techniques was made in 2019 by [5], where each method for the U-value assessment of walls has been deeply studied and discussed considering (i) theory, (ii) equipment, (iii) metrological performance, test conditions, and data acquisition, and (iv) data analysis, and finally the benefits and limitations of the different methods have been grouped. In the same year, another study [6] compared current approaches for in situ measurement of the U-value of walls. The work evaluates (i) the advantages and disadvantages of each method, (ii) limitations, (iii) reported deviations, and (iv) measurement procedure. Two macro-groups were found: methods that use the heat flow meter and those that do not. A recent work on the evaluation of the U-value of windows [7] analyzes experimental methods for their assessment, focusing on (i) laboratory and in situ procedures, (ii) investigated part of the window, (iii) data analysis, (iv) equipment, (v) measurement lasting, and (vi) pros and cons.

Despite the availability of studies on the U-value assessment of walls and windows, a contemporary study that (i) refers to in-situ techniques, (ii) analyzes the scientific literature on the research field (that is, thermal performance assessment) from the bibliometric and scientometric point of view, (iii) is updated on the most recent techniques for the U-value and R-value assessment, (iv) highlights the possibilities for both the opaque and transparent building envelope, (v) discusses both standard and innovative procedures, the outlooks given by artificial intelligence (AI), (vi) highlights the pros and cons of the techniques, and (vii) identifies the connections between the techniques is still missing.

2. Aims and Methods

This study aims at showing a completed, critical, and updated overview of the procedure for the assessment of the U-value of the building envelope directly in situ, hence excluding what concerns laboratory measurement. This paper contributes to the following specific aims:

- Providing a comprehensive review and classification of the techniques for the U-value measurement.
- Updating previous review studies, including some recent works that propose new methods.
- Highlighting the prospective that AI and the data-driven method currently open for the U-value retrieval or assessment.
- Visualizing the linking between the methods.

Short references to their theoretical bases are given for each method, but the main core is to highlight the pros and cons of each method, also discussing the most recent methods available in the literature that are not included in previous studies. Besides, challenges and practical advice are provided from the literature and direct experiences. Moreover, future steps and perspectives of all the techniques are discussed. Indeed, the ever-increasing employment of AI can lead to unprecedented results, also, in the U-value assessment. Finally, the linking between the techniques is also highlighted and discussed: in fact, for the definition of some parameters, probes' locations, or measurement deployment, methods often rely on one another.

The novelty of this research concerns: (i) the presence of a deep literature review based on bibliometric and scientometric techniques for rationalizing the selection and the mapping of scientific studies; (ii) an updated analysis of the literature compared to previous research; (iii) a definition of practical advice to help surveyors and designers in the energy audit of buildings based both on literature suggestions and personal experiences; (iv) a discussion of the theoretical basis of each procedure to help the readers in understanding the building physics principles; (v) the explication of the connection among different techniques; and (vi) a description of innovative techniques and future perspectives, especially connected to the use of AI.

The research methodology (Figure 1) is divided into three steps:

- Bibliometric and scientometric analysis of the topic based on the Scopus database, which helped in query definition and refinement. Results have been analyzed and displayed by using statistical analysis and science mapping (Section 3).
- Detailed and critical discussion of the topic, with a deeper description of the most relevant studies in the literature on both widely used and innovative techniques (Section 4).
- Identification of future perspectives (Section 4).

According to the results of the bibliometric analysis, in situ assessment procedures have been divided into widely used and innovative techniques. Widely used techniques are grouped in estimation (analogy with coeval buildings and theoretical method) and measurement (heat flux meter (HFM) measurement, simple hot box, quantitative infrared thermography (QIRT), and the thermometric method). Innovative methods are composed by the representative points method (RPM) and weighted area method (WAM). Finally, future perspectives were sketched out by a deep reading of the studies, identifying the new possibilities offered by AI.

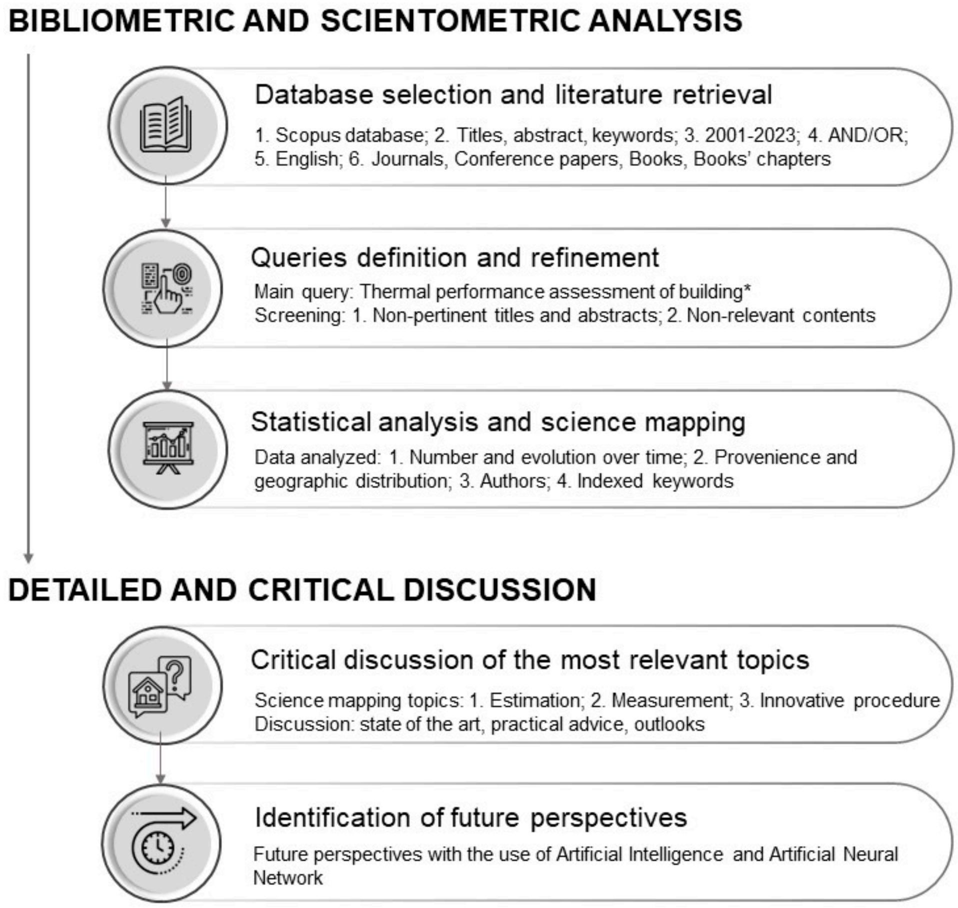

Figure 1. Flowchart of the research methodology (source: authors' elaboration).

3. Bibliometric and Scientometric Analysis

The Scopus database was selected for the bibliometric analysis, since its spectrum of publication has 20% more coverage than the Web of Science [8,9], guaranteeing a more complete overview of the studies. Google Scholar and ResearchGate were excluded for the low accuracy of the citation analysis that presents overlapped papers and citation records [8]. The bibliometric and the scientometric analysis allowed the retrieval of:

- Number of studies.
- Evolution of the studies during time.
- Geographic provenience and distribution of the publications.
- Authors.
- Indexed keywords.

First, statistical analysis illustrated time evolution, geographic distribution, and disciplinary fields of the publications (Section 3.1). Furthermore, authors and indexed keywords have been evaluated by the scientometric analysis to cluster bibliometric networks and to visualize data patterns (Section 3.2). This study was conducted using VOS viewer 1.6.19, the most widely open-source software for science mapping [10].

3.1. Bibliometric Analysis

To conduct the bibliometric analysis, different queries were introduced in the Scopus database considering the entire publication period. First, only thermal performance keywords have been considered (step 1), and then the combination between thermal performance and procedure keywords has been applied (step 2). The literature was searched in the Scopus database using the terms and Boolean operators shown below (Table 1): the resulting number of publications is, hence, due to the listed queries.

Table 1. Queries used and number of publications obtained for the topic "*thermal transmittance assessment of building**" (source: authors' elaboration, 16 March 2023).

Query	Number of Publications
TITLE-ABS-KEY: "*building*" * AND "*U-value*" * OR "*R-value*" *	1743
TITLE-ABS-KEY: "*building*" * AND KEY: "*U-value*" * OR "*R-value*" *	483
KEY: "*building*" * AND "*U-value*" * OR "*R-value*" *	361

TITLE-ABS-KEY = title, abstract, KEY = keywords; * = singular and plural; ■ = selected query.

The publications found considering TITLE-ABS-KEY were not focused on the U-value and R-value assessment of building elements. On the contrary, the ones based only on keywords (KEY) concerned specifically the research topic, but more appropriate results were found using TITLE-ABS-KEY for "*building**" and KEY for the technical keywords ("*U-value**" and "*R-value**"). Similarly, the number of publications was high using OR instead of AND, with many publications out of the research scope. The incorporation of other keywords such as "*thermal performance**" or "*wall**" significantly increased the sample, producing wider results not directly linked to the research queries (2,879,294 documents). According to this literature retrieval and selection, 483 publications have been extracted from the Scopus database for the query "*U-value and R-value assessment of building**". The statistical analysis was conducted from the data extracted by the Scopus database using Excel to illustrate the time and spatial distribution of the documents. The first document was published in 1981. Since then, the number of published papers significantly increased during the years, reaching almost 50 papers in both 2021 and 2022. From 2009, the literature on this topic experienced a quite exponential growth (Figure 2).

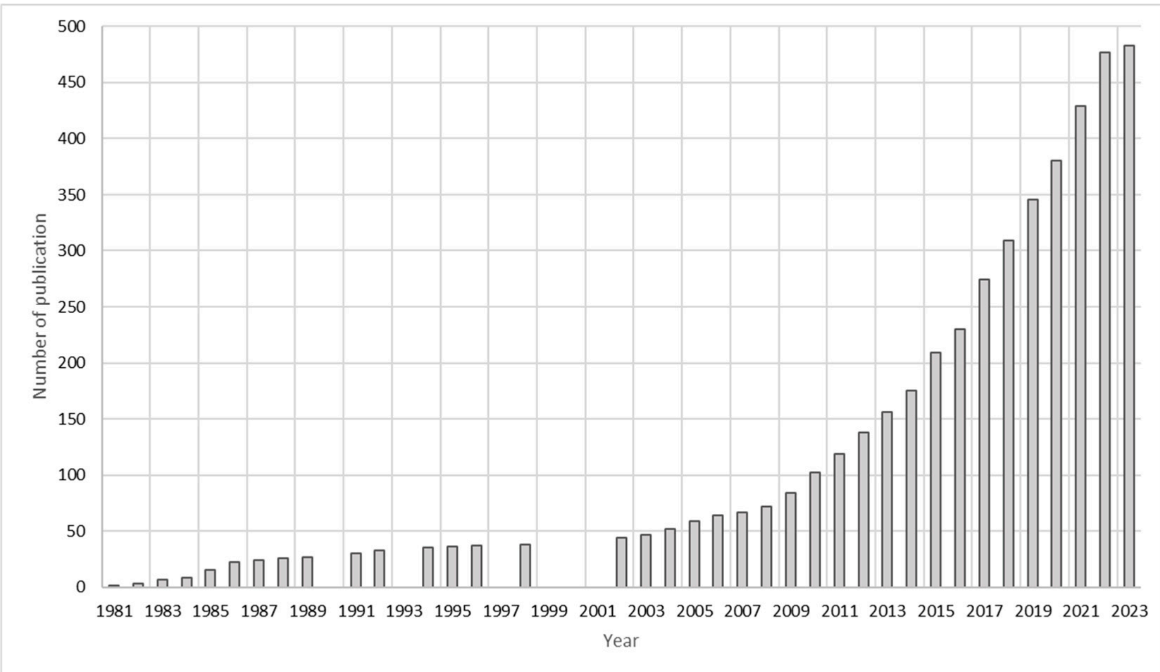

Figure 2. Cumulative number of publications during the years on the topic "*thermal transmittance assessment of building**" (source: authors' elaboration based on Scopus data).

The United States (n. 76) and the United Kingdom (n. 63) are the most active, followed by Canada (n. 31), China (n. 26), Italy (n. 26), Saudi Arabia (n. 24), Spain (n. 24), India (n. 23), and South Korea (n. 23). Studies on this topic are published more or less in each country, despite Europe and Asia being the most active continents (Figure 3).

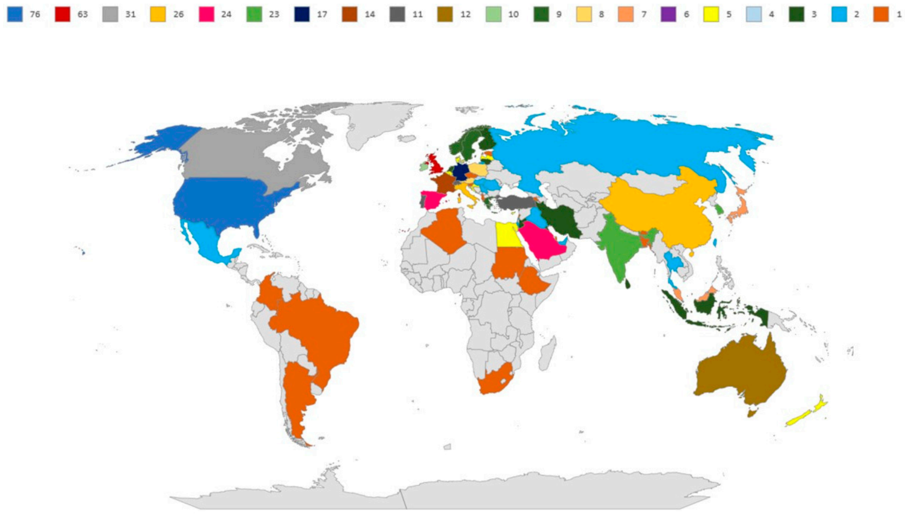

Figure 3. Geographic provenience and distribution of the publications on the topic "*thermal transmittance assessment of building**" (source: authors' elaboration based on Scopus data).

3.2. Scientometric Analysis

These publications were deeper analyzed by the science mapping technique with VOS viewer 1.6.19 to cluster authors and the co-occurrence network of keywords. First, authors were mapped to understand the most active researchers in this field. A co-authorship network adopting 2 minimum documents per author individuated 64 authors, with 1 author with 13 publications (H.N. Saber), 1 with 10 publications (E. Cuce), 1 with 8 publications (S.A. Al Sanea), and 4 with 7 publications (M Casal, A Ghosh, M Karti, and M.F. Zedan) (Figure 4).

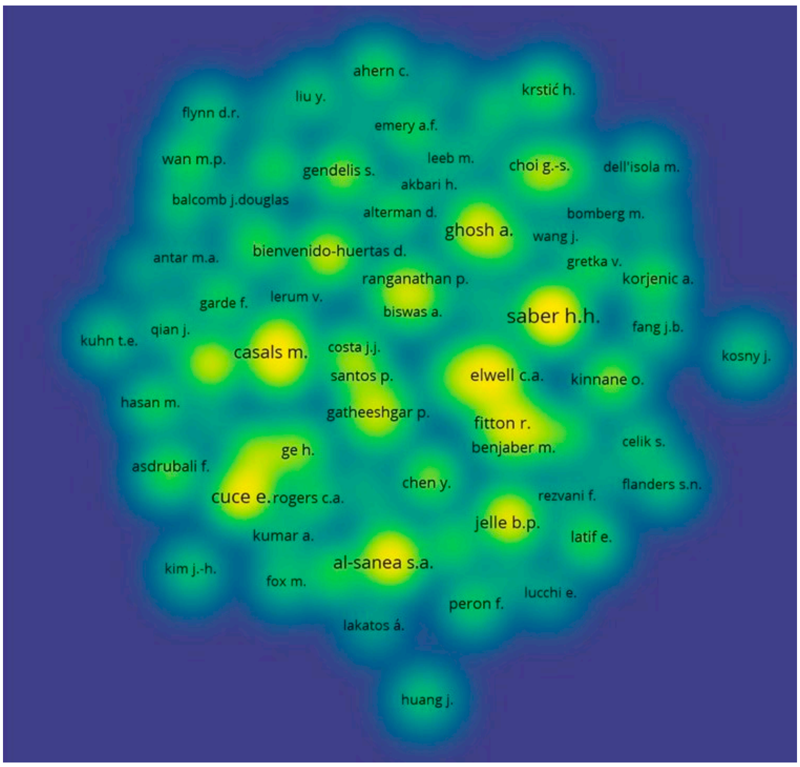

Figure 4. Density visualization of the authors with at least two publications or more on the topic "*thermal transmittance assessment of building**" (source: authors' elaboration using VOSviewer, based on Scopus data).

Then, indexed keywords were mapped to identify the hot topics and trends of the research theme. The co-occurrence network of keywords showed a total of 9665 terms and 213 co-occurrences. Colors identify the clusters of keywords, while the popularity of a keyword is indicated by its size. The proximity of keywords is interpreted as an indication of their similarity. Three clusters of research were automatically distinguished (filtering with a minimum occurrence of 10 times), and they can be referred to as (i) "*estimation*" on the analytical calculation, (ii) "*measurement*" on the field measurement, and (iii) "*innovative procedures*". The result is reported below (Figure 5).

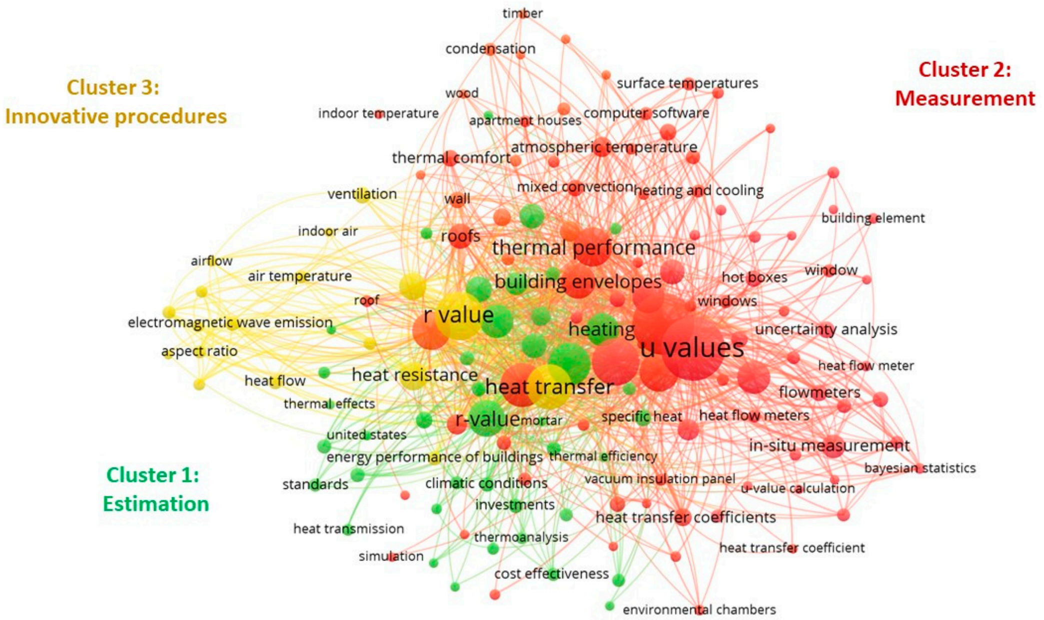

Figure 5. Co-occurrence network of keywords on the topic "*thermal transmittance assessment of building**" (source: authors' elaboration using VOSviewer, based on Scopus data).

According to these first results, a second scientometric analysis was conducted on the clusters "*estimation*" and "*measurement*" that have a huge amount of the literature. Queries and number of publications are reported below (Table 2).

Similarly to the first query, the publications found considering TITLE-ABS-KEY were not focused on the U-value or R-value assessment of building elements, while the ones found using only keywords (KEY) referred exactly to the research topic. In this case also, the number of publications was high using OR instead of AND, with many publications out of the research scope. According to this literature retrieval and selection, 13 publications have been extracted as data from the Scopus database for the query "*thermal transmittance assessment of building**" AND "*estimation*". In this case also, the publications were deeper analyzed by the science mapping technique to cluster authors and the co-occurrence network of keywords. First, 60 authors were found. The co-authorship network adopting a minimum of two documents per author individuated four authors, with one author with three publications (M. Casals) and three authors with two publications (M. Gangollels, K. Gaspar, and M. Gorgolewsky) (Figure 6).

The co-occurrence network of keywords showed a total of 827 terms and 40 co-occurrences. Three clusters of research were individuated (filtering with a minimum occurrence of three times): (i) "*building elements*" on geometrical and thermal features of the building envelope; (ii) "*numerical calculation*" on the analytical calculation of the thermal performance of building elements; and (iii) "*calculation procedure*" on the techniques for calculating these performances. The result is reported below (Figure 7).

According to this literature retrieval and selection, 94 publications have been extracted as data from the Scopus database for the query "*thermal transmittance assessment of building**" AND "*measurement*". In this case also, the publications were deeper analyzed by the science mapping technique to cluster authors and the co-occurrence network of keywords. First, 268 authors were found. The co-authorship network adopting a minimum of 2 documents per author individuated 33 authors, with 12 authors with 3 publications (M. Casals, M. Gangollels, K. Gaspar, M. Goncalves, D. Marin, D. Bienvenido-Huertas, F. Peron, C.A. Elwell, V. Gori, P. Biddulph, M. Domazetovic, and H. Krstic), and 33 authors with 2 publications (Figure 8).

Table 2. Queries used and number of publications obtained for topics "*estimation*" and "*measurement*" (source: authors' elaboration, 16 March 2023).

Query	Number of Publications
Thermal transmittance estimation of the building envelope	
KEY: "*building*" * AND "*U-value*" * OR "*R-value*" * OR TITLE-ABS-KEY: "*estimation*" *	15,182
KEY: "*building*" * AND "*U-value*" * OR "*R-value*" * OR TITLE-ABS-KEY: "*estimation*" * OR "*wall*" * OR "*thermal performance*" *	62,071
KEY: "*building*" * AND "*U-value*" * OR "*R-value*" * AND "*estimation*" *	13
Thermal transmittance measurement of the building envelope	
KEY [2]: "*building*" * AND "*U-value*" OR "*R-value*" * OR TITLE-ABS-KEY [1]: "*measurement*" *	32,248
KEY [2]: "*building*" * AND "*U-value*" * OR "*R-value*" * OR TITLE-ABS-KEY: "*measurement*" * OR "*wall*" * OR "*thermal performance*" *	60,770
KEY [2]: "*building*" * AND "*U-value*" * OR "*R-value*" * AND "*measurement*" *	94

TITLE-ABS-KEY = title, abstract, keywords; KEY = keywords; * = singular and plural; ■ = selected query.

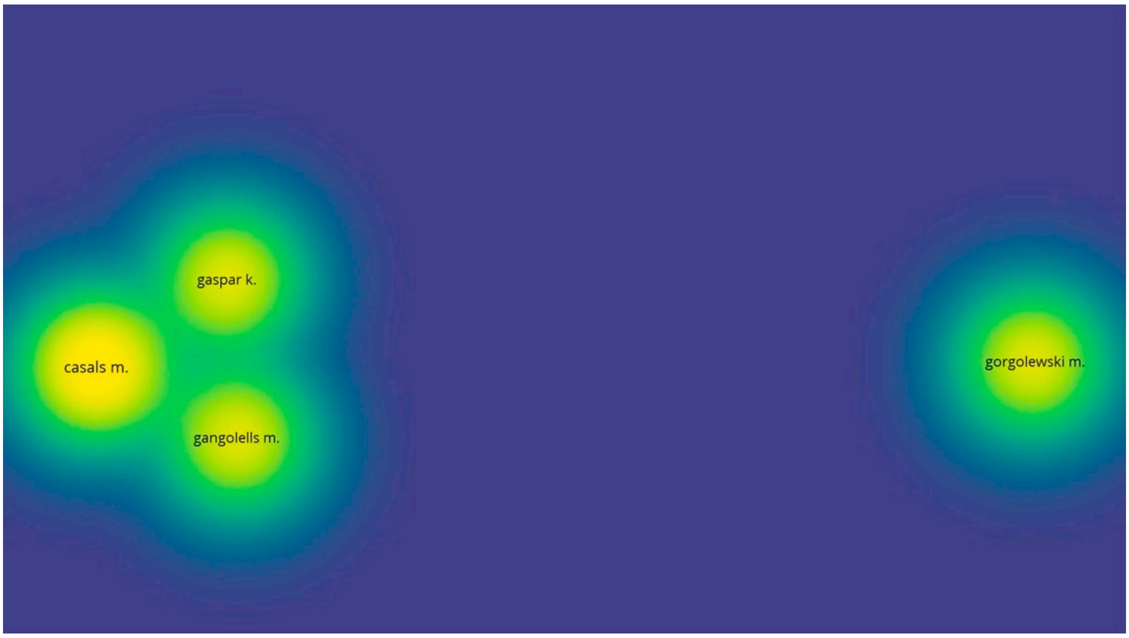

Figure 6. Density visualization of the authors with at least two publications on the topic "*thermal transmittance estimation of building**" (source: authors' elaboration using VOSviewer, based on Scopus data).

The co-occurrence network of keywords showed a total of 2315 terms and 209 co-occurrences. Five clusters of research were individuated (filtering with a minimum occurrence of three times): (i) "*heat flux meter measurement*"; (ii) "*simple hot box method*";

(iii) "*thermometric method*"; (iv) "*quantitative infrared thermography*"; and (v) "*comparison*". The result is reported below (Figure 9).

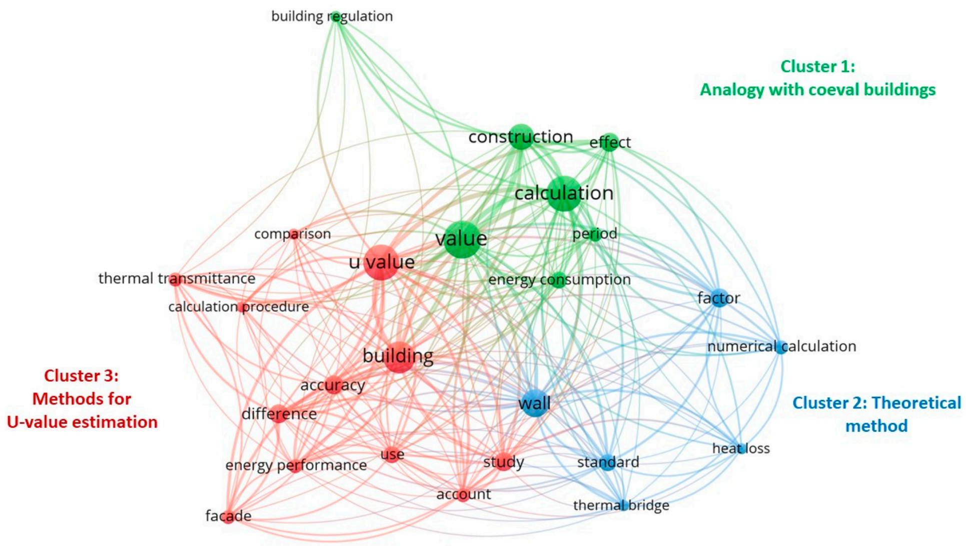

Figure 7. Co-occurrence network of keywords on the topic "*thermal transmittance estimation of building**" (source: authors' elaboration using VOSviewer, based on Scopus data).

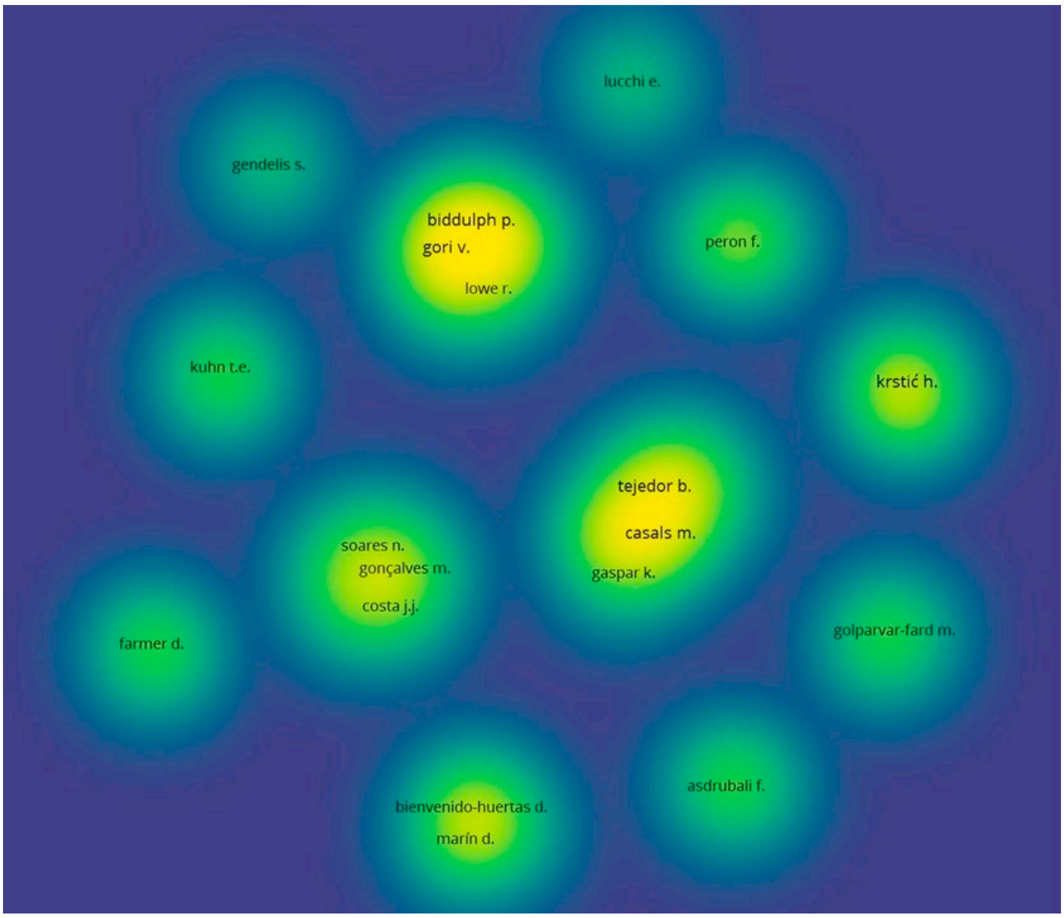

Figure 8. Density visualization of the authors with at least two publications on the topic "*thermal transmittance measurement of building**" (source: authors' elaboration using VOSviewer, based on Scopus data).

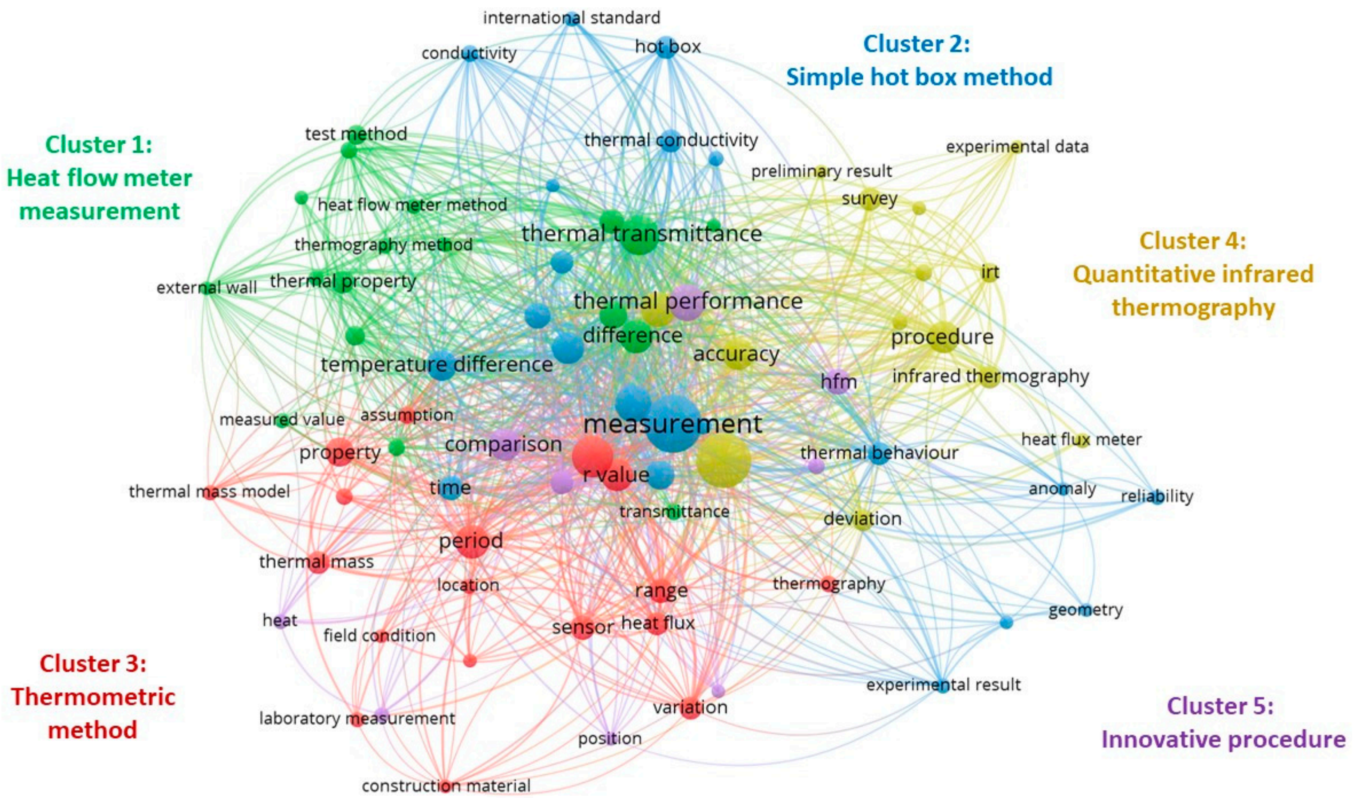

Figure 9. Co-occurrence network of keywords on the topic "*thermal transmittance measurement of building**" (source: authors' elaboration using VOS viewer, based on Scopus data).

4. U-Value Assessment

According to the bibliometric analysis, the methodologies for the U-value assessment of the building envelope can be divided into four main groups (Figure 10):

- Estimation realized without a measuring campaign. This group includes the analogy with coeval buildings and the theoretical method.
- Measurement or test realized with a measuring campaign, whether ruled by standard (e.g., HFM measurements and QIRT) or not, such as the simple hot box and thermometric methods.
- Innovative procedures that have been recently proposed in the literature, which require measurement and are quite a combination between HFM and QIRT. These are the representative points method and weighted area method.
- The future perspective of all the previous, which basically rest on the use of AI and the use of data, such as random forest, artificial neural network (ANN), and so on.

The first two groups are commonly employed, whilst the innovative procedures have been recently proposed in the literature, and the future perspectives represent the outbreak to come.

The accuracy of these approaches is related to reliable data availability, measurement procedures, and instrumentations. The literature experiences often propose different remarks on these approaches, depending on the feature of investigated buildings, device set-up, or measurement procedure. It is worth noting that some of these approaches are already regulated by technical standards adopted worldwide, while others do not have specific regulations yet. In the following sections, a synthesis of the different approaches is reported.

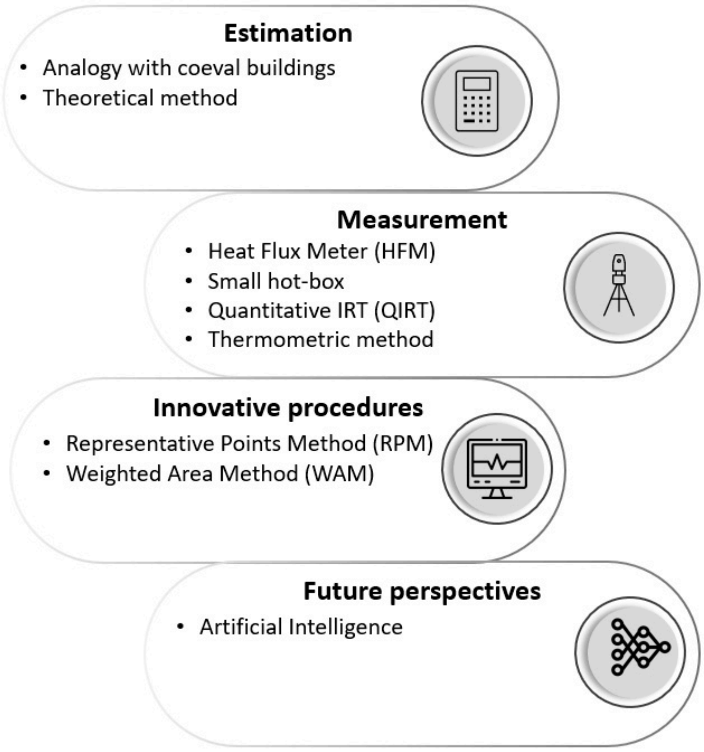

Figure 10. Methodologies for the U-value assessment of the building envelope (source: authors' elaboration).

4.1. Group 1: Estimation

This group refers to those methods devoid of measurements. Pertaining to this category are the following methods:

- Analogy with coeval buildings (Section 4.1.1).
- Theoretical method (Section 4.1.2).

The methods, however, require knowledge of wall features. Particularly, the first requires knowledge of the construction age (generally retrievable also from municipalities' building plans) and the recurring building type and materials used for a building of the same age. The second requires precise knowledge of the building layer typology, thickness, and conductivity, which are generally listed in the building project. Unfortunately, a disadvantage is that for some buildings (especially ancient ones) such plans are missing. Hence, to proceed without a measuring campaign, the only way is to identify a similar building, aged the same and possibly located nearby (to hypothesize that they are made of the same materials) and to assume that the thermal transmittance of the reference building is equal to the object of analysis.

4.1.1. Analogy with Coeval Buildings

This approach is applied mainly to existing buildings, especially when detailed information on building features and materials are missing. In these cases, the U-values of existing masonries are retrieved by referring to other well-known buildings with similar age, function, shape, thermal characteristic, and masonry texture [11,12]. This method is quick and cheap, but several factors may affect the reliability and the affordability of the results. The main problems refer to (i) incorrect information on the construction period [13,14], (ii) special characteristics of the building that are neglected by the analogy with coeval buildings [15], (iii) different wall texture and thickness [13–20], (iv) moisture contents or damage that affects the thermal performance [19,20], and (vi) the presence of refurbishment [13,15–17,19,20]. The difficulties related to the accurate identification of the thermal properties of existing masonries affect the total heat transfer through the element, producing U-values not adherent to the real behavior of the investigated building. In general, it results as an overestimation of the energy consumption of the whole building [13–20].

To obtain correct results, consolidated databases are needed. Positive elements are related to the applicability to the building stock analysis and energy policies. A winning experience in Europe was the TABULA Project [21], performed from 2009 to 2012 with the support of the Intelligent Energy Europe program of the European Union. Here, building typologies of 13 countries were characterized, grouping them by typical wall assemblies, sizes, ages, and further parameters to define a common procedure for comparing the energy performance of exemplary buildings. The tool developed in this framework [22] provides, amongst other data, the typical U-values of typical building elements in a given construction period. TABULA's follow-up is the EPISCOPE Project [23], launched in 2013 and still co-funded by the Intelligent Energy Europe program of the European Union. This continues and expands the outcomes of the previous one by conducting the elaboration of building stock models to assess the rates and status of refurbishment by implementing policy instruments. It would be interesting to use for energy purposes building databases that were born for other scopes. For instance, in the Italian experience, after some destroying events like earthquakes, a detailed survey of each building in each municipality involved in the seismic area is carried out to evaluate the entity and economic damage of each structure [24]. In this way, a huge amount of data has been collected, even geographical information system (GIS) references, whose primary scope could be the seismic risk assessment or the formulation of damage scenarios or prevention models. The same survey, which considers the building typology on such level (house number), could be of help to determine, at the same level, the building features and envelope typologies and transmittances. For instance, the CARTIS database is devoted to unreinforced and reinforced concrete residential buildings in more than 400 municipalities in Italy [25], and available data (beyond those for seismic purpose) are [26] masonry type, number of stories, construction periods, ring beams/tie rods, slab types, presence of mixed structures, roof materials, overall percentage of openings, average floor area, and so on. The interaction between multiple databases, or the database availability, could help in the identification of typical thermal transmittances even at the local level, such as minor centers.

The characteristics of this technique are reported below (Table 3).

Table 3. Characteristics of analogy with coeval building (source: authors' elaboration).

Features	Characteristic
Opaque building envelope	Retrievable by projects
Transparent building envelope	Retrievable by projects or defined by product datasheets
	Element not considered by databases
Building age	Retrievable by projects, which unfortunately could be missing
	Retrievable from past and current zoning plans and by the local building permission
U-value retrieval	Country databases can be used (when available and when freely accessible)
	Multiple databases could interoperate to have a detailed depiction even of small urban contests
	Time is mainly spent for the database retrieval
	Moisture content and damages are not considered
	Quite cheap and quick
Applicability	Walls, roofs, intermediate floors, ground-coupled surfaces such as basement walls and slab-on-grade floors, windows

4.1.2. Theoretical Method

This approach is ruled by International Standard ISO 6946 [4], and it allows the retrieval of the notional U-value (U). It starts from the assumption that each element of the assembly impedes the heat transfer as if it was a resistance in an electrical network crossed by the current. Adjacent layers behave as a series of resistances. Hence, the ith layer wall layer is assumed as a R-value (R), whose value (for thermally homogeneous layers) equals the ratio between the layer thickness (s) and its thermal conductivity (λ-value or λ) [(m K)/W], retrievable by means of executive design projects or technical reports:

$$R_i = \frac{s_i}{\lambda_i} \tag{1}$$

The wall assembly, indeed, offers a total thermal resistance given by the sum of the individual resistances, whose reciprocal is the thermal conductance (C-value, or C).

To calculate the thermal transmittance, the R-value of the internal $R_{s,in}$ and external $R_{s,out}$ surfaces of the walls must be added in series in the electrical network. Their values are the reciprocal of the convective heat transfer coefficient (h) [W/(m^2 K)] on both sides of the component:

$$U = \frac{1}{R_{tot}} = \frac{1}{R_{s,out} + \sum_{i=1}^{n} \frac{s_i}{\lambda_i} + R_{s,in}} \tag{2}$$

The standard is applicable also to elements with thermally inhomogeneous layers using a simplified method. Under the rules of International Standard ISO 6946 [4], it is possible to evaluate the h-value. In Annex A, the way of calculating the h-value for plane surfaces and for components with non-planar surfaces (like pillars) is detailed. The h-value is calculated by using a simple equation that involves the radiative and convective coefficients. For the evaluation of the radiative coefficient, knowledge of the hemispherical ε of the surface, the mean thermodynamic temperature of surface (T_s) [K], and its surroundings is needed. Several values are given for the external convective heat transfer coefficient (h_e) ((m^2·K)/W), according to heat flow direction (upward, horizontal, or downward); in the case of an external surface, a correlation involving the wind speed (υ) [m/s] adjacent to the surface is provided. In Annex B, the equations for the R-value calculation of airspace, both ventilated and unventilated, are given. Annex C provides the calculation procedure of the U-value of component with tapered layers (such as a pitched roof), while in Annex D, corrections to the U-value are given to consider the effect of air voids, mechanical fasteners, and inverted roofs. This approach is quick and cheap but requires a proper knowledge of material thicknesses and thermal properties to obtain reliable results. For this reason, the thermo-physical characterization of existing masonries is worthy of continuous research efforts. Several studies have been published so far with the aim of proposing (i) data defined by the design projects [16,19,20], (ii) low destructive techniques (LDT) for thermal performance characterization (i.e., coring or endoscope) [19,20], (iii) multidisciplinary approaches based on different non-destructive techniques (NDT) to reduce the deviation between calculated and measured U-value [16,19], (iv) adjusted algorithms for the masonries' thermal modeling [27], and (v) methods for accounting for the influence of moisture on the thermal performance [28]. In these cases, the assessment of the λ-value refers to standard values or databases (e.g., the Italian standard UNI 10351 [29] provided the λ-value, μ, and cp of the construction materials). The characteristics of this technique are reported below (Table 4). The uncertainty related to this method can be evaluated with the uncertainty propagation law. In the work by Ficco et al. [30], the uncertainty on the nominal U-value is evaluated by considering, for each wall layer, a rectangular distribution of the thermal conductivity value between the minimum and maximum values given by the standard. When sampling or an endoscope are used, the authors [30] employ once again the uncertainty propagation law, considering a relative uncertainty on thermal conductivity values of 3%.

Table 4. Characteristics of the theoretical method (source: authors' elaboration).

Features	Characteristic
Opaque building element	Building structure is retrievable by projects
	U-value can be identified by mini-destructive techniques, such as endoscope or coring
	U-value of the materials are listed by the standards, but they might not correspond to the real ones
Transparent building envelope	Easy calculation for glazing due to the transparency of the element
	Difficult calculation for windows' frames due to the structure of the element
	Thermal performances of the materials are listed by standards, but they might not correspond to the real ones
U-value retrieval	Quite simple calculation
Applicability	Walls, roofs, intermediate floors, ground coupled surfaces such as basement walls and slab-on-grade floors, windows

4.2. Group 2: Measurement

This cluster includes those techniques that require a measuring campaign. This implies, on one hand, that the final value is derived directly on the building object of investigation, avoiding the uncertainties of a hypothesis linked to the building age or layer thickness or material degradation. On the other hand, it entails (i) higher costs for equipment purchase, (ii) longer times, since a measurement campaign might require time, (iii) the possibility of measuring campaign repetition caused by, for instance, boundary condition variability or equipment misfunctioning, (iv) metrological errors, and (v) the need for data analysis. Pertaining to this category are the following methods:

- Heat flow meter measurement (Section 4.2.1).
- Simple hot box method (Section 4.2.2).
- Thermometric method (Section 4.2.3).
- Quantitative infrared thermography (Section 4.2.4).

4.2.1. Heat Flow Meter Measurement

HFM measurement is a non-destructive test (NDT) for quantifying directly in situ the R- and U-values by monitoring heat flux rate q through a building element and the indoor and outdoor environmental temperatures T_{in} and T_{out}:

$$U = \frac{\sum_{i=1}^{n} q_i}{\sum_{i=1}^{n} (T_{in,i} - T_{out,i})} \quad (3)$$

The HFM apparatus is composed of [31] (i) a thermally resistive HFM plate, (ii) minimum of two surface temperature probes applied on each side of the element under test, (iii) ambient temperature probes (generally, alternative to the surface temperature probes), and (iv) facing sheets to provide protection (eventually). This apparatus measures the heat flows through the walls and the internal and external surface temperature (T_s) (K) and/or air temperature (T_a) (K).

The international standard ISO 9869 [31] defined the procedure for measuring the U-value of "*plane building components*", consisting mainly of opaque layers perpendicular to the heat flow without significant lateral heat flow. Additionally, this procedure can be applied to quasi-homogeneous layers perpendicular to the heat flow, without thermal bridges and with small inhomogeneities. Its characteristics are reported below (Table 5).

Table 5. Characteristics of the HFM apparatus (source: authors' elaboration).

Features	Characteristic
HFM plate	Shape and dimension to be chosen according to the structure of the element [19,20]
	Low R-value for minimizing the perturbation caused by the instrument [31]
	High sensitivity for giving sufficiently large signal for the lowest heat flow rates measured [31]
	Same colors and emissivity as the building substrate [31]
T_s sensors	Thermocouples and flat resistance thermometers with an accuracy better than + 2% [31]
T_a sensors	Thermocouples with an accuracy better than + 2% [13]
Thermal conducting paste	λ value similar to the one of the HFM plate [14,16,19,20]
Tape	λ value similar to the one of the HFM plate [14,18]

The homogeneity of the building element should be investigated by IRT (in accordance with [32]), to place the HFM in a representative part of the whole element without the influence of thermal singularities, heat losses, relative humidity, and decay [31,33–35]. Obviously, the IRT survey should be free of all visual interferences (e.g., furnishings, curtains, wall hangings, and so on). Furthermore, the apparatus must be protected from potential sources of error, such as [31] (i) a not-perfect adherence to the building element, (ii) direct exposure to environmental conditions, (iii) the direct influence of heating, cooling, or fan devices, (iv) other potential thermal sources (i.e., radiators, computers, and lamps), or (vi) cracks and damaged masonries. The criteria for selecting the location of the HFM apparatus are reported below (Table 6).

Table 6. Location of the HFM apparatus (source: authors' elaboration).

Features	Characteristic
HFM plate	Mounting adjacent to the more stable temperature to avoid the effect of boundary conditions Use of a thermal conducting paste to the back for ensuring the direct thermal contact with the surface of element [14,15,28,31,36] Use of low-tack masking tape for reducing the heat flux perturbation generated by the HFM itself [14,28,36,37] Use of a guard ring realized with similar thermal properties and thickness mounted around the HFM to reduce the thermal exchange [31]
Ts sensors	Mounting adjacent to the more stable temperature to avoid the effect of boundary conditions Use of artificial screening and ventilated for protecting from the variations of the climatic parameters (i.e., sun radiation, υ, and outdoor temperature) [31]
Ta sensors	Needed only for measurement control and validation
HFM apparatus	Location on north orientation for minimizing the influence of climatic parameters (i.e., sun radiation, υ, and outdoor temperature) [14,37] Location in a central part of the north-facing walls (about half-way between window and corner, floor and ceiling) for minimizing the influence of vertical stratifications of temperature, heat sources, and thermal bridges [14,30,37] Location away of sources of heat, such as radiators, fan coils, and lamps, for minimizing the potential influence of heat sources and users on the inner surface [30]
Applicability	Walls, roofs, windows

The data shall be recorded continuously or at fixed intervals over a monitoring period (n) of complete days [31]. The duration of the test of depends on several factors [31] related to (i) the feature and nature of the building element (e.g., light or heavy structure, presence of internal or external insulation), (ii) the fluctuations and average of Ts and Ta (e.g., before and during measurement), and (iii) the method used for data analysis.

Different approaches to data can be used, such as the Bayesian approach proposed in [38].

The test may be stopped when the results after three subsequent nights do not differ by more than ±5%. For heavier elements [31], the analysis shall be carried out over a period that is an integer multiple of 24 h and shall be ended when (i) the test duration exceeds 72 h, (ii) the final R-value does not deviate by more than ±5% from the value obtained 24 h before, (iii) there is a deviation less than 5% between the R-values obtained in the first and in the last period, and (iv) the change in heat stored in the wall is more than 5% of the heat passing through the wall over the test period. A synthesis of the monitoring periods is reported below (Table 7).

Table 7. Monitoring period for HFM measurement (source: authors' elaboration).

Type	Duration
Standard period	Integer multiple of 24 h and at least consecutive 72 h (3 days) [31]
	It can be reduced reaching stable temperatures on both sides of the element [31,39]
Heavy building elements or thick walls	Integer multiple of 24 h and at least a consecutive 72 h (3 days) [31]
	7–30 days to consider the effects of the thermal storage effects related to the thermal inertia of the wall [16–20,30,33–35,40–43]
Light building elements*	Integer multiple of 24 h and at least a consecutive 72 h (3 days) [31]
	Data should be acquired only during night to avoid the impact of solar radiation [14]
Windows	Integer multiple of 24 h and at least a consecutive 72 h (3 days) [31]

* = with a specific heat capacity per unit area of less than 20 kJ/m'-K.

Two data analysis criteria can be used [31]: (i) the average method and (ii) the dynamic method. The first method requires long monitoring periods because it assumes that the R- or U-values are obtained by dividing the mean density of heat flow rate by the mean temperature difference (ΔT_s for the R-value or ΔTa for the U-value) [31]. This value is close to the real conditions when (i) the heat content of the element is the same at the beginning and the end of the measurement, and (ii) the HFM is not protected from direct solar radiation; the C-value is constant during the test [31]. The dynamic method uses the heat equation to obtain the steady-state properties of a building element when there are large Ta and heat flow rate variations. The test duration is shorter than the average method for medium and heavy elements, especially when high Ta variation occurs. The data must be reordered at fixed time intervals determined by the method used for data analysis. Typical recording intervals are from 0.5 h to 1 h for the average method and less for the dynamic method [15,40].

The accuracy of the measurement depends on [31] (i) calibration of the HFM devices (error about 5% with instruments calibrated every two years or more frequently), (ii) accuracy of the data logging system, (iii) random variations caused by the thermal contact between the sensors and the surface (variation of 5% with carefully installed instruments), (iv) operational errors that are due to modifications of the isotherms caused by the presence of the HFM devices (error about 2–3% with corrections based on finite-element analysis), (v) differences between air and radiant temperatures, and (vi) T_a and heat flow variations within the space. Particularly, the last problem can be reduced to 10% by reducing the Ta variations [31]. Errors are increased by large temperature fluctuations, heavy elements, short durations of the test, presence of solar radiation or strong thermal influences, and not-estimated operational errors [31]. The results are better with air temperature differences (ΔT_a) (K) higher than 10 K. Heat flow inversion, low ΔT_a, or low heat flow generate unacceptable uncertainties [16,35]. Similarly, moisture might decrease the U-value of the building element [28,30,36]. Thus, it must be determined precisely with gravimetric tests, monitoring, or IRT surveys [20,28]. Additionally, the filtering of the data during the periods with larger ΔT_a (up to 20%) improves the accuracy of the test [20,29,41–43].

4.2.2. Simple Hot Box Method

Laboratory tests overcome the problems caused by boundary conditions, but they require specific facilities, equipment, and skills and high costs. The small hot box (SHB) reproduces, in small scale, the hot box apparatus, which is a device capable of maintaining, at the boundaries of a specimen wall, stable and controlled conditions. The small hot box with two tiny chambers (one for the cold and the other for the hot environment) has been used also to assess wall hygrothermal performances [44].

A variation of the small hot box is the simple hot box, which uses only the hot chamber in adherence to the investigated wall, for the determination in situ of the U-value by means of HFM. Hence, its acronym is SHB-HFM. Therefore, the wall under examination faces on one side the ambient air temperature and on the other side a small chamber that can be heated up with an electric resistance. In [45], the authors find a relative difference with the design value of about 6% when the most unfavorable in situ conditions occurred. An extension of the previous work, published in 2017, [46] assessed the influence of the small hot box dimension on the inside temperature distribution, showing the income of parallel isotherm where it is advisable to locate probes, since it corresponds to a one-dimension (1D) heat transfer zone. Besides heat transfer capability, larger hot boxes suffer from increased weight and increase inconveniences in the structure for its support of the wall. Moreover, the bigger the chamber, the higher the possibility of including, in the chamber itself, thermal bridges. According to the authors, minimum box dimension (for the specific wall) depends on (i) wall thickness, whose increase determine the increase in the minimum box dimension to ensure the presence of a 1D heat transfer zone, (ii) wall equivalent thermal conductivity, whose increase corresponds to a decrease in thermal resistance and, therefore, in the heat dissipation zone increasing, causing an increase in minimum box dimension, and (iii) temperature difference on the two sides of the wall, although the authors proved that, for the investigated wall, a temperature gradient over 20 °C does not influence the minimum dimension. Finally, the minimum dimension can be obtained by a multi-factor coupling regression formula. In [47], the SHB-HFM was used on a historical building in Portugal, namely the "*tabique*" wall. In this case, two heat flux meters and temperature probes were placed in correspondence, on the two sides of the wall, through which a minimum temperature gradient of 20 °C between indoor and SHB was established. The work also provides the numerical model of the entire setup.

Given the fact that this equipment can be used even in summer, it is important that the following requirements are met: (i) the SHB (which, in this case, is placed outside) avoids thermal bridging; thus, its position should be varied and, as a consequence, its support structure; (ii) thermocouples are placed on the wall, in correspondence to the central zone of the chamber to avoid side effects; and (iii) temperature probes should be mounted far from the box sides and symmetrically with respect to the heat flux plate. The characteristics of the apparatus are summarized below (Table 8).

4.2.3. Thermometric Method

This method is also known as the temperature-based method (TBM) or air–surface temperature ratio (ASTR) method [6]. It starts from the equivalence between the heat flow from the indoor to the outdoor (which is proportional to the U-value and to the air temperature difference), and the heat that flows from the indoor toward the inner side of the wall via convection, as per Equation (4):

$$Q = U(T_{in} - T_{out}) = h_{in}(T_{in} - T_{s,\,in}) \tag{4}$$

where h_{in} is the convective coefficient and Ts is the inner surface temperature. Therefore, the law describing the method is a modification of (Equation (3)) by calculating the heat flux q as the convective heat flow occurring in the inner surface and is expressed by Equation (5):

$$U = \frac{h_{in}(T_{in} - T_{s,\,in})}{(T_{in} - T_{out})} \tag{5}$$

Table 8. Characteristics of the simple hot box method (source: authors' elaboration).

Features	Characteristic
Size	Depends on wall thickness, wall equivalent thermal conductivity, and temperature difference on the two sides of the wall
	Minimum dimension can be obtained by a multi-factor coupling regression formula
Probes number	Mounted on the two sides
Boundary conditions	Stable values and settled by the user
	The apparatus can be used in summer
Location	Positioning might be complex
	Box is mounted on a support structure, which needs to rest on the ground
	Walls of buildings not on the ground floor or without balconies are not investigable with this technique
Error	Difference between TBM and HFM ranging from 2–13%, or even higher if compared to the theoretical U-value [48,49]
Applicability	Walls

The main difference with the HFM is the way the heat flux q is evaluated: in HFM, it is physically measured with the flux plate, whilst in the THM, it is evaluated using the convection law. The convective heat transfer coefficient is gained by ISO 6946 [4], so it is a fixed value, although improvements in this sense are needed to identify the best value [50]. In fact, when performing in situ tests, the real convection could differ from this estimation. Therefore, the convective heat transfer coefficient is a key parameter for such a method [6,50,51], as well as for HFM and QIRT.

The literature [52] suggests having stable conditions while measuring to ensure as much as possible the temperature stability. Moreover, a good thermal gradient between inside and outside (at least 15 °C) is preferred. In the work [53], the TBM was employed to a double brick-layered wall, internally insulated, but the aim of the work was to employ the temperature measurement for enhancing building simulations. In [54], such measurement has been conducted to the north-facing wall to avoid incident solar radiation. In a recent work [48], a modular, scalable, and wireless device for this kind of measurement is conceived, employed, and tested with good results. The device can manage tens or hundreds of indoor and outdoor modules for temperature probes, and it also allows real-time data processing. This work specified that the best probes' locations should be identified with a preliminary thermographic inspection and that stable conditions are needed; hence, measurement duration is strictly necessary according to the deviation that the operator establishes. A great innovation, in this sense, is the possibility of automatically and dynamically adjusting test duration according to the conditions in each case. Moreover, in this work, measurements were taken also in summertime, overcoming an issue that HFM has. A deeper study from Bienvenido-Huertas et al. [52] also investigated the feasibility of this method during seasons other than winter, specifically in summer and autumn, concluding that a minimum of 5 °C gradient is vital for reliable measurements that, in general, should be performed in winter. Differences between TBM and HFM were found lower than 2% in [48], between 0.28 and 5% in [49], and in the order of 6–13% in [52], proving, in general, the reliability of this method, which was also tested in [53,54]; however, higher differences (in the order of 40–44%) were found in [55] by comparing with the notional U-value. A disadvantage of this method, in common with HFM, is that measurement is performed in single points; hence, to have the U-value of different portions of the same wall, measurements must be repeated. This has been overcome by QIRT, which allows the sketching of an entire wall by shooting its thermal map. The characteristics of the apparatus are summarized below (Table 9).

Table 9. Characteristics of the thermometric method (source: authors' elaboration).

Features	Characteristic
Ts sensor	Are the only measurement devices needed
	At least 1 sensor
Ta sensor	At least 2 sensors
Probes number	At least 3 probes
	Possibility of scaling when homemade systems are developed
	Preliminary IRT inspection is advisable
Test duration	Few hours [48,49]
	Possibility of automatically and dynamically adjust test duration according to the conditions [48]
Error	Difference between TBM and HFM ranging between 2–13%, or even higher if compared to the theoretical U-value [48,49]
Applicability	Walls

An approach similar to TBM, which considers the effect of convection, is that proposed by Jankovic et al. [56] and named the natural convection and radiation method (NCaR), which is basically referrable to the following equation:

$$U = \frac{\varepsilon\sigma \sum_j \left(T_i^4 - T_{s,in}^4\right)_j + C\sum_j \left(T_i - T_{s,in}\right)_j^{n+1}}{\sum_j \left(T_i - T_{out}\right)_j} \tag{6}$$

where ε is emissivity, σ is the Stefan–Boltzmann constant, j is the individual measurement, and C and n are constants, known by the literature. In this work [56], thermal imaging was used to measure wall emissivity, even though, according to the authors' statement, this step could be avoided by employing standardized emissivity. Moreover, in the work, eight correlations for the convective heat transfer coefficient were employed, and results were compared to those from HFM, showing the lower deviation when the ASHRAE correlation was used.

4.2.4. Quantitative Infrared Thermography

This method consists of applying infrared thermography to retrieve quantitative information on the investigated element [57], whilst in the previous methods, when employed, it was for qualitative purposes, i.e., to identify the best probes' locations. Being a noninvasive and nondestructive method, this approach is gaining more and more attraction, to the point that standard ISO 9869-2:2018 [31] has been released «(...) *to measure the thermal transmittance (U-value) of a frame structure dwelling with light thermal mass, typically with a* *daily thermal capacity calculated according to ISO 13786 below 30* $\mathrm{kJ/(m^2\,K)}$». However, the method is still under study, so there is no univocal equation for the U-value determination. Indeed, different approaches have been proposed in the literature, also according to the investigated side of the building and to the convective heat transfer coefficient to be employed. Some authors perform QIRT from inside the building [58–64], and one of the employed correlations is:

$$U = \frac{\varepsilon\sigma\left(T_{ref}^4 - T_{s,in}^4\right) + \frac{\left\{0.825 + \frac{0.387 Ra^{\frac{1}{6}}}{\left[1+\left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right\}^2 \lambda_{air}}{L}\left(T_{in} - T_{s,in}\right)}{\left(T_{in} - T_{out}\right)} \quad (7)$$

where T ref is the reflected temperature, Ra and Pr are Rayleigh and Prandtl numbers., respectively, and L is the wall height.

In other works, QIRT is employed from the outside [65–72], and one of the employed correlations, which also takes into account air speed v, is:

$$U = \frac{\varepsilon\sigma\left(T_{s,out}^4 - T_{out}^4\right) + 3.8054\ v\ \left(T_{s,out} - T_{out}\right)}{\left(T_{in} - T_{out}\right)} \quad (8)$$

Inside QIRT requires access to the building, with a low interference with the occupant's routine, but stable conditions for acquisitions are guaranteed, providing a controlled environment and, thus, good results. Outside QIRT allows the shooting of both small and large portions of buildings, but acquisition suffers for unstable conditions caused, for instance, by humidity and, most of all, wind gusts. This, however, has been an interesting investigating point for both inside and outside QIRT. These methods are employed under the hypothesis of steady-state flux, although the research interest is also in those techniques based on transient heat transfer, as in [73], where two thick walls were employed for tests, which demonstrates the reliability of the approach.

Accurate results require the avoidance of direct solar irradiance on the investigated surface, as well as the framing of objects that would interfere with the acquisition (trees or lampposts for the outside QIRT, furniture or curtains for the inside QIRT) or direct exposure to heating or cooling devices. Moreover, a good temperature gradient (10 °C) between inside and outside should be preferred; in this sense, the effort of scientists is to identify a formulation that could be employed with a low temperature difference. Such suggestions are confirmed by ISO 9869-2:2018, which also accounts for other limitations, such as the measurement period, which should be during night, and the difficulties of employment for low U-value walls. Measurement duration should consider the thermal mass of the building element. Indeed, lightweight walls can be inspected.

Parameters that affect the IRT quantitative measurement are emissivity, solar radiation, and wind [74]. The latter opens one of the main research questions on this method: how to properly account for the convective contribution. In this sense, some papers have been proposed: correlations using an external convective heat transfer coefficient and depending on wind speed and on dimensionless numbers were compared in [75], where 20 clusters were created and compared based on results from four tests on three different walls. Although it was difficult to assess a sort of ranking amongst the correlations, important conclusions were drawn, especially considering the convective or radiative contribution given. A similar work, based on outdoor QIRT, aimed at comparing 57 correlations with respect to the wind speed and, then, when a reduced wind speed was considered (between 0 m/s and 0.4 m/s) to match the conditions that occurred while performing measurement on a specimen wall. Results showed that suitability depends on wind class and on the equation used for the U-value calculus.

When internal convective heat transfer coefficients were employed [75], eight clusters were retrieved (analysis considered 25 equations based on temperature difference and 20 based on dimensionless numbers), and once again the radiative and convective contributions were assessed. Results showed that coefficients depending on dimensionless numbers are more suitable for internal QIRT. It is worth recalling that QIRT is being employed even for thermal bridges measurement, for instance in [76–82] and for windows' U-value assessment [7,83–85]. The characteristics of the apparatus are summarized below (Table 10).

Table 10. Characteristics of the QIRT method (source: authors' elaboration).

Features	Characteristic
IR-camera	Low-quality IT cameras are not suitable for quantitative measurement
T sensors	Temperatures can be metered only with the IR camera, although for the ease of the use, T probes are used
Location	Avoid framing interfering objects (e.g., threes, lightings, furniture, etc.)
Convection	Key aspect to be considered
Boundary conditions	Avoid solar radiation
	Avoid windy days
	Avoid wet or humid building elements

4.3. Group 3: Innovative Procedures

The following methods are based on both infrared thermography and heat flux measurement. Hence, they are a merger of QIRT and HFM. Such methods are named the representative points method (RPM) and the weighted area method (WAM). They were employed in the work by Atsonios et al. [86] on a lightweight steel-framed (LSF) wall with vertical metal studs, and the overall U-value considers the linear thermal bridges induced by the studs themselves but discards the point thermal bridges because of fasteners and screws. The work also validates these approaches with numerical simulations based on COMSOL Multiphysics® against the theoretical value according to ISO 10211 of a cold frame and of a hybrid frame lightweight wall, obtaining a relative error in the order of 2% for both approaches. Finally, to assess the reliability of the methods, regardless of the wall, a parametric analysis regarding the properties of the wall has been carried out by simulating more than 1000 cases obtained by varying (i) materials' thermal conductivity, (ii) stud thickness, and (iii) the convection heat transfer coefficient. For the RPM, the error on the overall U-value can be considered negligible for both wall typologies, whilst, for the WAM method, it is lower than 2% and 5% for the cold and hybrid LSF, respectively.

4.3.1. Representative Points Method (RPM)

This method assumes that there must be, in a wall with thermal anomalies like studs, points (called representative points) through which the amount of heat flux equals the heat flow through the whole wall. The IR images are here used for determining the spacing between studs and to calculate the temperature profile, and representative points are those where the average temperature over the width of the heat flux sensor intersects the temperature profile. Assuming then that heat flux plate is centered on the representative points and temperature probes in its correspondence, their measurements are integrated over the width of the flux plate.

The thermal transmittance of each *i*-th representative value can be calculated by HFM, following the same rules (Equation (9)), whilst the overall thermal transmittance is their average U-value (Equation (10)):

$$U_{i,repr} = \frac{\sum_j \left(\hat{q}_{HFM,j}\right)}{\sum_j \left(T_{in,j} - T_{out,j}\right)} \quad (9)$$

$$U_{overall} = \frac{1}{N}\sum_{i=1}^{N} U_{i,repr} \tag{10}$$

By repeating this approach on different portions of the wall, it is advisable to gather at least three $U_{overall}$, whose average value can be considered as the final U-value if the coefficient of variation of the single $U_{overall}$ is lower than 10%. The work also shows the dependency of the determination of the representative points on the convective heat transfer coefficient. Based on the results, the internal heat transfer coefficient affects more than the external heat transfer coefficient, for both the wall typologies investigated (cold frame and hybrid lightweight steel framed). Moreover, the percentage error on the $U_{overall}$ caused by the variation of the convective coefficient is lower for the hybrid wall with respect to the cold wall. As an example, the absolute variation of convective coefficient (whether internal or external) of the order of 2 W/m^2 K causes an error in the final U-value in the order of 4%. Finally, relative error is higher when the variation of the convective coefficient (whether internal or external) is negative with respect to a positive variation.

4.3.2. Weighted Area Method (WAM)

This method requires the application of two heat flux plates: one on the undisturbed wall and the other on the stud, each one with the correspondent temperature probes for internal and external surface temperature. The U-value was found in correspondence to the stud and to the current wall by using Equation (9). The IR images are used for determining the temperature profile. To this point, the length of the influenced area can be calculated by intersecting the temperature profile with a critical temperature, which considers the temperature on the undisturbed area, the average temperature, and the minimum average temperature over the width of the heat flux sensor placed on the stud. Hence, this graphical intersection between the critical temperature and the temperature profile defines the l_{stud}. With d being the distance between two consecutive studs, the overall thermal transmittance is calculated as per Equation (11):

$$U_{overall} = \frac{l_{stud}}{d}U_{stud} + \left(1 - \frac{l_{stud}}{d}\right)U_{clear} where\ \frac{l_{stud}}{d} = f_{stud} \tag{11}$$

Once again, it is suggested by the authors to gather at least three $U_{overall}$, whose average value can be considered as the final U-value if the coefficient of variation of the single $U_{overall}$ is lower than 10%.

The study [86] also investigated the effect of convection, showing that the internal convective heat transfer coefficient affects the f_{stud}, whilst the external heat transfer coefficient does not. Moreover, convection affects the f_{stud} of the cold wall more than of the hybrid. Even in this case, the relative error against the convective coefficient variation has been studied, showing that error is lower than 4% even for variation on the convective coefficient of up to 4 W/m^2 K and a negligible sensibility to positive or negative convective coefficient variation. The method has also been investigated considering the width of the flux plate: for a width between a few millimeters and 200 mm, relative error ranges between 0% and 4% for the hybrid LSF, with a V-shaped trend; relative error ranges between 1% and 8% for the cold LSF, with an increasing trend of circa 0.5%/cm.

4.4. Group 4: Future Perspectives

The increasing employment of AI is conquering even the building sector, especially for what concerns energy modeling and energy performance [87] and also the thermal assessment, such as the transmittance of wooden windows [88] or basement walls [89], or even thermal comfort [90]. Even in the field of building envelope thermal performance, AI uses data from the measurement methods described before. Indeed, the methods analyzed up to now refer to the data collection, whilst the future perspectives are given by the data prediction. However, to be able to predict values requires, as first instance, to analyze measured data. Hence, experimental data feed the networks that are, in this sense, trained to recognize or foresee the future behavior, or value, or trend of the feeding parameters (or their operation as well).

An ANN consists of a set of weighting coefficients, biases, and activation functions that process input variables to obtain output variables, which should be as close as possible to the target value. The ANN architecture consists of different layers: generally, an input layer, one or more hidden layers (which process the input), and the output layer. ANN models that have one output are named regression models, whilst those with more outputs are classification models. Input variables are linked to "*neurons*", which are in hidden layers, through functions that elaborate on each input through its weighting coefficient, add a bias, and process with an activation function. The latter can be a nonlinear function (like sigmoid or tanh), which establishes how much information passes from a hidden layer to the following, till reaching the output layer neuron. The ANN implementation includes three phases: training, validation, and testing. During the training and validation processes, the output is compared to the target value, and the error is used to correct the weighting matrix. Then, the testing is used to verify the potential generalization of the network. In 2020, the work by Gumbarević et al. [91] aimed at predicting the heat flux via multilayer percepton (MLP). Two input variables were given (indoor and outdoor air temperature) and three hidden layers (neurons). The dataset was made of 510 pieces of data, and three prediction models were run by using for the training, respectively, 128 (of the 510 data), 255, and 340 pieces of data, and the remaining for the validation. The work, beyond opening to the employment of such methods for the U-value assessment, states that better results were obtained by using half of the data for the testing and half of the data for validating the model.

In a later work [92], a similar approach was used by employing four ANN architectures with (i) 3 neurons in the hidden layer, (ii) 100 LSTM (long-short term memory) cells in the hidden layer, (iii) 100 GRU (gated recurrent units) cells in the hidden layer, and (iv) 50 LSTM and 50 GRU cells, respectively, in the first and second hidden layers. Once again, training was performed using one-quarter, one-half, and two-thirds of the entire dataset. Maximum difference was achieved with the multilayer perceptron with three neurons using one-quarter of the data for training; the minimum difference was achieved with 100 GRU and half of the data for training. As a general remark, according to the authors, MLP behaves better when the dataset is small. However, the GRU and LSTM (which belong to the class of recurrent neural network (RNN)) ensure stability and reliability with the long-lasting measurements with HFM. In [93], a multilayer perceptron was used to obtain results of ISO 9869-1 (with and without storage effects) by measuring the surface temperatures, avoiding measuring the heat flux, so by using the thermometric method. Several prediction models were used by working on a huge amount of the representative dataset: more than 22,800 simulated tests on typical walls of the Spanish building stock. MLP architecture with one, two, and three hidden layers was studied. It is worth noting that the input variables of such approaches were only temperatures, building construction period, wall thickness, and measurement duration. The two latter have less influence on the models than the others, whilst the building period causes average errors up to 0.83 W/m^2 K. Results confirm the possibility of retrieving the thermal transmittance without measuring the heat flux by combining results from ISO 9869; moreover, refinements are possible by using, for the internal heat transfer coefficient, the theoretical values.

Another work authored by Bienvenido-Huertas et al. [94] aimed at using an ANN on the results from the thermometric method to take into account of both the wall storage effect and some conductivity correction factors for the provincial capitals in Spain (depending on the temperature and moisture correction factors). In this case, 69 tests were used (three for model validations, the others for training), and two MLP were used: one having eight input layers, amongst which were the temperatures, the other having seven input layers with the temperature differences. The two were tested from 4 to 15 nodes in the hidden layer. Better results were retrieved with 14 hidden nodes and 8 input layers. Moreover, the models showed that valid results can be reached even with measuring campaigns shorter than the recommendations from researchers. Finally, with the MLP there is no need for data post-processing; thus, calculation times are reduced. Finally, in the work by Sadhukhan et al. [95], machine learning is used to process surface temperatures from thermal images to obtain the U-value, proposing a workflow based on three blocks (layers). The first layer is the database layer, where thermal images (even from aerial imagery and already processed as said before) are stored, and that also includes building energy consumption data, raw and annotated datasets, modes, and so on.

The second layer is the pre-processing and automation layer, needed for removing background or unwanted objects (such as trees, ground, and sky) and for enhancing the object detection (walls, windows, and doors). The third layer is the evaluation layer. The user request is sent to the database layer: if the request is a model to be trained, then the task refers to a Supervisely platform, which records the model weight and logs. This platform is web based, and it allows the organization of the data collected during the annotation, training, and testing phases, the latter carried out with few interactions. If the request is a model to be tested, it uses the automation layer, and model metrics like mean average precision (mAP) and mean intersection over union (mIoU) are evaluated and then uploaded on the Supervisely platform. Variables like wall and air temperatures, wind speed, and weather data are retrieved from other databases, as well as object coordinates. The final (cumulative) U-value is then obtained by averaging the U-values obtained by three different formulas. Results show that this approach can assess the U-value of multiple building elements, such as walls, doors, and windows, by also using the thermal images from unmanned aerial vehicles (UAVs). Once again, direct solar irradiance compromises the results: it is advisable to avoid such a condition. Given the complexity of this approach, the authors are open to future development, such as automating the pre-processing phase, correlating images over the seasons, and in comparison to the energy consumption, a pixel-by-pixel detection of hotspots, a gradual switch to a fully automatic data-capturing process. The methods based on AI require datasets from measurements or surveys. The greater the dataset, the more reliable the prevision. However, network characteristics (number of input layer, hidden layer, and percentage of training over testing data) influence the results.

5. Discussion

Over the years, and following technological improvements, several methods have been developed and others are under study for U-value assessment. A rough distinction between them can be the presence or absence of measurement. A distinction must be observed for the ANN methods, which rely on the previous. Some of the techniques are ruled on by international standards (theoretical method and HFM); others (such as QIRT) have recently been ruled on with some restrictions. Nevertheless, this topic is still under the attention of researchers to the point that new methods, such as RPM and WAM, have been proposed for merging with others (HFM and QIRT). What is clear, however, is the strict dependency of one to the other. Such linking is summarized in Figure 11.

Indeed, the theoretical method requires the knowledge of the wall stratigraphy, and in case some information is missing (like a layer thickness), it can rely on the analogy with a coeval building. The theoretical method provides values for the convective heat transfer coefficient needed, in absence of dedicated measurement, for the HFM, the QIRT, the simple hot box, and the thermometric method. The simple hot box method basically employs the HFM by maintaining controlled conditions over the outer surface. The HFM placement, indeed, can be supported by infrared thermography (even if in the qualitative approach). Finally, RPM and WAM require, per definition, the HFM and infrared thermography. Preliminary thermographic inspection (qualitative approach) is advised for probes located in HFM, TBM, RPM, and WAM.

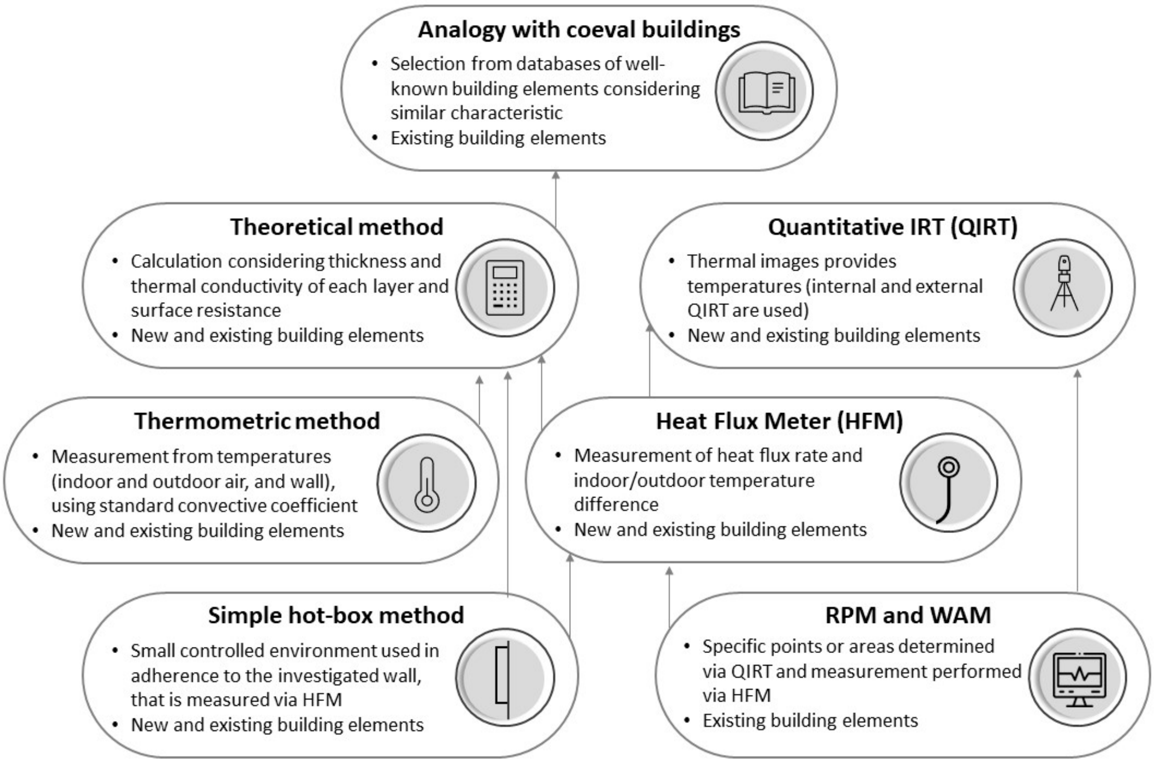

Figure 11. Methodology interconnections.

6. Conclusions

This work aims at widening the previous reviews on the U-value assessment of the building envelope, including the bibliometric and scientometric analysis, and describes the most recent applications, proposals, and outlooks in this field.

Results show the need for proper research keywords, failing which can lead to the discarding of useful papers within the topics, due to the paper database interrogation. According to the bibliometric analysis, indeed given the interrogations on a common literature database, this topic has been studied since 1981, with a significant increase since 2009, reaching almost 50 published documents in both 2021 and 2022. This number of papers was analyzed according to scientometric analysis to help in the identification of the research topics within the field, and to design a rational literature review. From this analysis, it emerged that, when keywords are pertinent but not specific, papers can escape from the research background. This is what happened for the innovative techniques for the U-value assessment of the building envelope. The scientometric analysis, moreover, allowed the clustering of the techniques into three groups: estimation, measurement, and innovative techniques. For each group, a detailed and critical discussion is reported.

Some key findings can be highlighted for each technique:

- Estimation techniques (which include analogy with coeval building and the theoretical method) are well-assessed and -used, as they allow a quick evaluation of the U-value. They provide ranges of variability of the U-value, not a specific value. Uncertainties are due to missing or incomplete or hypothesized data, such as building period, building features, layer thickness, and material characteristics.
- Analogy with coeval building is less accurate, but it is sufficient for quick assessments, for instance for obtaining in a glance the order of magnitude of the energy transmission of the building isle, similarly aged.
- Importance of complete databases for collecting and sharing data from different building typologies, ranging for age and region. Some winning experiences are milestones for this approach (e.g., TABULA), but even other databases realized at national or local scale, or even for other purposes (e.g., CARTIS), can provide useful information.

- Importance of sharing data among databases. For instance, databases built for purposes other than energy efficiency (like seismic analysis or post-seismic scenarios) can provide capillary information at local scale, entailing even field surveys.
- The theoretical method requires a detailed knowledge of the wall stratigraphy, made possible, for instance, by coring, endoscope, or using air duct holes. Where it is not possible to have such detailed information, it is possible to refer to typical data, so referring to the analogy with coeval buildings.
- Measurement methods (which include the heat flux meter measurement, simple hot box, quantitative infrared thermography, and thermometric method) suffer for typical uncertainties, such as operative conditions (that might differ from the ideal ones or from those prescribed by standards), equipment misfunctioning, data cleaning, or subjective interpretation from the worker.
- Heat flux meter (HFM) measurement is well-known and assessed: the standard provides rules and recommendations, and the literature is enlarging the possibilities of this method. It is a long-lasting technique, especially for heavy walls, and duration can be also compromised by boundary environmental condition. However, HFM data already gathered from both researchers and practitioners can be included in databases, where data can be also georeferenced; it is even better if they are made open-access.
- The thermometric method is still not ruled by an international standard, and it is quite simple to use as it requires only to measure one quantity: the temperature. Hence, the heat flux is not directly measured, like the HFM. Some researchers have proved that measurement duration can be reduced to a few hours when particular boundary conditions are met. Moreover, some self-made equipment opens the possibility of scaling up the number of measurement points, with restrained cost (besides those for engineering).
- The simple hot box (SHB) method avoids the strict dependency of the HFM to boundary conditions, but this is realized by using a device (the box), whose positioning might be complex. In fact, the box is mounted on a support structure that needs to rest on the ground. Hence, walls of buildings not on the ground floor or without balconies are not investigable with this technique.
- The quantitative infrared thermography (QIRT) technique is now ruled by a standard, but it still represents an open research field (indoor/outdoor QIRT, convective coefficient correlation, lasting, etc.). If some boundary conditions are met, it allows a rapid evaluation of several buildings. Unfortunately, the needed equipment (the IR camera) is expensive for accurate measurement, although it can be used for several other purposes and investigations.
- The representative points method (RPM) and weighted area method (WAM) are similar for the approach, as they are based on IRT for accurate temperature profile definition but perform the measurement via HFM. In this sense, these two techniques merge QIRT and HFM. They have been successfully employed on lightweight walls, providing low error (0–8%).
- Artificial intelligence (AI) and artificial neural networks (ANNs) require a good knowledge of AI potentials and a dataset retrieved by in situ measurement. In this sense, this approach needs further development and a data source. The literature on the application of AI for U-value assessment is still scarce, so it can be a good investigation field.

Furthermore, some common points can be highlighted considering the interaction among the different approaches and the contribution of AI in the U-value assessment of building elements, as follows:

- Approaches are linked, and the U-value assessment can include more than one method per time.
- Convection is a key point for all the measurement techniques. The convective coefficient is a key point for all the techniques (except for SHB-HFM, which reproduces at small-scale laboratory conditions). Its theoretical value might be different from the

one occurring in situ. The research activities, for all the listed measurement methods, are devoted to find proper or better correlations and, hence, the coefficient to be used.
- Test duration can vary, also considering the wall thermal inertia.
- Test duration can be reduced, if data collected during short-term campaigns are good enough for the feed and artificial neural network.
- Approaches with artificial intelligence are still not so common. They require good datasets and trials on models' designs, in terms of input layer, number of hidden layers and neurons, percentage of data to be employed for model training and testing, and so on.
- An integrated approach using AI and thermal imagery has been proposed. This method, however, requires also collecting annotations on the building and on the thermal images.
- Attempts for automatic thermal images processes can be undertaken (the literature from other fields, such as material testing, will be of help), also, to reduce the processing time.

Future work could be devoted to a deep analysis and application of AI to the other measurements of the U-value to widen the knowledge of the possibilities in this field, as well as to the study of the thermal performance of roofs coupled with drones and unmanned aerial vehicles (UAV).

Author Contributions: Conceptualization and methodology, I.N., E.L.; software, E.L.; investigation, formal analysis, and data curation, I.N., E.L.; writing, I.N., E.L.; visualization, I.N., E.L.; funding acquisition, E.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

U-value or U	Thermal transmittance (W/(m^2 K))
R-value or R	Thermal resistance (W/(m^2 K))
HFM	Heat flux meter
QIRT	Quantitative infrared thermography
IRT	Infrared Thermography
SHB	Small hot box
RPM	Representative points method
WAM	Weighted area method
AI	Artificial intelligence
ANN	Artificial neural network
RNN	Recurrent neural network
TITLE-ABS-KEY	Title, abstract, keywords
KEY	Keywords
LDT	Low-destructive technique
NDT	Non-destructive technique
TBM	Temperature-based method
ASTR	Air–surface temperature ratio
RPM	Representative points method
WAM	Weighted area method
LSTM	Long-short term memory
GRU	Gated recurrent units
mAP	Mean average precision
mIoU	Mean intersection over union
UAV	Unmanned aerial vehicle

s	Layer thickness (m)
λ or λ-value	Thermal conductivity ((mK)/W)
q	Heat flux (W/m^2)
T_{in}	Indoor air temperature (K)
T_{out}	Outdoor air temperature (K)
T_{ref}	Reflected temperature (K)
T_s	Surface temperature (K)
T_a	Generic air temperature (K)
ΔT_s	Surface temperature difference (K)
ΔT_a	Air temperature difference
σ	Stefan–Boltzmann constant (W/(m^2 K^4))
h_{in}	Indoor convective heat transfer coefficient (W/(m^2 K))
ε	emissivity
Ra	Rayleigh number
Pr	Prandtl number
L	Wall height (m)
v	Air speed (m/s)

References

1. IEA. *Buildings*; Tracking Report—September 2022; IEA: Paris, France, 2022. Available online: https://www.iea.org/reports/buildings (accessed on 21 February 2023).
2. Lucchi, E. Applications of the infrared thermography in the energy audit of buildings: A review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3077–3090. [CrossRef]
3. Nardi, I.; Lucchi, E.; de Rubeis, T.; Ambrosini, D. Quantification of heat energy losses through the building envelope: A state-of-the-art analysis with critical and comprehensive review on infrared thermography. *Build. Environ.* **2018**, *146*, 190–205. [CrossRef]
4. *Standard ISO 6946*; Building Components and Building Elements. Thermal Transmittance and Thermal Resistance. Calculation Method. ISO (International Organization for Standardization): Genève, Switzerland, 2008.
5. Bienvenido-Huertas, D.; Moyano, J.; Marín, D.; Fresco-Contreras, R. Fresco-Contreras Review of in situ methods for assessing the thermal transmittance of walls. *Renew. Sustain. Energy Rev.* **2019**, *102*, 356–371. [CrossRef]
6. Teni, M.; Krstić, H.; Kosiński, P. Review and comparison of current experimental approaches for in-situ measurements of building walls thermal transmittance. *Energy Build.* **2019**, *203*, 109417. [CrossRef]
7. Simões, N.; Moghaddam, A.; da Silva, M.G. Review of the Experimental Methods for Evaluation of Windows' Thermal Transmittance: From Standardized Tests to New possibilities. *Buildings* **2023**, *13*, 703. [CrossRef]
8. Falagas, M.E.; Pitsouni, E.I.; Malietzis, G.A.; Pappas, G. Comparison of PubMed, Scopus, Web of Science, and Google Scholar: Strengths and weaknesses. *FASEB J.* **2008**, *22*, 338–342. [CrossRef]
9. Cabeza, L.F.; Chàfer, M.; Mata, É. Comparative analysis of web of science and Scopus on the energy efficiency and climate impact of buildings. *Energies* **2020**, *13*, 409. [CrossRef]
10. Andersen, N.; Swami, V. Science mapping research on body image: A bibliometric review of publications in Body Image, 2004–2020. *Body Image* **2021**, *38*, 106–119. [CrossRef] [PubMed]
11. Ascione, F.; Bianco, N.; De Masi, R.F.; Mauro, G.M.; Musto, M.; Vanoli, G.P. Experimental validation of a numerical code by thin film heat flux sensors for the resolution of thermal bridges in dynamic conditions. *Appl. Energy* **2014**, *124*, 213–222. [CrossRef]
12. Ascione, F.; Ceroni, F.; De Masi, R.F.; de'Rossi, F.; Pecce, M.R. Historical buildings: Multidisciplinary approach to structural/energy diagnosis and performance assessment. *Appl. Energy* **2017**, *185*, 1517–1528. [CrossRef]
13. Siviour, J.B. Experimental U-values of some house walls. *Build. Serv. Eng. Res. Technol.* **1994**, *15*, 35–36. [CrossRef]
14. Cesaratto, P.G.; De Carli, M. A measuring campaign of thermal conductance in situ and possible impacts on net energy demand in buildings. *Energy Build.* **2013**, *59*, 29–36. [CrossRef]
15. Doran, S. Safety and Health Business Plan: Field investigations of the thermal performance of construction elements as built. *BRE East Kilbride Glasg.* **2001**, 78132.
16. Rye, C.; Scott, C. *SPAB Research Report n.1: U-Value Report*; SPAB: London, UK, 2011.
17. Lucchi, E. Non-invasive method for investigating energy and environmental performances in existing buildings. In *Architecture and Sustainable Development, Proceedings of the 27th International Conference on Passive and Low Energy Architecture, Louvain-la-Neuve, Belgium, 13–15 July 2011—PLEA 2011*; Bodart, M., Evrard, A., Eds.; Presses Universitaires de Louvain: Louvain-la-Neuve, Belgium; pp. 571–576.
18. Rhee-Duverne, S.; Baker, P. *Research into the Thermal Performance of Traditional Brick Walls*; English Heritage: London, UK, 2013.
19. Lucchi, E. Thermal transmittance of historical brick masonries: A comparison among standard data, analytical calculation procedures, and in situ heat flow meter measurements. *Energy Build.* **2017**, *134*, 171–184. [CrossRef]
20. Lucchi, E. Thermal transmittance of historical stone masonries: A comparison among standard, calculated and measured data. *Energy Build.* **2017**, *151*, 393–405. [CrossRef]

21. TABULA Database. Available online: https://episcope.eu/welcome (accessed on 24 February 2023).
22. Available online: https://webtool.building-typology.eu/#bm (accessed on 24 February 2023).
23. Available online: https://episcope.eu/iee-project/episcope/ (accessed on 15 March 2023).
24. Available online: https://www.protezionecivile.gov.it/it/approfondimento/scheda-aedes (accessed on 15 March 2023).
25. Brando, G.; Cianchino, G.; Rapone, D.; Spacone, E.; Biondi, S. A CARTIS-based method for the rapid seismic vulnerability assessment of the minor Italian historical centres. *Int. J. Disaster Risk Reduct.* **2021**, *63*, 102478. [CrossRef]
26. Basaglia, A.; Cianchino, G.; Cocco, G.; Rapone, D.; Terrenzi, M.; Spacone, E.; Brando, G. An automatic procedure for deriving building portfolios using the Italian "CARTIS" online database. *Structures* **2021**, *34*, 2974–2986. [CrossRef]
27. Sassine, E. A practical method for in-situ thermal characterization of walls. *Case Stud. Therm. Eng.* **2016**, *8*, 84–93. [CrossRef]
28. Litti, G.; Khoshdel, S.; Audenaert, A.; Braet, J. Hygrothermal performance evaluation of traditional brick masonry in historic buildings. *Energy Build.* **2015**, *105*, 393–411. [CrossRef]
29. *Standard UNI 10351*; Materiali da costruzione—Proprietà termoigrometriche—Procedura per la Scelta dei Valori di Progetto. UNI (Ente Italiano di Normazione): Milano, Italy, 2021.
30. Ficco, G.; Iannetta, F.; Ianniello, E.; Alfano, F.; Dell'Isola, M. U-value in situ measurement for energy diagnosis of existing buildings. *Energy Build.* **2015**, *104*, 108–121. [CrossRef]
31. *Standard ISO 9869*; Thermal Insulation. Building Elements. In-Situ Measurement of Thermal Resistance and Thermal Transmittance. ISO (International Organization for Standardization): Genève, Switzerland, 2014.
32. *Standard ISO 6781*; Thermal Insulation. Qualitative Detection of Thermal Irregularities in Building Envelopes. Infrared Method. ISO (International Organization for Standardization): Genève, Switzerland, 1983.
33. Baker, P. *U-Values and Traditional Buildings: In Situ Measurements and Their Comparisons to Calculated Values*; Historic Scotland: Edinburgh, UK, 2011.
34. Lucchi, E.; Roberti, F.; Troi, A. Definition of an experimental procedure with the hot box method for the thermal performance evaluation of inhomogeneous walls. *Energy Build.* **2018**, *179*, 99–111. [CrossRef]
35. Williamson, J.B.; Stinson, J.; Garnier, C.; Currie, J. In-situ monitoring of thermal refurbishment on pre-1919 properties in Scotland. *Edinb. Scott. Energy Cent.* **2013**, *2*, 26–33.
36. Adhikari, R.; Lucchi, E.; Pracchi, V. Experimental Measurements on Thermal Transmittance of the Opaque Vertical Walls in the Historical Buildings. In Proceedings of the PLEA 2012—28th Conference, Opportunities, Limits & Needs Towards an Environmentally Responsible Architecture, Lima, Peru, 7–9 November 2012; Reiser, J., Jiménez, C., Biondi Antúnez de Mayolo, S., Eds.; pp. 1248–1256.
37. Cesaratto, P.; De Carli, M.; Marinetti, S. Effect of different parameters on the in situ thermal conductance evaluation. *Energy Build.* **2011**, *43*, 1792–1801. [CrossRef]
38. Rodler, A.; Guernouti, S.; Musy, M. Bayesian inference method for in situ thermal conductivity and heat capacity identification: Comparison to ISO standard. *Constr. Build. Mater.* **2019**, *196*, 574–593. [CrossRef]
39. Ahmad, A.; Maslehuddin, M.; Al-Hadhrami, L.M. In situ measurement of thermal transmittance and thermal resistance of hollow reinforced precast concrete walls. *Energy Build.* **2014**, *84*, 132–141. [CrossRef]
40. Building Research Establishment (BRE). *Field Investigations of the Thermal Performance of Construction Elements as Built*; Client Report No. 78132; BRE: Watford, UK, 2000.
41. Baker, P. *In Situ U-Value Measurements in Traditional Buildings, Preliminary Results*; Historic Scotland: Edinburgh, UK, 2008.
42. Andreotti, M.; Calzolari, M.; Davoli, P.; Dias Pereira, L.; Lucchi, E.; Malaguti, R. Design and construction of a new metering hot box for the hygrothermal measurement in dynamic condition of historic masonries. *Energies* **2020**, *13*, 2950. [CrossRef]
43. Tejedor, B.; Lucchi, E.; Bienvenido-Huertas, D.; Nardi, I. Non-destructive techniques (NDT) for the diagnosis of heritage buildings: Traditional procedures and futures perspectives. *Energy Build.* **2022**, *263*, 112029. [CrossRef]
44. Vereecken, E.; Roels, S. A comparison of the hygric performance of interior insulation systems: A hot box–cold box experiment. *Energy Build.* **2014**, *80*, 37–44. [CrossRef]
45. Meng, X.; Gao, Y.; Wang, Y.; Yan, B.; Zhang, W.; Long, E. Feasibility experiment on the simple hot box-heat flow meter method and the optimization based on simulation reproduction. *Appl. Therm. Eng.* **2015**, *83*, 48–56. [CrossRef]
46. Meng, X.; Luo, T.; Gao, Y.; Zhang, W.; Shen, E.; Long, E. A new simple method to measure wall thermal transmittance in situ and its adaptability analysis. *Appl. Therm. Eng.* **2017**, *122*, 747–757. [CrossRef]
47. Roque, E.; Vicente, R.; Almeida RM, S.F.; Mendes da Silva, J.; Vaz Ferreira, A. Thermal characterisation of traditional wall solution of built heritage using the simple hot box-heat flow meter method: In situ measurements and numerical simulation. *Appl. Therm. Eng.* **2020**, *169*, 114935. [CrossRef]
48. Andújar Márquez, J.M.; Martínez Bohórquez, M.Á.; Gómez Melgar, S. A New Metre for Cheap, Quick, Reliable and Simple Thermal Transmittance (U-Value) Measurements in Buildings. *Sensors* **2017**, *17*, 2017. [CrossRef]
49. Kim, S.H.; Kim, J.H.; Jeong, H.G.; Song, K.D. Reliability field test of the air–surface temperature ratio method for in situ measurement of U-values. *Energies* **2018**, *11*, 803. [CrossRef]
50. Kim, S.H.; Lee, J.H.; Kim, J.H.; Yoo, S.H.; Jeong, H.G. The feasibility of improving the accuracy of in situ measurements in the air-surface temperature ratio method. *Energies* **2018**, *11*, 1885. [CrossRef]

51. Evangelisti, L.; Scorza, A.; De Lieto Vollaro, R.; Sciuto, S.A. Comparison between Heat Flow Meter (HFM) and Thermometric (THM) Method for Building Wall Thermal Characterization: Latest Advances and Critical Review. *Sustainability* **2022**, *14*, 693, Erratum in Sustainability **2022**, *14*, 13398. [CrossRef]
52. Bienvenido-Huertas, D.; Rodríguez-Álvaro, R.; Moyano, J.J.; Fernando, R.; Marín, D. Determining the U-Value of Façades Using the Thermometric Method: Potentials and Limitations. *Energies* **2018**, *11*, 360. [CrossRef]
53. Vučićević, B.; Turanjanin, V.; Bakić, V.; Jovanović, M.; Stevanović, Ž. Experimental and numerical modelling of thermal performance of a residential building in Belgrade. *Therm. Sci.* **2009**, *13*, 245–252. [CrossRef]
54. Cuerda, E.; Guerra-Santin, O.; Neila, F.J.; Romero, N. Evaluation and comparison of building performance in use through on-site monitoring and simulation modelling. In Proceedings of the 3rd IBPSA-England Conference BSO 2016, Newcastle, UK, 12–14 September 2016.
55. Buzatu, G.; Stan-Ivan, F.; Mircea, P.; Manescu, L. Thermal transmittance determination for different components of buildings. In Proceedings of the 2017 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM) & 2017 Intl Aegean Conference on Electrical Machines and Power Electronics (ACEMP), Brasov, Romania, 25–27 May 2017; pp. 227–232.
56. Jankovic, A.; Antunovic, B.; Preradovic, L. Alternative method for on site evaluation of thermal transmittance. *Facta Univ. Ser. Mech. Eng.* **2017**, *15*, 341–351. [CrossRef]
57. Kirimtat, A.; Krejcar, O. A review of infrared thermography for the investigation of building envelopes: Advances and prospects. *Energy Build.* **2018**, *176*, 390–406. [CrossRef]
58. Fokaides, P.A.; Kalogirou, S.A. Application of infrared thermography for the determination of the overall heat transfer coefficient (U-Value) in building envelopes. *Appl. Energy* **2011**, *88*, 4358–4365. [CrossRef]
59. Ham, Y.; Golparvar-Fard, M. An automated vision-based method for rapid 3D energy performance modeling of existing buildings using thermal and digital imagery. *Adv. Eng. Inform.* **2013**, *27*, 395–409. [CrossRef]
60. Tzifa, V.; Papadakos, G.; Papadopoulou, A.G.; Marinakis, V.; Psarras, J. Uncertainty and method limitations in a short-time measurement of the effective thermal transmittance on a building envelope using an infrared camera. *Int. J. Sustain. Energy* **2017**, *36*, 28–46. [CrossRef]
61. Danielski, I.; Fröling, M. Diagnosis of Buildings' Thermal Performance—A Quantitative Method Using Thermography Under Non-steady State Heat Flow. *Energy Procedia* **2015**, *83*, 320–329. [CrossRef]
62. Tejedor, B.; Casals, M.; Gangolells, M.; Roca, X. Quantitative internal infrared thermography for determining in-situ thermal behaviour of façades. *Energy Build.* **2017**, *151*, 187–197. [CrossRef]
63. Marshall, A.; Francou, J.; Fitton, R.; Swan, W.; Owen, J.; Benjaber, M. Variations in the U-Value Measurement of a Whole Dwelling Using Infrared Thermography under Controlled Conditions. *Buildings* **2018**, *8*, 46. [CrossRef]
64. Tejedor, B.; Casals, M.; Gangolells, M. Assessing the influence of operating conditions and thermophysical properties on the accuracy of in-situ measured U-values using quantitative internal infrared thermography. *Energy Build.* **2018**, *171*, 64–75. [CrossRef]
65. Albatici, R.; Tonelli, A.M.; Chiogna, M. A comprehensive experimental approach for the validation of quantitative infrared thermography in the evaluation of building thermal transmittance. *Appl. Energy* **2015**, *141*, 218–228. [CrossRef]
66. Nardi, I.; Ambrosini, D.; de Rubeis, T.; Sfarra, S.; Perilli, S.; Pasqualoni, G. A comparison between thermographic and flow-meter methods for the evaluation of thermal transmittance of different wall constructions. *J. Phys. Conf. Ser.* **2015**, *655*, 012007. [CrossRef]
67. Albatici, R.; Tonelli, A.M. Infrared thermovision technique for the assessment of thermal transmittance value of opaque building elements on site. *Energy Build.* **2010**, *42*, 2177–2183. [CrossRef]
68. Dall'O', G.; Sarto, L.; Panza, A. Infrared Screening of Residential Buildings for Energy Audit Purposes: Results of a Field Test. *Energies* **2013**, *6*, 3859–3878. [CrossRef]
69. Nardi, I.; Sfarra, S.; Ambrosini, D. Quantitative thermography for the estimation of the U-value: State of the art and a case study. *J. Phys. Conf. Ser.* **2014**, *547*, 012016. [CrossRef]
70. Kim, J.; Lee, J.; Jang, C.; Jeong, H.; Song, D. Appropriate conditions for determining the temperature difference ratio via infrared camera. *Build. Serv. Eng. Res. Technol.* **2015**, *37*, 272–287. [CrossRef]
71. Marino, B.M.; Muñoz, N.; Thomas, L.P. Estimation of the surface thermal resistances and heat loss by conduction using thermography. *Appl. Therm. Eng.* **2017**, *114*, 1213–1221. [CrossRef]
72. Mahmoodzadeh, M.; Gretka, V.; Hay, K.; Steele, C.; Mukhopadhyaya, P. Determining overall heat transfer coefficient (U-Value) of wood-framed wall assemblies in Canada using external infrared thermography. *Build. Environ.* **2021**, *199*, 107897. [CrossRef]
73. Yang, Y.; Wu, T.V.; Sempey, A.; Dumoulin, J.; Batsale, J.-C. Short time non-destructive evaluation of thermal performances of building walls by studying transient heat transfer. *Energy Build.* **2019**, *184*, 141–151. [CrossRef]
74. Tejedor, B.; Lucchi, E.; Nardi, I. Application of Qualitative and Quantitative Infrared Thermography at Urban Level: Potential and Limitations. In *New Technologies in Building and Construction*; Lecture Notes in Civil Engineering; Bienvenido-Huertas, D., Moyano-Campos, J., Eds.; Springer: Singapore, 2022; Volume 258.
75. Bienvenido-Huertas, D.; Bermúdez, J.; Moyano, J.; Marín, D. Comparison of quantitative IRT to estimate U-value using different approximations of ECHTC in multi-leaf walls. *Energy Build.* **2019**, *184*, 99–113. [CrossRef]
76. Baldinelli, G.; Bianchi, F.; Rotili, A.; Costarelli, D.; Seracini, M.; Vinti, G.; Asdrubali, F.; Evangelisti, L. A model for the improvement of thermal bridges quantitative assessment by infrared thermography. *Appl. Energy* **2018**, *211*, 854–864. [CrossRef]

77. Bianchi, F.; Baldinelli, G.; Asdrubali, F. A quantitative infrared thermography method for the assessment of windows thermal transmittance methodology. In Proceedings of the 10th International Conference on Applied and Theoretical Mechanics, Salerno, Italy, 3–5 June 2014; pp. 137–143.
78. Asdrubali, F.; Baldinelli, G.; Bianchi, F.; Costarelli, D.; Rotili, A.; Seracini, M.; Vinti, G. Detection of thermal bridges from thermographic images by means of image processing approximation algorithms. *Appl. Math. Comput.* **2018**, *317*, 160–171. [CrossRef]
79. Nardi, I.; Ambrosini, D.; Paoletti, D.; Sfarra, S. Combining infrared thermography and numerical analysis for evaluating thermal bridges in buildings: A case study. *Int. J. Eng. Res. Appl.* **2015**, *5*, 67–76.
80. François, A.; Ibos, L.; Feuillet, V.; Meulemans, J. Building thermal bridge heat losses quantification by infrared thermography, Steady-state evaluation and uncertainty calculation. *J. Phys. Conf. Ser.* **2019**, *1343*, 012171. [CrossRef]
81. O'Grady, M.; Lechowska, A.A.; Harte, A.M. Infrared Thermography Technique as an in-situ method of assessing the heat loss through thermal bridging. *Energy Build.* **2017**, *135*, 20–32. [CrossRef]
82. O'Grady, M.; Lechowska, A.A.; Harte, A.M. Quantification of heat losses through building envelope thermal bridges influenced by wind velocity using the outdoor infrared thermography technique. *Appl. Energy* **2017**, *208*, 1038–1052. [CrossRef]
83. Baldinelli, G.; Bianchi, F. Windows thermal resistance: Infrared thermography aided comparative analysis among finite volumes simulations and experimental methods. *Appl. Energy* **2014**, *136*, 250–258. [CrossRef]
84. Park, S.; Kim, S.; Jeong, H.; Do, S.L.; Kim, J. In Situ Evaluation of the U-Value of a Window Using the Infrared Method. *Energies* **2021**, *14*, 1904. [CrossRef]
85. O'Grady, M.; Lechowska, A.A.; Harte, A.M. Application of infrared thermography technique to the thermal assessment of multiple thermal bridges and windows. *Energy Build.* **2018**, *168*, 347–362. [CrossRef]
86. Atsonios, I.A.; Mandilaras, I.D.; Kontogeorgos, D.A.; Founti, M.A. Two new methods for the in-situ measurement of the overall thermal transmittance of cold frame lightweight steel-framed walls. *Energy Build.* **2018**, *170*, 183–194. [CrossRef]
87. Al-Habaibeh, A.; Sen, A.; Chilton, J. Evaluation tool for the thermal performance of retrofitted buildings using an integrated approach of deep learning artificial neural networks and infrared thermography. *Energy Built Environ.* **2021**, *2*, 345–365. [CrossRef]
88. Buratti, C.; Barelli, L.; Moretti, E. Application of artificial neural network to predict thermal transmittance of wooden windows. *Appl. Energy* **2012**, *98*, 425–432. [CrossRef]
89. Bienvenido-Huertas, D.; Pérez-Ordóñez, J.L.; Moyano, J.; Seara-Paz, S. Towards an in-situ evaluation methodology of thermal resistance of basement walls in buildings. *Energy Build.* **2020**, *208*, 109643. [CrossRef]
90. Palladino, D.; Nardi, I.; Buratti, C. Artificial neural network for the thermal comfort index prediction: Development of a new simplified algorithm. *Energies* **2020**, *13*, 17. [CrossRef]
91. Gumbarević, S.; Milovanović, B.; Gaši, M.; Bagarić, M. Application of Multilayer Perceptron Method on Heat Flow Method Results for Reducing the in-situ Measurement Time. *Eng. Proc.* **2020**, *2*, 8272.
92. Gumbarević, S.; Milovanović, B.; Gaši, M.; Bagarić, M. Thermal Transmittance Prediction Based on the Application of Artificial Neural Networks on Heat Flux Method Results. 2021. Available online: http://arxiv.org/abs/2103.14995 (accessed on 16 March 2023).
93. Bienvenido-Huertas, D.; Rubio-Bellido, C.; Pérez-Ordóñez, J.L.; Moyano, J. Optimizing the evaluation of thermal transmittance with the thermometric method using multilayer perceptrons. *Energy Build.* **2019**, *198*, 395–411. [CrossRef]
94. Bienvenido-Huertas, D.; Moyano, J.; Rodríguez-Jiménez, C.E.; Marín, D. Applying an artificial neural network to assess thermal transmittance in walls by means of the thermometric method. *Appl. Energy* **2019**, *233–234*, 1–14. [CrossRef]
95. Sadhukhan, D.; Peri, S.; Sugunaraj, N.; Biswas, A.; Selvaraj, D.F.; Koiner, K.; Rosener, A.; Dunlevy, M.; Goveas, N.; Flynn, D.; et al. Estimating surface temperature from thermal imagery of buildings for accurate thermal transmittance (U-value): A machine learning perspective. *J. Build. Eng.* **2020**, *32*, 101637. [CrossRef]