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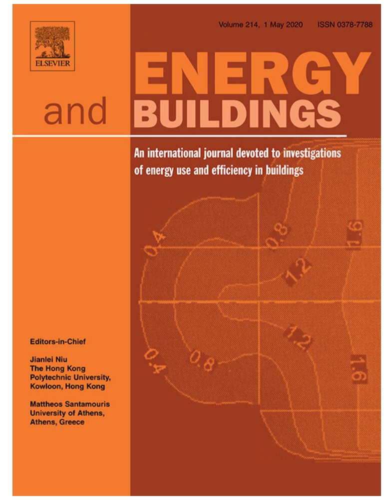


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# Non-Destructive Techniques (NDT) for the diagnosis of heritage buildings: traditional procedures and futures perspectives

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**Abstract**

It is estimated that EU cultural heritage (CH) buildings represent 30% of the total existing stock. Nevertheless, all actions in terms of refurbishment need a deep knowledge based on the diagnosis of the built quality. For this reason, the paper aims to provide a comprehensive review about the applicability of non-destructive techniques (NDT) and advanced modelling technologies for the diagnosis of heritage buildings. Considering a time span of two decades (2001-2021), a bibliometric analysis was performed, using data statistics and science mapping. Subsequently, the most relevant studies on this topic were evaluated for each technique. The main findings revealed that: (i) most of studies were conducted on Southern European countries; (ii) 36% of publications were journal papers and only 2% corresponded to reviews; (iii) "photogrammetry" and "laser applications" were identified as consolidated techniques for historic preservation, but they are only linked with HBIM and deep learning; (iv) a significant gap on quantitative NDT was detected and consequently, future researches should be performed to propose a common diagnosis protocol; (v) artificial neural networks have several barriers (i.e. data privacy, network security and quality of datasets). Hence, a holistic approach should be adopted by the European countries.

**Keywords:** Non-destructive techniques (NDT); Heritage buildings; Photogrammetry; Laser Scanning; Infrared thermography (IRT); Heat flux meter (HFM); Airtightness measurements; Heritage Building Information Modelling (HBIM); Artificial Neural Networks (ANN)

## 1. INTRODUCTION

The notion of Cultural Heritage (CH) is characterized by a ‘semantic transfer’ related to the generalization of its use with the meanings of a patrimony, a monument, or a cultural property [1]. The United Nation Educational, Scientific and Cultural Organization (UNESCO) divided CH in tangible and intangible [2]. The first category is composed by movable (e.g. paintings, paintings, sculptures, manuscripts, pictures, furniture, rare collections, and specimens), immovable (e.g. architectural works, monuments, and archaeological sites), and underwater (e.g. shipwrecks, underwater ruins, and underwater cities) CH [3], characterized by a «(…) *universal value from the point of view of history, art or science*» [4]. The second category is composed by traditions, performing arts, and rituals that express collective memories as well as by traditional and local identities [1]. Inside immovable CH, architectural works are divided into historic and historical buildings. Historic buildings are important constructions that have an influential role in history [5] (i.e. listed churches, old palaces, castles, monuments, and so on). They are characterized by three essential attributes: (i) sufficient age (that for the European legislative framework is equal or more than 50-70 years); (ii) relatively high degree of physical integrity; and (iii) historical significance [5]. Historical buildings are traditional constructions without specific artistic or aesthetical significance, normally built using local resources, pre-industrial materials, and techniques [6] (i.e. rural or vernacular buildings, traditional building stock, historical towns, and so on). The common responsibility to preserve them for future generations is universally recognized [7].

It is estimated that the amount of European CH buildings is 30% of the total existing stock [8]. About 35% of these buildings were erected 50 years old and almost 75% of them have low energy performance [9]. While the efficiency of new buildings has steadily improved over time, most of Europe's existing building stock has yet to be affected by energy performance requirements. Only about 1% of the building stock is renovated each year [9]. In fact, buildings built up to 1900 can reduce their energy demand by up to 60% with modest energy retrofits [10,11] or to 50% to 80% with major renovations [12]. The EU Union recognizes the importance of the improvement of energy efficiency and decarbonization on the existing building stock for mitigating the climate change and favoring the energy transition. This policy started with the Energy Performance of Buildings Directives (EPBD) [13,14] that focused on a roadmap for reducing energy consumption both in new construction and retrofit of the existing buildings. Along this line, the Energy Efficiency Directives (EED) [13,15] include instruments and measures to modernize the buildings sector and increase building renovations. It should be noted that refurbishment plays a crucial role to drive energy efficiency also in the European Green Deal [16] for the recovery of the COVID-19 pandemic.

Within this context, an increasing number of European programs was detected to finance projects focused on the retrofit of CH buildings. Some examples of projects are: Open Heritage, STORM, CLIC, ROCK, RIBUILD, HERICOAST, HERITAGECARE and FINCH among others [17,18]. In this direction, some initiatives also arose. The Renovation Wave [19] aims to double annual energy renovation rates in ten years, to cut greenhouse gas emissions, increase the quality of life, and generate new jobs in the green construction sector. In this direction, The initiative of the New European Bauhaus [20] is moving for the co-creation and the networking of new ideas and projects on building renovation. Despite this, each intervention (i.e. extension, adaptation, refurbishment, addition, retrofit, requalification, regeneration) of an heritage building requires physical changes, and may include visual and spatial changes [21]. This situation may irreversibly alter its authenticity [22]. Thus, all actions in terms of renovation require a deep knowledge on the diagnosis of the building elements to support the selection of technologies and solutions (i.e. enhancement of energy efficiency and human comfort, preservation of heritage and traditional values - including meanings, appearances and sustainable issues). Currently, the literature still presents a gap.

Taking into account the aspects mentioned above, the aim of this paper was to provide a detailed framework about the applicability of qualitative and quantitative non-destructive techniques (NDT) and their future perspectives for the diagnosis of CH buildings. This included a complete overview on the procedures, tools and measuring equipment for the evaluation of building elements, especially the envelopes. For this purpose, the paper was structured in several sections. Section 2 defines the research methodology. Section 3 presents a state-of-the art of NDT and advanced modelling technologies for CH buildings using a bibliometric analysis. Section 4 and 5 assess relevant studies to perform qualitative and quantitative diagnosis (i.e. HFM, IRT, photogrammetry, laser scanning, airtightness measurements). Section 6 identifies the future perspectives of NDT techniques, focusing on the interoperability of the mentioned methods in HBIM projects and the use of artificial neural networks (ANN). Finally, the most significant aspects are summarized in Section 7.

## 2. RESEARCH METHODOLOGY

The study of heritage buildings involves a variety of procedures and expertise, since a multidisciplinary approach is the best way to have a deep knowledge of the building itself from different points of view (historical, architectural, seismic, energetic…) [23–26]. To have a depiction of the building features as much complete as possible, beyond the study of the related documentation (which helps to define the evolutions and modifications over the time), in-situ investigations are useful if not compulsory at time [27]. However, the investigation of those aspects often entails the use of instrumentation and equipment which might (or even requires to) stimulate or damage the building itself: sampling, vibrations, hydraulic flat jacks, thermal shocks. Therefore, methods for building diagnosis can be grouped as destructive, semi-destructive and non-destructive (NDT). Considering the gap on the literature, the main objective was to carry out a critical review about the existing NDT to diagnose heritage buildings (Figure 1).

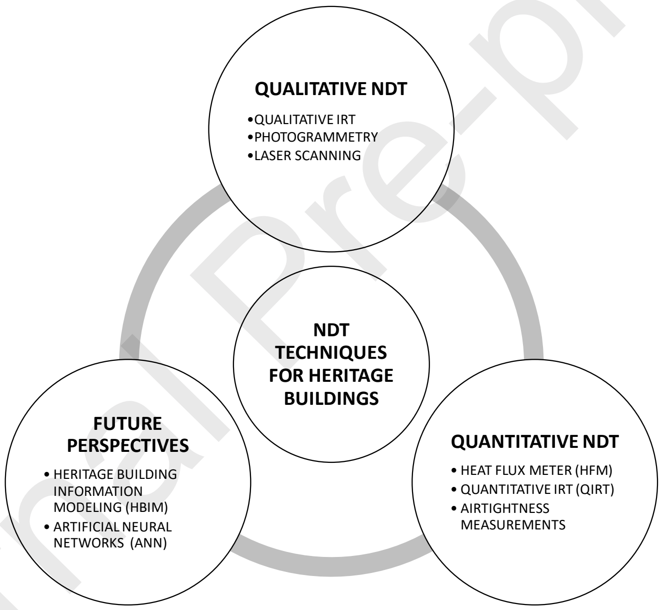



Figure 1. NDT techniques for heritage buildings

(Source: Elaborated by the authors)

To this purpose, the research methodology was focused on two steps (Figure 2). Firstly, a bibliometric analysis was conducted, applying a time span of two decades (from 2001 to 2021) and taking Scopus database as reference. According to some authors [28–30], Scopus database offers an expanded spectrum of publications (i.e. journal papers, books, conference papers etc). Indeed, it has a 20% more coverage than Web of Science. Alternative options like Google Scholar or Researchgate were excluded due to inconsistent accuracy for citation analysis [29,30]. The data statistics from Scopus allowed to determine the geographic distribution of the publications, the document type publication and the analysis of the authors. To identify the hot topics and trends, the keywords were evaluated by science mapping. Ren et al. [31] and Andersen et al. [32] stated that science mapping can be defined as a quantitative approach that apply statistics and visualization techniques, to classify and to analyze bibliographic networks in a specific area. Along this line, some authors highlighted that VOSviewer was the most widely used open-source software for science mapping, detecting the relationship among different terms of publications [29,30,33,34]. In the second step of the methodology, a review of the most relevant studies on this scientific field was carried out. In this stage, the goal was to provide enough knowledge for the employment of NDT in the diagnosis of heritage buildings, and to analyze the interoperability among technologies (NDT – HBIM and NDT – ANN).

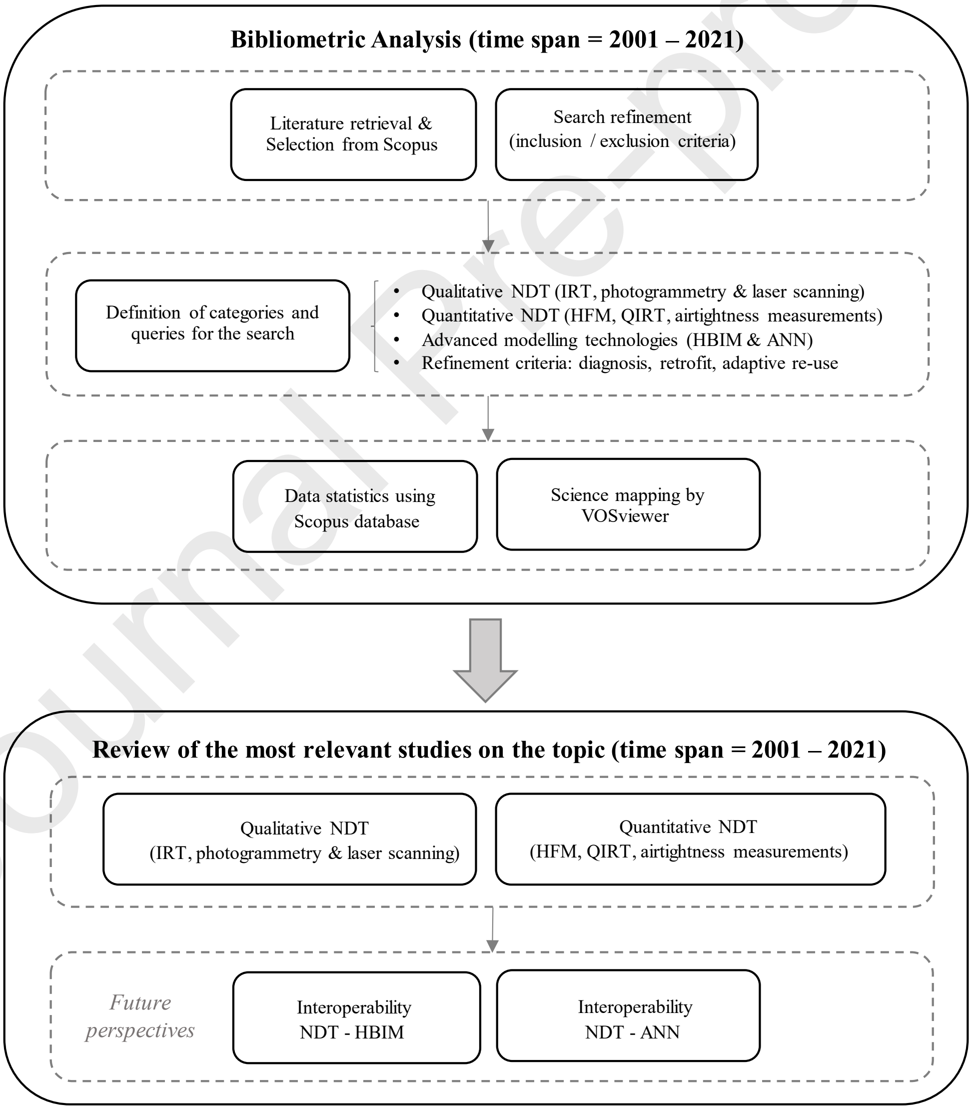



Figure 2. Flowchart of research methodology

(Source: Elaborated by the authors)

# 3. BIBLIOMETRIC ANALYSIS OF NDT FOR HERITAGE BUILDINGS

## 3.1. Definition of categories and queries for the search

As shown in Section 2, it was required to conduct a literature retrieval and search refinement (inclusion / exclusion criteria) in the bibliometric analysis. As a result, different queries for each category were introduced in Scopus, combining the keywords related to: CH, NDT techniques, HBIM and ANN. Subsequently, the application of the mentioned technologies was evaluated in terms of diagnosis, retrofit and adaptive re-use of CH buildings. Considering a period of 20 years (2001 – 2021), the queries and their respective results from Scopus Database are shown in Tables 1 - 2.

Table 1. Queries used for categories 1 to 7 and number of publications obtained

| Category | | Query | Publications (2001 – 2021) |
|---|---|---|---|
| | | ***Qualitative NDT for CH buildings*** | |
| 1 | IRT | TITLE-ABS-KEY ("historic building" OR "heritage building" OR “historic preservation” AND "infrared thermography" OR “IR technique” OR “IR thermography” OR "IRT" OR “qualitative infrared thermography”) | 93 |
| 2 | Photogrammetry & Laser Scanning | TITLE-ABS-KEY (“historic building” OR “heritage building” OR “historic preservation” AND “photogrammetry” OR “laser scanning” OR “TLS” OR “SFM”) | 808 |
| | | ***Quantitative NDT for CH buildings*** | |
| 3 | HFM | TITLE-ABS-KEY ("historic building" OR "heritage building" OR “historic preservation” AND “in-situ measurement” OR “monitoring” AND "heat flux meter" OR “heat flux method” OR "HFM" AND “thermal performance” OR “energy diagnosis” OR “hygrothermal assessment”) | 2 |
| 4 | QIRT | TITLE-ABS-KEY ("historic building" OR "heritage building" OR “historic preservation” AND "quantitative infrared thermography" OR "QIRT") | 2 |
| 5 | Airtightness | TITLE-ABS-KEY (“historic building” OR “heritage building” OR “historic preservation” AND “airtightness” OR “blower door test” OR “fan pressurization method” OR “tracer gas measurements”) | 40 |
| | | ***Advanced modelling technologies for CH buildings*** | |
| 6 | HBIM | TITLE-ABS-KEY (“historic building” OR “heritage building” OR “historic preservation” AND “HBIM” OR “heritage building information modelling”) | 278 |
| 7 | ANN | TITLE-ABS-KEY (“historic building” OR “heritage building” OR “historic preservation” AND “artificial neural network” OR “ANN” OR “machine learning” OR “ML” OR “deep learning” OR “DL”) | 299 |

It can be observed that the number of publications is very low for quantitative NDT techniques (HFM, quantitative IRT and airtightness measurements). Hence, this emphasizes that it is necessary more research on the diagnosis of the built quality of heritage buildings for their future refurbishments without damage.

Table 2. Queries used for categories 8 to 12 and number of publications obtained

| **Category** | | **Query** | **Publications (2001 – 2021)** |
|---|---|---|---|
| | | ***Future perspectives: Interoperability between NDT and advanced modelling technologies*** | |
| 8 | NDT and future perspectives | TITLE-ABS-KEY (“historic building” OR “heritage building” OR “historic preservation” AND **“NDT”** OR **“non-destructive testing”** OR “infrared thermography” OR “IR technique” OR “IR thermography” OR “IRT” OR “heat flux method” OR “HFM” OR “photogrammetry” OR “laser scanning” OR “TLS” OR “SFM” OR “airtightness” OR “blower door test” OR “fan pressurization method” OR “tracer gas measurements” OR “HBIM” OR “heritage building information modelling” OR “artificial neural networks” OR “ANN” OR “machine learning” OR “ML” OR “deep learning” OR “DL”) | 1511 |
| 9 | All terms included | TITLE-ABS-KEY (“historic building” OR “heritage building” OR “historic preservation” AND **“in-situ measurements”** OR **“monitoring”** OR “NDT” OR “non-destructive testing” OR “infrared thermography” OR “IR technique” OR “IR thermography” OR “IRT” OR “heat flux method” OR “HFM” OR “photogrammetry” OR “laser scanning” OR “TLS” OR “SFM” OR “airtightness” OR “blower door test” OR “fan pressurization method” OR “tracer gas measurements” OR “HBIM” OR “heritage building information modelling” OR “artificial neural networks” OR “ANN” OR “machine learning” OR “ML” OR “deep learning” OR “DL”) | 2648 |
| | | ***Refinement criteria: diagnosis, retrofit and adaptive use of CH buildings*** | |
| 10 | Diagnosis | TITLE-ABS-KEY (“historic building” OR “heritage building” OR “historic preservation” AND “**diagnosis**” AND “in-situ measurements” OR “monitoring” OR “NDT” OR “non-destructive testing” OR “infrared thermography” OR “IR technique” OR “IR thermography” OR “IRT” OR “heat flux method” OR “HFM” OR “photogrammetry” OR “laser scanning” OR “TLS” OR “SFM” OR “airtightness” OR “blower door test” OR “fan pressurization method” OR “tracer gas measurements” OR “HBIM” OR “heritage building information modelling” OR “artificial neural networks” OR “ANN” OR “machine learning” OR “ML” OR “deep learning” OR “DL”) | 130 |
| 11 | Retrofit | TITLE-ABS-KEY (“historic building” OR “heritage building” OR “historic preservation” AND “**retrofit**” AND “in-situ measurements” OR “monitoring” OR “NDT” OR “non-destructive testing” OR “infrared thermography” OR “IR technique” OR “IR thermography” OR “IRT” OR “heat flux method” OR “HFM” OR “photogrammetry” OR “laser scanning” OR “TLS” OR “SFM” OR “airtightness” OR “blower door test” OR “fan pressurization method” OR “tracer gas measurements” OR “HBIM” OR “heritage building information modelling” OR “artificial neural networks” OR “ANN” OR “machine learning” OR “ML” OR “deep learning” OR “DL”) | 86 |
| 12 | Adaptive re-use | TITLE-ABS-KEY (“historic building” OR “heritage building” OR “historic preservation” AND “**adaptive re-use**” AND “in-situ measurements” OR “monitoring” OR “NDT” OR “non-destructive testing” OR “infrared thermography” OR “IR technique” OR “IR thermography” OR “IRT” OR “heat flux method” OR “HFM” OR “photogrammetry” OR “laser scanning” OR “TLS” OR “SFM” OR “airtightness” OR “blower door test” OR “fan pressurization method” OR “tracer gas measurements” OR “HBIM” OR “heritage building information modelling” OR “artificial neural networks” OR “ANN” OR “machine learning” OR “ML” OR “deep learning” OR “DL”) | 3 |

During the literature retrieval and selection, it was noted that the incorporation of keywords like "in-situ measurements" or "monitoring" increased significantly the sample (2648 documents). Nevertheless, Scopus only allows to download the bibliometric data of 2000 documents with citation information, abstract and keywords, funding details and tradenames among others. For more than 2000 documents, only citation information can be achieved. This aspect influences directly to subsequent tasks, such as data statistics and science mapping, since the maximum data to compute should be 1511 documents (Table 2). Concerning the refinement criteria, keywords like "diagnosis" or "retrofit" or "adaptive re-use" allowed to know how NDT could have an essential role in the assessment of the built quality for renovation procedures of CH buildings.

**3.2. Overview of the research field**

With the purpose of conducting science mapping with VOSviewer, the category 8 "NDT and future perspectives" (Table 2) was computed. Figure 3 displays the co-occurrence network of keywords for a time span of 20 years (2001 – 2021), with a total of 752 items and 37694 links. The colors allow to identify the categories or clusters where the researchers promoted their works in laboratory or in the built environment, while the size of the circles refers to the weight of the relevant topics. From 1511 publications, 6 macro-areas of research or clusters were created (filtering with a minimum occurrence of five times). The findings revealed that "photogrammetry" and "laser applications" are consolidated techniques for historic preservation. This aspect is corroborated by Figure 4, where the trend of the scientific production increased rapidly from 2009 to 2021, with more than 740 publications.

Regarding the distance between clusters, this indicates how the strong is the relationship among items in terms of citations. By way of example, HBIM studies (cluster 5) could require knowledge and competencies from deep learning (cluster 3) with a large dataset and qualitative NDT techniques (Figure 3) such as photogrammetry (cluster 2) or laser scanning (cluster 6). Especially, when technicians have to develop architectural restorations with complex building elements, digital representations based on virtual reality etc However, when technicians conduct building diagnosis, gathered data from heat flux method or infrared thermography (cluster 1) is not used for updating HBIM models (Figure 3). This explains why the trends of the number of publications were different between advanced modelling technologies (HBIM or ANN) and quantitative NDT (HFM, QIRT and airtightness measurements), as seen in Figure 4. The areas of research like HBIM and ANN increased more than 260 publications from 2016 to present, while the growth of airtightness studies was 31 publications in the same period of time. However, the main concern about the use of ANN could be data privacy and network security (see keywords of clusters 3 and 4).

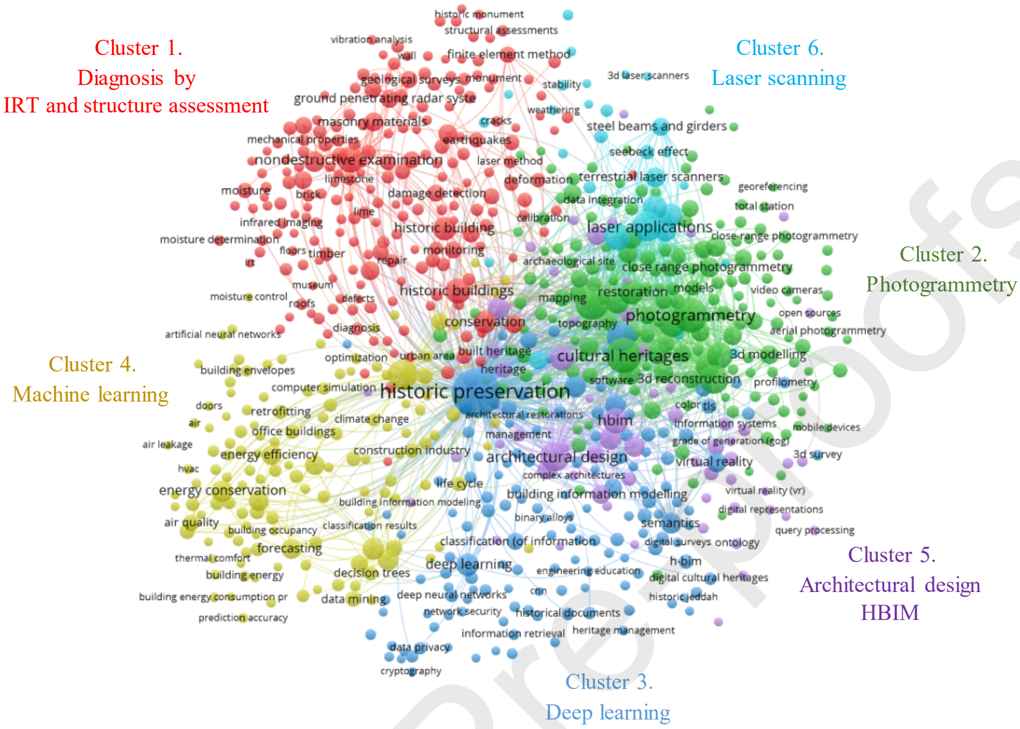



Figure 3. Co-occurrence network of keywords on “NDT and future perspectives”

(Source: Prepared by the authors using VOSviewer, based on Scopus data)

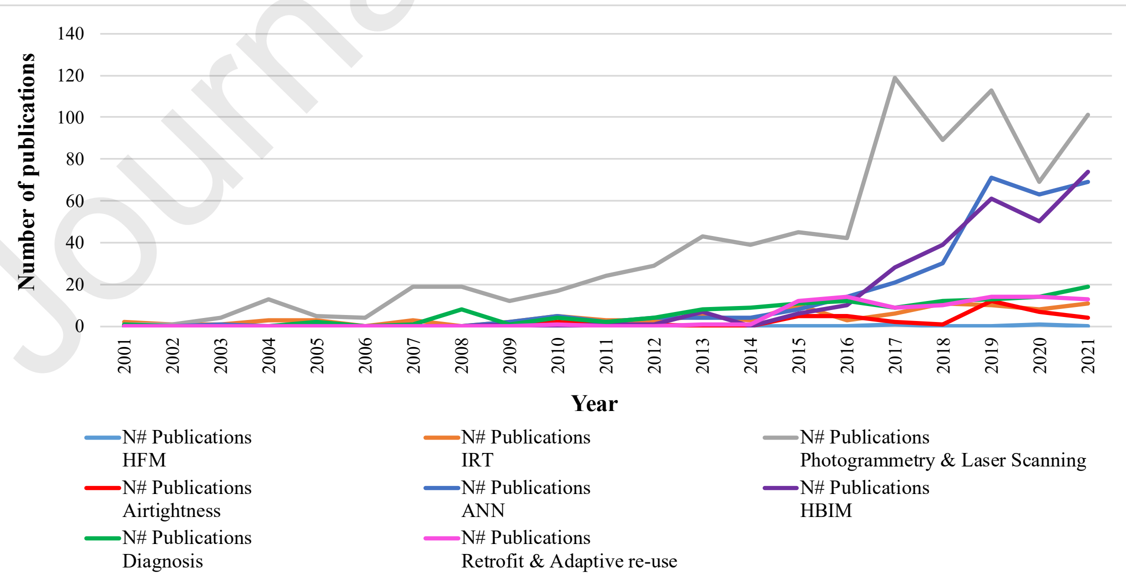



Figure 4. Number of publications per year. Period span from 2001 to 2021

(Source: Prepared by the authors using Scopus data)

After determining the relationship between NDT and advanced modelling technologies, it could be interesting to know what is the role of these techniques in the refurbishment of CH buildings. The historic preservation is an essential action to transmit cultural values to future generations. The retrofit strategies should ensure a reduction of energy consumption and environmental impact without causing any damage in the structures [34]. Figure 5 shows the mainstream of keywords in retrofit and adaptive re-use of heritage buildings and their co-occurrence relationship, considering the use of non-destructive techniques and advanced modelling technologies (HBIM and ANN). For this analysis, the options of "All keywords" and "Full Counting" were chosen in VOSviewer Software. The minimum occurrences of each keyword was set at 3, computing a network of 114 nodes (961 keywords in all documents) and a total of 3057 links. In fact, a total of five clusters can be distinguished with different colors. Cluster #1 (red color) contains 35 items related to: architectural design, retrofit strategies, masonry constructions, preventive conservation (through photogrammetry, laser scanning or BIM), structural analysis and structural health monitoring (including damage detection or seismic design). Cluster #2 (green color) covers 26 items that mainly refer to: energy conservation, energy efficiency, building energy performance, dynamic simulation of buildings, cost effectiveness, investments, energy savings, and sustainable development. Cluster #3 (blue color) with 23 items emphasizes the energy utilization of heritage buildings, in terms of: usefulness of the building (i.e. offices, commerce, housing), building characteristics (envelopes, doors, etc), indoor air quality, ventilation strategies, heating and cooling systems. Actually, the large-scale deployment of sensor networks for long-term monitoring could provide enough real-time data for the development of predictive control on building management systems (BMS) for HVAC facilities based on machine learning. However, the number of applications in this field is still very limited [35,36]. Cluster #4 (yellow color) with 19 items involves hygrothermal performance of heritage buildings and characterization of construction materials. Here, it is extrapolated that HFM and IRT (using wireless monitoring or remote sensing) could be implemented for the detection of moisture problems, as well as the assessment of the thermal insulation of walls (structural partitions) or the use of aerogel-enhanced systems for building energy retrofits. In fact, the term of "thermal insulation" appears as one of renovation solutions for CH buildings. Normally, to maintain the aesthetic and cultural aspects of the façade, the technicians decide to improve the thermal transmittance from inside the building [34]. Finally, Cluster #5 (violet color) is more focused on the thermal performance of timber-framed buildings. Taking into account the information mentioned above, the efforts of researchers were more concentrated on structural assessment in the last two decades.

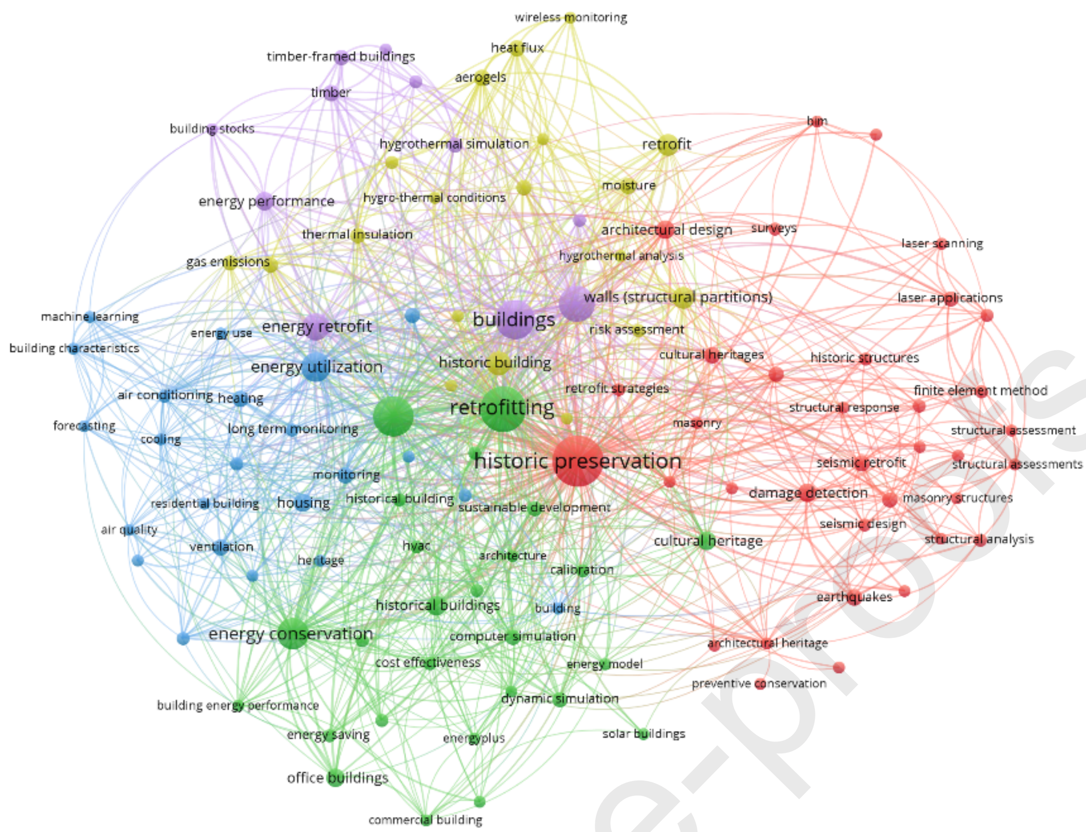



Figure 5. Co-occurrence network of keywords on “Retrofit and adaptive use of heritage buildings” (Source: Prepared by the authors using VOSviewer, based on Scopus data)

### 3.3. Geographic distribution of the publications

From Figures 6 to 9, the ten countries with a higher number of publications were plotted for all the categories established in Tables 1-2 (except HFM and QIRT with a number of documents less than 2). It is possible to notice that the interest on this topic is concentrated on Southern European countries (i.e. Italy, Spain, France, Portugal, Greece). According to Ramos et al.[18] , 31163 heritage listed buildings are located in this region of Europe. However, there is an absence of preventive conservation practices based on a systematic and integrated approach, especially to perform regular inspections and monitor the built environment. The existing preventive plans are not planned to minimize deterioration processes in mid or long-term [18]. This justifies the importance of proposing a common protocol for conducting measurement campaigns to diagnose CH building by NDT.

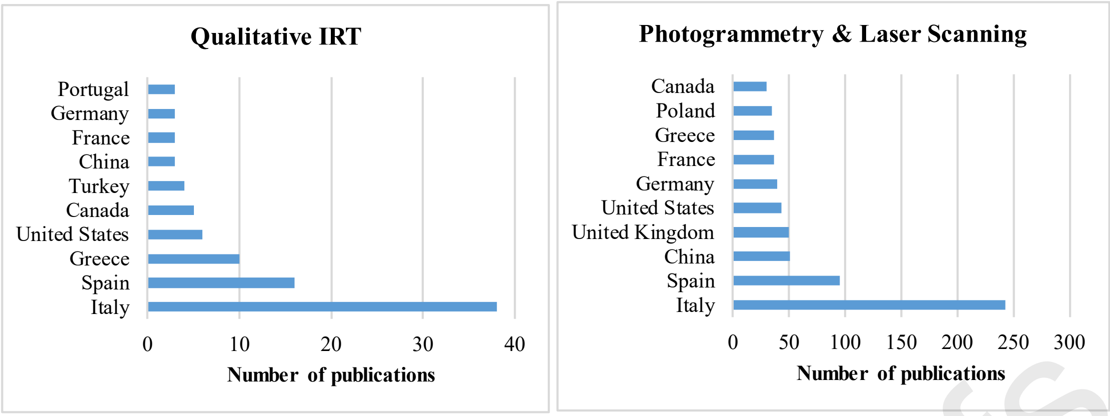



Figure 6. Qualitative NDT. Publications for the top 10 countries from 2001 to 2021

(Source: Prepared by the authors using Scopus data)

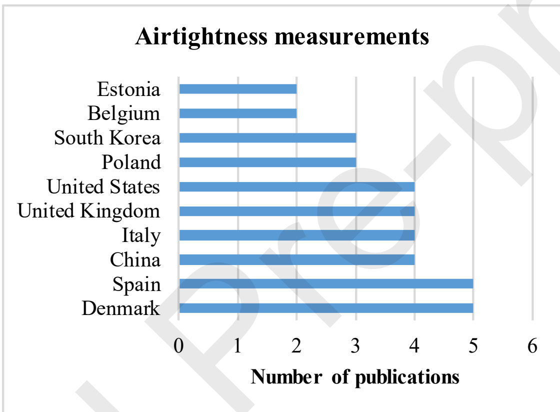



Figure 7. Quantitative NDT. Publications for the top 10 countries from 2001 to 2021

(Source: Prepared by the authors using Scopus data)

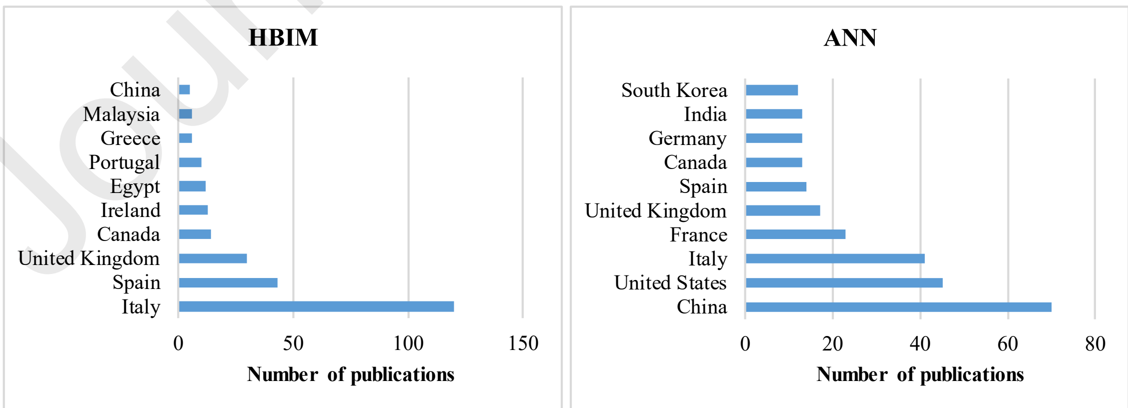
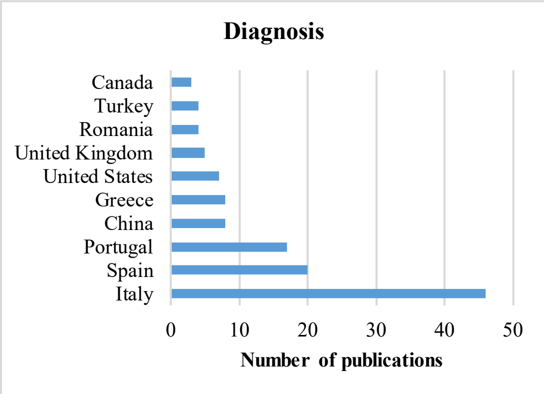



Figure 8. Advanced modelling technologies. Publications for the top 10 countries from 2001 to 2021

(Source: Prepared by the authors using Scopus data)



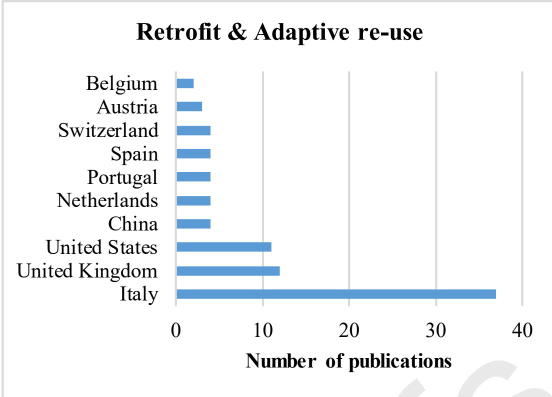




Figure 9. Diagnosis, Retrofit & Adaptive re-use. Publications for the top 10 countries from 2001 to 2021

(Source: Prepared by the authors using Scopus data)

### 3.4. Document type distribution

Figure 10 displays the document type distribution for each category mentioned in Tables 1 – 2. For the research areas with a greater scientific production, it can be reported that more than 50% of documents were grey literature (i.e. conference papers, book chapters, short surveys and so on). Specifically, the percentage of journal papers were: 27.22% for photogrammetry and laser scanning (220 documents), 39.21% for HBIM (109 documents) and 44.48% for ANN (133 documents). In the case of the category entitled "NDT and future perspectives", journal papers represented 36.00% of the sample (544 documents) Nevertheless, only 2.25% were attributed to review articles (34 documents in 20 years). Hence, there is still a research gap to cover.

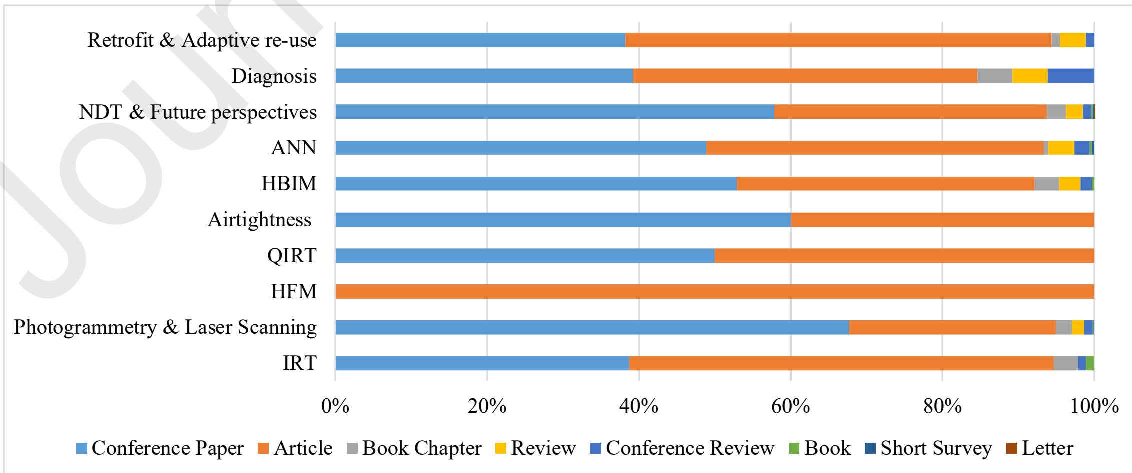



Figure 10. Document type distribution for each category from 2001 to 2021

(Source: Prepared by the authors using Scopus data)

### 3.5. Analysis of authors

Figure 11 presents the co-authorship network for “NDT and future perspectives” category, using the extracted data from Scopus database and adopting a minimum of documents per author equal to 5. The ten authors with a greater number of publications in this topic were reported below: Dr. Fabrizio Banfi with 23 documents (Politecnico di Milano -Italy-, h-index 18); Dr. Rafaella Brumana with 20 documents (Politecnico di Milano –Italy-, h-index 21); Dr. Mattia Previlati with 17 documents (Politecnico di Milano –Italy-, h-index 21); Dr. Antonia Moropolou with 16 documents (National Technical University of Athens –Greece-; h-index 37); Dr. Maurice Murphy with 15 documents (Trinity College of Dublin –Ireland-; h-index 10); Dr. Flavio Rinaudo with 14 documents (Politecnico di Torino –Italy-, h-index 17); Dr. Grazia Tucci with 14 documents (Università degli Studi di Firenze –Italy-, h-index 13); Dr. Andreas Georgopoulos with 12 documents (National Technical University of Athens –Greece-; h-index 17); Dr. Filiberto Chiabrando with 11 documents (Politecnico di Torino –Italy-, h-index 21); Dr. Elisabetta Rosina with 11 documents (Politecnico di Milano –Italy-, h-index 12). With respect to collaborations between these authors, the strong relationships were given by the institution of origin.

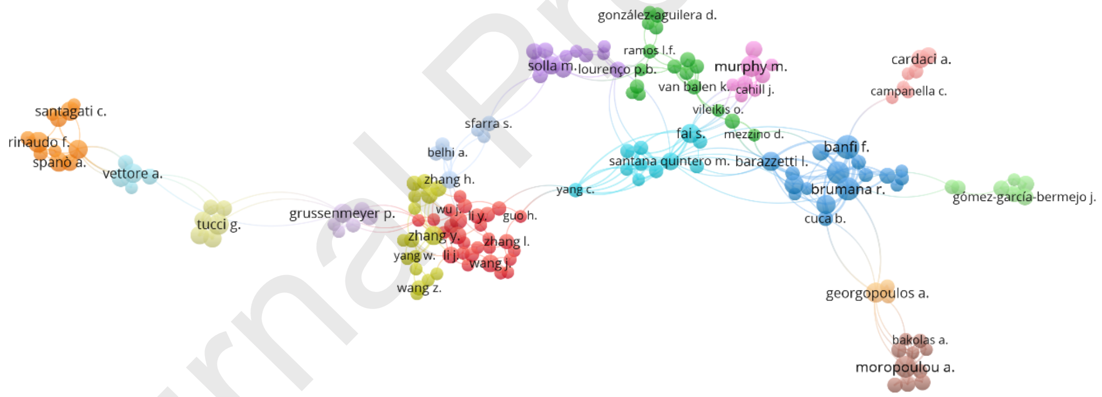



Figure 11. Density visualization of bibliographic coupling on “NDT and future perspectives”

(Source: Prepared by the authors using Scopus data)

To observe the relatedness of items based on the number of references, the bibliographic coupling map of “NDT and future perspectives” was plotted as a density visualization (Figure 12). It should be pointed out that two documents are bibliographically coupled if the same study is cited in both publications. In terms of photogrammetry and laser scanning, the most influential papers corresponded to Remondino et al. [37] and Armesto-González et al. [38] (454 and 123 cites respectively). Remondino et al. reviewed the existing 3D measurement sensors and 3D modelling techniques to develop image-based 3D digital documentation of heritage buildings. In contrast, Armesto-González et al. combined the terrestrial laser scanning with digital image processing techniques for damage detection in historical buildings. Concerning HBIM, the studies more useful for the scientific community were performed by Murphy et al. [39] (256 cites) and Bruno et al [40] (97 cites). Finally, the authors in the periphery were also attractive. Avdelidis's paper [41] was the most frequently cited in terms of qualitative IRT (203 cites), since the authors established the foundations for the assessment of the physicochemical behaviour of historic structures after a restoration or reparation actions. Amasyali's research [42], with 581 cites, was taken as reference for studies focused on data-driven building energy consumption prediction models using machine learning algorithms. Along this line, Ascione's research [43] (112 cites) was a clear example of how to develop energy retrofit solutions of an educational ancient building by the combination of on-site monitoring and diagnosis (HFM and IRT). This made possible to calibrate the numerical models and to ensure potential energy savings and environmental benefits.

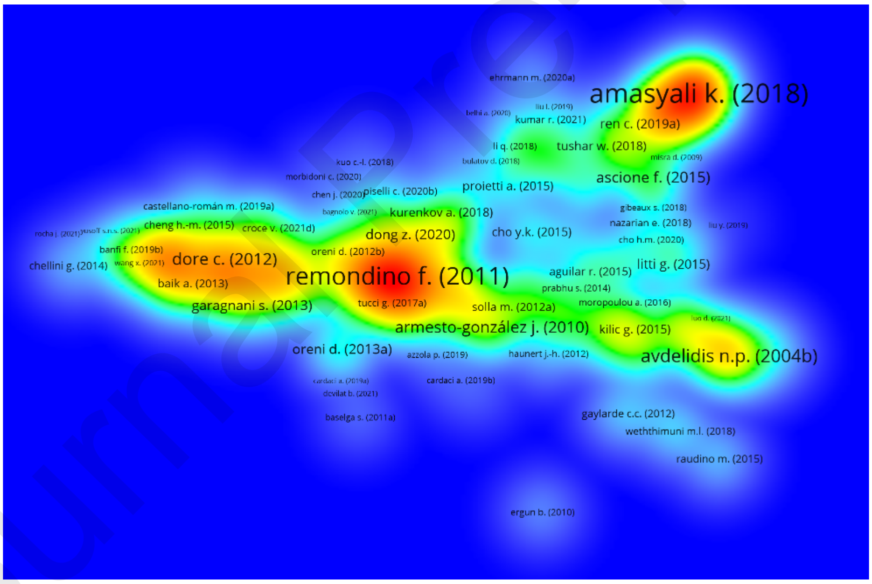



Figure 12. Density visualization of bibliographic coupling on "NDT and future perspectives"

(Source: Prepared by the authors using Scopus data)

## 4. RELEVANT STUDIES TO PERFORM QUALITATIVE DIAGNOSIS TECHNIQUES IN HERITAGE BUILDINGS

The employment of qualitative NDT on heritage buildings could provide different information about anomalies (i.e. cracks, moisture, thermal bridges etc). El Masri at al. [44] carried out a literature review on six NDT techniques executed in the construction industry sector (i.e. samples evaluated in laboratory, residential and non-residential buildings): IRT, Ultrasound, Through Wall Imaging Radar, LiDAR/Laser scanning, Close-Range Photogrammetry, and Ground Penetrating Radar), acting like a "review of reviews". Notably, these aforementioned methods can be coupled with each other and also with other approaches, like Finite Element Methods [45], to fulfill the knowledge. However, the same type of analysis was not performed for heritage buildings. This section covers this gap, explaining the most common methods (qualitative IRT, photogrammetry and laser scanning).

### 4.1. Qualitative infrared thermography (IRT)

Thermographic inspections consist of the reading, processing, and elaboration of thermal images, that represent in false-colour the temperature map of the investigated object. Building audits and diagnosis (which can be carried out according to three levels of knowledge) can employ thermography from both a qualitative and quantitative point of view [46]. A qualitative approach (IRT) implies the identification of the hotter and colder points of the object with respect to the surrounding, thus correlating the anomaly with the detected temperature difference [47]. Therefore, this approach helps to evidence the thermal pattern and to assess where (and how extended) thermal anomalies are (i.e. location of thermal irregularities). As a whole, building diagnosis has largely benefitted from IRT, due to its broad employment [48,49].

The use of IRT for building investigation is quite common for identifying (evident or incoming) issues [50], detachment [51], and critical points of large portions of the building envelope, thanks to the advantages of being a contactless technique. In fact, papers and works that employ IRT into heritage building are devoted to the opaque envelope, including: (i) identification of cracks [52–55]; (ii) health and structural state [27,41,56]; (iii) moisture, humidity or rising damp [57–63]; and (iv) air leakages [43]. Another classification can be made according to the investigated object, like for instance: (i) buildings (residential or tertiary) [27,64]; (ii) places of worship (i.e. museums, churches, mosque, etc) [25,53,55]; and (iii) monuments and archaeological sites (not included in the previous classes) [56,62,65]. The IRT, when is coupled with other NDT techniques, can provide a full understanding of building features, also allowing to retrieve possible phase construction of the building itself, due to the possibility of identifying different materials under the plaster covering [64,66].

### 4.2. Photogrammetry & Laser Scanning

One of the most important aspects in the analysis of heritage buildings is their geometry. Heritage buildings do not usually have technical documentation of the project. Likewise, this documentation does not reflect the current state of the building (i.e. structural defects) [67,68]. Given this circumstance, virtual models are an opportunity to have a precise knowledge of the geometry of the building [69]. The 3D survey is carried out through 2 techniques (Figure 13): Structure from Motion (SfM) based on photogrammetry and Terrestrial Laser Scanner (TLS). The main studies on this topic are summarized in Table 3 and briefly explained below.

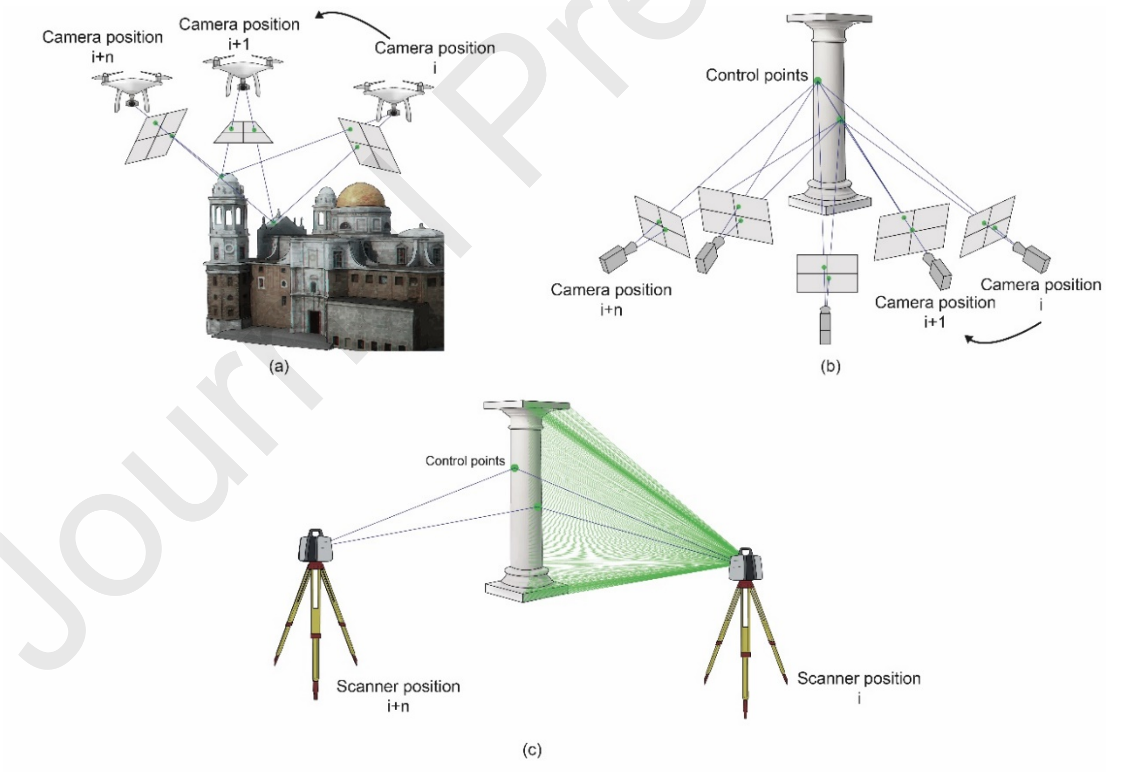



Figure 13. 3D survey schemes: (a) aerial photogrammetry, (b) ground photogrammetry and (c) TLS.

(Source: Elaborated by the authors)

Table 3. The most relevant studies on TLS and SfM (2001 – 2021)

| Author | Year | Country | LS | Element | Technique | A | Application |
|---|---|---|---|---|---|---|---|
| Grussenmeyer et al [70] | 2008 | France | OUT | Wall | SfM, TLS | --- | SfM vs. TLS |
| Brumana et al. [71] | 2014 | Albania | IN, OUT | Structure | SfM, TLS | --- | 3D model |
| Remondino et al. [69] | 2014 | Italy | IN, OUT | Structure | TLS | ± 0.2-5 mm | State-of-the-art |
| Bolognesi et al. [72] | 2015 | Italy | OUT | Wall | SfM, TLS | --- | UAV in CH |
| Ramos et al. [73] | 2015 | Spain | OUT | Structure | TLS | ± 2.6 -3.4 mm | Structure modelling |
| Pierdicca et al. [74] | 2016 | Peru | OUT | Wall | SfM | --- | Archaeology |
| Erenoglu et al. [75] | 2017 | Turkey | OUT | Wall | SfM UAV | ± 2 - 3 mm | UAV in CH |
| Tumeliene et al. [76] | 2017 | Lithuania | IN | Paintings | SfM | --- | 3D model |
| Antón et al. [77] | 2018 | Spain | IN | Structure | TLS | --- | 3D model |
| Moyano et al. [78] | 2020 | Spain | IN | Structure | TLS | ±2.5 mm | BIM Archaeology |
| Balado et al. [79] | 2021 | Portugal | OUT | Structure | TLS | ± 10.6 mm | Automatic modelling |
| Gómez-Zurdo et al. [80] | 2021 | Spain | OUT | Structure | SfM UAV | ± 2 mm | Deformation control |
| Moyano et al. [68] | 2021 | Spain | OUT | Wall | SfM, TLS UAV | --- | SfM vs. TLS |

**LS: Location of sensors*

Photogrammetry is the science whose goal is to know the positions and dimensions of objects in space [76]. This is achieved through measurements made from the intersection of two or more photos. With a single photo, two-dimensional information on the geometry and position of the object is obtained. However, working with two photos gives a stereoscopic view (i.e., three-dimensional information) [78]. There are two photogrammetry techniques: (i) aerial photogrammetry (with Unmanned Aerial Vehicle (UAV)); (ii) and ground photogrammetry. In aerial photogrammetry, photos are taken from cameras mounted on flying devices (e.g., drones), being useful for surveying inaccessible elements [80]. To generate these models, at least two images taken from different perspectives of the same location need to overlap to estimate the locations of the points belonging to the different objects that appear in the photographs. In contrast, terrestrial photogrammetry uses a camera located on the earth's surface that is placed in different positions. By obtaining images from different perspectives with one methodology or another, SfM automatically obtains high-resolution three-dimensional data. The use of control points is essential to be able to obtain suitable geometries.

TLS allows to obtain a 3D point cloud of objects located around the scanner [79], since it is based on sending an infrared laser beam towards the center of a rotating mirror. The mirror deflects the laser in vertical rotation around the environment being scanned and light scattered from objects in the environment is reflected to the scanner [81]. Depending on the technology of the scanner used, the maximum scanning distance can range from 100 to 300 m [81]. The effectiveness of the scan depends on many factors, such as distance, angle of incidence of the beam, surface properties of the scanned object, visibility limitations and environmental conditions during the test. These restrictions force in many cases to carry out scans from several locations and later unify them in the same model. Cloud registration requires the use of targets to materialize control points. The use of SfM or TLS varies depending on the objective pursued: large and irregular geometries are obtained through TLS, while SfM is more suitable for small areas whose pictorial information is important [70,71,77]. Nevertheless, some studies have assessed the advantages of using both in combination [37,73,74]. In any case, the differences between the two methods and the advantages of each technique have focused many of the recent studies. The first aspect is economic, since the use of low-cost techniques is interesting for these studies [72]. In this sense, the cost of cameras used with SfM is usually cheaper than TLS technology [82]. In this sense, any type of camera can be used with SfM, although the most recommended are single-lens reflex (SLR) cameras. Likewise, the type of positioning and the difficulties in measuring determine the type of equipment to be used. In this sense, the automatic positioning approaches [83], mobile laser scanners [84], and UAV [85] allow to improve the obtaining of the point cloud. UAV can be especially interesting in high points of the buildings [75,86]. Despite this, the results obtained with TLS tend to be more accurate than UAV [87]. Likewise, the approach to performing SfM for outdoor spaces (e.g., courtyards) was evaluated by Moyano et al. [78], although the results were not satisfactory. Thus, the use of SfM would be more suitable for short-range elements, obtaining satisfactory results [88].

## 5. RELEVANT STUDIES TO PERFORM QUANTITATIVE DIAGNOSIS TECHNIQUES IN HERITAGE BUILDINGS

The quantitative diagnosis mainly aims to assess thermal properties and airtightness of a building. It should be noted that both aspects can directly influence on energy performance, human comfort, and indoor air quality [89,90]. However, no studies have been performed on heritage buildings. Thermal characteristics are mainly defined by the thermal transmittance (U-value), that quantifies the amount of heat that passes through the building envelope when a enough temperature difference (10 – 15ºC) occurs between the two sides [89,91,92]. The assessment of a building element depends on layout, stratigraphy, water content, conservative state, and application techniques. For its evaluation (Figure 14), it is possible to refer to the following NDT methods: (i) the theoretical method (regulated by ISO 6946 [93]); (ii) the heat flow meter (HFM) method (regulated by ISO 9869-1 [94]); (iii) the thermometric method [95] (based on ISO 9869-1 [94]); (iv) internal [91,96] or external [97,98] quantitative infrared thermography (QIRT); and (v) simple hot box method [99,100].

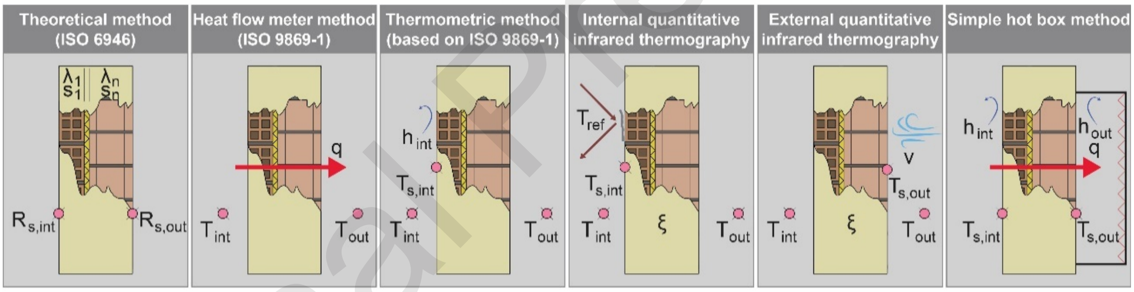



Figure 14. NDT techniques for assessing thermal behavior of building envelopes

(Source: Prepared by the authors)

Some of these methods constitute the basis for international standards and have been largely employed, some are still ongoing studies to refine, and some have not been employed on heritage buildings. The theoretical method calculates the U-value starting from the knowledge of the thickness of each layer of the building skin (retrieved from documentation and building projects, or by analogy with coeval buildings), and the corresponding thermal conductivity (technical standards or material datasheets and databases can help) [93]. This procedure can be used in steady-state conditions, for homogeneous or multi-layer building elements. Nevertheless, this situation is more theoretical than real because heritage elements are typically inhomogeneous (i.e.different materials, cavities with air movements, joints, different thicknesses, etc)

[101–104]. Thus, the absence of databases of pre-industrial materials and technologies as well as the non-homogeneities of traditional structures affect the analytical calculation of their thermal performances. This calculation is also influenced by the differences between standard and real surface resistances for spoiled and damaged masonries, as well as by the moisture content of the building element [101,102]. HFM is an NDT procedure for measuring the U-value of a building component directly in situ. The measuring apparatus is composed by a heat flux plate and two or more temperature sensors for measuring the temperature difference between indoor and outdoor environment. A data-logger stores the data acquired by the sensors, at fixed time rates. This approach is the basis for the thermometric method, where the heat flux is computed as the convective heat flow occurring in the inner surface. Concerning quantitative IRT, different approaches have been proposed in literature. In fact, some authors perform QIRT from inside of the building [91,96,105–109], and others form the outside [97,98,110–114]. These methods are conducted under the hypothesis of steady-state flux, although the research interest is also in those techniques based on transient heat transfer [115]. Finally, the airtightness of the building envelope is measured with the tracer gas and the fan pressurization method, and it is quite important for old buildings being particularly subject to air infiltration.

**5.1. Heat Flux Meter (HFM)**

HFM has been employed as in-situ NDT technique, especially in existing masonries for avoiding the inaccuracies in the assessment of stratigraphy, material properties, damage, decay, moisture content, and application techniques [101,102,104]. However, few studies are strictly focused on heritage buildings (i.e. Lucchi et al.[101] or Roque et al.[116]), as seen in Table 4. Most of them do not contain the terms "historic building" or "heritage building" and "HFM" in the title, abstract or list of keywords of the articles. For this reason, Scopus database did not cover these studies for the subsequent bibliometric analysis about HFM.

The procedure is defined by the International standard ISO 9869 [94] that outlines the apparatus and the calibration, installation, and data-processing techniques. Despite this, the literature found several metrological and practical issues that have an impact on the result especially on heritage components [102,117,118], such as: (i) measurement location; (ii) inhomogeneities of the building element; (iii) heat flux perturbation generated by the HFM; and (iv) influence of boundary conditions. For minimizing the potential influence of these uncertainties, the apparatus must be located in north-facing areas, protecting the outer surface from whether perturbation by a proper screen. Similarly, indoor location must avoid the influence of heat sources, such as thermal and electrical devices. Besides, to reduce the influence of vertical temperature stratification, it must be inserted about half-way between window and corner, floor, and ceiling [117]. Furthermore, IRT support the proper installation of sensors [101]. On the contrary, several experiments proved that masonries are sufficiently homogeneous for obtaining feasible results using standardized surface heat-transfer coefficients [101–103].

This technique is suitable particularly for valuable building elements thanks to the absence of invasive and intrusive trials, which generally are not allowed by Heritage Authorities. However, this method cannot be properly defined as non-invasive. It requires to enter the building to be measured and to fix the probes in specific point of the wall and, if necessary, to repeat the measurement in several points when there is the suspect of non-uniform U-value across the wall (i.e. under windows where, especially in old buildings, it might happen that wall is thinner). Moreover, the thermal glue or paste which is employed to fix probes (thus enhancing the conduction) stains the wall itself. Hence, some works are devoted to the solution of this inconvenience. For instance, in the research [119], the non-perfect thermal contact of the heat flow meter was investigated, by assessing the test duration and the accuracy of the final results when a PVC film was interposed between the plate and the wall. For this reason, in many cases on old masonries, the flux plate and temperature probes should be fixed by adhesive tapes [104].

Several studies have been published on the HFM measurement of ancient masonries. For example, [120] and [121] compared the analytical calculation and the HFM measurement of different typical Italian brick and stone masonries that belong to different historical periods. Similar studies were carried out on traditional masonries in Scotland and England [117,122,123]. In all these studies, traditional building elements had a better measured thermal performance than the analytical, in the range 20-30%. In [124], some typical wall assemblies were studied, and particularly one from the Greece tradition. The paper aimed at assessing the influence of the data processing method starting from HFM data. In [118], six wall assemblies were investigated, some of which were historic building. In [116], the authors developed a new approach to cover the limitations of HFM in Portuguese internal walls from historic buildings erected in late nineteenth century. In [64], an analysis from a historical building undergone to seismic and energetic refurbishment was proposed.

Table 4. The most relevant studies on HFM (2001 – 2021)

| Author | Year | Country | LS | Element | CP | TD | A | Application |
|---|---|---|---|---|---|---|---|---|
| BRE [123] | 2000 | UK | IN | Façades Housing + Schools | >1995 | 7 days | 20% | Database for traditional masonries |
| Baker et al. [117] | 2011 | UK | IN | Façades Housing | 1880 - 1970 | 14 days | --- | Baseline data for U-value |
| Williamson et al. [122] | 2013 | UK | IN | Façades Housing | < 1919 | 7 days | --- | Energy retrofit |
| De Berardinis et al. [121] | 2014 | Italy | IN | Historic masonry Housing | --- | >7 days | --- | Energy retrofit |
| Evangelisti et al. [120] | 2015 | Italy | IN | Façades Housing | 1800 - 2000 | 8-12 days | 17-153% | Energy retrofit |
| Ficco et al. [118] | 2015 | Italy | IN | Façades Housing | 1965 -2015 | <7 days | 8-50% | Energy retrofit |
| Atsonios et al. [124] | 2017 | Greece | IN | Façades Housing | --- | 28 days | 6-18% | Energy performance |
| Nardi et al. [64] | 2017 | Italy | IN OUT | Historic mansory Tertiary building | 1930 | 168h | --- | Energy retrofit |
| Lucchi [102] | 2017 | Italy | IN | Historic masonry Tertiary buildings | 1300 -1800 | 14 days | 7-54% | Database for stone masonries |
| Lucchi et al. [125] | 2018 | Italy | IN | Mock-up Laboratory | --- | 144h | --- | Influence of heterogenities |
| Evangelisti et al. [126] | 2020 | Italy | IN | Façades Tertiary building | 2020 | 7-18 days | 20-60% | Energy saving measures |
| Gumbarevic et al. [127] | 2020 | Croatia | IN | Laboratory | --- | 4 days | 0.78 -9% | ANN |
| Roque et al. [116] | 2020 | Portugal | IN | Tabique wall Historic building | 1800 -1900 | 72h | 1-5% | Energy performance |
| Gaspar et al. [119] | 2021 | Spain | IN | Old façades Housing | 1960 -2005 | 7 days | 5% | Enhancement measured U-value |
| Gumbarevic et al. [128] | 2021 | Croatia | | Laboratory | --- | 4 days | 1-9% | ANN |

**LS: Location of sensors; CP: Construction Period; TD: Test Duration; A: Accuracy*

HFM was also largely employed as reference for other techniques (i.e. quantitative IRT), without losing the attention of researchers, that still work on its refinement. For instance, in [126], the HFM method was employed for two seasons (summer and winter) on different sides (north and south walls) of a recently built building, to assess the importance of the external environmental conditions and of the data refinement. In terms of calibration, some works are still ongoing [127–129].

**5.2. Quantitative Infrared Thermography (QIRT)**

QIRT means that the thermal image is post-processed to obtain a quantitative information, also from a spatial-temporal correlation, for an in-depth evaluation (i.e. characterization of a defect or U-value). A clear classification and technique definition is available in [130,131], and hybrid approaches have also been proposed [132]. QIRT applied to the building envelope has been recently proposed in literature, and many research groups have been working on it since its first proposal in 2008 [133]. It is noticeable the growing interest in the last years and spread of research groups working on this topic, evidence of the need for a quick and reliable NDT technique for the U-value assessment. Nevertheless, historical buildings represent a research gap in this sense, especially in the EU. As mentioned in Section 3, only two studies of QIRT were detected [134,135]. Grinzato [134] applied QIRT to analyze the decay of CH buildings covered by frescoes, while Tavukçuoglu [135] combined QIRT and ultrasonic pulse velocity (UPV) to monitor and to evaluate the thermal performance of historical structures with anomalies (i.e. moisture, thermal bridges, etc). Therefore, this subsection discusses the most relevant papers on QIRT in existing buildings published from 2018 to 2021, highlighting the significant aspects for future protocols based on heritage buildings.

In [136], QIRT was implemented in laboratory to determine the U-value of traditional glazing, comparing Korean standard window performance evaluation with HFM results. In [137], the authors aimed at assessing the U-value via external QIRT on wood-framed wall assemblies, reproducing in an experimental structure. The work highlighted some practical advices as well as the need for proper Region of Interest (ROI) selection, to reduce errors. In the work by Papadakos et al. [138], the envelope of an existing building (made by porous clay bricks or perforated bricks) was investigated with HFM, theoretical method and via QIRT. The method allowed to identify (via Ishikawa method) those parameters that affect the heat flux and the temperature evaluation in QIRT, and consequently the U-value. An auxiliary target set-up is proposed, as well as a complete sensitivity analysis. In [90], the 2D U-value map was proposed as a method for accurately investigating surfaces which had partial anomalies/non-uniform thermal pattern, like walls of historic building, whose masonries are made of brick and stone. The aim was to achieve a simpler processed thermogram, thanks to which obtaining the U-value under the steady-state heat transfer hypothesis presented in previous studies [91]. In [139], it was employed for thermal bridge quantification in a climatic chamber, where measurements were carried out by replicating typical EU construction technologies. This is relevant especially for heritage buildings, whose thermal pattern often reveals non-uniformity and thermal bridges, whose energy losses might be relevant. The possibility of quantifying such energy expenditure avoiding destructive or invasive methods is of utmost importance.  The efforts in this field are now devoted to the assessment of the influence of the convective heat transfer coefficient on the results from the application of the several QIRT methods and equations. For the convective heat transfer coefficient (CHTC), Bienvenido-Huertas et al. [140] applied nearly 50 correlation evaluations depending on wind speed, and about 10 depending on dimensionless numbers. A clustering was computed (by Ward method) to help to "group" those correlations and, therefore, the corresponding U-value obtained by external QIRT employed on 3 multi-leaf walls. Moreover, the percentage contribution of radiative and convective fluxes on the total heat flux was also shown for each cluster. Results demonstrated that it is still quite difficult to establish a unique and more appropriate CHTC for all the approaches, but there are some equations (and some clusters) that are more suitable than others. In a later study [141], the analysis of the internal correlations with dimensionless numbers allowed to obtain better results than in the external approach. A later contribution from Nardi et al [142] aimed at assessing the span of CHTC from 57 correlations at different wind speed classes (within the range of applicability of QIRT method), and then by employing such correlations on a reduced wind speed range (coherent to the experimental set up) to the U-value equations for QIRT, to compare results with the conventional CHTC. Also in [143] the CHTC issue was addressed, by developing a methodology for its determination, valid for low-rise building. Finally, a key-point for the QIRT employment is the hypothesis of steady-state heat transfer coefficient, which is of course a simplification of the complex dynamics of the phenomena. In [144], it was analysed the impact of stationary and dynamic regimes on QIRT. For the purpose, heavy multi-leaf walls in two EU Countries were investigated (also via HFM method), and a discussion on boundary conditions was proposed.

### 5.3. Airtightness measurements

Airtightness and air infiltration affect energy performance, human comfort, and indoor air quality (IAQ) of a building. From one side, the high airtightness performances have positive impacts on the reduction of energy consumptions but they can negatively influence the IAQ in terms of ventilation rate and pollutant concentration [145]. On the other side, the decrease in ventilation rates coincides with the growth of allergic diseases (i.e. asthma, inflammation, respiratory infections, allergy, sick building syndrome) related to the exposure to chemical (e.g. volatile and semi-volatile organic compounds, cleaning chemical agents, traffic related pollutants, environmental tobacco smoke) and biological (e.g. molds, virus, spores, cells, fragments, and bacteria) agents [146,147]. Low ventilation rates affect also the human productivity and comfort perceptions [146,147]. Similarly, they favor the concentration of chemical and biological pollution and dust [146,147] that may damage heritage artifacts, collections, archives, and building surfaces [148,149]. A balance between ventilation requirements for human comfort, IAQ, pollution concentration, heritage conservation, and energy savings is needed especially in historic buildings [147].

Air infiltrations in a building depend on [6,147,150]: (i) building age; (ii) geometry (e.g. area/volume index, building shape, dimension); (iii) building type (e.g. single or multifamily building, villa, detached building, tower); (iv) building use; (v) constructive technology and materials (e.g. precast or traditional construction, bricks, stone, wood); (vi) type of component (e.g. wall, roof, windows, doors, chimney); (vii) conservation state (e.g. level of damage, type of decay); (viii) construction quality; (ix) environmental conditions (e.g. wind velocity, air temperature differences ($\Delta T$; °C) between indoor and outdoor environment); and (x) characteristic of the surroundings (e.g. wind direction, shadows, orientation). Martín-Garín et al. [151] listed the main sources of the air leakage points in historic buildings in the following building elements: (i) wall joints and joints in window frames; (ii) ducts in the building envelope for water, gas, or ventilation; (iii) electrical devices (lighting, plugs, switchboards, switches); (iv) cracks and cavities; (v) joints in baseboards and floorboards. Feijó-Muñoz [152] and Colijn et al. [153] tried to identify the leakage paths in Spaniard and Dutch traditional houses using the IRT. The main problems were found in window frames, rolling shutters, pipes, ducts, and construction joints. Similarly, d'Ambrosio Alfano et al. [154] noticed that absence of sealing systems is a critical point in the building stock, especially for windows and chimneys. Also, despite a correlation between the airtightness and the workmanship quality was discovered, no statistically significant results were obtained for the reduced sample size of data and the difficulty of isolating the variables [153].

Diagnostics of natural ventilated buildings is difficult [155,156]. This problem increases in CH buildings characterized by high air flow rate through the building envelope. Qualitative assessments are complex due to the thermal buoyancy created by the difference in air density (generated by the pressure difference inside and outside the building [155]  Also, meteorological conditions cause high variability of instantaneous values of ventilation airflows [155]. Quantitative assessments can be divided in instantaneous and continuous measurements. Two instruments are used for instantaneous quantitative tests: anemometer or a barometer. The first measures the air velocity in a room while the second measures the airflow in exhaust and supply outlets [155]. Continuous quantitative test methods contemplate the tracer gas measurement, and the fan pressurization method, also called Blower Door Test (BDT).

### 5.3.1. Tracer gas measurements

The tracer gas test is a direct measurement of the air infiltration rates in a building. Three different measurements of the gas concentration are used [6,156,157]: (i) the constant injection; (ii) the constant concentration; and (iii) the concentration decay. This method depends on the weather conditions and is limited to the measurement period [6,158]. The accuracy of these methods is related to reiterate measurements: on the contrary a single measurement gives limited information on the building infiltration [159]. The first two methods are more accurate, but they require long times as well as expansive and sophisticated equipment [32]. Also, these measurements need larger time span that is not always applicable to the buildings in use, where some elements (doors, windows or the ventilation ducts) cannot be closed for long time [6]. The concentration decay method is the most widely practiced especially in huge CH buildings like churches, museum halls, palaces, and castles, due to its simplicity, low cost, and reduced times [6,157]. It permits also to reduce the impact of the surrounding climate (e.g. wind speed, wind direction, indoor-outdoor $\Delta T$) in natural ventilated buildings [160]. In this case, the tracer gas is distributed into a building and mixed using fans to achieve a satisfactory uniformity. The gas then naturally decays thanks to the dilution with air infiltrations from outdoors [6,157]. The gas concentration is monitored with a series of calibrated sensors placed in the rooms [157]. The air change rate (ACR) value is calculated according to the concentration decay by a mathematical regression [157]. Several limitations are found on this test. The most important is related to the accuracy in natural ventilated buildings. For example, Buggenhout et al. [161] demonstrated an error of 86% in naturally ventilated rooms where is difficult to reach a perfect air mix. The most consistent results have been found in during winter seasons [162]. Another aspect is related to the user behavior, such as window or door opening habits and use of exhaust fans [162,163]. Only few studies have been found on CH buildings [6], but they confirm the results obtained in naturally ventilated buildings. Hamid et al [164] selected the concentration decay method in naturally ventilated CH buildings in Sweden to reduce the impact of the boundary conditions related to the presence of natural ventilation. Besides this method, a passive tracer gas decay measurement was conducted to obtain average values of the ACR over a longer time. These tests were conducted simultaneously during and after office hours, showing the influence of occupant on the ACR. The ACR after office hours was lower in summer than in winter due to smaller differences in the indoor-outdoor ΔT. On the contrary, during office hours in summer the ACR resulted almost twice then in winter for the impact of the occupants (window opening) [6]. Similarly, Hayati [158] estimated an overall uncertainty of ±10-15% in the airing measurements of huge churches using tracer gas concentrations before and after airing.

### 5.3.2. Fan pressurization method

The fan pressurization method is an experimental measurement of the air flow rates across the building envelope over a range of induced pressure difference (ΔP) between the indoor and the outdoor environment (Figure 15). This data permits to measure the air permeability (q) and n value under a ΔP, defined as the air leakage rate across the building envelope respectively per the envelope area and per the internal volume [159]. This method is used for a wide variety of qualitative and quantitative purposes [159]: (i) to measure and to document the air tightness and the air permeability of a building; (ii) to estimate the indoor air changes and the natural ventilation performances; (iii) to control construction quality; (iv) to compare the air permeability of similar buildings; (v) to localize the infiltration areas in a building; (vi) to identify the causes of air leakages; (vi) to reduce the air infiltrations with a renovation of an existing building. The international standard ISO 9972 [159] defined the procedure for measuring the air permeability of a single zone building or a part of building through this method. It can be also applied to a multi-zone building, simply opening the interior doors or by inducing equal pressures in adjacent zones. This method is not valid for single building elements. The reference ΔP in the BDT is 50 Pa. Thus, the measured parameters are the air leakage rate at 50 Pa (q50) and the air change rate at 50 Pa (n50). The accuracy of the test depends on the equipment, the environmental conditions, and the building features. The equipment is composed by: (i) a fan for creating a Δp across the building envelope to ensure a constant air flow at different pressures; (ii) a pressure device for detecting the Δp with an accuracy of ± 2 Pa in the range 0÷60 Pa; (iii) mobile telescopic door to insert on the building element; and eventually (iv) monitoring device for measuring the indoor and outdoor air temperature.

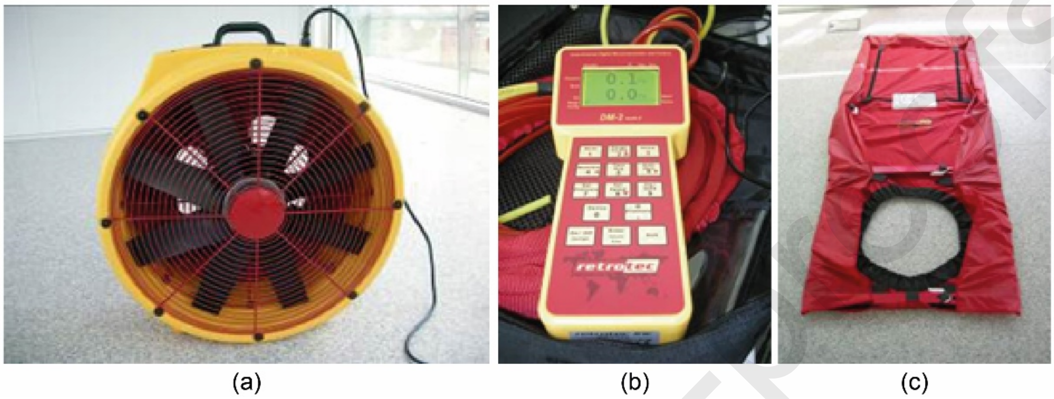



Figure 15. The equipment used for the fan pressurization method: a) fan, b) pressure device, c) mobile telescopic door. (Source: Elaborated by the authors)

Ideal environmental conditions for the test are small indoor-outdoor ΔT and low wind speeds (<6 m/s or < level 3 on Beaufort scale), while strong winds and high ΔT must be avoided. Similarly, high building dimensions affects the result: to obtain acceptable results, the product between ΔT and the internal height must be less than 500 mK [154]. The advantage of this method is that their results are less affected by climatic conditions [159]. Notably, the research on this topic follows the standard methodology, without adding new procedures dedicated to heritage buildings. Quantitative measurements were carried out mainly on recent or new buildings, in general from 1950 to onwards [153,165,166]. Dimitroulopoulou [147], thanks to a huge literature review, discovered a correlation between ventilation rates and geographical locations (higher in Scandinavia, The Netherlands, Greece, and Portugal thank other Countries), building volumes (higher in smaller buildings), number of people, room functions (i.e. bedrooms), and habits (i.e. opening). Also, some studies established a relationship between airtightness, building age, and construction type [165,167], but without a specific focus on traditional or heritage buildings. In general, older and smaller dwellings have higher normalized leakage areas than newer and larger houses [167]. Chan et al. [167] found a direct correlation between airtightness, year of construction, and floor area in single-family detached dwellings in United States. The years of construction were divided into four categories (before 1950; 1950–1980; 1980–1995; after 1995). Older buildings had higher n50 values thank post-war buildings. Another study grouped the dwellings in three categories based on year of construction (pre-1975 that means from 1941 to 1974; 1975-1980; 1980-2008) [165]. Leakage paths were non-uniform across the building ages and, as result, new constructions were automatically assumed more airtightness than older ones. To reinforce this theory, Sherman and Dickerhoff [168] observed smaller leakages in recent homes (built after 1980) due high performance of building materials and techniques (e.g. weather-stripped windows, air barriers, high windows airtightness), and less damage (e.g. cracks, decay). Only one study was focused specifically on heritage buildings. Martín-Garín et al. [151] realized several BDT on XIX Century heritage dwellings in San Sebastian (Spain) for identifying a relationship between geometric features and measured airtightness degree. A wide variety of airtightness degrees at 50 Pa was found: the n50 value was in the range 68-37.12 $h^{-1}$ while the q50 value varied between 0.50-20.46 $m^3/m^2h$. In addition, 30% of samples had airtightness < 4 $h^{-1}$, 50% in the range 4-16 $h^{-1}$, and 20% in the range >16 $h^{-1}$, with an average value of 9 $h^{-1}$. This study confirmed the contrast between the airtightness performances in historical and recent buildings. The reasons were ascribed to morphology, construction solutions, presence of cracks and joints. Similarly, Feijó-Muñoz et al. [152,166] analyzed a representative sample of the existing residential stock built between 1880 and 2011 in Spain with the BDT. The dwellings had a massive construction system, prevailing with brick masonry, and natural ventilation systems. The mean n50 value was 6.1 $h^{-1}$ for single-family dwellings and 7.1 $h^{-1}$ for multi-family housing. The mean measured n50 value by Feijó-Muñoz et al. [166] in other historical and recent buildings in the Mediterranean area of Spain and the Canary Islands was heighten (8.43 $h^{-1}$). Akkurt et al. [6] reported the infiltration rates in historical buildings for different typologies and locations from the literature review. The data was based mainly on tabular values, but also on the BDT and the tracer gas dilution method. A specific trend for the variation of the n50 value per hour was not proved by the literature for the variety of construction habits and the state of conservation and repair [6,169]. Despite this, there is a general agreement that this value is high for poor construction tightness made by permeable or damaged materials (e.g. wooden construction) and for large openings [6]. Only museum buildings showed low infiltration rates due to the severe microclimatic control imposed by the conservation requirements. Also, the n50 value of non-retrofitted buildings was found 30–42% bigger than the one for retrofitted buildings [150].

## 6. FUTURE PERSPECTIVES

### 6.1. Interoperability between NDT techniques and HBIM projects

HBIM (Heritage Building Information Modelling) is focused on the recognition and segmentation of each building element of a cultural asset [170–172]. Nevertheless, the creation of a model for this type of construction by a BIM software may be limited [173]. Modelling heritage building needs both technical information (e.g. geometrical shape, dimensions, materials, construction techniques, conservation conditions, etc) and historical information for restoration [25,40,174,175]. According to Castellano-Román et al. [176], there are several dimensions in HBIM: 3D (analytical survey based on metric capture), 4D (historical evolution of the asset), 5D (diagnosis and characterization of the structural damage), 6D (cultural environment and infrastructures of supply in the territory) and 7D (preventive conservation of the building). Furthermore, the authors established five levels of knowledge that are not directly related to the level of detail or accuracy: LOK100 (location and orientation of heritage asset), LOK200 (dissemination with basic structures modelling as well as legal and graphical documentation), LOK300 (advanced research with complex structures modelling), LOK400 (criteria for conservation and intervention projects) and LOK500 (investment plan for periodic programs of management and maintenance).

In recent years, NDT techniques (i.e. radio frequency identification technique –RFID-, infrared thermography –IRT-, laser scanning, photogrammetry) and IoT were combined in architectural surveys to create a 3D BIM model [25,40]. However, some limitations were highlighted: (i) difficult implementation of the platform [177]; (ii) limited interoperability between BIM tools and diagnostic tools (i.e. digital cameras, IR cameras, laser scanners) [40,175,177–179]; (iii) level of detail (LOD) and level of information (LOI) of the model, especially for irregular structures [174,177,180,181]; (iv) complex detection of surfaces with non-optimal optical properties (i.e. high transparency or reflectance) [25,40]; (v) high time consumption for data management [40,175]; (vi) use of different tools for post-processing [25,40]; (vii) expensive technical resources [40]; (viii) complex recognition and segmentation of building elements [40,175]; and (x) difficulties of workflows from point clouds to BIM through manual procedures[173,175,182–184]; and (x) lack of BIM knowledge of all stakeholders, especially those who are not from AEC (Architecture, Engineering and Construction) industry [185].

To solve part of the exposed drawbacks, some multidisciplinary approaches with BIM –NDT integration [25,186], algorithms based on Poisson and Ball Pivoting surface reconstruction [40,180], or GIS models for heterogeneous semantic data [174] were developed. Ham et al. [186] determined thermal properties of structural components of an existing building (i.e. U-value, thermal conductivity) by thermography. Subsequently, these properties were mapped and associated with parametric objects in gbXML format into the BIM model. In this way, the thermal property was used as an input of energy performance in energy simulations, reducing the gap between the architectural information represented in the model and the actual data. However, the authors noted that two things were necessary to be achieved: an automated system for the generation of BIM through captured images and a complete as-built information of the building. Song et al. [187] evaluated the trends and potentials of BIM-GIS integration in ACE industry. The authors enumerated a set of benefits of BIM-GIS integration: (i) project cost control through the prediction of cost scenarios with clustering; (ii) spatio-temporal statistical analysis for HSE (Health, Safety and Environment) management; (iii) simulation of construction works to reduce time of execution. Nevertheless, BIM-GIS integration could also present some barriers, such as non-unified criteria and information loss during the extraction and simplification of data between platforms [174,187]. Bruno et al. [40] carried out a literature review about HBIM from 2004 to 2017. The authors pointed out that building diagnosis and monitoring are still ongoing in terms of enhancement of energy simulation, structural reinforcement and HBIM. For this reason, they suggested the development of a guideline with the integration of several methods for the assessment of the heritage building in order to create a BIM model. This included the use of photogrammetry and topography to detect anomalies, radar tests to identify structural elements, ultrasonic tests to estimate the composition of the building elements, and vibration tests to determine the dynamic response and simulation by finite elements; HFM and IRT were not considered. Delegou et al. [25] performed a multidisciplinary approach for heritage buildings. For historic and architectural data, past restoration projects and bibliographical research were conducted. For the geometric documentation, photogrammetry and laser scanning were applied. In the first technique, the 3D textured model was created by Structure from Motion (SfM) and Multi-View Stereo (MVS). In the second technique, a DDSM (Dense Digital Surface Model) was developed. For building materials characterization, three techniques were implemented: Digital Microscopy (DM), Infrared thermography (IRT) and Ground Penetrating Radar (GPR). The authors pointed out that the integration of NDT with architectural data allowed to extract information of building materials, to identify the preservation state of the building and to obtain a thematic map for planning conservation interventions. However, the collaboration and data management among different stakeholders (architects, engineers, scientists) was required.

Concerning facility management (FM), few previous studies showed practical examples of BIM as a potential post-construction management of the building operative stage [188]. Piselli et al. [188] developed HBIM and MEP (Mechanical-Electrical-Plumbing) models in the same platform, to combine the updated database of the architectural features of the building with site monitoring data (i.e. energy consumption, environmental parameters of the building systems). The main potential of the proposal was the generation of an automated sheet for facility management applications (i.e. maintenance tasks and indoor environmental control) in retrofitted heritage buildings. However, sub-models for each facility of the MEP model were needed, using the same reference system to guarantee the precision of the general model. Mora et al. [181] proposed a methodology that integrated geometrical data from a wearable mobile laser system (WMMS) and environmental data from an in-situ monitoring network, without requiring any GIS method. This represented an enhancement in the computation of KPIs (Key Performance Indicators) for the evaluation of the preventive state of the historical building and the bioclimatic conditions. Dias Pereira et al. [189] stated that higher education heritage buildings also need a multidisciplinary intervention framework that should englobe: (i) assessment of IEQ parameters (thermal comfort plus air quality) and energy consumption; (ii) implementation of non-invasive in-situ monitoring of thermal performance of construction elements, to characterize the thermos-physical properties of building façades; (iii) use of innovative construction solutions and renewable energy systems; (iv) implementation of BIM in intervention plans (i.e. 3D laser scanning); (v) computation of dynamic simulations in future scenarios with climatic and tourism data; (vi) open-access libraries for BIM model. Along this line, several authors affirmed that the renewable energy integration in heritage buildings could be challenging, since the lack of space is often a constraint in the projects of refurbishment [188,190,191]. In the case of BIPV systems (Building Integrated Photovoltaic), the integration of them in heritage buildings depends on: the state of the roof, visual impact and preservation of the structures [192].

Within this context, more effective interoperability is required by means of the improvement of the access protocol in terms of consecutive conservation phases as well as centralization of information in the CDE (Common Data Environment) [175,185]. The existing BIM platforms with CDE (i.e. PetroBIM, Arches

Project, 3DHOP) are not work platforms and consequently, they do not synchronize information in real time with BIM models [Palomar et al., 2020]. In addition, a semantic segmentation of the element morphology cannot be performed by existing HBIM softwares if the process of transformation of 3D point clouds is not automatic [68,175] or the buildings are not assumed as structures with repetitive patterns [174]. In fact, Yang et al. [174] highlighted that the reduction of manual work in the scan-to-BIM process for buildings led to the development of a high quantity of commercial tools and algorithms, but only for new buildings with regular shapes. Hence, complex historical buildings are excluded of automatic segmentation. The excessive standardization of ICT approaches, the interdisciplinary features of the restoration projects and the heterogeneity of aspects related to data (i.e. format, accessibility, models) are considered as important drawbacks for HBIM [178,185].

### 6.2. Interoperability between artificial neural networks (ANN) and NDT techniques

Artificial neural networks are defined as a flexible mathematical modelling method that allows the computer to execute an assigned task without human intervention [193,194]. ANN can be divided into two categories, supervised learning or unsupervised learning. The difference between them is mainly based on input dataset dimensionality (i.e. sequence of input – output pairs to develop a real-valued function) and use of clustering (overlapping or hierarchical clusters to assign data points into groups with similarities) [194,195]. Despite the increasing trend of the use of Machine Learning (ML) and Deep Learning in heritage buildings, some barriers were detected in the literature (Figure 16): (i) ANN are still limited in this research field due to access, quality of datasets and processing time [195,196]; (ii) supervised learning methods (e.g., classification and regression trees (CART), Random Forests (RF), and support vector regression (SVR), and unsupervised learning methods (e.g., clustering) were generally implemented on small datasets without public access; (iii) algorithms need normalization of input data before the learning process [197]; (iv) common applications were focused on the classification of materials or objects (i.e. stone tools, potteries, ceramic artefacts or ancient paintings) [194,195]; and (v) high processing power is needed for DL algorithms [193].

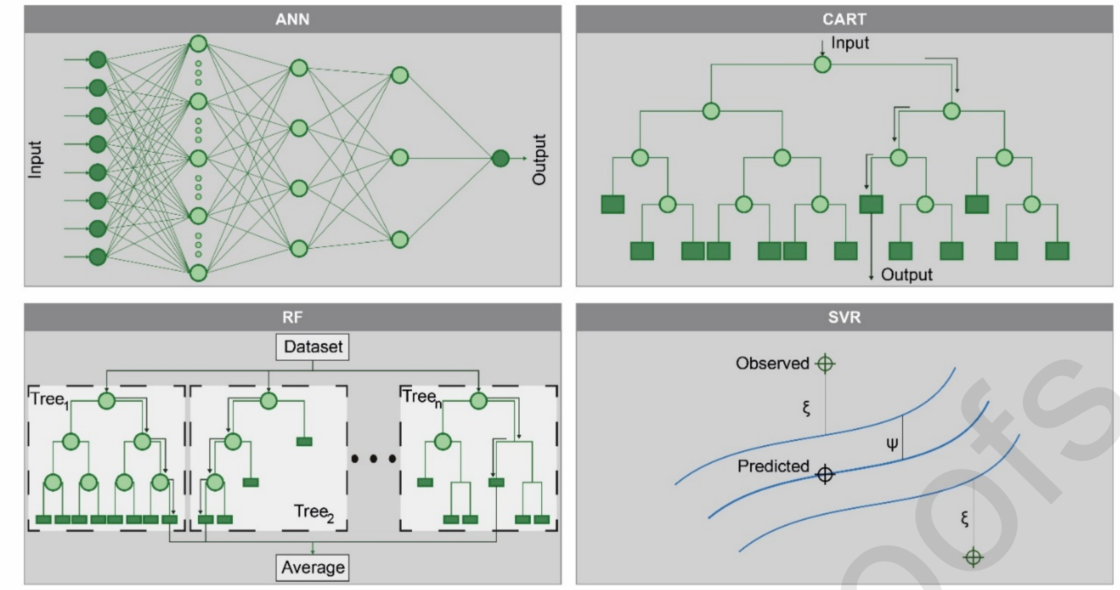



Figure 16. Sketch of ANN and supervised learning methods

(Source: Elaborated by the authors)

The most recent DL (Deep Learning) works that combined IRT with neural networks (i.e. Faster Region Convolution Neural Network –R-CNN-, Deep Inception Neural Network –DINN-, spatial DL model –VGG- etc) were mainly focused on the subsurface defect detection and segmentation methods for metal elements and composite materials [198–202]. In terms of cultural heritage and thermography, most of the data processing algorithms were not automated, which could increase the technician's subjectivity and reduce the precision of IRT results [194]. For this reason, Garrido et al. [194] implemented Mask R-CNN (Mask Region – Convolution Neural Network) and active thermography to carry out defect detection and semantic segmentation of defect areas in marqueteries and artistic objects from a thermogram automatically.

ANN were also applied to HFM method [127,128,203], to reduce the measurement time, with encouraging results. However, paper related to the application of HFM on heritage building are of reduced amount, if compared to the ones that employ HFM. The main issue in papers identification relies in the lack of proper keywords (both for historic and historical buildings) are quite scarce. The scientific community, although being quite sensible to the topic of heritage buildings, does not remark this point in keyword definition. This is also confirmed by the recent reviews on the U-value assessment that (undoubtedly) treat the HFM method, where bare works are classified as referring to historical buildings.

Concerning photogrammetry or other techniques, few studies were detected. Zou et al. [204] developed a routine inspection of heritage buildings that used a Faster R-CNN for 2D object detection with high accuracy. The method could be integrated with UAVs and a GPS system. Condorelli et al. [205] applied DL in film footage of historical archives to create a 3D model of lost architectural heritage, as a photogrammetric reconstruction. This proposal improved the well-known methods and facilitated information for the cultural memory of the future. Wojtkowska et al. [196] used laser scanning and ANN to determine deformation of heritage structures with a precision of 3%. In this way, an effective monitoring of a structure could be conducted without any physical intervention or any limited set of data points.

## 7. DISCUSSION AND CONCLUSIONS

The main contribution of this review paper was the development of a detailed framework about the use of qualitative and quantitative NDT for the diagnosis of CH buildings in last two decades (2001 – 2021), including the advanced modelling technologies (i.e. HBIM and ANN) and future trends in terms of retrofit and adaptive re-use of heritage buildings. For this reason, two steps were carried out: (i) bibliometric analysis, based on data statistics and science mapping; (ii) assessment of the most relevant studies on this field. The main outcomes of this work are highlighted hereafter.

- The analysis of the geographic distribution of publications highlighted that most of studies were located on the Southern European countries (i.e. Italy, Spain, France, Portugal, Greece). This was also reflected on the analysis of authors. Nevertheless, no integrated and systematic approaches were developed to propose common preservation plans at urban area. Indeed, the document type distribution showed that only 2.25% of the scientific production corresponded to review articles and the percentage of journal papers was found to be 36%. In the case of HFM and QIRT, only two documents for each technique were detected. This emphasizes the necessity of conducting new studies on the diagnosis of the built quality of heritage buildings for their future refurbishments, preserving cultural and aesthetic values.

- The findings of science mapping revealed two main aspects, which was supported by the analysis in-depth of the most significant studies on the topic. Firstly, "photogrammetry" and "laser applications" were identified as consolidated techniques for historic preservation. In fact, over 740 publications were obtained from 2009 to 2021. Furthermore, HBIM projects could be strongly related to these techniques and deep learning, but the applications would be focused on architectural restorations instead of diagnosis of CH buildings. According to the relevant studies on TLS and SfM, virtual models can be an excellent opportunity to have enough information of the geometry of complex construction elements, although the applicability of these techniques depends on several factors (i.e. accuracy, cost, position of the equipment, area to analyze). The second aspect derived from the science mapping is that collected data from quantitative NDT (HFM, QIRT or airtightness measurements) was not considered for creating or updating HBIM models. This could be justified by the large number of sensors to install in heritage walls if HFM is implemented, due to the high degree of heterogeneity given in historic masonries. In the case of tracer gas measurement, the diagnosis of natural ventilated heritage buildings is really complicated, since they are characterized by high air flow rate through the building envelope. Regarding the fan pressurization method, the standard methodology does not incorporate specific procedures for heritage buildings. From previous studies, only museums could present low infiltration rates, since severe microclimatic control must be imposed to fulfil with conservation conditions of artworks. Hence, multidisciplinary approaches with BIM –NDT integration are required, to support the centralization of information in the CDE (Common Data Environment) and to enhance the communication between stakeholders. Notably, most of the construction projects of existing buildings are not available or updated.

- According to [17,206], one of the best strategies to reduce the demand of construction materials (and their embodied energy) in the built environment could be the adaptive re-use of cultural heritage (ARCH) buildings, at local and regional level. Nevertheless, a deep energy retrofit is required to increase the resilience of this type of buildings and to ensure their long-term usability. Consequently, technicians should have the enough knowledge about diagnosis to apply correctly non-destructive techniques [18]. The science mapping about retrofitting and adaptive re-use of CH buildings allowed to identify five clusters or macro areas: (i) architectural design and structural health monitoring; (ii) energy efficiency and cost effectiveness; (iii) energy utilization; (iv) hygrothermal performance and characterization of materials; (iv) thermal performance of timber structures. In the case of the third cluster, one of the future trends is the implementation of predictive controls for HVAC systems based on machine learning. It should be noted that ANN facilitate the decision–making without human intervention. However, they are still ongoing. The main barriers are related to the quality and normalization of datasets, data privacy, and network security. In terms of diagnosis, the drawbacks would be more related to the detection and segmentation of defect areas in building materials.

To sum up, this research demonstrated that a holistic approach should be adopted, integrating policies related to preservation and valorisation of CH buildings. Through the bibliometric analysis and the assessment of previous studies, it was observed that a lack of interoperability among NDT techniques exists. Hence, this paper offered a complete perspective to understand the main networks and trends on the topic, which could facilitate the definition and implementation of strategies to comply with the Sustainable Development Goals (SDG). The information reported could be used by researchers, energy auditors, heritage authorities, police-makers and industries involved in the renovation and conservation of CH buildings.

## DECLARATION OF COMPETING INTEREST

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

## CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

**Blanca Tejedor**: Conceptualization, Methodology, Investigation, Writing –Original Draft, Writing – Review & Editing. **Elena Lucchi**: Conceptualization, Investigation, Writing – Original Draft, Visualization. **Iole Nardi**: Investigation, Writing – Original Draft. **José David Bienvenido-Huertas**: Investigation, Writing – Original Draft, Visualization.

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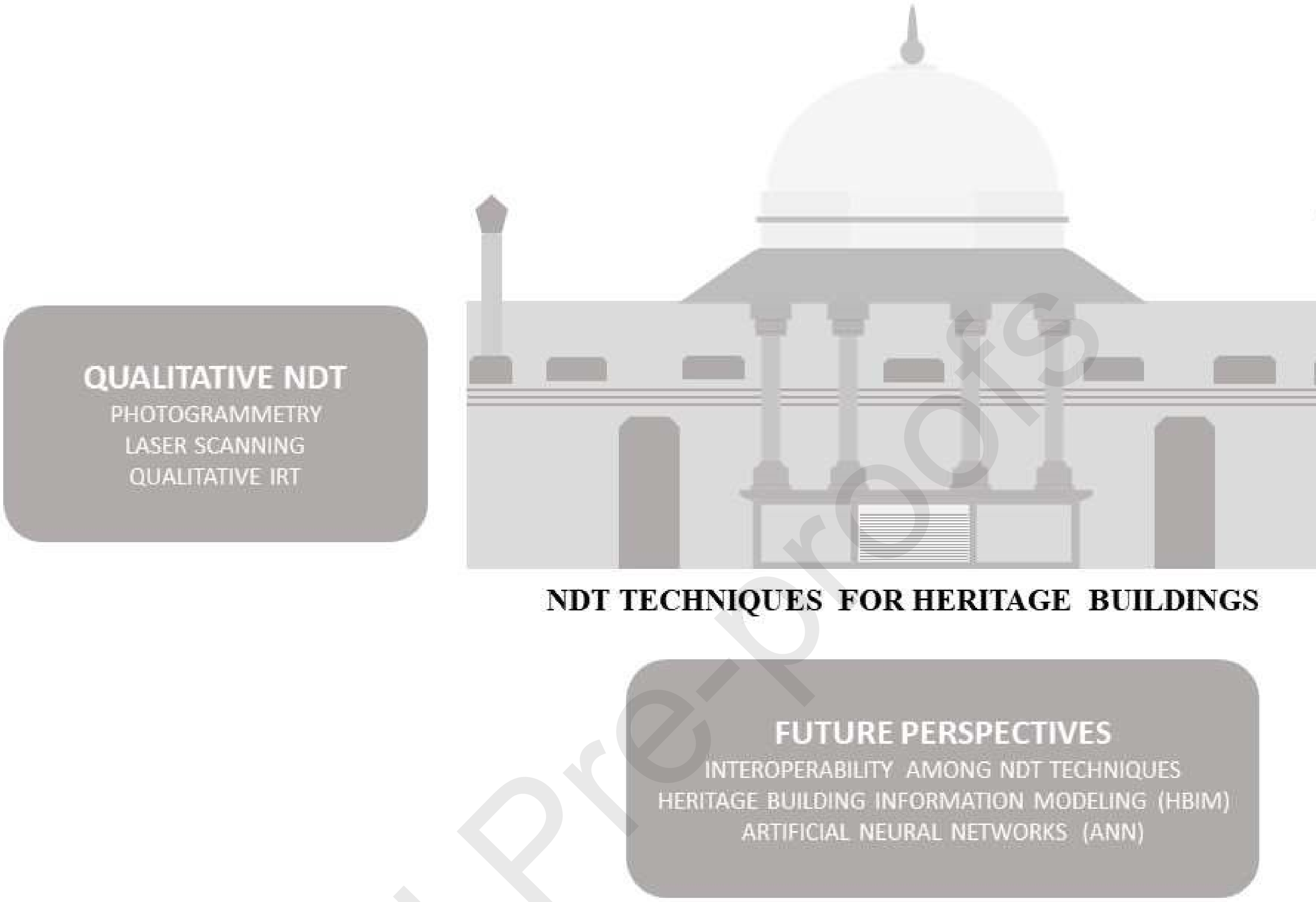
- A review on NDT was carried out (studies ranged from 2001 to 2021)
- A gap still exists for quantitative IRT and HFM in CH buildings
- Standards related to airtightness tests do not include procedures for CH buildings
- Lack of interoperability between NDT techniques
- Multidisciplinary approaches with BIM –NDT integration are needed


QUALITATIVE NDT
PHOTOGRAMMETRY
LASER SCANNING
QUALITATIVE IRT
NDT TECHNIQUES FOR HERITAGE BUILDINGS
FUTURE PERSPECTIVES
INTEROPERABILITY AMONG NDT TECHNIQUES
HERITAGE BUILDING INFORMATION MODELING (HBIM)
ARTIFICIAL NEURAL NETWORKS (ANN)