

# Non-destructive testing, digitization, and digital twins in historic buildings: a systematic review

*Ensaaios não destrutivos, digitalização e gêmeos digitais em edifícios históricos: uma revisão sistemática*

*Ensayos no destructivos, digitalización y gemelos digitales en edificios históricos: una revisión sistemática*

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**Júlia Amâncio Fonseca\*** 

Federal Center for Technological Education of Minas Gerais; Department of Civil Engineering; Graduate Program in Civil Engineering. Belo Horizonte (MG), Brazil.  
[juliafonsecan@gmail.com](mailto:juliafonsecan@gmail.com)

**Rachel Jardim Martini Santos** 

Federal Center for Technological Education of Minas Gerais; Department of Civil Engineering; Graduate Program in Civil Engineering. Belo Horizonte (MG), Brazil.

**Rogério Cabral de Azevedo** 

Federal Center for Technological Education of Minas Gerais; Department of Civil Engineering; Graduate Program in Civil Engineering. Belo Horizonte (MG), Brazil.

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\* Corresponding author.

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## Abstract

The preservation of built heritage is an essential practice, as these assets embody historical, cultural, and technical values whose degradation or loss irreversibly compromises collective memory. Buildings of historical interest require constant inspection and monitoring, which, in many cases, should not cause changes or damage to their structure. Given this, this article seeks to investigate techniques for monitoring the health of buildings of historical interest. To this end, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was used to guide the selection and analysis of scientific articles, allowing for the preparation of a systematic literature review (SLR) in a structured manner. The research focused on non-destructive testing and digitization techniques and the creation of digital twins, which are directly related to studies on the characterization and documentation of built heritage. The results revealed that visual inspection, Ground Penetrating Radar (GPR), and Infrared Thermography (IRT) are widely used for the characterization of historic buildings. Digitization for the creation of digital twins in built heritage has been carried out through photography, photogrammetry, and mobile laser scanning, with the aim of monitoring deterioration processes, among other contributions to the field of conservation.

**Keywords:** Non-destructive testing; Monitoring; Built heritage; PRISMA; Systematic review.

## Resumo

A preservação do patrimônio construído é uma prática essencial, pois esses bens reúnem valores históricos, culturais e técnicos cuja degradação ou perda compromete, de forma irreversível, a memória coletiva. As edificações de interesse histórico exigem inspeções e monitoramentos constantes que, em muitos casos, não devem causar alterações ou danos em sua estrutura. Diante disso, este artigo busca investigar técnicas para acompanhamento da saúde de edificações de interesse histórico. Para isto, empregou-se o método Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), que orientou a seleção e a análise dos artigos científicos, permitindo a elaboração de uma revisão sistemática de literatura (RSL) de forma estruturada. O enfoque da pesquisa foi nos ensaios não destrutivos e nas técnicas de digitalização e criação de gêmeos digitais, que se relacionam diretamente aos estudos de caracterização e documentação do patrimônio construído. Os resultados revelaram que a inspeção visual, o Ground Penetrating Radar (GPR) e a Termografia Infravermelha (IRT) são amplamente utilizados para a caracterização de edifícios históricos. A digitalização para a criação de gêmeos digitais no patrimônio construído vem sendo realizada por meio de fotografias, fotogrametria e varredura a laser móvel, com o intuito de monitorar processos de deterioração, entre outras contribuições para a área da conservação.

**Palavras-chave:** Ensaios não destrutivos; Monitoramento; Patrimônio construído; PRISMA; Revisão sistemática.

## Resumen

La preservación del patrimonio construido es una práctica esencial, ya que estos bienes reúnen valores históricos, culturales y técnicos cuya degradación o pérdida compromete de manera irreversible la memoria colectiva. Las edificaciones de interés histórico requieren inspecciones y monitoreos constantes que, en muchos casos, no deben causar alteraciones ni daños en su estructura. En este contexto, el presente artículo tiene como objetivo investigar técnicas para el seguimiento del estado de conservación de edificaciones de interés histórico. Para ello, se empleó el método Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), que orientó la selección y el análisis de los artículos científicos, permitiendo la elaboración de una revisión sistemática de la literatura (RSL) de forma estructurada. La investigación se centró en los ensayos no destructivos y en las técnicas de digitalización y creación de gemelos digitales, que se relacionan directamente con los estudios de caracterización y documentación del patrimonio construido. Los resultados revelaron que la inspección visual, el Ground Penetrating Radar (GPR) y la Termografía Infrarroja (IRT) son ampliamente utilizados para la caracterización de edificios históricos. La digitalización para la creación de gemelos digitales en el patrimonio construido se ha realizado mediante fotografías, fotogrametría y escaneo láser móvil, con el objetivo de monitorear los procesos de deterioro, entre otras contribuciones al campo de la conservación.

**Palabras-clave:** Ensayos no destructivos; Monitoreo; Patrimonio construido; PRISMA; Revisión sistemática.

## 1 Introduction

Material cultural heritage represents a set of assets of historical and constructive value, whose preservation is associated with memory and identity. In the current scenario, historic buildings are exposed to various environmental and structural factors that hinder the maintenance of their useful life, such as weathering, seismic events, and natural aging. In view of the degradation that occurs in buildings of historical interest and the need for maintenance over time, it is essential to identify wear and tear and have the means to guide interventions (Novais et al., 2024; Chik et al., 2024).

Studies indicate that, in the current decade, the degradation of buildings of historical interest has been influenced by air pollution and climate change, in addition to the emergence of pathological manifestations over the course of aging. Climate change presents new challenges for the protection and conservation of built heritage, especially in urban areas, where its effects tend to be intensified (Garrido et al., 2020; Sardella et al., 2020; Ricciardi et al., 2021).

Linked to this, the digitization of built heritage has been understood as a strategy for documenting, analyzing, and managing buildings of historical interest. Non-destructive data acquisition techniques, such as laser scanning and photogrammetry, allow the reproduction of built heritage, making it accessible to people in different parts of the world. Although digitization presents challenges because it involves a multidisciplinary approach, it enables accessibility and the production of databases on historical heritage, contributing to restoration projects for these buildings (Vieira et al., 2023).

In the context of built heritage preservation, the concept of digital twins, presented as digital models, is understood as a three-dimensional representation based on the modeling of information on buildings of historical interest (3D-HBIM). This model allows the condition of buildings of historical interest to be demonstrated in detail and in real time. Digital twins are used to capture and virtually represent physical data that has cultural significance and contributes to preventive conservation through simulations, based on Structural Health Monitoring (SHM) data (Jouan; Hallot, 2020; Lucchi, 2023; Galiano-Garrigós et al., 2024).

Given the scenario of using integrated digital tools, which include monitoring systems and digital twins, applied to built heritage, this research aims to (i) investigate how the use of non-destructive testing aids in the preservation of buildings of historical interest and (ii) present the contributions that digitization techniques or digital twins offer to historical buildings. To achieve the proposed objectives, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) systematic review method was adopted. The findings may assist researchers in learning about data acquisition techniques for buildings of historical interest.

## 2 Materials and Methods – Systematic Literature Review

For the Systematic Literature Review (SLR), the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) method was adopted, widely recognized by its transparency, reproducibility, and methodological rigor. The PRISMA protocol has been used in recent studies in the field of Civil Engineering and the built environment (Costa;

Lima, 2023; Noeme et al., 2023; Marcondes; Luiz Rutz Silva, 2022; Page et al., 2022), especially in reviews involving multiple techniques and methodological approaches.

The methodological process followed the guidelines established by PRISMA 2020, structured in the stages of identification, screening, eligibility, and inclusion of studies. The application of these stages ensured the careful selection of scientific articles aligned with the research objectives, reducing bias and ensuring the traceability of the review process.

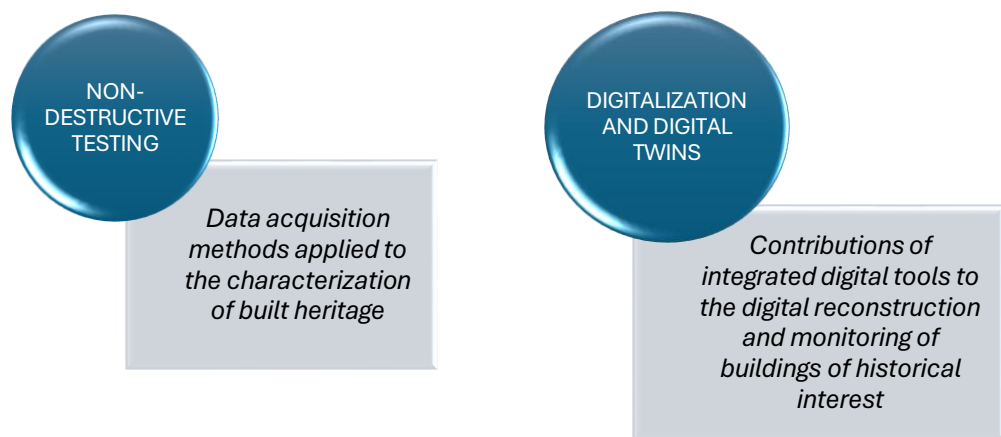
In this study, two research approaches were defined, each associated with a specific objective and respective research questions:

(i) How do non-destructive tests help preserve built heritage?

(ii) What conclusions have been obtained with digital monitoring techniques in buildings of historical interest?

These approaches guided both the search strategy and the selection criteria for the studies, as illustrated in Figure 1.

**Figure 1:** Research approaches and specific objectives.



Source: Authors (2025).

## 2.1 Bibliographic selection

The bibliographic search was conducted in relevant scientific databases — Scopus and Web of Science — and covered articles published without time restrictions, up to the deadline of November 12, 2024. We opted to use advanced search, considering the occurrence of terms in the title, abstract, and keywords, in order to ensure greater thematic adherence of the results.

The combinations of search terms were defined based on the research approaches and objectives of the study, as shown in Table 1. After initial identification, all retrieved records were exported to the Mendeley reference manager, where duplicate records were removed.

**Table 1:** Number of articles found with the searches.

Combination of search terms	Scopus	Web of Science
"heritage buildings" AND "digitalization"	72	06
"heritage buildings" AND "non-destructive testing"	54	21
"heritage buildings" AND "digital twins"	51	09

During the screening stage, titles and abstracts were read, excluding articles that were not directly related to built heritage, did not use non-destructive testing or digital techniques, or dealt exclusively with other types of buildings. Next, during the eligibility phase, the full texts of the remaining articles were analyzed in their entirety.

The inclusion criteria adopted were:

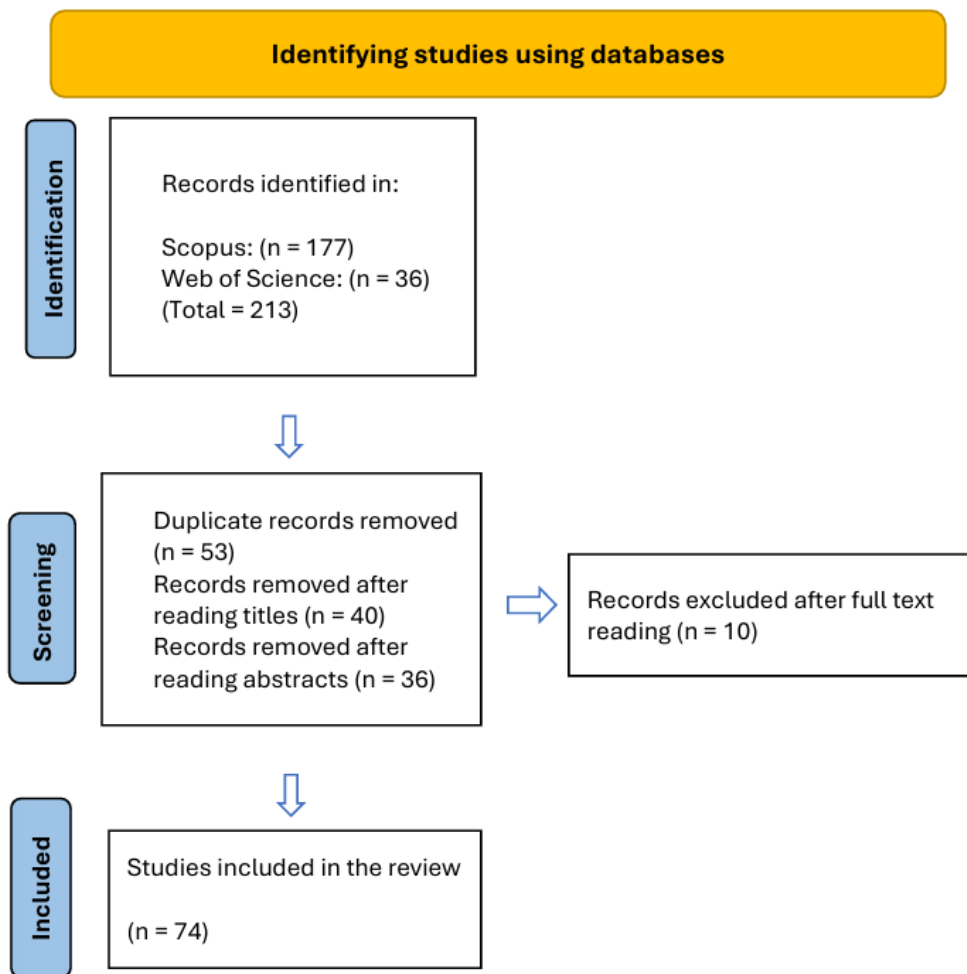
- studies applied to buildings of historical interest or built heritage;
- use of non-destructive testing for inspection, diagnosis, or monitoring;
- application of scanning techniques, digital modeling, or digital twins;
- peer-reviewed articles published in scientific journals.

The exclusion criteria included:

- duplicate studies between databases;
- works that did not present practical application or relevant methodological discussion;
- publications such as event abstracts, technical notes, editorials, or book chapters.

The selection process followed the steps of the PRISMA flowchart, shown in Figure 2, which demonstrates the methodological procedure adopted.

Figure 2: Steps for selecting articles.



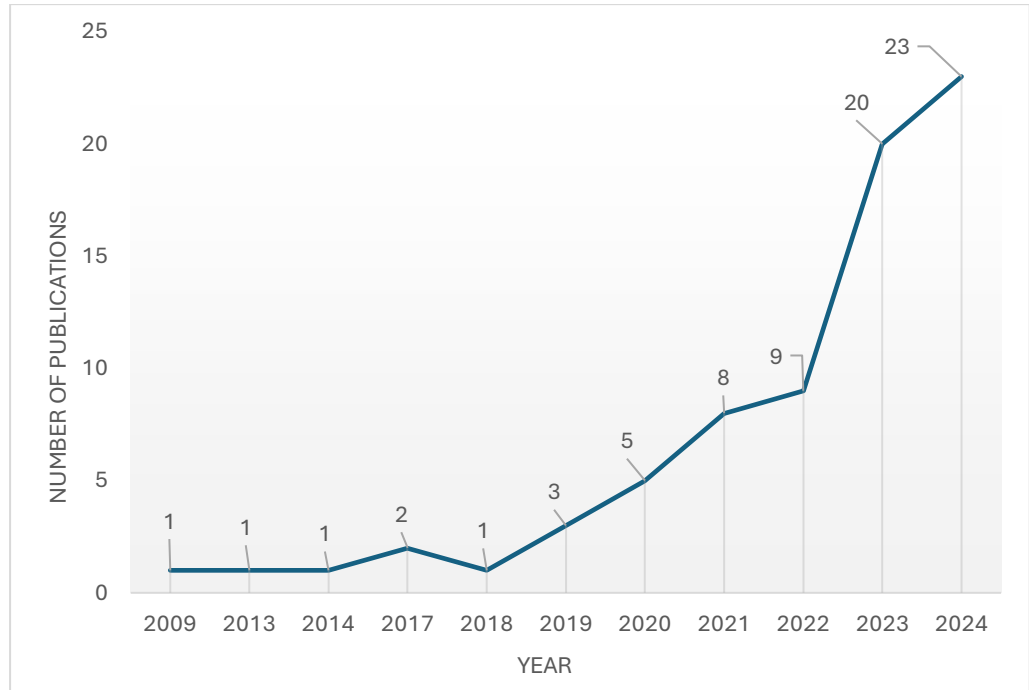
Source: Adapted from Page et al. (2021).

## 2.2 Bibliometric analysis

In this section, the scientific relevance of the journals was evaluated. The final research portfolio consisted of 74 publications. The bibliometric analysis was conducted based on contemporary criteria of scientific relevance, considering the indexing of journals in international databases, such as Scopus and Web of Science, as well as widely accepted bibliometric indicators, such as *CiteScore* and *Journal Impact Factor* (JIF), when available.

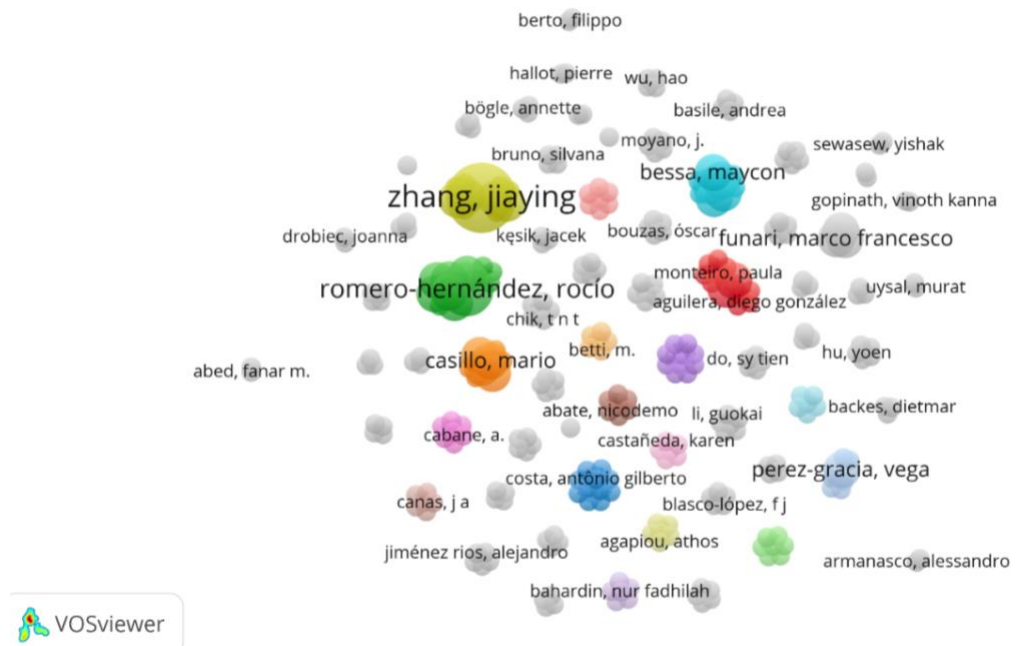
The temporal evolution of publications related to the use of non-destructive testing and digital technologies applied to built heritage was analyzed based on the total number of articles included in the review, as shown in Figure 3. The first study identified was published in 2009, indicating the beginning of the systematic application of these techniques in the heritage context. From 2019 onwards, there has been significant and continuous growth in the number of publications, reflecting technological advances, the expansion of the use of digital tools, and increased scientific interest in non-invasive monitoring and conservation strategies for historic buildings.

**Figure 3:** Temporal evolution of publications related to the topic, from 2009 to 2024.



The relevance of authors and keywords was analyzed using VOSviewer software (Van Eck; Waltman, 2023). Observing the network of authors, it is noticeable that they are divided into groups with no connections between them, reflecting the lack of collaboration between groups of authors and institutions. This can be justified by the fact that most studies are from different countries or regions, which does not allow for joint studies by these authors. Figure 4 shows the image generated.

**Figure 4:** VOSviewer of authors.

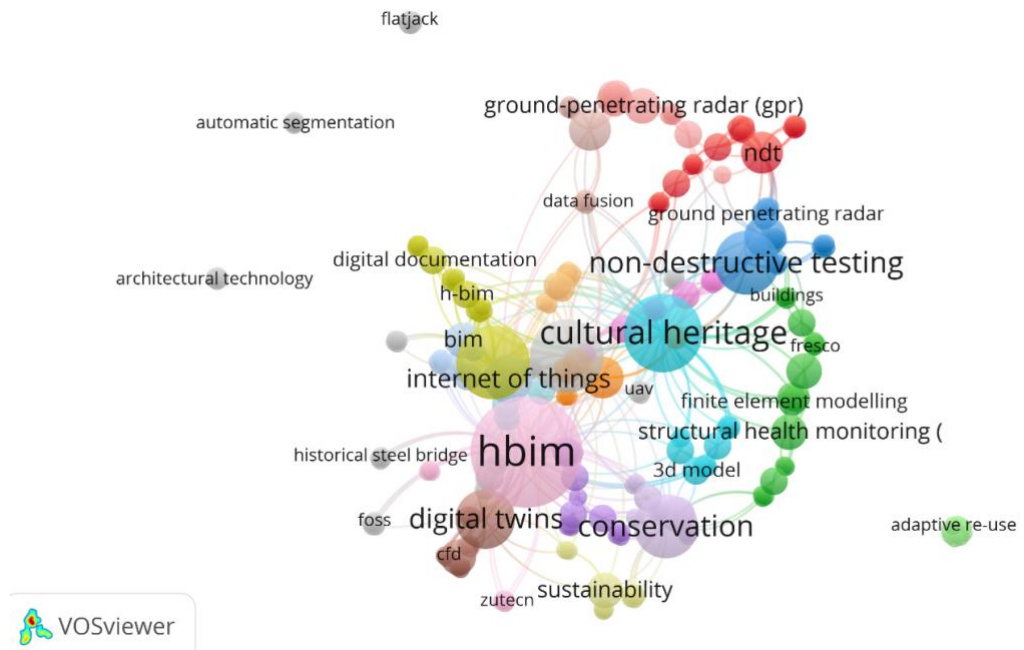


Source: VOSviewer (2025).

In view of the keyword co-occurrence network created, considering the selected articles, 281 keywords were grouped by the software. The keywords that stood out the most were,

respectively: (i) HBIM, (ii) cultural heritage, (iii) heritage buildings, (iv) conservation, (v) non-destructive testing, and (vi) digital twins. Figure 5 clearly shows that several terms are connected due to the formation of networks. The themes related to non-destructive testing, digitization, and digital twins show a strong relationship in the context of cultural heritage studies.

**Figure 5:** VOSviewer of keywords.



Source: VOSviewer (2025).

The studies analyzed covered different geographical contexts, including Europe, Asia, the Middle East, and Latin America, with an emphasis on countries with significant heritage collections, such as Italy, Spain, China, Turkey, and Brazil. Even so, there are fewer indexed publications from other historically relevant regions, which reinforces the need to expand international scientific production in this field.

### 3 Results and discussions

When considering the 74 articles read in the RSL, the authors sought answers to the two research questions that guided this production. Of the total number, 20 (twenty) articles direct answers to research question (i) "How do non-destructive tests help in the preservation of built heritage?"; 47 (forty-seven) articles addressed research question (ii) "What conclusions have been obtained with digital monitoring techniques in buildings of historical interest?" and 7 (seven) articles contributed to answering both questions simultaneously.

#### 3.1 Non-destructive testing

The research focus related to non-destructive testing is fundamental in the study of built heritage, as it allows us to understand how these techniques can be applied to the characterization of historical construction systems, which directly contributes to answering the first research question.

Recent studies show that different non-destructive testing (NDT) methods enable the identification of construction techniques and deterioration mechanisms without the need

for invasive interventions or damage to historical structures. In this context, infrared thermography has been used to detect internal discontinuities, map areas with moisture, identify voids, and estimate the texture and heterogeneity of masonry under layers of plaster, paint, or frescoes (Gusella; Cluni; Liberotti, 2020; Patrucco et al., 2022; Froner et al., 2024).

Furthermore, it is observed that NDTs are seen as less invasive means of studying the structural behavior of masonry in historic buildings, reducing the need for invasive techniques. Another important factor regarding the use of these techniques in historic buildings is the possibility of revealing historical details covered by previous restorations (Frąckiewicz; Raszczuk; Jasieńko, 2024; Santos-Assunção et al., 2014; Pérez-Gracia et al., 2013; Artopoulos et al., 2024; Guadagnuolo et al., 2023; Pérez-Gracia et al., 2009; Vidovszky, 2017; Martínez-Soto et al., 2021; Yalçiner; Büyüksaraç; Kurban, 2019).

In this context, GPR has proven useful for locating the position of beams, material replacements, buried objects, pavement layers, damaged sections in different construction scenarios, and structural characteristics such as the presence of voids or infiltrations. In addition, non-destructive testing is also used for thermal analysis of buildings and to identify cracks in historic buildings. Several authors report that non-destructive testing, when used alone for diagnostic purposes, is not exclusively recommended, as it is subject to factors that can affect the behavior of the test. Therefore, they recommend combining different techniques or, in some cases, using semi-destructive methods (Pérez-Gracia et al., 2009; Artopoulos et al., 2024; Chik et al., 2024; Gopinath; Ramadoss, 2021).

In addition, limitations of ENDS, such as the use of GPR, were observed. In some historic buildings, indirect measurements and restricted physical space can generate results that are subject to multiple valid interpretations. In addition to these uncertainties, there are also difficulties in accessing upper areas of walls due to the high heights and weight of the equipment's antennas. In view of this, in the characterization stage of a heritage site, some authors recommend various non-destructive techniques, which can be combined to complement each other and enable better restoration planning. X-ray testing is an example of a non-destructive method that has been used to study structural elements in wrought iron in historic buildings (Santos-Assunção et al., 2014; Perez-Gracia; Solla; Fontul, 2024; Pehlivan, 2023; Vidovszky, 2017).

Studies conducted to diagnose wooden parts have generated a qualitative assessment to specify the locations of biological deterioration and internal defects in the wood. Non-destructive testing provides information about the mechanical characteristics of wood without compromising the integrity of the structure (Drobiec; Nowogońska, 2023; Raposo et al., 2017).

Non-destructive techniques have been used to indicate the presence of moisture in historic buildings or groundwater in the surrounding area (Yalçiner; Büyüksaraç; Kurban, 2019; Muradov et al., 2022) and to assist in conservation status diagnostics prior to rehabilitation and restoration interventions in plaster structures (Torres-González et al., 2021).

Indirect non-destructive techniques, such as sonic and ultrasonic testing, evaluate mechanical parameters in buildings; however, because they are based on quantities that are difficult to compare, such as pulse propagation velocity, for example, they require

specific tools and advanced processing. Furthermore, these techniques are also useful for identifying pathological manifestations and contribute to the preventive conservation of historic buildings (Armanasco; Foppoli, 2020; Diz-Mellado et al., 2021; Hidalgo-Sánchez et al., 2023).

In addition, visual inspection is defined by some authors as a non-destructive characterization process to assess the condition of a historic building and the most simplified methodology for identifying pathological manifestations. This is justified by the fact that sensory analysis is an accessible means that, together with other techniques, generates interesting diagnoses (Rubens et al., 2023; Bertolin; Berto, 2024).

The visual inspection presented in standard NBR 16747 (ABNT, 2020) is a sensory analysis procedure that enables an initial assessment of pathological manifestations in structural elements, masonry, and, coatings, in addition to allowing the identification of the types of materials and construction processes used in the building. In addition, it is during the visual inspection stage that photographs and documentation of the building's state of conservation at that moment are taken, which can be useful to aid in future diagnoses, adding information from different investigative methods, which generates more in-depth analyses for future restoration projects.

### **3.2 Digitization and digital twins**

The research focus on "digitization and digital twins" contributes to studies on the preservation of buildings of cultural interest by enabling the use of technologies to obtain data. Thus, identifying how the use of integrated digital tools assists in the monitoring of historic buildings answers the second research question.

The use of integrated digital tools in the built heritage sector has contributed to the production of quality technical documentation by monitoring deterioration processes over time. These resources have been applied to conventional masonry structures as well as metal and wooden structures, the latter being particularly susceptible to high rates of degradation when exposed to environmental agents.

Among the main integrated digital tools in the literature, the following stand out:

- (i) three-dimensional scanning techniques, based on data acquired through photogrammetry and laser scanning, which allow the generation of detailed three-dimensional models and the obtaining of geometric and constructive information, including the internal configuration of structural elements such as columns (Bouzas et al., 2022; Froner et al., 2024; Puerto et al., 2024);
- (ii) data analysis and integration strategies, based on the combination of information from non-destructive testing, sensors, and digital models, enabling the identification of deterioration patterns and the assessment of structural performance over time ( Santos-Assunção et al., 2014; Patrucco et al., 2022; Artopoulos et al. 2024; Cecere et al. 2024); and
- (iii) intelligent sensing systems, including the use of smart bricks, capable of incorporating sensors to monitor physical parameters such as deformations, thermal variations, and humidity, providing continuous data for monitoring the structural health of historic buildings. When integrated, these approaches expand diagnostic capabilities, favor preventive maintenance strategies, and contribute to decision-making in interventions compatible with the heritage value of

buildings (Jiménez Rios et al., 2024; Monchetti et al., 2023; Sarhan; Abed, 2021; Wang et al., 2023; Intrigila et al., 2024; Hussein et al., 2024).

Digitization allows the creation of virtual copies of elements and artifacts of built heritage, offering the advantages of detailed documentation and no need for direct physical intervention. In addition, it makes the building accessible to a wider audience, as it is shared virtually. Consequently, it contributes to the preservation of heritage and knowledge of construction techniques (Vieira et al., 2023; Lucchi, 2023; Resta; Bögle; Mondino, 2024; Nguyen et al., 2023; Lin et al., 2024; Martinelli; Calcerano; Gigliarelli, 2022; Oostwegel et al., 2022; Mohd Nurfaizal Baharuddin et al., 2023; Cinquepalmi; Tiburcio, 2023; Tang et al., 2024; Khalil; Stravoravdis; Backes, 2021; Hou et al., 2024; Zhang et al., 2022; Moyano et al., 2023; Bertolin; Berto, 2024).

Digital models, called digital twins, document the geometry, environments, and complex parts of the historic building, in addition to adding semantic enrichment. Thus, they enable the diagnosis of deterioration of built heritage, especially in situations of difficult access, natural disasters, or damage caused by human actions. Data collection, carried out through the Scan-to-HBIM process, assists construction experts in restoration actions (Hussein et al., 2024; Milosz; Kęsik; Montusiewicz, 2024; Di Filippo et al., 2018; Nguyen et al., 2023; Vieira et al., 2023a; Sewasew; Tesfamariam, 2023; Abd ElWahab; Bakr; Raslan, 2019; Sánchez-Aparicio et al., 2020; Baik et al., 2021; Penjor et al., 2024; Moyano et al., 2021).

Furthermore, digital twins integrated with historical building performance simulation tools provide information on the energy behavior of these buildings and support decision-making related to interventions aimed at improving energy efficiency and reducing costs in the sustainable management of historical buildings. In addition, they contribute to greater data reliability and user safety (Massafra; Predari; Gulli, 2022; Cheng et al., 2024; Karatzas et al., 2024; Trento; Wurzer; Coraglia, 2019; Zhang et al., 2023a; Galiano-Garrigós et al., 2024; Vuoto; Funari; Lourenço, 2024; Zhang et al., 2023b; Casillo et al., 2024; Vuoto; Funari; Lourenço, 2023; Chacón et al., 2024; Jouan; Hallot, 2020; Cortés Meseguer; García Valldecabres, 2023).

As for the challenges related to the application of digital twins to built heritage, aspects related to the need for multidisciplinary approaches to data collection and analysis were highlighted. On the other hand, some authors emphasize this multidisciplinary nature as an advantage, as it allows for a more comprehensive assessment of damage to historic buildings. This stage is considered complex, as it requires professionals with prior knowledge of specific software, in addition to knowledge about the materials that make up the historic building for the production of modeling that approximates the real object (Lucchi, 2023; Nguyen et al., 2023; Martinelli; Calcerano; Gigliarelli, 2022; Rubens et al., 2023).

In short, three-dimensional models have been identified as useful for preserving and documenting heritage, considering the tracking of changes and degradation throughout the useful life of historic buildings. Digital twins have been described as one of the main technological trends for the conservation and enhancement of cultural heritage, being pointed out as fundamental for monitoring, managing, and supporting actions to protect historic buildings (Yiğit; Uysal, 2024; Cardinali et al., 2023; Capolupo et al., 2020; Casillo et al., 2022).

### 3.3 Main techniques and conclusions

In order to summarize the application of non-destructive testing and technological means in the field of built heritage, Table 2 shows the relevant information obtained from the literature.

**Table 2:** Non-destructive techniques and integrated digital tools with their respective applications

Reference	Type(s) of NDT and techniques	Applications
[Froner et al., 2024; Patrucco et al., 2022; Gusella; Cluni; Liberotti, 2020]	Infrared thermography	Understanding of construction techniques and masonry wear
[Frąckiewicz; Raszczuk; Jasieńko, 2024; Santos-Assunção et al., 2014; Pérez-Gracia et al., 2013; Artopoulos et al., 2024; Guadagnuolo et al., 2023; Pérez-Gracia et al., 2009; Chik et al., 2024; Yalçiner; Büyüksaraç; Kurban, 2019]	GPR/ GPR combined with seismic tomography	Assessment of structural integrity, beam position, surface and subsurface monitoring of historic buildings
[Vidovszky, 2017]	X-ray testing	Investigating wrought iron structural elements
[Martínez-Soto et al., 2021]	Surface wave spectral analysis	Evaluation of elastic modulus, shear modulus, and Poisson's ratio
[Muradov et al., 2022, Yalçiner; Büyüksaraç; Kurban, 2019]	Microwave combined with photogrammetry and laser scanning/GPR technologies	Identification of moisture or groundwater in the vicinity of the building
[Gusella; Cluni; Liberotti, 2020; Artopoulos et al., 2024]	Infrared thermography	Characterization of masonry texture and thermal evaluation of buildings
[Drobiec; Nowogońska, 2023; Raposo et al., 2017; Torres-González et al., 2021; Hidalgo-Sánchez et al., 2023]	Ultrasonic and sclerometric technology (or wood hammer test), visual inspection, resistograph, and moisture meter/ Plaster: Visual inspection, durometer (hardness and moisture), infrared thermography (discontinuities, detachments, and moisture), and GPR (identification of metal fixings and presence of voids)	Identification of internal defects in the quality of wooden parts, mechanical characteristics of wooden parts/ Diagnosis of the state of conservation of plaster structures, such as hardness
[Diz-Mellado et al., 2021; Hidalgo-Sánchez et al., 2023; Bertolin; Berto, 2024]	Visual inspection (damage mapping), photogrammetric surveys (for visualizations), thermography (moisture problems, differences between materials, or cracks in walls), laser level (angular distortions of structural elements), Vibration testing (accelerometer to measure structural rigidity), GPR (to confirm documentary hypotheses about the subsoil), laser scanners	Identification of construction flaws through the combination of ENDS and contribution to preventive conservation
[Froner et al., 2024; Patrucco et al., 2022, Artopoulos et al., 2024; Intrigila et al., 2024; Hussein et al., 2024; Puerto et al., 2024; Bouzas et al., 2022; Wang et al., 2023; Monchetti et al., 2023, Cecere et al., 2024, Sarhan; Abed, 2021; Rubens et al., 2023; Capolupo et al., 2020]	Cameras, photogrammetry, terrestrial laser scanning, and thermography	Monitoring of deterioration processes
[Santos-Assunção et al., 2014; Jiménez Rios et al., 2024]	GPR, seismic tomography/ Smart materials	Obtaining information about the internal structure of columns
[Vieira et al., 2023a; Sewasew; Tesfamariam, 2023; Abd ElWahab; Bakr; Raslan, 2019; Sánchez-Aparicio et al., 2020; Baik et al., 2021; Penjor et al., 2024; Moyano et al., 2021; Lucchi, 2023; Zhang et al., 2023a; Lin et al., 2024; Nguyen et al.,	Unmanned Aerial Vehicle (UAV), laser scanner, software to generate three-dimensional models	Data to recreate the structure and geometry of historic buildings for maintenance, retrofitting, or restoration processes of historic buildings/Assistance in

2023; Morero et al., 2023; Tang et al., 2024; Khalil; Stravoravdis; Backes, 2021; Moyano et al., 2023]		decision-making with the preparation of technical documents for built heritage
[Vieira et al., 2023a; Resta; Bögle; Mondino, 2024; Lucchi, 2023; Cortés Meseguer; García Valldecabres, 2023; Cardinali et al., 2023; Capolupo et al., 2020]	Cameras, sensors, modeling software	Virtual knowledge of heritage in various locations around the world/ Virtual tours/ Appreciation of historical heritage
[Cheng et al., 2024; Hou et al., 2024; Zhang et al., 2022; Massafra; Predari; Gulli, 2022; Trento; Wurzer; Coraglia, 2019; Karatzas et al., 2024]	Thermodynamic simulations in software	Improvement of thermal or energy performance of historic buildings/ Possibility of performing simulations
[Martinelli; Calcerano; Gigliarelli, 2022; Oostwegel et al., 2022; Mohd Nurfaizal Baharuddin et al., 2023; Galiano-Garrigós et al., 2024; Cinquepalmi; Tiburcio, 2023; Vuoto; Funari; Lourenço, 2024; Zhang et al., 2023a; Casillo et al., 2024; Vuoto; Funari; Lourenço, 2023; Chacón et al., 2024; Jouan; Hallot, 2020; Cortés Meseguer; García Valldecabres, 2023; Yiğit; Uysal, 2024; Cardinali et al., 2023; Bertolin; Berto, 2024; Casillo et al., 2022]	Photogrammetry, terrestrial laser scanning, geodetic surveying, computational resources (software)	Contributions to the planning, maintenance, preventive conservation, and sustainable protection of built heritage

#### 4 Final considerations

Based on a systematic literature review conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, the following main conclusions were identified:

- (i) Non-destructive visual inspection techniques, Ground Penetrating Radar (GPR), and infrared thermography are widely used to characterize historic buildings;
- (ii) Non-destructive testing mainly enables: understanding of the construction technique and wear and tear of masonry, assessment of the integrity of structures; identification of moisture or water in the building's surroundings, characterization of the texture of the masonry, thermal assessment of the building, identification of pathological manifestations, and contribution to preventive conservation;
- (iii) The most commonly used methods for digitizing and applying digital twins to buildings of historical interest were photography, photogrammetry, and mobile laser scanning;
- (iv) Digitization and digital twins contribute to historic buildings by monitoring deterioration processes, obtaining information about the internal structure of columns; recreating the structure and geometry of historic buildings for maintenance, retrofitting, or restoration processes; assisting in decision-making through documents created for technical collections; providing virtual knowledge of heritage sites around the world; virtual tours, appreciation of historical heritage, improvement of the thermal or energy performance of historic buildings with simulations, and contributions to the planning, maintenance, preventive conservation, and sustainable protection of built heritage.
- (v) Combined approaches of non-destructive testing and technological resources can improve the monitoring of the behavior of building elements and support decision-making in future interventions, in order to strengthen strategies for the sustainable preservation of built heritage.

However, it was observed that the scientific production analyzed presents some studies from European countries and some regions of Asia, where preservation policies and investments in heritage monitoring technologies are more consolidated. On the other hand, there are some studies from countries that have extensive and diverse sets of buildings of historical interest, such as those located in Latin America, Africa and part of the Middle East, which may indicate progress in scientific research on built heritage in these regions.

Furthermore, it should be noted that the conclusions presented are conditioned by the selected bibliography and the analytical frameworks defined by the research approaches and questions adopted. The analysis highlights the need to expand studies focused on the application of non-destructive techniques in buildings of historical interest, especially when integrated with technological resources such as digitization and digital twins.

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## References

- ABD ELWAHAB, Heba Allah; BAKR, Ali F.; RASLAN, Rania A. Towards a parametric plug-in for conservation of built heritage. **Alexandria Engineering Journal**, v. 58, n. 1, p. 325–331, 2019. DOI: <https://doi.org/10.1016/j.aej.2018.12.001>.
- ARMANASCO, Alessandro; FOPPOLI, Dario. A flat jacks method for in situ testing of brick masonry shear characteristics. **Construction and Building Materials**, v. 262, p. 119840, 2020. DOI: <https://doi.org/10.1016/j.conbuildmat.2020.119840>.
- ARTOPOULOS, Georgios et al. Data-Driven Multi-Scale Study of Historic Urban Environments by Accessing Earth Observation and Non-Destructive Testing Information via an HBIM- Supported Platform. **International Journal of Architectural Heritage**, v. 18, n. 6, p. 920–939, 2024. DOI: <https://doi.org/10.1080/15583058.2023.2199408>.
- BAIK, Ahmad et al. Applying Digital Methods for Documenting Heritage Building in Old Jeddah: A Case Study of Hazzazi House. **Digital Applications in Archaeology and Cultural Heritage**, v. 21, p. e00189, 2021. DOI: <https://doi.org/10.1016/j.daach.2021.e00189>.
- BERTOLIN, Chiara; BERTO, Filippo. Sustainable management of heritage buildings in long-term perspective (SyMBoL): current knowledge and further research needs. **International Journal of Building Pathology and Adaptation**, v. 42, n. 1, p. 1–17, 2024. DOI: <https://doi.org/10.1108/IJBPA-02-2023-0015>.
- BOUZAS, Óscar et al. Structural health control of historical steel structures using HBIM. **Automation in Construction**, v. 140, p. 104308, 2022. DOI: <https://doi.org/10.1016/j.autcon.2022.104308>.
- CAPOLUPO, Alessandra et al. Integration of terrestrial laser scanning and UAV-SFM technique to generate a detailed 3D textured model of a heritage building. **Proceedings of SPIE**, 2020. DOI: <https://doi.org/10.1117/12.2574034>.

- CARDINALI, Vieri et al. An oriented H-BIM approach for the seismic assessment of cultural heritage buildings: Palazzo Vecchio in Florence. **Buildings**, v. 13, n. 4, p. 913, 2023. DOI: <https://doi.org/10.3390/buildings13040913>.
- CASILLO, Mario et al. Revolutionizing cultural heritage preservation: an innovative IoT-based framework for protecting historical buildings. **Evolutionary Intelligence**, v. 17, n. 5–6, p. 3815–3831, 2024. DOI: <https://doi.org/10.1007/s12065-024-00959-y>.
- CASILLO, Mario et al. Revolutionizing cultural heritage preservation: an innovative IoT-based framework for protecting historical buildings. **Evolutionary Intelligence**, v. 17, n. 5–6, p. 3815–3831, 27 out. 2024.
- CECERE, L. et al. IoT and digital twin: a new perspective for cultural heritage predictive maintenance. **Procedia Structural Integrity**, v. 64, p. 2181–2188, 2024. DOI: <https://doi.org/10.1016/j.prostr.2024.09.334>.
- CHACÓN, R. et al. Material characterization for HBIM data structures on a masonry arch bridge. In: **Bridge Maintenance, Safety, Management, Digitalization and Sustainability**. London: CRC Press, 2024. p. 2370–2378.
- CHENG, Jack C. P. et al. Thermal performance improvement for residential heritage building preservation based on digital twins. **Journal of Building Engineering**, v. 82, p. 108283, 2024. DOI: <https://doi.org/10.1016/j.jobe.2023.108283>.
- CHIK, T. N. T. et al. A review of structural health monitoring in heritage building due to cracking issues. **IOP Conference Series: Earth and Environmental Science**, v. 1347, n. 1, p. 012071, 2024. DOI: <https://doi.org/10.1088/1755-1315/1347/1/012071>.
- CINQUEPALMI, Federico; TIBURCIO, Virginia Adele. Sustainable restoration of cultural heritage in the digital era. **Vitruvio – International Journal of Architectural Technology and Sustainability**, v. 8, n. 2, p. 76–87, 2023. DOI: <https://doi.org/10.4995/vitruvio-ijats.2023.20545>.
- CORTÉS MESEGUER, Luis; GARCÍA VALLDECABRES, Jorge. Digital twins: HBIM information repositories to centralize knowledge and interdisciplinary management of architectural heritage. **Vitruvio – International Journal of Architectural Technology and Sustainability**, v. 8, n. 2, p. 64–75, 2023. DOI: <https://doi.org/10.4995/vitruvio-ijats.2023.20534>.
- COSTA, Felipe Vaz; LIMA, Gilson Brito Alves. Uso do instrumento PRISMA e de análise de dados como suporte ao levantamento e categorização de KPIs de SSO. **Exacta**, v. 21, n. 1, p. 101–129, 2023. DOI: <https://doi.org/10.5585/exactaep.2021.18027>.
- DI FILIPPO, Andrea et al. Use of a wearable mobile laser system in seamless indoor 3D mapping of a complex historical site. **Remote Sensing**, v. 10, n. 12, p. 1897, 2018. DOI: <https://doi.org/10.3390/rs10121897>.
- DIZ-MELLADO, Eduardo et al. Non-destructive testing and finite element method integrated procedure for heritage diagnosis: the Seville Cathedral case study. **Journal of Building Engineering**, v. 37, p. 102134, 2021. DOI: <https://doi.org/10.1016/j.jobe.2020.102134>.
- DROBIEC, Joanna; NOWOGOŃSKA, Beata. Restrictions and new possibilities of technical and conservation diagnostics of wood in heritage buildings. **Civil and Environmental**

- Engineering Reports**, v. 33, n. 2, p. 106–116, 2023. DOI: <https://doi.org/10.59440/ceer/174568>.
- FIDELES, Bruna Tayna Macedo et al. Levantamentos digitais como suporte à inspeção em edificações: uma aplicação no Acquário Ceará. **Concreto & Construções**, v. 51, n. 114, p. 58–64, 2024. DOI: <http://dx.doi.org/10.4322/1809-7197.2024.114.0006>.
- FRĄCKIEWICZ, Piotr; RASZCZUK, Krzysztof; JASIEŃKO, Jerzy. Identification of alterations in the structure of historical masonry walls using the GPR method accompanied with architectural survey in the former Piast Gymnasium in Brzeg. **Civil and Environmental Engineering Reports**, v. 34, n. 4, p. 32–42, 2024. DOI: <https://doi.org/10.59440/ceer/191566>.
- FRONER, Yacy Ara et al. Data collection for cultural heritage risk management: the damage map through heritage building information modeling (HBIM) project applied to the façade of St Francis of Assisi, Ouro Preto, Brazil. **Studies in Conservation**, v. 69, n. sup1, p. 98–107, 2024. DOI: <https://doi.org/10.1080/00393630.2024.2379132>.
- GALIANO-GARRIGÓS, Antonio et al. The influence of visitors on heritage conservation: the case of the Church of San Juan del Hospital, Valencia, Spain. **Applied Sciences**, v. 14, n. 5, p. 2065, 2024. DOI: <https://doi.org/10.3390/app14052065>.
- GARRIDO, Iván et al. Development of thermal principles for the automation of the thermographic monitoring of cultural heritage. **Sensors**, v. 20, n. 12, p. 1–20, 2020. DOI: <https://doi.org/10.3390/s20123392>.
- GOPINATH, Vinoth Kanna; RAMADOSS, Ravi. Review on structural health monitoring for restoration of heritage buildings. **Materials Today: Proceedings**, v. 43, p. 1534–1538, 2021. DOI: <https://doi.org/10.1016/j.matpr.2020.09.318>.
- GUADAGNUOLO, Mariateresa et al. Simplified methods for the evaluation of mechanical properties of tuff masonry walls in Campania (Italy). **Procedia Structural Integrity**, v. 44, p. 878–885, 2023. DOI: <https://doi.org/10.1016/j.prostr.2023.01.114>.
- GUSELLA, Vittorio; CLUNI, Federico; LIBEROTTI, Riccardo. Feasibility of a thermography nondestructive technique for determining the quality of historical frescoed masonries: applications on the Templar Church of San Bevignate. **Applied Sciences**, v. 11, n. 1, p. 281, 2020. DOI: <https://doi.org/10.3390/app11010281>.
- HIDALGO-SÁNCHEZ, Francisco M. et al. NDT spatial data integration for monumental buildings: technical information management for the Royal Alcazar of Seville. **Building Research & Information**, v. 51, n. 6, p. 625–647, 2023. DOI: <https://doi.org/10.1080/09613218.2022.2162476>.
- HOU, Huiying (Cynthia) et al. Digital twin application in heritage facilities management: systematic literature review and future development directions. **Engineering, Construction and Architectural Management**, v. 31, n. 8, p. 3193–3221, 2024. DOI: <https://doi.org/10.1108/ECAM-06-2022-0596>.
- HUSSEIN, Khalid Ahmed et al. Digital preservation of heritage urban facades: an integrated approach using historic building information modeling and shape grammar analysis. **Digital Applications in Archaeology and Cultural Heritage**, v. 35, p. e00383, 2024. DOI: <https://doi.org/10.1016/j.daach.2024.e00383>.

- INTRIGILA, Claudio et al. HBIM for conservation and valorization of structural heritage: the Stylite Tower at Umm ar-Rasas, Jordan. **Journal of Cultural Heritage**, v. 70, p. 397–407, 2024. DOI: <https://doi.org/10.1016/j.culher.2024.10.010>.
- JIMÉNEZ RIOS, Alejandro et al. Industry 5.0: towards an enhanced built cultural heritage conservation practice. **Journal of Building Engineering**, v. 96, p. 110542, 2024. DOI: <https://doi.org/10.1016/j.jobbe.2024.110542>.
- JOUAN, Pierre; HALLOT, Pierre. Digital twin: research framework to support preventive conservation policies. **ISPRS International Journal of Geo-Information**, v. 9, n. 4, p. 228, 2020. DOI: <https://doi.org/10.3390/ijgi9040228>.
- KARATZAS, Stylianos et al. Digital twins-enabled heritage buildings management through social dynamics. **Journal of Cultural Heritage Management and Sustainable Development**, 2024. DOI: <https://doi.org/10.1108/JCHMSD-08-2023-0136>.
- KHALIL, Ahmed; STRAVORAVDIS, Spyridon; BACKES, Dietmar. Categorisation of building data in the digital documentation of heritage buildings. **Applied Geomatics**, v. 13, n. 1, p. 29–54, 2021. DOI: <https://doi.org/10.1007/s12518-020-00322-7>.
- LIN, Guiye et al. Three-dimensional documentation and reconversion of architectural heritage by UAV and HBIM: a study of Santo Stefano Church in Italy. **Drones**, v. 8, n. 6, p. 250, 2024. DOI: <https://doi.org/10.3390/drones8060250>.
- LUCCHI, Elena. Digital twins for the automation of the heritage construction sector. **Automation in Construction**, v. 156, p. 105073, 2023. DOI: <https://doi.org/10.1016/j.autcon.2023.105073>.
- MARCONDES, Renato; SILVA, Silvio Luiz Rutz da. O protocolo PRISMA 2020 como uma possibilidade de roteiro para revisão sistemática em ensino de ciências. **Revista Brasileira de Pós-Graduação**, Brasília, v. 18, n. 39, p. 1–19, 2023. DOI: <https://doi.org/10.21713/rbpg.v18i39.1894>.
- MARTINELLI, Letizia; CALCERANO, Filippo; GIGLIARELLI, Elena. Methodology for an HBIM workflow focused on the representation of construction systems of built heritage. **Journal of Cultural Heritage**, v. 55, p. 277–289, 2022. DOI: <https://doi.org/10.1016/j.culher.2022.03.016>.
- MARTÍNEZ-SOTO, Fernando et al. Spectral analysis of surface waves for non-destructive evaluation of historic masonry buildings. **Journal of Cultural Heritage**, v. 52, p. 31–37, 2021. DOI: <https://doi.org/10.1016/j.culher.2021.09.002>.
- MASSAFRA, A.; PREDARI, G.; GULLI, R. Towards digital twin-driven cultural heritage management: a HBIM-based workflow for energy improvement of modern buildings. **The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences**, v. XLVI-5/W1-2022, p. 149–157, 2022. <https://doi.org/10.5194/isprs-archives-XLVI-5-W1-2022-149-2022>.
- MIŁOŻ, Marek; KĘSIK, Jacek; MONTUSIEWICZ, Jerzy. Three-dimensional digitization of documentation and perpetual preservation of cultural heritage buildings at risk of liquidation and loss: the methodology and case study of St Adalbert’s Church in Chicago. **Electronics**, v. 13, n. 3, p. 561, 2024. DOI: <https://doi.org/10.3390/electronics13030561>.

- MOHD NURFAISAL BAHARUDDIN et al. Conservation digitalization through heritage building information modelling (HBIM): online database theoretical review. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, v. 33, n. 1, p. 317–332, 2023. DOI: <https://doi.org/10.37934/araset.33.1.317332>.
- MONCHETTI, S. et al. The research project “Charming Pistoia”: an integrated HBIM project for preservation and maintenance of heritage structures. *Procedia Structural Integrity*, v. 44, p. 1988–1995, 2023. DOI: <https://doi.org/10.1016/j.prostr.2023.01.254>.
- MOREIRA DE ARAÚJO, Francisca Noeme; QUEIROZ, Marcelo Victor Alves Bila; EL AOUAR, Walid Abbas. Telemedicina, telessaúde e digitalização: revisão sistemática utilizando o protocolo PRISMA (2020–2022). *Revista de Administração em Saúde*, São Paulo, v. 23, n. 91: e350, abr.–jun. 2023. Disponível em: <https://cqh.org.br/ojs-2.4.8/index.php/ras/article/view/350>.
- MORERO, Laura et al. The use of a heritage building information model as an effective tool for planning restoration and diagnostic activities: the example of the Troia Cathedral rose window. *Acta IMEKO*, v. 12, n. 4, p. 1–8, 2023. DOI: <https://doi.org/10.21014/actaimeko.v12i4.1511>.
- MOYANO, J. et al. Integration of dynamic information on energy parameters in HBIM models. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, v. XLVIII-M-2-2023, p. 1089–1096, 2023. DOI: <https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-1089-2023>.
- MOYANO, Juan et al. Semantic interpretation of architectural and archaeological geometries: point cloud segmentation for HBIM parameterisation. *Automation in Construction*, v. 130, p. 103856, 2021. DOI: <https://doi.org/10.1016/j.autcon.2021.103856>.
- MURADOV, Magomed et al. Non-destructive system for in-wall moisture assessment of cultural heritage buildings. *Measurement*, v. 203, p. 111930, 2022. DOI: <https://doi.org/10.1016/j.measurement.2022.111930>.
- NGUYEN, Thu Anh et al. Practical workflow for cultural heritage digitalization and management: a case study in Vietnam. *International Journal of Construction Management*, v. 23, n. 13, p. 2305–2319, 2023. DOI: <https://doi.org/10.1080/15623599.2022.2054268>.
- NOVAIS, A. L. M. et al. **Coordenadoria de Patrimônio Cultural: 20 anos de atuação especializada do MPMG**. Belo Horizonte: DIPE, 2024. Disponível em: [https://www.mpmg.mp.br/data/files/23/14/39/64/863A091017A50CF8760849A8/Livro\\_digital\\_MP\\_livro\\_20anos.pdf](https://www.mpmg.mp.br/data/files/23/14/39/64/863A091017A50CF8760849A8/Livro_digital_MP_livro_20anos.pdf).
- OOSTWEGEL, Laurens Jozef Nicolaas et al. Digitalization of culturally significant buildings: ensuring high-quality data exchanges in the heritage domain using OpenBIM. *Heritage Science*, v. 10, n. 1, p. 10, 2022. DOI: <https://doi.org/10.1186/s40494-021-00640-y>.
- PAGE, Matthew J. et al. A declaração PRISMA 2020: diretriz atualizada para relatar revisões sistemáticas. *Epidemiologia e Serviços de Saúde*, v. 31, n. 2, 2022. DOI: <https://doi.org/10.26633/RPSP.2022.112>.

- PAGE, Matthew J. et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. **BMJ**, v. 372, p. 1–9, 2021. DOI: <https://doi.org/10.1136/bmj.n71>.
- PATRUCCO, Giacomo et al. 3D Data Fusion for Historical Analyses of Heritage Buildings Using Thermal Images: The Palacio de Colomina as a Case Study. **Remote Sensing**, v. 14, n. 22, p. 5699, 11 nov. 2022. DOI: <https://doi.org/10.3390/rs14225699>.
- PEHLIVAN, Gamze Fahriye. Condition and characterization analysis of a twentieth century cultural heritage through non-destructive testing (NDT) methods: the case of the Sivas industry school ironworking atelier in Turkey. **Heritage Science**, v. 11, n. 1, p. 62, 28 mar. 2023. DOI: <https://doi.org/10.1186/s40494-023-00889-5>.
- PENJOR, Tshering et al. Heritage building information modeling (HBIM) for heritage conservation: Framework of challenges, gaps, and existing limitations of HBIM. **Digital Applications in Archaeology and Cultural Heritage**, v. 35, p. e00366, 2024. DOI: <https://doi.org/10.1016/j.daach.2024.e00366>.
- PÉREZ-GRACIA, V. et al. Radar exploration applied to historical buildings: A case study of the Marques de Llió palace, in Barcelona (Spain). **Engineering Failure Analysis**, v. 16, n. 4, p. 1039–1050, 2009. DOI: <https://doi.org/10.1016/j.engfailanal.2008.05.007>.
- PÉREZ-GRACIA, V. et al. Non-destructive analysis in cultural heritage buildings: Evaluating the Mallorca cathedral supporting structures. **NDT & E International**, v. 59, p. 40–47, out. 2013. DOI: <https://doi.org/10.1016/j.ndteint.2013.04.014>.
- PEREZ-GRACIA, Vega; SOLLA, Mercedes; FONTUL, Simona. Analysis of the GPR signal for moisture detection: application to heritage buildings. **International Journal of Architectural Heritage**, v. 18, n. 2, p. 230–253, 8 fev. 2024. DOI: <https://doi.org/10.1080/15583058.2022.2139652>.
- PUERTO, Andrés et al. Building information modeling and complementary technologies in heritage buildings: A bibliometric analysis. **Results in Engineering**, v. 22, p. 102192, 2024. DOI: <https://doi.org/10.1016/j.rineng.2024.102192>.
- RAPOSO, Patrícia C. et al. Non-Destructive Structural Wood Diagnosis of a Medieval Building. **Procedia Structural Integrity**, v. 5, p. 1147–1152, 2017. DOI: <https://doi.org/10.1016/j.prostr.2017.07.024>.
- RESTA, Laura Fernandez; BÖGLE, Annette; MONDINO, Daniel. Enhancing heritage building preservation with MCDM and HBIM: A research proposal. **Procedia Structural Integrity**, v. 64, p. 2165–2172, 2024. DOI: <https://doi.org/10.1016/j.prostr.2024.09.330>.
- RICCIARDI, Maria et al. Investigations on historical monuments' deterioration through chemical and isotopic analyses: an Italian case study. **Environmental Science and Pollution Research**, v. 29, p. 29409–29418, 2022. DOI: <https://doi.org/10.1007/s11356-021-15103-x>.
- RUBENS, Tallis et al. Digitalization based on high-resolution scanning and HBIM tools for damage assessment of the José de Alencar house. **Journal of Building Pathology and Rehabilitation**, v. 8, n. 1, p. 30, 30 jun. 2023. DOI: <https://doi.org/10.21203/rs.3.rs-2361581/v1>.

- SÁNCHEZ-APARICIO, Luis Javier et al. Web-GIS approach to preventive conservation of heritage buildings. **Automation in Construction**, v. 118, p. 103304, 2020. DOI: <https://doi.org/10.1016/j.autcon.2020.103304>.
- SANTOS-ASSUNÇÃO, Sonia et al. Assessment of Complex Masonry Structures with GPR Compared to Other Non-Destructive Testing Studies. **Remote Sensing**, v. 6, n. 9, p. 8220–8237, 29 ago. 2014. DOI: <https://doi.org/10.3390/rs6098220>.
- SARDELLA, Alessandro et al. Risk mapping for the sustainable protection of cultural heritage in extreme changing environments. **Atmosphere**, v. 11, n. 7, 1 jul. 2020. DOI: <https://doi.org/10.3390/atmos11070700>.
- SARHAN, Hussein R.; ABED, Fanar M. The Feasibility of Using UAV Structure from Motion Photogrammetry to Extract HBIM of the Great Ziggurat of UR. **Iraqi Journal of Science**, v. 62, n. 11, p. 4518–4528, 24 dez. 2021. DOI: [https://doi.org/10.24996/ijs.2021.62.11\(SI\).31](https://doi.org/10.24996/ijs.2021.62.11(SI).31).
- SEWASEW, Yishak; TEFAMARIAM, Solomon. Historic building information modeling using image: Example of port city Massawa, Eritrea. **Journal of Building Engineering**, v. 78, p. 107662, 2023. DOI: <https://doi.org/10.1016/j.jobe.2023.107662>.
- SUTHERLAND, Neil et al. InfraRed Thermography and 3D-Data Fusion for Architectural Heritage: A Scoping Review. **Remote Sensing**, v. 15, n. 9, p. 2422, 2023. DOI: <https://doi.org/10.3390/rs15092422>.
- Tang, Whai Tak et al. Digitalisation of asset management in Chinese temples in Hong Kong. **HKIE Transactions**, v. 30, n. 3, p. 34–43, 28 mar. 2024. DOI: <https://doi.org/10.33430/V30N3THIE-2022-0053>.
- TORRES-GONZÁLEZ, M. et al. Analysis of the state of conservation of historical plasterwork through visual inspection and non-destructive tests. The case of the upper frieze of the Toledanos Room (The Royal Alcázar of Seville, Spain). **Journal of Building Engineering**, v. 40, p. 102314, 2021. DOI: <https://doi.org/10.1016/j.jobe.2021.102314>.
- TRENTO, Armando; WURZER, Gabriel; CORAGLIA, Ugo Maria. **A Digital Twin for Directing People Flow in Preserved Heritage Buildings**. São Paulo: Editora Blucher, dez. 2019. Disponível em: <http://www.proceedings.blucher.com.br/article-details/34213>.
- VAN ECK, N. J.; WALTMAN, L. **VOSviewer manual: version 1.6.20**. Leiden: CWTS, 2023. Disponível em: [https://www.vosviewer.com/documentation/Manual\\_VOSviewer\\_1.6.20.pdf](https://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.20.pdf).
- VASCONCELOS, Ana Raina Carneiro et al. Applications of Smart and Self-Sensing Materials for Structural Health Monitoring in Civil Engineering: A Systematic Review. **Buildings**, v. 14, n. 8, 2345, 2024. DOI: <https://doi.org/10.3390/buildings14082345>.
- VIDOVŠKY, István. Diagnostic Method for Revealing Major Risk Factors of Wrought Iron Building Structure Elements. **Procedia Engineering**, v. 196, p. 181–186, 2017. DOI: <https://doi.org/10.1016/j.proeng.2017.07.189>.
- VIEIRA, Mylene M. et al. Strategy for HBIM implementation using high-resolution 3D architectural documentation based on laser scanning and photogrammetry of the José de Alencar theatre. **Digital Applications in Archaeology and Cultural Heritage**, v. 30, p. e00287, 2023. DOI: <https://doi.org/10.1016/j.daach.2023.e00287>.

- VIEIRA, Mylene M. et al. Semi-automatic scan-to-BIM procedure applied to architectural ornaments of Nossa Senhora do Rosário Church, Aracati-CE. **Research Square**, 29 fev. 2024. Preprint. DOI: <https://doi.org/10.21203/rs.3.rs-3988894/v1>.
- VUOTO, Annalaura; FUNARI, Marco Francesco; LOURENÇO, Paulo B. On the Use of the Digital Twin Concept for the Structural Integrity Protection of Architectural Heritage. **Infrastructures**, v. 8, n. 5, p. 86, 4 maio 2023. DOI: <https://doi.org/10.3390/infrastructures8050086>.
- VUOTO, Annalaura; FUNARI, Marco Francesco; LOURENÇO, Paulo B. Shaping Digital Twin Concept for Built Cultural Heritage Conservation: A Systematic Literature Review. **International Journal of Architectural Heritage**, v. 18, n. 11, p. 1762–1795, 21 nov. 2024. DOI: <https://doi.org/10.1080/15583058.2023.2258084>.
- WANG, Ru et al. HTSM Platform: A novel way to achieve resource-optimized conservation processes for heritage buildings. **Journal of Cleaner Production**, v. 423, p. 138540, 2023. DOI: <https://doi.org/10.1016/j.jclepro.2023.138540>.
- YALÇINER, C. Çağlar; BÜYÜKSARAÇ, Aydın; KURBAN, Yunus Can. Non-destructive damage analysis in Kariye (Chora) Museum as a cultural heritage building. **Journal of Applied Geophysics**, v. 171, p. 103874, 2019. DOI: <https://doi.org/10.1016/j.jappgeo.2019.103874>.
- YİĞİT, Abdurahman Yasin; UYSAL, Murat. Automatic crack detection and structural inspection of cultural heritage buildings using UAV photogrammetry and digital twin technology. **Journal of Building Engineering**, v. 94, p. 109952, 1 out. 2024. DOI: <https://doi.org/10.1016/j.jobbe.2024.109952>.
- ZHANG, Jiaying et al. Automatic relative humidity optimization in underground heritage sites through ventilation system based on digital twins. **Building and Environment**, v. 216, p. 108999, 2022. DOI: <https://doi.org/10.1016/j.buildenv.2022.108999>.
- ZHANG, Jiaying et al. Predictive control of HVAC by multiple output GRU - CFD integration approach to manage multiple IAQ for commercial heritage building preservation. **Building and Environment**, v. 245, p. 110802, 2023a. DOI: <https://doi.org/10.1016/j.buildenv.2023.110802>.
- ZHANG, Jiaying et al. Multi-indicator adaptive HVAC control system for low-energy indoor air quality management of heritage building preservation. **Building and Environment**, v. 246, p. 110910, 2023b. DOI: <https://doi.org/10.1016/j.buildenv.2023.110910>.