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Review

From Crowdsourcing to TLS–BIM/HBIM Workflows for Cultural Heritage Documentation and Structural Assessment: A Review

Elias Christoforou [1], Theoklitos Klitou [1,2], Ourania Douni [2], Eleni Apostolidou [1], Nicholas Afxentiou [1,2], Nikolaos Schetakis [3,4], Georgios Xekalakis [1], Petros Christou [1], Alessio Di Iorio [5], Georgios Stavroulakis [3] and Paris Fokaides [1,2,*]

[1] School of Engineering and Applied Sciences, Frederick University, 7 Frederickou Str., 1036 Nicosia, Cyprus; res.ce@frederick.ac.cy (E.C.); res.kt@frederick.ac.cy (T.K.); st006676@stud.fit.ac.cy (E.A.); res.an@frederick.ac.cy (N.A.); g.xekalakis@frederick.ac.cy (G.X.); eng.cp@frederick.ac.cy (P.C.)
[2] Euphyia Tech Ltd., 2 Kolokotroni Str., 2048 Nicosia, Cyprus; ourania@euphyia-tech.com
[3] School of Production Engineering and Management, Technical University of Crete, 73100 Chania, Greece; nischetakis@tuc.gr (N.S.); gestavroulakis@tuc.gr (G.S.)
[4] Quantum Innovation Pc, 37 Aristotelous Str., 73100 Chania, Greece
[5] Alma Sistemi SRL, Guidonia, 00012 Rome, Italy; adi@alma-sistemi.com
* Correspondence: p.fokaides@frederick.ac.cy; Tel.: +357-22-394-394

Abstract

The integration of advanced terrestrial laser scanning (TLS) techniques into building information modelling (BIM) workflows has significantly enhanced the digitization and preservation of cultural heritage sites. In this context, crowdsourcing can operate as a complementary upstream mechanism for enriching heritage inventories, supporting participatory mapping, collecting preliminary condition observations, and prioritizing assets for subsequent expert-led TLS acquisition, HBIM modelling, and structural assessment. This paper explores the application of TLS within BIM for the structural assessment and the long-term monitoring of historic structures. The reviewed studies show how high-resolution TLS data can support the development and updating of geometry-informed structural models, enabling detailed structural assessment and effective management strategies. The reviewed case studies demonstrate the practical benefits of integrating TLS with BIM, such as improved accuracy in structural assessments, enhanced data processing capabilities, and the creation of comprehensive digital twins. These advancements facilitate better-informed decision-making and targeted preventive measures, contributing to the resilience and preservation of cultural heritage assets. The results underscore the contribution of TLS–BIM/HBIM workflows to condition-informed documentation, structural assessment, conservation planning, and long-term heritage management. This research was supported by the ERA4CH project, which aims to protect European cities' cultural heritage from earthquake risks through innovative monitoring and management tools.

Keywords: building information modelling (BIM); historic building information modelling; terrestrial laser scanning (TLS); cultural heritage preservation; structural assessment; digital twin; remote sensing; structural health monitoring

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1. Introduction

Cultural heritage (CH) represents the legacy of past human activities and encompasses a vast range of items at varying scales, including small artifacts, museum exhibits, cultural landscapes, historical buildings, ancient monuments, city centers, and archeological sites.

Ensuring the preservation of these valuable cultural assets for future generations is a collective responsibility of humanity and a key objective of public policy [1].

The significance of preserving our heritage is acknowledged both nationally and internationally. Towards this direction, research efforts for the development of tools, methodologies and effective mitigation strategies to serve this scope have been intensified. Over the years, numerous documents, guidelines, and protocols have been issued by leading cultural heritage organizations, including the International Centre for the Preservation and Restoration of Cultural Property (ICCROM) [2], UNESCO, and the European Commission [3].

Cultural heritage buildings in Europe, which is estimated to amount 30% of the total existing stock [4], are exposed to different threats and are often subject to unique challenges due to their age, construction materials, and architectural details, and may suffer from age-related wear and tear that can compromise their structural integrity. Specifically, cultural heritage buildings are susceptible to damage due to deformations caused by environmental degradation, erosion, and collapse caused by natural disasters, excessive human intervention in the process of preservation and development, as well as inappropriate intervention such as replacement of existing materials and colors in the process of restoration [5].

Thus, continuous monitoring and documentation of those assets with significant cultural, historical, and architectural value, is increasingly vital for their preservation. Regular monitoring is essential for early detection of problems such as foundation settling, material degradation, and structural deformations caused by environmental factors or uncontrolled human activity. Moreover, continuous monitoring can provide valuable information regarding the structural stability of those buildings, enabling continuous assessment and compliance verification with building codes and standards, ensuring that structures meet required safety specifications.

Heritage intervention projects involve many stakeholders with a variety of backgrounds (e.g., engineers, archeologists, restorers, etc.) which usually work separately, so dispersed (or diverse or unharmonized) data are produced. Thus, the need for the development of solutions to improve the management of heritage building projects needs to be highlighted [6,7]. Also, the comprehensive assessment of heritage buildings' sustainability performance needs also more attention [8].

Despite substantial progress in reality capture and digital modelling, the literature on integrating terrestrial laser scanning (TLS) point clouds with building information modelling (BIM) and Historic BIM (HBIM) for assessment purposes remains fragmented. Existing studies often emphasize geometric documentation and model creation (scan-to-BIM/HBIM), while fewer works explicitly connect (i) the chosen TLS acquisition and point-cloud processing pipeline, (ii) BIM/HBIM information structuring and interoperability, and (iii) the resulting outputs required for engineering assessment, including structural condition, monitoring, and assessment of cultural heritage assets. Furthermore, prior reviews on TLS–BIM integration have not consistently reported transparent review protocols, which limits reproducibility and makes it difficult to identify robust open research directions.

The reference to crowdsourcing reflects the broader information chain required for large-scale heritage assessment. In this review, crowdsourcing is not treated as a replacement for expert survey, TLS acquisition, HBIM modelling, or structural analysis. Instead, it is positioned as an upstream data-enrichment mechanism that can support preliminary inventories, participatory mapping, geotagged photographic documentation, visible damage reporting, and prioritization of assets requiring detailed assessment. This role is consistent with the ERA4CH framework, where crowdsourced and field-collected data can be structured through digital forms and GIS-based platforms to support rapid screening and decision-making before detailed TLS–BIM/HBIM workflows are deployed.

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This review addresses the following research questions:

Q1. What end-to-end TLS–BIM/HBIM workflows are reported for cultural heritage documentation, monitoring and structural assessment?

Q2. Which assessment objectives are supported by these workflows (e.g., condition/pathology mapping, deformation monitoring, damage identification, HBIM generation, and structural-analysis model preparation) and how are the resulting outputs validated?

Q3. What technical, methodological, and operational barriers limit the adoption of TLS–BIM/HBIM workflows for assessment-oriented cultural heritage applications?

Q4. How can TLS–BIM/HBIM be complemented by additional data sources and technologies (e.g., photogrammetry, UAV-based methods, ALS/MLS, street-level imagery, sensor data, and satellite InSAR) to support multi-scale heritage documentation, monitoring, and structural assessment?

The paper is organized into the following sections: Section 2 details the review design, including the Scopus search strategy, eligibility criteria, PRISMA-based screening, and the analytical approach used to synthesize evidence. Section 3 presents and discusses the review findings in four parts: (i) crowdsourcing as an upstream data-enrichment mechanism for preliminary inventory, participatory mapping, and rapid screening; (ii) complementary remote-sensing and image-based data sources that support multi-scale heritage monitoring; (iii) laser scanning technologies and their implications for stability monitoring; and (iv) TLS–BIM/HBIM integration workflows and assessment-oriented synthesis. Section 4 concludes by summarizing the main insights and outlining priorities for future research.

2. Materials and Methods

2.1. Data Sources and Data Collection Methodology

The literature corpus for this study was retrieved from Scopus, a widely used bibliographic database, indexing peer-reviewed research across engineering, geomatics, construction, and built-heritage domains. A structured search was conducted using Scopus Advanced Search with the Boolean query TITLE-ABS-KEY (“terrestrial laser scanning” OR “TLS” OR “laser scanning”) AND (“HBIM” OR “heritage building information modeling” OR “building information modeling”) AND (“cultural heritage” OR “heritage preservation” OR “cultural preservation” OR “heritage conservation”) applied to titles, abstracts, and author keywords to ensure topical relevance. To capture developments over time, the search was restricted to publications dated 1 January 2000–17 May 2026.

Following PRISMA 2020 guidance [9,10], the search returned 193 records (n = 193) (Figure 1). No duplicates were detected (n = 0); therefore, 193 records proceeded to title and abstract screening. During screening, 1 record was excluded for not meeting the predefined eligibility language criteria (i.e., English language) while 31 studies were also excluded since they were missing relevant keywords (e.g., TLS and/or BIM/HBIM) or were not focused on cultural heritage and relevant subject categories, thus leaving 161 reports for full-text assessment (n = 161). All assessed full texts met the inclusion criteria and no full-text exclusions were made (n = 0). Consequently, 161 studies were included in the qualitative synthesis (n = 161). In this work, the R language tool (version 4.5.2), Bibliometrix R-package (version 5.4.1) was used [11].

2.1.1. Evolution of Studies per Year

Figure 2 illustrates the annual evolution of publications included in the bibliographic review. The chronological distribution of the studies shows that the field has expanded rapidly in recent years. The coded studies range from 2012 to 2026, but more than half of the corpus was published between 2023 and 2026. This confirms that HBIM-based heritage documentation and conservation is a rapidly expanding research area, with increasing attention to digital twins, AI-assisted workflows, monitoring, and management-oriented applications in the most recent literature.

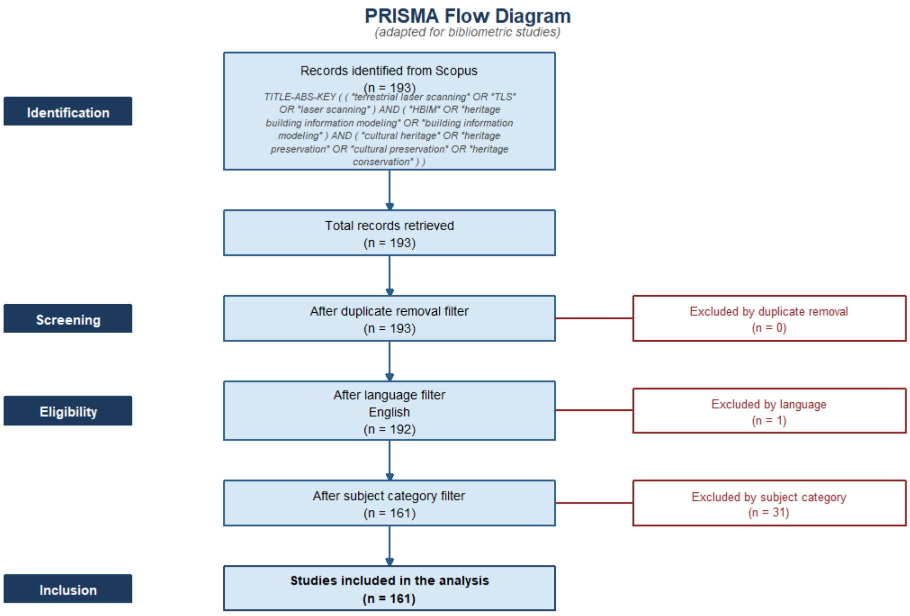


Figure 1. PRISMA workflow.

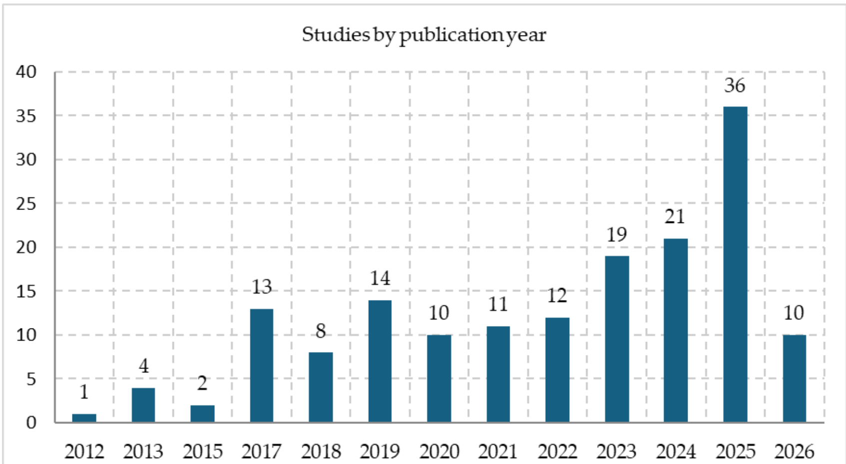


Figure 2. Year of publication of included articles.

2.1.2. Keywords Collaboration-Network

Figure 3 visualizes the keyword co-occurrence network of the included Scopus studies (2000–2026) derived using the VOSviewer (v1.6.21). Keyword co-occurrence analysis was performed using author keywords and indexed keywords, with a minimum co-occurrence threshold of 30, and four main thematic clusters were derived, namely, cultural heritages (yellow), architectural design (blue), historic preservation (red), building information modelling/bim (green/purple).

2.1.3. Q1–Q4 Methodological Mapping Table

To ensure a direct link between the research questions and the evidence synthesis, a structured coding framework was applied to the included studies. The framework captured the workflow stages, assessment objectives, validation practices, technical and operational barriers, and complementary data sources relevant to Q1–Q4. Table 1 summarizes the relationship between each research question, the coded variables, the corresponding analytical outputs, and the Results and Discussion subsection in which the findings are reported.

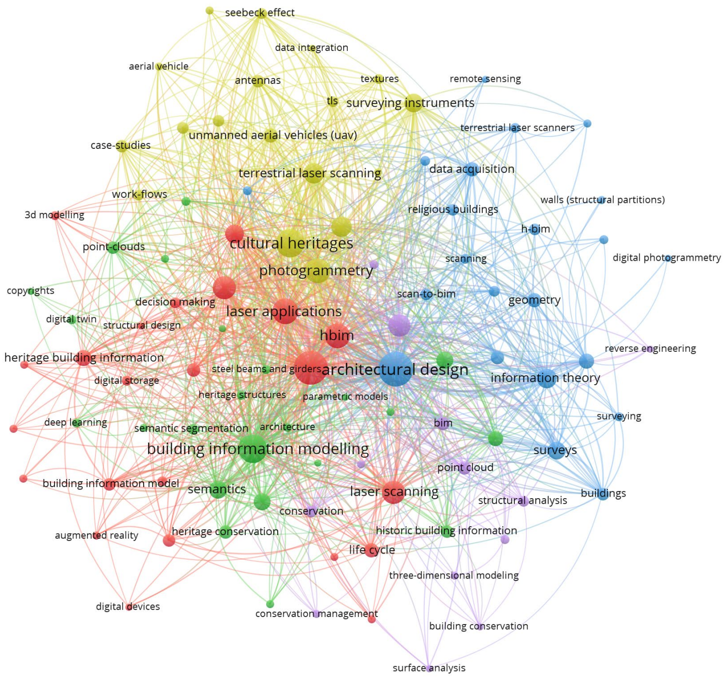


Figure 3. Keyword co-occurrence network.

Table 1. Alignment of the research questions with coded variables, analytical outputs, and Results and Discussion subsections.

RQ	Coded Variables	Analytical Output	Results Section
Q1	Acquisition, registration, processing, segmentation, HBIM generation, semantic enrichment, model preparation	Workflow synthesis	Section 3.4.1
Q2	Documentation, damage/pathology mapping, deformation monitoring, structural inputs, validation type	Assessment and validation synthesis	Section 3.4.2
Q3	Occlusion, registration, automation, uncertainty, interoperability, cost, expertise	Barrier synthesis	Section 3.4.3
Q4	Photogrammetry, UAV, ALS/MLS, sensors, GIS, InSAR, integration type	Multi-source integration synthesis	Section 3.4.4

The coded categories were non-mutually exclusive because a single study could address more than one workflow stage, assessment objective, validation method, barrier, or complementary technology.

2.2. Similar Works and Positioning

The integration of reality-capture technologies with BIM/HBIM for cultural heritage (CH) has been reviewed from multiple perspectives, including bibliometric mapping, workflow-oriented synthesis, and case-based methodological demonstrations. Table 2 summarizes representative and closely related works.

Table 2. Related works and comparison to this study.

Study	Review Design/Protocol	Data Source(s) + Time Window + Size	Main Scope/Emphasis	Key Outputs
Wang & Zakaria (2025) [12]	Mixed-methods: scientometric analysis (CiteSpace) + systematic review	Web of Science Core Collection, 2005–2024; 813 initially retrieved; refined to 484 records for analysis	Broad "3D visualization technologies" for architectural heritage conservation (includes BIM, laser scanning, LiDAR, photogrammetry, digital twins, etc.)	Macro-level mapping of field structure, hotspots, evolution trends, and thematic directions through knowledge maps and cluster refinement
Xiao et al. (2025) [13]	Systematic bibliometric review combining CiteSpace, VOSviewer, manual close reading, and GPT-assisted semantic mining	Web of Science and Scopus, 2000–2025; 967 articles	Surface protection technologies for earthen sites, with emphasis on digitalization, intelligent monitoring, sustainability, LiDAR, GIS, BIM, DT, IoT, VR/AR, and multi-source technological integration	Identifies a transition from point-based monitoring to spatial modelling and integrated intelligent monitoring; proposes a triadic framework of intelligent monitoring, technological integration, and collaborative application
Liu et al. (2023) [14]	Systematic review using PRISMA	Scopus + Web of Science, 2012–2022; initial 378 records → 58 included	Static TLS for HBIM development (survey planning, acquisition, processing, HBIM creation)	Extracts state-of-the-art practices; identifies major gaps (survey guidelines; automation from TLS to BIM entities; long-term monitoring/change detection)
Borkowski & Kubrat (2024) [15]	Review + workflow + case studies (scan-to-BIM methodology)	Not PRISMA-style; proposes workflow and demonstrates 3 BIM models (fort, plant, castle)	Integration of laser scanning + photogrammetry + BIM; practical pipeline from point clouds to BIM; focuses on implementation constraints	Provides stepwise scan-to-BIM workflow; shows model development decisions (e.g., LOD), software pipeline, and interoperability considerations (e.g., IFC)
Huang et al. (2025) [16]	Empirical spatial-analysis study using historical-map digitization, space syntax, and GIS	Historical maps of ancient Wenzhou City from 1566, 1765, 1876, and 1949	Urban-form evolution and functional transformation of a traditional water town, focusing on street/water networks and architectural functional attributes	Demonstrates how GIS and spatial syntax can quantify historical urban morphology and support planning/protection strategies for traditional settlements

Broad bibliometric studies, such as Wang & Zakaria (2025) [12] and Xiao et al. [13], are valuable for mapping the technological evolution of digital heritage research. Wang & Zakaria (2025) [12] examine architectural heritage conservation through a broad "3D visualization technologies" lens using knowledge mapping and thematic synthesis over a large Web of Science corpus, providing an overview of research trends and thematic concentrations. Xiao et al. [13], for example, review 967 Web of Science and Scopus records on earthen-site surface conservation and identify a transition from point-based monitoring to LiDAR/GIS-based spatial modelling and integrated intelligent monitoring systems involving BIM, digital twins, IoT, VR/AR, and multi-source fusion. However, their scope concerns earthen-site surface protection and broad technological trends rather than the specific TLS–BIM/HBIM workflow and its assessment-grade outputs.

More focused contributions, such as Liu et al. [14] and Borkowski and Kubrat [15], address TLS acquisition, point-cloud processing, scan-to-HBIM modelling, and implementation constraints. These studies are directly relevant to the technical workflow examined here, but their emphasis remains primarily on documentation and model generation. Liu et al. (2023) [14] follow a PRISMA-guided approach focused on static terrestrial laser scanning (TLS) for HBIM development, emphasizing acquisition and processing practices and identifying limitations related to guidance and automation in HBIM generation. Borkowski & Kubrat (2024) [15] present an implementation-oriented scan-to-BIM workflow supported by a small number of case studies, with emphasis on practical modeling steps and integration considerations.

In contrast, Huang et al. [16] demonstrate the value of GIS and space syntax for analyzing historical urban morphology, using digitized maps of ancient Wenzhou City from 1566, 1765, 1876, and 1949 to examine the evolution of street/water networks and urban functions. Although not focused on TLS or HBIM, this study is relevant because it shows how spatial data and GIS-based interpretation can support heritage protection at the urban scale.

Building on these contributions, this study adopts a targeted scope restricted to the TLS–BIM–CH intersection (Scopus, 2000–2026; PRISMA-style screening) and structures the synthesis according to assessment-driven requirements, with particular attention to TLS-informed BIM/HBIM outputs relevant to structural assessment, monitoring, and preservation decision support, alongside a structured synthesis and research agenda.

3. Results and Discussion

3.1. Crowdsourcing for Preliminary Inventory, Participatory Mapping, and Rapid Screening

In the context of cultural heritage documentation and risk-oriented assessment, crowdsourcing can be understood as the structured use of contributions from a large and diverse group of participants to generate, enrich, validate, or contextualize digital information about heritage assets. Rather than replacing expert survey, diagnostic inspection, or engineering assessment, it provides an upstream data-enrichment layer that can support preliminary inventories, participatory mapping, metadata improvement, geotagging, photographic documentation, visual condition reporting, and the prioritization of assets requiring detailed investigation. This is particularly relevant because cultural heritage datasets are often incomplete, dispersed, heterogeneous, and difficult to update at scale, especially across extensive historic urban areas or territorial heritage portfolios [17–20].

In assessment-oriented workflows, crowdsourcing therefore plays a mainly preparatory and complementary role. Citizen-contributed photographs, geolocated observations, mobile forms, street-level imagery, UAV imagery, and web-based mapping tools can provide broad spatial coverage and rapid updates where large numbers of heritage buildings must be screened before detailed survey campaigns are feasible. These inputs can help establish asset location, apparent use, visible façade condition, accessibility constraints, and possible indicators of damage or vulnerability; however, they should be interpreted as screening-level evidence rather than assessment-grade geometric or structural data. Crowdsourcing can help identify buildings or urban areas requiring detailed documentation, while TLS, photogrammetry, UAV-LiDAR, and HBIM remain necessary for high-resolution geometry, deformation measurement, crack mapping, semantic modelling, monitoring, and structural or seismic assessment. Thus, the relationship is not a single automated chain from crowdsourcing to structural assessment, but a multi-level information pathway in which crowdsourced observations guide the deployment of more precise survey and modelling techniques [21–24].

A practical example of this role, with focus on potential seismic hazards, is the use of Rapid Visual Screening (RVS), where crowdsourcing or distributed field-data collection can be structured through FEMA P-154-based forms and implemented using tools such as ArcGIS Survey123, distinguished between Level 1 or 2 data collection approaches, building-type classification, vertical and plan irregularity identification, soil type, final RVS score, and the relation between screening score and collapse probability. Mobile or web-based RVS forms can structure observations on building typology, apparent irregularities, occupancy, visible damage, and site conditions. These data can then be integrated into GIS-based platforms to support prioritization, risk mapping, and selection of assets for subsequent TLS survey and HBIM development [25–27].

Nevertheless, crowdsourcing introduces well-known limitations that must be explicitly managed. These concerns include data quality, long-term sustainability, validation of contributions, expert authority, accuracy, and the risk that low-quality contributions may create additional data-cleaning burdens. For this reason, crowdsourced heritage data should be accompanied by validation protocols, contributor guidance, controlled vocabularies, geolocation checks, photographic evidence, expert review, and, where possible, cross-comparison with authoritative records or high-resolution survey data. Its value for seismic or structural assessment depends less on the volume of contributions alone and more on whether these contributions are sufficiently standardized, of approved quality, traceable, and verifiable to support expert decision-making.

Accordingly, in the present review, crowdsourcing is treated as a complementary data-enrichment and prioritization mechanism rather than as a substitute for TLS–BIM/HBIM or engineering analysis. It can expand the spatial and temporal coverage of heritage inventories, support public engagement, assist post-event damage reporting, and identify assets requiring detailed documentation. However, assessment-grade outputs—such as deformation quantification, structural-element recognition, HBIM generation, numerical model updating, and seismic vulnerability assessment—require controlled survey methods, validated geometric data, expert interpretation, and engineering modelling. This framing clarifies the role of crowdsourcing within the broader digital heritage workflow while avoiding the overstatement that crowdsourced data alone can support structural or seismic risk assessment.

3.2. Complementary Remote-Sensing and Image-Based Data Sources for Multi-Scale Heritage Monitoring

Although this review focuses on TLS–BIM/HBIM integration for cultural heritage applications, several complementary data sources can support broader monitoring and assessment workflows. These sources are not substitutes for TLS in high-resolution geometric documentation, but they can improve prioritization, coverage, and temporal continuity in multi-scale heritage monitoring.

At the portfolio scale, street-level imagery and machine-learning approaches can support rapid vulnerability screening when detailed surveys are not yet available. Such methods can assist in identifying building typologies, visible façade characteristics, and potential exposure indicators, thereby helping stakeholders prioritize assets for detailed TLS acquisition and BIM/HBIM development. However, these approaches provide indirect proxies rather than assessment-grade geometric information and should therefore be used with explicit attention to uncertainty and model bias [23].

Satellite SAR/InSAR and multi-temporal InSAR techniques offer a different type of complementary input by enabling large-scale, non-intrusive monitoring of ground and structural deformation over time. In the context of cultural heritage, these methods are particularly relevant for early-warning screening, post-event assessment, and the identification of areas requiring closer investigation. Their value lies in temporal continuity and regional coverage, whereas TLS remains more suitable for local high-resolution documentation, deformation quantification, and integration into BIM/HBIM-based digital twins [28].

At the asset scale, UAV photogrammetry and UAV-LiDAR can complement TLS by improving access to roofs, upper façades, and other difficult-to-reach areas. A practical multi-sensor strategy therefore combines broad-area screening tools, such as street-level imagery or InSAR, with targeted UAV and TLS surveys for detailed geometric capture. BIM/HBIM can then function as the integration environment in which geometry, semantics, and monitoring records are structured for documentation, conservation planning, and seismic-risk-related decision support. In this sense, complementary data sources are most useful when they strengthen, rather than displace, the central TLS–BIM/HBIM workflow [29].

3.3. Building Stability Monitoring and Utilization of Laser Scanning Technologies

Monitoring the stability of buildings is a critical aspect to ensure the safety and durability of structures. By monitoring stability, potential issues that could lead to structural failures, which can have catastrophic consequences, including loss of life, property damage, and significant economic impacts can be identified.

Regular monitoring is essential for early detection of problems such as foundation settling, material degradation, and structural deformations caused by environmental factors. For example, buildings in seismic zones require continuous monitoring to detect problems caused by earthquakes. Similarly, structures exposed to harsh weather conditions, such as heavy snowfall, high winds, or flooding, need to be regularly assessed for stability to prevent sudden collapses. Moreover, stability monitoring supports compliance with building codes and standards, ensuring that structures meet required safety specifications.

Specifically for heritage buildings, stability monitoring is also vital for preserving those assets with significant cultural, historical, and architectural value. Heritage buildings often encounter unique challenges due to their age, construction materials, and architectural details, and may suffer from age-related wear and tear that can compromise their structural integrity. Thus, monitoring the structural health of historic structures is essential as:

- They are prone to deterioration over time and external activities can compromise their stability. This deterioration reduces structural integrity and heightens safety concerns during ongoing use and preservation efforts.
- During maintenance or renovation, historic buildings and landmarks are subjected to additional forces that can limit their resilience. Deformation monitoring helps teams understand the impact of their work, ensuring that they can extend the usable life of these structures without causing damage. This ensures that restoration activities can proceed safely.
- Protection during nearby construction is also critical. Ground disturbances from adjacent construction projects can introduce stress to the structure, leading to deformation or distortions. Early warnings of such movements can prevent damage to the structure.
- Documenting historical changes, such as cracks or object alignments, is essential for maintaining structural monitoring records throughout a building's lifetime. This documentation aids in preservation for future generations and provides a history of changes, which can be invaluable if a disaster occurs.
- Environmental changes significantly impact older structures, which were not built to modern standards. Severe weather events, erosion, and natural shifts in the Earth's

surface can cause instability and damage. Monitoring these events and their effects is vital for the preservation and continued use of historic structures.

By employing LiDAR and laser scanning technologies for monitoring heritage buildings, stakeholders can gain valuable insights into their structural health and detect any signs of deterioration or instability early on. These technologies provide detailed spatial data that enable comprehensive assessments of the building's condition, including identifying cracks, deformations, and other structural issues that may compromise its stability.

Furthermore, monitoring heritage buildings using LiDAR and laser scanning allows for the development of tailored conservation and maintenance strategies. By accurately documenting the building's current state and tracking changes over time, key decisions regarding repairs, restoration, and preventive measures can be taken by the stakeholders.

In the event of natural disasters or unforeseen events, such as earthquakes or floods, real-time monitoring of heritage buildings becomes crucial for rapid response and emergency interventions. LiDAR and laser scanning technologies enable quick assessment of damage and help prioritize rescue and recovery efforts, minimizing further deterioration and loss of CH.

For the selection of the most appropriate survey method to be applied, the size and complexity of the object, as well as its accessibility are taken into consideration. Also, the availability of the appropriate equipment and the budget are important considerations. Figure 4 depicts the difference between available techniques in terms of object complexity (points captured) and object size.

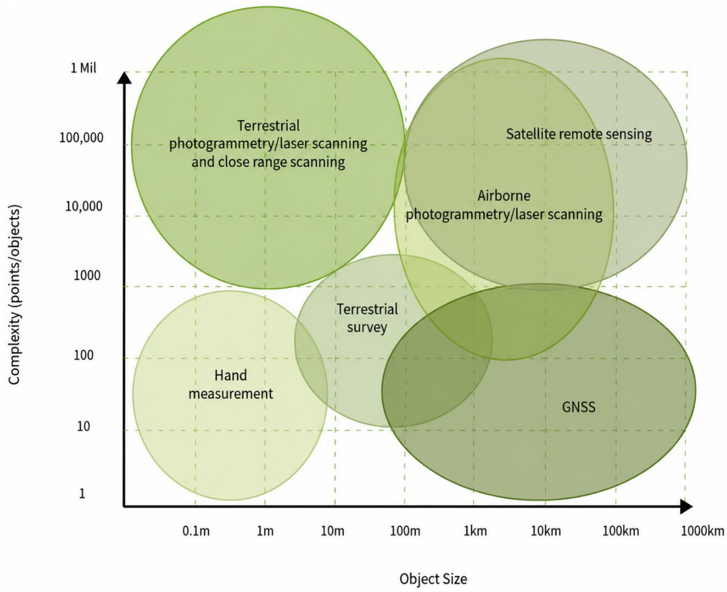


Figure 4. Survey techniques defined by object complexity (points captured) and size. Adapted from Boardman et al. [30].

3.3.1. Traditional Methods of Stability Monitoring

Traditional methods of building stability monitoring include visual inspections, manual surveying, and the use of basic measurement tools such as plumb lines, levels, and theodolites or IR thermography. Visual inspections involve competent inspectors examining the structure for visible signs of damage or deformation, such as cracks, tilting, or material deterioration (Figure 5). Manual surveying techniques, including triangulation and leveling, are used to measure displacements and deformations over time.

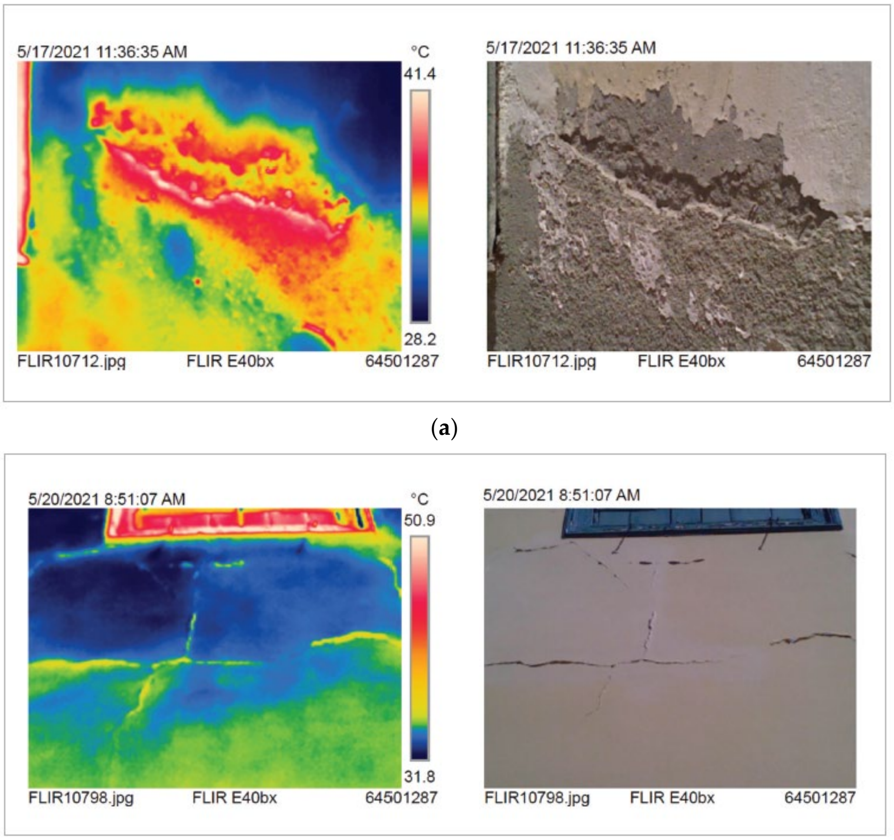
Figure 5. Visual examination of residential building in Nicosia, Cyprus.

Although these methods can be effective and provide detailed assessment of the visual condition of heritage assets, are often labor-intensive, time-consuming, and subject to human error. Additionally, in terms of assessing building's stability, these methods may not provide the comprehensive data needed for a thorough assessment. As expected, access to certain parts of a structure can also be challenging, making it difficult to conduct a thorough examination and evaluation. Despite these limitations, traditional methods have laid the foundation for more advanced monitoring techniques and are still used in conjunction with modern technologies.

Selected studies in which visual examination of cultural heritage buildings was combined with other methods for condition assessment are presented below.

Xystouris et al. (2021) [31] investigated the effect of climate change on the degradation of heritage buildings' in the historic core of two cities in Cyprus, by employing IR thermography. Specifically, the effect of weathering due to climate change was examined for porous limestone derived from specific regions in the island, and locally produced adobe brick. The authors identified four principal weathering mechanisms affecting building façades under subtropical climatic conditions. The most frequent and damaging mechanism was moisture-related deterioration, caused by rising damp (Figure 6a), rainwater infiltration through façade cracks, and high atmospheric humidity, which can promote repeated evaporation cycles and salt crystallization. Thermal expansion was the second most significant mechanism, as substantial day–night surface temperature fluctuations generated material stresses, cracking, and further water penetration (Figure 6b). Carbon dioxide deposition, observed through façade blackening and discoloration, was found to have a comparatively limited impact and could be addressed relatively easily. Microbial and plant growth was the least common of the four mechanisms and generally occurred in damp, shaded areas with cracks or mortar voids. Although all identified mechanisms are potentially influenced by climate change, the authors concluded that longer-term monitoring is required to establish a direct relationship between climate change and accelerated building deterioration.

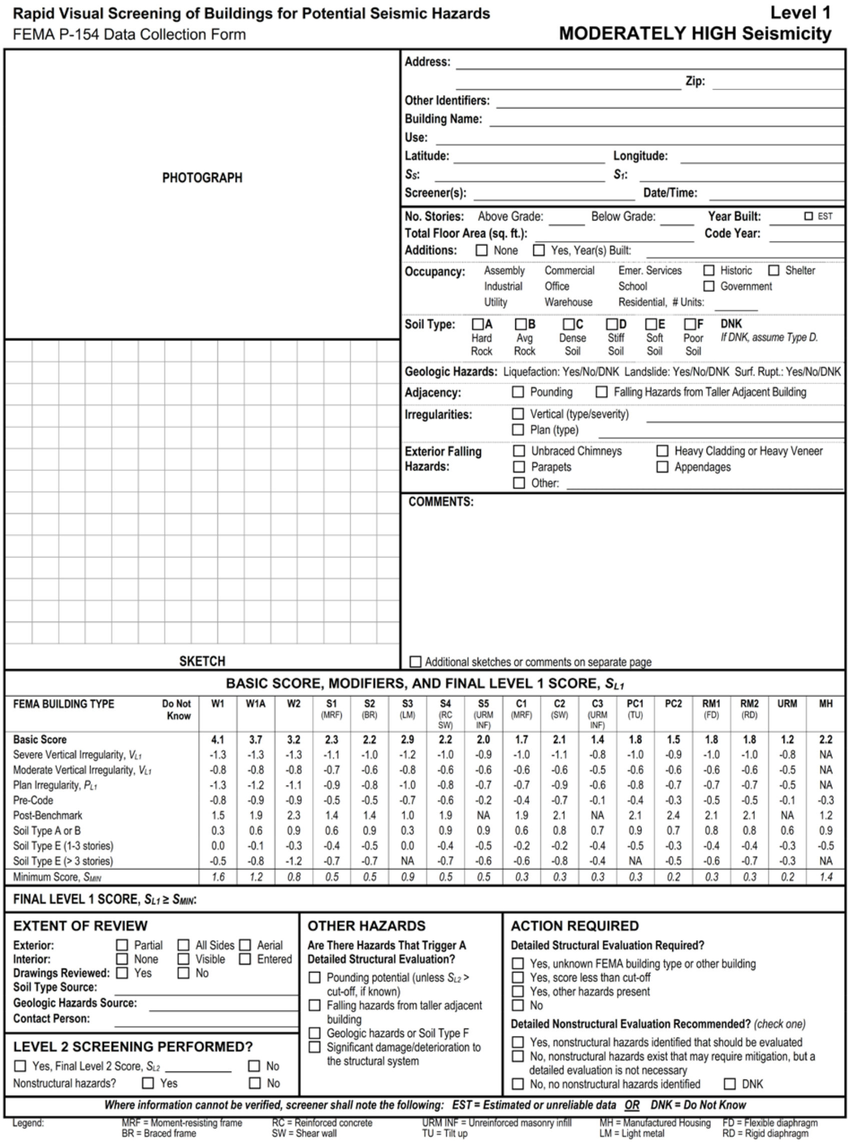
Bektas and Kegyes-Brassai (2023) [32] applied the FEMA P-154 Level 1 Rapid Visual Screening methodology to assess the seismic vulnerability of 20 unreinforced masonry residential buildings in Győr, Hungary. The FEMA approach was selected because it provides a rapid and comparatively low-cost means of screening a large building stock using observable characteristics, including building type, age relative to seismic-code adoption, soil conditions, and plan or vertical irregularities. Using the moderate-seismicity screening form, the authors found that all 20 buildings obtained final scores below FEMA's recommended cut-off value of 2.0, indicating that each building warranted further professional assessment. More specifically, 15% of the buildings were classified as having a high probability of Grade 4 damage and a very high probability of Grade 3 damage, while the remaining 85% had a high probability of Grade 3 damage and a very high probability of Grade 2 damage. The study therefore demonstrated the usefulness of FEMA P-154 as a prioritization tool for identifying potentially vulnerable buildings, although the authors noted that the method is conservative and recommended detailed vulnerability assessments, particularly for the three buildings with the lowest scores and combined plan and vertical irregularities.



(b)

Figure 6. (**a**) rising damp/salt crystallization; (**b**) the cracking directly related to thermal expansion of the materials due to prolonged sun exposure and repeated temperature fluctuations. Adapted from Xytouris et al. [31].

Haryanto et al. (2020) [33] evaluated the seismic vulnerability of a seven-story reinforced-concrete academic building at Jenderal Soedirman University, Indonesia, using FEMA P-154 Rapid Visual Screening (Figure 7) together with the more detailed FEMA 310 Tier 1 procedure. The building was assessed as both a concrete moment-resisting frame (C1) and a concrete frame with unreinforced masonry infill walls (C3), producing Level 1 scores of 3.6 and 1.4, respectively. Because the C3 score was below the FEMA cut-off value of 2.0, the authors concluded that a more detailed structural evaluation was required. The Tier 1 assessment also identified several noncompliant conditions, including a soft-story deficiency, interference from infill walls, excessive column shear stress, inadequate column-tie spacing, insufficient joint reinforcement, and the presence of unreinforced masonry elements. These findings demonstrate that combining rapid screening with FEMA 310 checklists can reveal vulnerabilities that may not be apparent from visual inspection alone, while also providing a basis for prioritizing mitigation measures or progressing to a Tier 2 evaluation.



Rapid Visual Screening of Buildings for Potential Seismic Hazards
FEMA P-154 Data Collection Form

Level 1
MODERATELY HIGH Seismicity

PHOTOGRAPH

Address:
Zip:
Other Identifiers:
Building Name:
Use:
Latitude: **Longitude:**
S_S: S_1:
Screener(s): **Date/Time:**

No. Stories: Above Grade: Below Grade: **Year Built:** ☐ EST
Total Floor Area (sq. ft.): **Code Year:**
Additions: ☐ None ☐ Yes, Year(s) Built:
Occupancy: Assembly Commercial Emer. Services ☐ Historic ☐ Shelter
Industrial Office School ☐ Government
Utility Warehouse Residential, # Units:
Soil Type: ☐A Hard Rock ☐B Avg Rock ☐C Dense Soil ☐D Stiff Soil ☐E Soft Soil ☐F Poor Soil **DNK** *If DNK, assume Type D.*
Geologic Hazards: Liquefaction: Yes/No/DNK Landslide: Yes/No/DNK Surf. Rupt.: Yes/No/DNK
Adjacency: ☐ Pounding ☐ Falling Hazards from Taller Adjacent Building
Irregularities: ☐ Vertical (type/severity) ☐ Plan (type)
Exterior Falling Hazards: ☐ Unbraced Chimneys ☐ Heavy Cladding or Heavy Veneer ☐ Parapets ☐ Appendages ☐ Other:
COMMENTS:

SKETCH

☐ Additional sketches or comments on separate page

BASIC SCORE, MODIFIERS, AND FINAL LEVEL 1 SCORE, S_{L1}

FEMA BUILDING TYPE	Do Not Know	W1	W1A	W2	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	S5 (URM INF)	C1 (MRF)	C2 (SW)	C3 (URM INF)	PC1 (TU)	PC2	RM1 (FD)	RM2 (RD)	URM	MH
Basic Score		**4.1**	**3.7**	**3.2**	**2.3**	**2.2**	**2.9**	**2.2**	**2.0**	**1.7**	**2.1**	**1.4**	**1.8**	**1.5**	**1.8**	**1.8**	**1.2**	**2.2**
Severe Vertical Irregularity, V_{L1}		-1.3	-1.3	-1.3	-1.1	-1.0	-1.2	-1.0	-0.9	-1.0	-1.1	-0.8	-1.0	-0.9	-1.0	-1.0	-0.8	NA
Moderate Vertical Irregularity, V_{L1}		-0.8	-0.8	-0.8	-0.7	-0.6	-0.8	-0.6	-0.6	-0.6	-0.6	-0.5	-0.6	-0.6	-0.6	-0.6	-0.5	NA
Plan Irregularity, P_{L1}		-1.3	-1.2	-1.1	-0.9	-0.8	-1.0	-0.8	-0.7	-0.7	-0.9	-0.6	-0.8	-0.7	-0.7	-0.7	-0.5	NA
Pre-Code		-0.8	-0.9	-0.9	-0.5	-0.5	-0.7	-0.6	-0.2	-0.4	-0.7	-0.1	-0.4	-0.3	-0.5	-0.5	-0.1	-0.3
Post-Benchmark		1.5	1.9	2.3	1.4	1.4	1.0	1.9	NA	1.9	2.1	NA	2.1	2.4	2.1	2.1	NA	1.2
Soil Type A or B		0.3	0.6	0.9	0.6	0.9	0.3	0.9	0.9	0.6	0.8	0.7	0.9	0.7	0.8	0.8	0.6	0.9
Soil Type E (1-3 stories)		0.0	-0.1	-0.3	-0.4	-0.5	0.0	-0.4	-0.5	-0.2	-0.2	-0.4	-0.5	-0.3	-0.4	-0.4	-0.3	-0.5
Soil Type E (> 3 stories)		-0.5	-0.8	-1.2	-0.7	-0.7	NA	-0.7	-0.6	-0.6	-0.8	-0.4	NA	-0.5	-0.6	-0.7	-0.3	NA
Minimum Score, S_{MIN}		*1.6*	*1.2*	*0.8*	*0.5*	*0.5*	*0.9*	*0.5*	*0.5*	*0.3*	*0.3*	*0.3*	*0.3*	*0.2*	*0.3*	*0.3*	*0.2*	*1.4*

FINAL LEVEL 1 SCORE, $S_{L1} \geq S_{MIN}$:

EXTENT OF REVIEW
Exterior: ☐ Partial ☐ All Sides ☐ Aerial
Interior: ☐ None ☐ Visible ☐ Entered
Drawings Reviewed: ☐ Yes ☐ No
Soil Type Source:
Geologic Hazards Source:
Contact Person:

LEVEL 2 SCREENING PERFORMED?
☐ Yes, Final Level 2 Score, S_{L2} ☐ No
Nonstructural hazards? ☐ Yes ☐ No

OTHER HAZARDS
Are There Hazards That Trigger A Detailed Structural Evaluation?
☐ Pounding potential (unless S_{L2} > cut-off, if known)
☐ Falling hazards from taller adjacent building
☐ Geologic hazards or Soil Type F
☐ Significant damage/deterioration to the structural system

ACTION REQUIRED
Detailed Structural Evaluation Required?
☐ Yes, unknown FEMA building type or other building
☐ Yes, score less than cut-off
☐ Yes, other hazards present
☐ No
Detailed Nonstructural Evaluation Recommended? *(check one)*
☐ Yes, nonstructural hazards identified that should be evaluated
☐ No, nonstructural hazards exist that may require mitigation, but a detailed evaluation is not necessary
☐ No, no nonstructural hazards identified ☐ DNK

Where information cannot be verified, screener shall note the following: EST = Estimated or unreliable data OR DNK = Do Not Know

Legend: MRF = Moment-resisting frame; BR = Braced frame; RC = Reinforced concrete; SW = Shear wall; URM INF = Unreinforced masonry infill; TU = Tilt up; MH = Manufactured Housing; LM = Light metal; FD = Flexible diaphragm; RD = Rigid diaphragm

Figure 7. FEMA P-154 data collection form [25].

3.3.2. Advancements in Monitoring Techniques

Advancements in technology have significantly enhanced the methods available for monitoring building stability. Modern techniques such as LiDAR and laser scanning offer high precision, extensive coverage, and the ability to capture detailed 3D data of structures. These methods enable continuous and remote monitoring, reducing the need for physical inspections and enhancing overall safety. Additionally, the integration of these technologies with software tools allows for sophisticated data analysis, real-time monitoring, and automated reporting, providing a more comprehensive and accurate assessment of building stability.

LiDAR and laser scanning can capture huge numbers of data points in short time, creating highly detailed and accurate 3D models of the examined structures. These models can be analyzed to detect even minor deformations and changes in the building's geometry, providing a comprehensive assessment of its stability. Nevertheless, the value of these datasets depends on survey design, registration accuracy, repeatability, and validation. Continuing advances in sensor performance, processing algorithms, and change-detection methods are improving their precision and operational suitability for heritage-building monitoring.

3.3.3. Suitability of Laser Scanning Technologies for Heritage-Asset Monitoring and Structural Assessment

Laser scanning technologies are widely used in cultural heritage because they provide dense, non-contact three-dimensional documentation of geometrically complex and fragile assets. For the purposes of heritage monitoring and structural assessment, the most relevant distinction is not the physical operating principle of each scanner, but the suitability of different platforms and acquisition strategies for specific assessment outputs. Terrestrial laser scanning (TLS) is generally the most appropriate method for high-resolution building-scale documentation, including façades, interiors, vaults, masonry surfaces, structural elements, deformation patterns, and visible damage. Mobile laser scanning (MLS), airborne laser scanning (ALS), UAV-LiDAR, and close-range scanning can complement TLS where wider spatial coverage, faster acquisition, roof access, upper-façade documentation, or difficult site accessibility is required.

The selection of a scanning method should be guided by the scale of the heritage asset, the required geometric accuracy and level of detail, site accessibility, the extent of line-of-sight obstructions, the available budget, and the intended use of the resulting data.

TLS is particularly suitable when the objective is to generate accurate point clouds for HBIM modelling, dimensional control, deformation analysis, crack mapping, or structural model preparation. Its main advantages are high point density, non-contact acquisition, repeatability, and the ability to capture irregular geometries that are difficult to document using manual methods. These characteristics make TLS especially useful for historic masonry buildings, monuments, towers, churches, archeological structures, and other assets where structural irregularities and construction heterogeneity are important.

However, TLS and related laser scanning methods should not be considered as automatically assessment-grade. Their reliability depends on scan planning, registration quality, point-cloud density, control-point distribution, surface reflectance, line-of-sight conditions, and validation against independent measurements where possible. Common limitations include line-of-sight obstructions behind architectural details or vegetation, restricted access to roofs and upper façades, difficulty capturing narrow spaces, large data volumes, registration errors, and the need for substantial post-processing before point clouds can be converted into HBIM or structural-analysis inputs. In addition, laser scanning records geometry and surface condition, but it does not directly provide material properties, internal construction details, boundary conditions, or mechanical parameters required for structural or seismic analysis.

At the instrument level, triangulation, pulse/time-of-flight (TOF), and phase-shift scanners offer distinct performance trade-offs. Table 3 summarizes their principal advantages, limitations, and typical heritage applications; the stated suitability is indicative because actual performance remains instrument- and survey-dependent.

For assessment-oriented TLS–BIM/HBIM workflows, laser scanning should therefore be understood as a source of geometric and diagnostic evidence. It can support the identification of wall inclinations, out-of-plane deformations, settlements, geometric asymmetries, cracks, material loss, and other visible damage indicators. It can also provide the geometric basis for HBIM generation, finite-element idealization, model updating, and condition-informed conservation planning. Nevertheless, the transition from point cloud to structural assessment requires additional interpretation, including semantic segmentation, element recognition, damage classification, geometric simplification, uncertainty control, and integration with engineering assumptions.

Table 3. Comparative characteristics of principal laser-scanning measurement technologies.

Technology	Main Advantages	Main Limitations	Typical Heritage Applications
Triangulation	Very high accuracy and fine spatial resolution at close range; effective for small, intricate surfaces and ornamental detail.	Short operating range; sensitive to ambient light, surface reflectance, and stable instrument-target geometry; generally unsuitable for whole-building capture.	Sculptures, carvings, decorative elements, artefacts, and localized crack or surface-detail documentation.
Pulse/ time-of-flight (TOF)	Long measurement range, broad spatial coverage, and comparatively low spurious point noise; suitable for large interiors, façades, and site-scale geometry.	Typically lower point-acquisition rate and fine-detail resolution than phase-shift systems; accuracy is affected by pulse detection, timing electronics, signal strength, and target reflectance.	Building-scale and site-scale surveys, towers, façades, interiors, landscapes, and assets requiring long stand-off distances.
Phase shift	High acquisition speed and dense point clouds at short-to-medium range; well suited to detailed geometric documentation and repeated surveys.	Range ambiguity and generally shorter effective range than TOF; sensitivity to signal strength, noise, oscillator stability, atmospheric effects, and reflective or dark surfaces.	Detailed façades and interiors, masonry geometry, deformation mapping, and complex architectural components.

A practical implication for cultural heritage studies is that no single scanning platform is sufficient for all documentation and assessment tasks. TLS is preferable for high-fidelity building-scale documentation; UAV photogrammetry or UAV-LiDAR can improve coverage of roofs and inaccessible upper parts; MLS and ALS are more suitable for street-scale or urban-scale screening; and traditional monitoring instruments remain valuable for local, high-frequency, or point-specific displacement measurements. The strongest workflows are therefore multi-source and assessment-driven: the survey method is selected according to the required scale, accuracy, accessibility, monitoring frequency, validation needs, and final use of the data within HBIM, structural modelling, or conservation decision-making.

Table 4 presents a comparative synthesis of survey and monitoring methods used in cultural heritage documentation and structural assessment. It summarizes the main applications, advantages, limitations, and assessment suitability of TLS, UAV-based methods, MLS, ALS, and traditional monitoring techniques, highlighting that method selection should depend on scale, required accuracy, accessibility, validation needs, and the intended use of the data within HBIM or structural-analysis workflow [34–42].

3.3.4. Laser Scanning Integration with Other Monitoring Systems—Structural Health Monitoring (SHM) Systems and Internet of Things (IoT)

Structural health monitoring (SHM) systems involve the use of sensors and data acquisition technologies to assess structural condition continuously or at defined intervals. Contemporary SHM architectures increasingly incorporate Internet of Things (IoT) connectivity, enabling smart sensors to acquire, preprocess, transmit, and store measurements such as strain, vibration, temperature, humidity, inclination, and crack opening for near-real-time analysis [42].

Laser scanning and SHM provide complementary evidence. SHM systems can monitor various parameters, such as strain, temperature, and vibration, which can indicate potential issues affecting the stability of a structure. The data from SHM systems can be combined with the detailed spatial data from LiDAR and laser scanning. Their integration can link measured strain, vibration, or environmental changes with observed deformation, displacement, and surface damage, thereby improving diagnosis and supporting threshold-based alerts, maintenance planning, and model updating.

Table 4. Comparative suitability of laser scanning and complementary monitoring methods for cultural heritage documentation and structural assessment.

Method	Best Suited for	Main Advantages	Main Limitations	Suitability for Structural Assessment
TLS	Building-scale façades, interiors, masonry geometry, deformation and damage mapping	High point density, accurate 3D geometry, non-contact acquisition, repeatable surveys	Occlusion, large datasets, registration error, access constraints, post-processing burden	High when validated and linked to engineering interpretation
UAV photogrammetry/ UAV-LiDAR	Roofs, towers, upper façades, inaccessible areas	Flexible acquisition, improved coverage, useful for visual and geometric documentation	Weather and flight restrictions, variable accuracy, limited detail for fine cracks depending on resolution	Moderate to high as complement to TLS
MLS	Street-scale heritage documentation and façade screening	Fast acquisition, useful for urban portfolios and rapid surveys	Variable point density, positioning errors, traffic/urban occlusion	Moderate for screening; limited for detailed assessment
ALS	Urban/territorial context, terrain, exposure and hazard mapping	Broad spatial coverage, useful for inventories and terrain context	Lower detail for individual building damage or cracks	Low to moderate for individual assets; useful for context
Traditional monitoring	Crack gauges, levelling, total stations, visual inspection	Low-cost, targeted, repeatable at selected points	Sparse coverage, manual effort, observer dependency	High for local measurements, limited for full 3D geometry

In this framework, the geometric digital twin derived from scanning can be progressively enriched with sensor histories, inspection records, and analytical models to form a structural digital twin. However, effective integration requires synchronized timestamps, stable reference systems, sensor calibration, uncertainty management, interoperable data structures, and periodic validation of both sensor and point-cloud measurements. For example, strain sensors can detect stress in a building's materials, while LiDAR can capture any resulting deformations in the structure's geometry. This integrated approach allows for more accurate and real time detection of stability issues, enabling response to potential issues and proactive maintenance and repair efforts. In other words, the geometric digital twin provided by scanners can be upgraded through modelling and health monitoring into a structural digital twin.

3.3.5. Integration of TLS with Multi-Source Diagnostics and Structural Modelling

Several studies have been conducted recently, reviewing the role BIM can play in CH preservation efforts. A systematic review study was conducted by Sánchez-Aparicio et al. [1] in which previous works have been evaluated, where the 3D point cloud has been applied for the detection of damage in historical constructions. The study revealed a growing trend in this approach, particularly in the structural field where the TLS is the most commonly used sensor due to its capacity of capturing reality with great density and accuracy, allowing for the extraction of different type of damages related to the geometry of the elements such as deflections or out-of-plane deformations. Also, the capability of 3D point clouds to store radiometric information (i.e., in the form of intensity and/or digital levels) which can be utilized for detecting other types of damage (e.g., moisture or crusts) was highlighted. Ding et al. [43] conducted a systematic literature review study aiming to determine the application fields and development trends of BIM and architectural heritage in China. In the work carried out by Rashdi et al. [44], scan-to-BIM methodology has been analyzed in details, focused on the 3D point clouds of LiDAR and photogrammetry, point-cloud processing and highlighted the importance of integrating multisource. The study also reviewed different open BIM standards.

Li et al. [45] examined the application of 3D LiDAR in the preservation of built heritage from a multidisciplinary perspective and provides an overview of 3D LiDAR and its integration with other technologies, covering key trends, methods, applications, challenges, and future technological advancements in heritage sites. Through an analysis of existing studies on 3D LiDAR and multi-technology collaboration, the review highlights the growing diversity in its applications and demonstrates how combining it with other technologies can yield valuable insights when addressing specific issues.

Ascione et al. [46] followed a synergic approach to investigate the behavior of a historical masonry building, namely the University of Sannio, Palazzo Bosco Lucarelli in South Italy, with reference to both its structural and energy performance. The proposed diagnosis approach has required accurate archival research and the collection of many geometrical features. In situ surveys were also conducted to identify structural details and to define the thermo-physical properties of the building materials. Moreover, this phase also involved the audit of technical plant and the identification of functional zones. The structural finite-element model, validated through dynamic in situ test results, was used to evaluate the safety level concerning gravity loads and seismic actions as outlined by the Italian national code.

The level of integration of TLS with other technologies, namely photogrammetry and thermography, for the detection and characterization of building anomalies was extensively assessed in the study conducted by Gomes and Tomé [47]. Following a literature review, the authors suggested a methodological approach which integrates TLS, aerial digital photogrammetry (ADP), thermography and traditional non-destructive methods aiming to conduct visual diagnosis and mapping of pathologies of their case study building (i.e., Moorish Castel in Sintra, Portugal). The methodology consists of the following stages:

1. Use of traditional non-destructive techniques on a pilot zone and comparison of results with the thermographic analysis;
2. Geometric modelling using TLS and ADP;
3. Comparison of the results obtained with aerial thermograms and with thermograms captured more closely to the surface of the walls;
4. Visual identification of pathologies based on the point-cloud elevations obtained with TLS and ADP, together with the inputs from the thermogram results.

In the literature, the Neoria masonry structure at the Venetian harbor of Chania has been extensively studied [48–53]. Geometrical information about the structure were obtained by utilizing terrestrial or aerial scanners and the existing drawings were updated and enriched thorough new measurements which resulted to a fully three-dimensional model with adequate details able to support structural analysis. Areas with different material properties were analyzed and various construction materials were color coded and further investigated by using various destructive and non-destructive testing techniques. Finite-element models were created following an analytical investigation of structure's damages. The most important deteriorations of those detected were chosen to be included in the structural model.

Furthermore, in the study, a parametric analysis was carried out to check the sensitivity of the ultimate load due to the estimated coefficient of friction between the masonry stones and the number of masonry stones that make up one arch. The failure mechanism obtained from the parametric models was correlated with the on-site observation (i.e., the longitudinal cracks on arch). From the collapse type and the performance of the overall two-dimensional model it was observed that the most vulnerable areas were the extreme vaults. The finite-element models were developed on commercial platforms using the Newton–Raphson incremental–iterative procedure to deal with the nonlinear nature of the problem. For the structure of Neoria, which is investigated in the mentioned article, an extended finite-element (XFEM) model [54] has been developed in Abaqus [55] to capture the transverse cracks. It allows for cracks to be modelled independently of the mesh, permitting the propagation of the crack along an arbitrary, solution-based path. A simplified 3-dimensional geometry of the full structure is considered, similar to the full structure in the traditional FEA. According to the results of this investigation, the longitudinal cracks, which were observed on the conventional finite-element analysis with similar load conditions, are also observed under the extended finite-element model. In addition, analysis results indicate that the existing longitudinal cracks do not propagate. However, further future investigation needs to be conducted in order to provide more details for the interaction between longitudinal and transverse cracks and the influence of their interaction on the structural response.

3.4. TLS-BIM/HBIM Integration for Heritage Buildings: A Literature Synthesis

Table 5 summarizes the explicit methodological use of selected technologies across the 161 studies. Because the matrix does not itself capture workflow sequence, validation, barriers, or integration maturity, these dimensions were examined through a separate qualitative full-text coding process described below. Columns 3–14 represent selected methods and technologies identified as recurring components of the reviewed studies and their associated workflows.

To enhance coding reliability, all studies were re-examined using predefined operational criteria for each category in Table 5. An "X" was assigned only when the corresponding method or technology was explicitly reported in the full text, particularly in the methodology, workflow, or results sections. Following this consistency check, the matrix was revised to correct coding errors and resolve ambiguous cases.

As the coding was conducted by a single reviewer, inter-reviewer reliability could not be assessed; this is acknowledged as a limitation of the review.

Building on this coding framework, the following synthesis interprets the evidence in Table 5 in direct relation to the four research questions. First, it examines the end-to-end TLS–BIM/HBIM workflows reported for cultural heritage documentation, monitoring, and structural assessment (Q1). Second, it considers the assessment objectives supported by these workflows and the extent to which their outputs were validated (Q2). Third, it identifies the principal technical, methodological, and operational barriers affecting implementation and wider adoption (Q3). Finally, it evaluates how complementary technologies and data sources, including photogrammetry, UAV-based methods, ALS/MLS, street-level imagery, sensor data, GIS, and InSAR, are used alongside TLS–BIM/HBIM to support multi-scale heritage documentation, monitoring, and assessment (Q4).

The analysis therefore moves beyond reporting the frequency of individual technologies and focuses on how they are combined within assessment-oriented workflows, what outputs they produce, and where methodological limitations remain. Particular attention is given to validation, since the presence of TLS, BIM, or HBIM within a study does not by itself demonstrate that the resulting geometric, semantic, or structural outputs are sufficiently reliable for assessment-grade use.

Table 5. Comparative matrix of the included studies.

Ref:	Year	Laser Scanning/ TLS	Photogrammetry/ SfM	UAV/ UAS	Point Cloud	Scan-to-BIM/ HBIM	Digital Twin	GIS/ Geospatial	NDT	GPR	Infrared Thermography	ML/AI/ Segmentation	VR/AR/ Immersive	IoT	Damage/ Decay Mapping
[56]	2022	X			X	X	X								
[57]	2025	X	X				X						X		
[58]	2025	X	X			X									
[59]	2019	X													
[60]	2022	X													
[61]	2025	X				X	X								
[62]	2025	X				X									
[63]	2021	X	X	X	X									X	
[64]	2020	X	X		X	X									
[65]	2017	X			X	X								X	
[66]	2018	X	X		X										
[67]	2019	X	X		X										
[68]	2025	X	X	X	X									X	X
[69]	2022	X	X			X							X		
[70]	2022	X	X		X	X							X		
[71]	2024	X	X	X	X	X								X	X
[72]	2026	X	X	X	X	X	X	X				X		X	
[73]	2020	X			X	X									X
[74]	2021	X			X	X									
[75]	2021	X			X	X									
[76]	2024	X	X	X				X							
[77]	2025	X			X										
[78]	2015	X	X										X		
[79]	2024	X		X											
[80]	2019	X	X		X	X									
[81]	2025	X	X			X							X		
[82]	2026	X	X	X									X		

Table 5. *Cont.*

Ref:	Year	Laser Scanning/ TLS	Photogrammetry/ SfM	UAV/ UAS	Point Cloud	Scan-to-BIM/ HBIM	Digital Twin	GIS/ Geospa-tial	NDT	GPR	Infrared Ther-mogra-phy	ML/AI/ Segmentation	VR/AR/ Immer-sive	IoT	Damage/ Decay Map-ping
[83]	2019	X	X												
[84]	2017	X	X												
[85]	2018	X			X										X
[86]	2023	X				X							X		
[87]	2025	X	X												
[88]	2025	X			X	X	X					X	X		
[89]	2024	X	X		X							X			
[90]	2019	X	X										X		
[91]	2017	X	X		X										
[92]	2025				X										
[93]	2025	X	X	X	X										X
[94]	2026	X	X	X	X			X				X			X
[95]	2017	X			X										
[96]	2025	X	X									X			
[97]	2017	X	X		X								X		
[98]	2024														
[99]	2026	X	X	X		X							X	X	X
[100]	2025	X	X				X							X	X
[101]	2026	X	X				X					X			
[102]	2023		X		X	X									
[103]	2021	X	X		X										
[104]	2024					X							X		
[105]	2019	X													X
[106]	2025	X	X			X						X			X
[107]	2024	X	X					X							
[108]	2020	X													X
[109]	2017	X	X	X	X									X	

Table 5. *Cont.*

Ref:	Year	Laser Scanning/ TLS	Photogrammetry/ SfM	UAV/ UAS	Point Cloud	Scan-to-BIM/ HBIM	Digital Twin	GIS/ Geospatial	NDT	GPR	Infrared Thermography	ML/AI/ Segmentation	VR/AR/ Immersive	IoT	Damage/ Decay Mapping
[110]	2012	X	X					X							
[111]	2013	X	X												
[112]	2013	X	X												
[113]	2015	X													X
[114]	2026	X			X	X									
[115]	2022	X										X			X
[116]	2021	X												X	
[117]	2017	X													
[118]	2025	X	X	X	X			X							
[119]	2023	X	X	X	X										
[120]	2020	X		X				X	X	X					X
[121]	2017	X	X												
[122]	2024	X	X						X		X				X
[123]	2017	X	X		X										
[124]	2013	X	X		X								X		
[125]	2013	X	X		X										
[126]	2023	X	X		X			X							
[127]	2024	X	X		X							X	X	X	X
[128]	2024	X	X	X	X	X						X		X	
[129]	2021	X	X					X	X		X			X	
[130]	2023	X	X											X	
[131]	2022							X							
[132]	2024	X	X											X	X
[133]	2023	X													
[134]	2023	X		X									X	X	
[135]	2023	X			X										
[136]	2018	X	X												
[137]	2025	X			X										X

Table 5. *Cont.*

Ref:	Year	Laser Scanning/ TLS	Photogrammetry/ SfM	UAV/ UAS	Point Cloud	Scan-to-BIM/ HBIM	Digital Twin	GIS/ Geospatial	NDT	GPR	Infrared Thermography	ML/AI/ Segmentation	VR/AR/ Immersive	IoT	Damage/ Decay Mapping
[138]	2024	X			X								X		
[139]	2025	X	X				X					X	X	X	
[140]	2025	X	X	X											
[141]	2024	X	X	X									X		
[142]	2021	X	X		X										
[143]	2023	X	X		X									X	
[144]	2023		X												
[145]	2025	X											X		
[146]	2020	X	X	X	X										
[147]	2024	X					X					X	X	X	
[148]	2020	X			X	X						X			
[149]	2020	X			X		X								
[150]	2021	X	X		X		X					X			
[151]	2022	X													
[152]	2025	X	X												
[153]	2025	X	X					X							
[154]	2019	X			X			X							
[155]	2022	X	X					X							
[156]	2023	X				X									
[157]	2023	X			X	X	X						X		
[158]	2020	X	X		X	X						X			X
[159]	2023	X			X							X			X
[160]	2024	X		X			X					X			X
[161]	2025	X	X		X	X									
[162]	2025	X	X		X							X			
[163]	2023	X												X	
[164]	2025	X			X			X						X	
[165]	2017	X	X									X			X

Table 5. *Cont.*

Ref:	Year	Laser Scanning/ TLS	Photogrammetry/ SfM	UAV/ UAS	Point Cloud	Scan-to-BIM/ HBIM	Digital Twin	GIS/ Geospatial	NDT	GPR	Infrared Thermography	ML/AI/ Segmentation	VR/AR/ Immersive	IoT	Damage/ Decay Mapping
[166]	2022				X										
[167]	2024	X													
[168]	2020		X											X	X
[169]	2022	X	X		X				X		X			X	
[170]	2019	X	X	X									X		
[171]	2023	X	X		X								X		
[172]	2025	X	X		X							X		X	X
[173]	2018	X	X												
[174]	2024	X													X
[175]	2025	X													
[176]	2019	X	X											X	
[177]	2023	X													
[178]	2025	X		X											
[179]	2019	X			X									X	X
[180]	2019	X	X		X										
[181]	2023					X									
[182]	2022	X													
[183]	2025	X	X			X						X			
[184]	2018	X													
[185]	2018	X	X												
[186]	2019	X	X												X
[187]	2021														
[188]	2021	X													
[189]	2022	X	X		X										
[190]	2025	X	X		X							X		X	
[191]	2020	X		X				X	X	X	X	X			X
[192]	2019	X	X												
[193]	2025	X			X										

Table 5. *Cont.*

Ref:	Year	Laser Scanning/TLS	Photogrammetry/SfM	UAV/UAS	Point Cloud	Scan-to-BIM/HBIM	Digital Twin	GIS/Geospatial	NDT	GPR	Infrared Thermography	ML/AI/Segmentation	VR/AR/Immersive	IoT	Damage/Decay Mapping
[194]	2025	X	X		X		X					X			
[195]	2019	X	X			X									
[196]	2024	X													
[197]	2024	X		X											
[198]	2018	X	X	X											
[199]	2026	X	X				X							X	
[200]	2017	X	X		X										X
[201]	2021	X	X										X		
[202]	2025	X	X		X										X
[203]	2017	X			X										X
[204]	2023				X	X									
[205]	2024	X	X												
[206]	2025	X													X
[207]	2024	X	X	X		X									
[208]	2026	X	X	X											X
[209]	2018	X			X										X
[210]	2025	X	X	X								X		X	X
[211]	2017	X													
[212]	2026	X	X		X								X		
[213]	2025	X	X	X											
[214]	2025	X			X		X								
[215]	2026	X	X	X	X								X	X	X
[216]	2023	X			X							X			

3.4.1. End-to-End TLS–BIM/HBIM Workflows (Q1)

The reviewed literature workflows generally follow a sequence from data acquisition to information-based assessment, although not all studies implement every stage. The principal stages include survey planning and TLS acquisition, point-cloud registration and processing, segmentation or structural-element recognition, HBIM generation, semantic enrichment, condition or damage mapping, and preparation of outputs for monitoring, conservation planning, or structural analysis. The strongest workflows preserve the relationship between the original point cloud, derived geometry, semantic objects, diagnostic evidence, and subsequent analytical models, rather than treating the HBIM model as an isolated final product.

The development of TLS–BIM/HBIM workflows builds on a substantial body of research on historic building information modelling, scan-to-HBIM procedures, and point-cloud-based semantic modelling. Early works introduced HBIM as a method for adding intelligence to laser- and image-based surveys of historic architecture, while later studies and guidelines further formalized HBIM procedures for architectural heritage documentation and information management [217–219]. Subsequent reviews have consolidated the field by examining heritage building information modelling, the integration of HBIM with other information techniques, and the role of complementary technologies in heritage-building workflows [220–222]. Within this development, TLS and point-cloud data have become central to the production of geometrically accurate, semantically enriched, and assessment-oriented HBIM models, although challenges remain regarding point-cloud operability, semantic structuring, interoperability, and the translation of survey data into usable conservation or assessment outputs [223–225].

The reviewed corpus does not reveal a single universally standardized workflow. Instead, it shows a family of related pipelines that share seven recurring stages: purpose definition, controlled acquisition, point-cloud processing, geometric reconstruction, semantic enrichment, assessment, and validation/update [144].

Projects first define the intended use, acceptable tolerance, scan density, coordinate reference, Level of Detail/Level of Information Need, and final deliverables. Purpose is critical because a documentation model, a deterioration map and a finite-element model require different abstractions. Banfi (2019) [80] formalized this through Grades of Generation and Grades of Accuracy, while in their study, Santagati et al. [186] emphasized modelling tolerance for ruined and deformed heritage.

Static TLS is normally the principal metric source for visible façades, interiors and structural elements. Total stations or GNSS provide control and georeferencing; UAV photogrammetry fills roof and upper-façade gaps; close-range photography improves texture; and mobile/handheld scanning accelerates interiors. Integrated examples include the Zee Ain village workflow [63], the Old Great North Road workflow [82], and the TLS-UAV wooden-church workflow of Bac-Bronowicz, Piech, and Wojciechowska (2026) [72].

Scans are registered, georeferenced, denoised and cropped. Point clouds may then be segmented into architectural classes, converted to meshes, or retained as evidential reference layers. The segmentation bottleneck is widely documented: manual interpretation remains dominant, although CANUPO, Random Forest and deep-learning approaches have been tested [89,103,150].

Four strategies recur: manual object creation; semi-automatic fitting of planes, profiles, primitives or NURBS; AI-assisted classification followed by model propagation; and hybrid point-cloud/mesh/parametric representation. Andriasyan et al. (2020) [64] automated conversion through Rhino-Grasshopper-ArchiCAD, while in [102] they used bidirectional Rhino-Grasshopper-Revit exchange, and in [103] they combined Random Forest segmentation with template propagation.

HBIM objects are linked to material, chronology, construction technique, pathology, crack, intervention history, photographs, archival evidence, structural role and uncertainty [71]. Aricò et al. (2024) [58] created a BIM-based decay abacus; and Dudzińska and Borkowski (2026) [114] explicitly recorded evidence source and uncertainty for reconstructed components.

Documentation workflows produce drawings, inventories and information repositories. Monitoring workflows compare repeat surveys or compare measured clouds with reference geometry. Structural workflows simplify point-cloud-derived geometry and transfer it to FEM environments; examples include CLOUD2FEM for an earthquake-damaged fortress [84], HBIM-to-FEM modelling of a parabolic concrete vault [56,202], and the broader survey-to-FEA review by Turchetti et al. (2025) [202].

Outputs are checked using registration residuals, control points, cloud-to-model deviations, independent measurements, expert inspection, diagnostic tests or structural calibration. The strongest workflows also define future re-survey and update procedures, whereas many papers stop after one-off model production [147].

3.4.2. Assessment Objectives and Validation Practices (Q2)

The reviewed studies use TLS–BIM/HBIM workflows for several related but distinct assessment objectives, including geometric documentation, HBIM generation, condition and pathology mapping, deformation monitoring, crack and damage identification, restoration and maintenance planning, historical reconstruction, and structural-analysis model preparation. These objectives impose different accuracy and validation requirements. A workflow suitable for visual documentation, for example, may not provide sufficient evidence for deformation measurement or structural-model preparation. Validation must therefore be interpreted in relation to the intended output rather than as a single generic measure of model quality.

Geometric documentation and HBIM generation:

The most frequent objective is production of plans, elevations, sections, inventories, as-is models and searchable databases. Validation includes registration residuals, control/check points, dimensional checks and cloud-to-model deviations. Al-Bayari and Shatnawi (2022) [60] reported a mean error of 0.61 cm and standard deviation of 0.75 cm; Bac-Bronowicz et al. (2026) [72] reported 0.8–3.2 cm differences between UAV-only and integrated reconstructions, while correctly framing them as internal consistency rather than independent absolute accuracy.

Condition and building pathology mapping:

Workflows map moisture, biological growth, surface loss, detachment, corrosion, discoloration and missing components. TLS supplies metric location, while high-resolution imagery support interpretation. Aricò et al. (2024) [71] and Nieto-Julián et al. (2025) 159 demonstrate progressively richer decay, crack and intervention mapping. Validation is commonly expert-led, using field inspection, photographs, thermography or conservation records [31].

Deformation and displacement monitoring:

Objectives include wall inclination, floor/ceiling deformation, vault distortion, settlement and temporal change. Yaagoubi and Miky (2018) [209] compared measured point clouds against an idealized BIM and reported distortions up to 22 cm. Moyano et al. (2022) [149] compared Dynamo-based deformation analysis with CloudCompare and reported worst-case differences of roughly 0.5–1.17 cm.

Crack and damage identification:

HBIM stores crack position, orientation, width, chronology and association with prior repairs. Nieto-Julián et al. (2025) [160] integrated TLS, UAV data and archival imagery for expert-validated crack and deterioration mapping. AI-assisted methods remain promising but require contextual oversight because surface reflectance, texture and shadow can be confused with genuine defects [89,128].

Restoration and maintenance planning:

HBIM supports quantity estimation, treatment assignment, maintenance prioritization and documentation of interventions. Cuperschmid et al. [105] integrated pathology records into the Glass House HBIM; Ciuffreda et al. (2024) [98] linked diagnostic data, structural assessment and maintenance planning; and Sarıcaoğlu and Saygı (2022) used a data-enriched NURBS/HBIM workflow for conservation decisions at an archeological site [189].

Structural-analysis model preparation:

TLS-derived geometry is converted into beam, shell or solid models for static, dynamic and seismic analyses. Bitelli et al. (2018) [84] applied CLOUD2FEM to an earthquake-damaged fortress; Abbate et al. (2022) [56] compared alternative representations for a parabolic vault; and del Rio et al. (2020) [108] linked bridge HBIM, deterioration records and FEM-oriented information. Validation is much less common than geometric checking and may use observed damage, material tests, modal data or sensitivity analyses.

Historical reconstruction:

Current geometry is combined with archival photography, drawings and analogies. Dzwierzynska and Prokop (2022) [115] directly compared photograph-based and TLS-based reconstruction; Borkowski and Winiarska (2025) [87] reconstructed a demolished villa from LiDAR, surviving components and archives; and Dudzińska and Borkowski (2026) [114] separated surveyed, inferred and hypothetical components through provenance and uncertainty metadata.

3.4.3. Technical, Methodological, and Operational Barriers (Q3)

Despite major advances in data acquisition and modelling, the main barriers occur after point-cloud generation. These include incomplete coverage and occlusion, complex and deteriorated geometries, large datasets, manual or semi-manual reconstruction, uncertain modelling tolerances, limited automation, interoperability losses, weak validation practices, specialist skill requirements, and insufficient planning for long-term model maintenance. The central challenge is therefore not simply to acquire dense geometric data, but to convert heterogeneous evidence into a semantically coherent, validated, interoperable, and maintainable assessment system.

Technical barriers:

Occlusion and incomplete coverage; complex or deteriorated geometry; large datasets; predominantly manual reconstruction; limited AI transferability; incompatible file formats; loss of semantics and geometry during exchange; and weak native support for hybrid point-cloud, mesh and parametric data. These issues are consistently reported by Croce et al. (2023) [103], Gil et al. (2024) [128] and Turchetti et al. (2025) [202].

Methodological barriers:

No universal heritage-specific standards exist for Level-of-Detail/Level-of-Interest, modelling tolerance, pathology classification, uncertainty or validation. Studies also differ in whether deviations are treated as noise or as evidence of structural history. Santagati et al. [185] emphasize that deformation may be diagnostically meaningful, while Kuruc et al. (2024) [138] show how generalization can become modelling error if procurement requirements are unclear.

Validation and reproducibility barriers:

Many studies report manufacturer specifications or visual correspondence rather than project-specific independent checks. Closed-source routines, undocumented parameters and inconsistent metrics make replication difficult. Bac-Bronowicz et al. (2026) explicitly distinguish internal consistency from absolute accuracy, illustrating the need for clearer reporting [72].

Operational and institutional barriers:

Equipment, software, computing, storage, specialist labor, repeat surveys and long-term maintenance are costly. Effective implementation requires geomatics, conservation, architecture, structural engineering, database and programming expertise. Fragmented professional roles and poorly specified procurement often create isolated deliverables rather than shared lifecycle systems [144].

3.4.4. Complementary Data Sources and Multi-Scale Integration (Q4)

TLS functions most effectively as the high-accuracy, building-scale metric backbone of a broader multi-source system. Complementary technologies contribute different evidence types: photogrammetry provides high-resolution texture and orthophotos; UAV and ALS improve coverage of roofs, upper façades, sites, and surrounding terrain; MLS supports rapid street-scale acquisition; non-destructive testing provides information on concealed material conditions; monitoring sensors capture temporal behavior; GIS/HGIS and InSAR provide territorial context; archival records support historical reconstruction; and immersive tools facilitate interpretation, consultation, and field-based updating. The value of integration therefore lies not in replacing TLS, but in combining data sources according to scale, accessibility, temporal frequency, and assessment objective.

Photogrammetry:

On the one hand, close-range and terrestrial photogrammetry adds high-resolution texture, paintings and fine surface detail. TLS provides robust geometry; photogrammetry improves radiometric interpretation and pathology mapping [63,168]. On the other hand, UAV photogrammetry and UAV LiDAR extends coverage to roofs, towers, domes, difficult terrain and large sites. UAV data should complement rather than replace TLS, filling shadow zones and adding site context [119,210].

Mobile, personal and handheld laser scanning:

This enables rapid interiors and circulation-space capture but may suffer trajectory drift and lower absolute accuracy. Integrated static TLS/HMLS workflows balance speed and precision [171].

ALS, street-level imagery and mobile mapping:

ALS links buildings to terrain and landscape hazards; street-level and 360-degree systems provide rapid visual inventories. Matterport-type data can support lower-tolerance geometry or fill limited gaps, although TLS remains the stronger metric reference [145].

Thermography, and other NDT methods:

Infrared, GPR, ultrasonic and related NDT methods reveal moisture, material differences, delamination, voids and hidden structural conditions. Solla et al. (2020) [191] integrated TLS, UAV, thermography and GPR in BIM. The need for common quantitative diagnostic protocols was highlighted and identified in [4].

Structural and environmental sensors:

Accelerometers, tiltmeters, crack meters, strain gauges, temperature and humidity sensors enable continuous monitoring, threshold alerts and FEM calibration. Mazzetto (2024) [147] frames this as a shift from reactive documentation to preventive digital-twin conservation.

GIS and HGIS:

This connects component and building information with urban, cadastral, territorial, landscape and hazard data. Baik et al. [78] integrated JHBIM with 3D GIS; Fernandez Dionizio et al. (2025) exported HBIM through IFC into an HGIS geodatabase for multi-scale conservation.

AR, VR and immersive interfaces:

This supports remote consultation, public interpretation, on-site annotation and field-to-HBIM feedback. Bounouioua et al. (2025) [88] linked AI-assisted HBIM and VR; Clini et al. (2026) [99] used AR-oriented workflows for inspection and updating.

Satellite InSAR:

InSAR is underrepresented in the uploaded corpus but can screen wide-area subsidence, slope instability and slow ground deformation. It is a territorial prioritization tool rather than a substitute for building-scale TLS. A defensible multi-scale hierarchy is: InSAR/ALS for regional screening → UAV/mobile mapping for site context → static TLS for detailed geometry → imaging/NDT for component diagnosis → sensors for continuous monitoring → HBIM/HGIS for integration.

3.5. Knowledge Gaps and Future Research Directions

Although TLS–BIM/HBIM workflows have advanced considerably in cultural heritage documentation, several gaps continue to limit their use in assessment-oriented practice. A first priority is the development of standardized validation protocols. The reviewed literature applies heterogeneous accuracy indicators, registration measures, modelling tolerances, and comparison procedures, making it difficult to compare results across studies or determine whether an output is suitable for documentation, deformation monitoring, damage mapping, or structural analysis. Future research should therefore define task-specific validation criteria covering point-cloud accuracy, registration quality, geometric model fidelity, HBIM representation, damage-detection performance, and structural-model calibration. Validation should also include independent measurements and explicit reporting of uncertainty wherever possible.

A second gap concerns the semantic enrichment of HBIM. While point clouds can capture complex heritage geometry in considerable detail, the conversion of geometric data into meaningful architectural, material, pathological, and structural information remains largely manual or semi-automated. Future HBIM environments should support more consistent representation of irregular masonry, construction phases, material decay, cracks, deformations, previous interventions, and structural relationships. This will require improved ontologies, controlled vocabularies, heritage-specific object libraries, and more reliable links between geometric objects and diagnostic evidence.

Automated damage detection also remains an important research frontier. Machine-learning and computer-vision methods show potential for identifying cracks, surface loss, displacement, moisture-related deterioration, and other visible pathologies from point clouds and images. However, their performance is often affected by limited training datasets, inconsistent annotation, surface texture, lighting, occlusion, and variations in construction materials. Future studies should develop openly available, expert-validated heritage datasets and evaluate automated methods across different building types and damage conditions. Human-in-the-loop approaches may be particularly valuable, combining algorithmic screening with specialist verification.

Another major challenge is the integration of HBIM with structural-analysis models. TLS-derived HBIM can provide detailed geometry and condition information, but structural models require simplification, idealization, material properties, boundary conditions, connection assumptions, and load definitions. The transfer from HBIM to finite-element or other analytical environments is therefore not automatic and may introduce substantial uncertainty. Future research should develop transparent workflows for converting geometric and semantic information into analysis-ready models, while preserving traceability between the point cloud, HBIM elements, modelling assumptions, and structural results.

Uncertainty propagation should be addressed throughout the complete workflow. Errors may arise during acquisition, registration, filtering, segmentation, geometric reconstruction, semantic classification, damage interpretation, and structural idealization. These uncertainties are frequently considered independently, although they can accumulate and influence the final assessment. Future studies should quantify how uncertainty is transferred between workflow stages and examine how it affects structural indicators, monitoring thresholds, and conservation decisions. Probabilistic or sensitivity-based approaches may provide a more transparent basis for evaluating the reliability of assessment outcomes.

Multi-source data fusion represents another important direction. TLS can provide detailed building-scale geometry, but complementary sources such as photogrammetry, UAV imagery, UAV-LiDAR, MLS, ALS, InSAR, environmental sensors, non-destructive testing, archival records, and crowdsourced observations provide different spatial, temporal, and diagnostic information. Future research should move beyond the simple co-occurrence of technologies and demonstrate genuine integration through co-registration, common reference systems, interoperable data structures, and coordinated interpretation. Such integration would allow heritage assessment to connect territorial screening, building-scale documentation, local damage diagnosis, and long-term monitoring.

Finally, the practical adoption of TLS–BIM/HBIM by heritage authorities remains limited by cost, technical expertise, software dependence, data volume, unclear responsibilities, and the absence of long-term information-management strategies. Future research should therefore evaluate not only technical feasibility but also organizational implementation. Future HBIM research should also strengthen the connection between digital heritage documentation and broader sustainability objectives, including low-carbon renovation, material reuse, circular-economy strategies, and the reconciliation of heritage preservation with energy-transition goals [226,227]. Priority should be given to simplified workflows, open data formats, scalable levels of detail, model-maintenance protocols, staff training, and decision-support interfaces suited to conservation agencies and local authorities. Demonstration projects should assess whether the proposed systems improve inspection planning, intervention prioritization, maintenance scheduling, and communication among engineers, architects, conservators, archeologists, and public authorities.

Overall, future progress depends on moving from isolated digital documentation exercises toward validated, interoperable, and maintainable assessment systems. The main research challenge is no longer only the production of detailed three-dimensional models, but the transformation of heterogeneous survey and diagnostic data into reliable information that can support structural assessment and conservation decision-making.

4. Conclusions

In conclusion, this paper has explored different approaches to heritage-asset preservation, emphasizing the critical role of crowdsourcing and the integration of advanced technologies such as laser scanning and the integration with BIM, to support cultural heritage documentation, monitoring, and seismic-risk-relevant assessment.

Overall, the evidence indicates that TLS–BIM/HBIM workflows are evolving from static geometric documentation toward integrated systems for condition assessment, monitoring, structural-model preparation, and conservation management. However, workflow maturity remains uneven. Acquisition and geometric reconstruction are comparatively well established, whereas semantic automation, independent validation, interoperability, uncertainty propagation, and structural-model verification remain less consistently developed. The most robust approaches are hybrid and purpose-driven, retaining point clouds, meshes, parametric objects, images, diagnostic records, sensor data, and numerical models according to their respective functions rather than forcing all information into a single representation.

Q1 (workflows): The literature consistently reports an end-to-end pipeline consisting of (i) acquisition planning and multi-station scanning, (ii) registration, cleaning, and quality control of point clouds, (iii) scan-to-BIM/HBIM modelling, and (iv) semantic enrichment to enable traceable, updateable digital twins for heritage assets.

Q2 (assessment objectives and validation): Reported assessment objectives concentrate on condition/pathology documentation, deformation/change detection from repeat surveys, and the extraction of geometry suitable for structural interpretation. While many studies demonstrate geometric accuracy, validation is less consistently reported for assessment-grade outputs (e.g., repeatability of change metrics, thresholds for crack/deformation proxies, and independent verification of detected damage).

Q3 (technical barriers): The principal barriers to operational adoption remain as limited automation from point clouds to semantically rich HBIM objects, interoperability constraints across platforms/standards, and insufficient reporting of uncertainty propagation from acquisition and registration through to derived assessment indicators.

Q4 (multi-scale integration): A key operational pattern emerging from the literature is a multi-scale strategy in which portfolio-scale screening (street-level imagery and/or InSAR deformation trends) is used to prioritize assets and identify hotspots, followed by asset-scale diagnosis using TLS/UAV geometry, with results consolidated within BIM/HBIM for prioritization, intervention planning, and long-term monitoring.

Priority directions for future work include: (1) benchmarked automation for scan-to-HBIM object generation, (2) standardized validation and uncertainty reporting for registration and change detection, (3) heritage-specific semantic libraries and interoperability pathways and (4) operational multi-sensor fusion workflows linking InSAR/UAV/TLS observations to BIM/HBIM for pre- and post-event seismic decision support.

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absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

ALS, airborne laser scanning; BIM, building information modelling; CH, cultural heritage; GPR, Ground-Penetrating Radar; HBIM, historic building information modelling; IFC, Industry Foundation Classes; InSAR, Interferometric Synthetic Aperture Radar; IoT, Internet of Things; LiDAR, Light Detection and Ranging; MTInSAR, multi-temporal InSAR; NDT, non-destructive test; RVS, Rapid Visual Screening; SAR, Synthetic Aperture Radar; SfM, Structure from Motion; SHM, structural health monitoring; TLS, terrestrial laser scanning; UAS, unmanned aerial system; UAV, unmanned aerial vehicle; VR/AR, virtual reality/augmented reality.

References

1. Sánchez-Aparicio, L.; del Blanco García, F.; Mencías-Carrizosa, D.; Villanueva, P.; Aira-Zunzunegui, J.; Sanz-Arauz, D.; Pierdicca, R.; Pinilla, J.; García Gago, J.M. Detection of damage in heritage constructions based on 3D point clouds. A systematic review. *J. Build. Eng.* **2023**, *77*, 107440. [CrossRef]
2. Morel, H.; Megarry, W.; Potts, A.; Hosagrahar, J.; Roberts, D.C.; Arikan, Y.; Brondizio, E.; Cassar, M.; Flato, G.; Forgesson, S.; et al. *Global Research and Action Agenda on Culture, Heritage and Climate Change*; ICOMOS & ICSM CHC: Charenton-le-Pont, France; Paris, France, 2022.
3. Pritchard, D.; Rigauts, T.; Ripanti, F.; Ioannides, M.; Brumana, R.; Davies, R.; Avouri, E.; Cliffen, H.; Joncic, N.; Osti, G.; et al. *Study on Quality in 3D Digitisation of Tangible Cultural Heritage*; European Commission: Brussels, Belgium, 2021. Available online: https://digital-strategy.ec.europa.eu/en/library/study-quality-3d-digitisation-tangible-cultural-heritage (accessed on 20 February 2026).
4. Tejedor, B.; Lucchi, E.; Bienvenido-Huertas, D.; Nardi, I. Non-Destructive Techniques (NDT) for the Diagnosis of Heritage Buildings: Traditional Procedures and Futures Perspectives. *Energy Build.* **2022**, *263*, 112029. [CrossRef]
5. Coombes, M.A.; Viles, H.A. Integrating nature-based solutions and the conservation of urban built heritage: Challenges, opportunities, and prospects. *Urban For. Urban Green.* **2021**, *63*, 127192. [CrossRef]
6. Jordan-Palomar, I.; Tzortzopoulos, P.; García-Valldecabres, J.; Pellicer, E. Protocol to manage heritage building interventions using heritage building information modelling (HBIM) [Article]. *Sustainability* **2018**, *10*, 908. [CrossRef]
7. Penjor, T.; Banihashemi, S.; Hajirasouli, A.; Golzad, H. Heritage Building Information Modelling (HBIM) for Heritage Conservation: Framework of Challenges, Gaps, and Existing limitations of HBIM. *Digit. Appl. Archaeol. Cult. Herit.* **2024**, *35*, e00366. [CrossRef]
8. Fokaides, P.A. Development of a Heritage Life Cycle Assessment (H-LCA) framework: Integrating sustainability metrics and cultural preservation in heritage buildings. *Energy Rep.* **2025**, *14*, 4437–4448. [CrossRef]
9. Page, M.; Mckenzie, J.; Bossuyt, P.; Boutron, I.; Hoffmann, T.; Mulrow, C.; Shamseer, L.; Tetzlaff, J.; Akl, E.; Brennan, S.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef] [PubMed]
10. Tricco, A.; Lillie, E.; Zarin, W.; O'Brien, K.; Colquhoun, H.; Levac, D.; Moher, D.; Peters, M.; Weeks, L.; Hempel, S.; et al. PRISMA extension for scoping reviews (PRISMA-ScR): Checklist and explanation. *Ann. Intern. Med.* **2018**, *169*, 467–473. [CrossRef] [PubMed]
11. Aria, M.; Cuccurullo, C. Bibliometrix: An R-tool for comprehensive science mapping analysis. *J. Inf.* **2017**, *11*, 959–975. [CrossRef]
12. Wang, J.; Zakaria, S.A. Design Application and Evolution of 3D Visualization Technology in Architectural Heritage Conservation: A CiteSpace-Based Knowledge Mapping and Systematic Review (2005–2024). *Buildings* **2025**, *15*, 1854. [CrossRef]
13. Xiao, Y.; Chen, Y.; Huang, Y.; Yan, Y. Surface Protection Technologies for Earthen Sites in the 21st Century: Hotspots, Evolution, and Future Trends in Digitalization, Intelligence, and Sustainability. *Coatings* **2025**, *15*, 855. [CrossRef]
14. Liu, J.; Azhar, S.; Willkens, D.; Li, B. Static Terrestrial Laser Scanning (TLS) for Heritage Building Information Modeling (HBIM): A Systematic Review. *Virtual Worlds* **2023**, *2*, 90–114. [CrossRef]
15. Borkowski, A.S.; Kubrat, A. Integration of Laser Scanning, Digital Photogrammetry and BIM Technology: A Review and Case Studies. *Eng* **2024**, *5*, 2395–2409. [CrossRef]
16. Huang, Y.; Shi, Z.; Chen, Y.; Zhou, K.; Ying, Z.; Zheng, L.; Yang, S. Urban form evolution and transformation of traditional water towns based on space syntax and GIS: Evidence from ancient Wenzhou city (16th to the 20th century). *Front. Earth Sci.* **2025**, *13*, 1520643. [CrossRef]
17. Ridge, M.; Blickhan, S.; Ferriter, M.; Mast, A.; Brumfield, B.; Wilkins, B.; Cybulska, D.; Burgher, D.; Casey, J.; Prytz, Y.B. 3. Why work with crowdsourcing in cultural heritage? In *The Collective Wisdom Handbook: Perspectives on Crowdsourcing in Cultural Heritage—Community Review Version*, 1st ed.; Digital Scholarship at the British Library: London, UK, 2021. [CrossRef]

18. Ralli, M.; Bekiaris, S.; Kaldeli, E.; Menis-Mastromichalakis, O.; Sofou, N.; Tzouvaras, V.; Stamou, G. CrowdHeritage: Improving the Quality of Cultural Heritage Through Crowdsourcing Methods. In *2020 15th International Workshop on Semantic and Social Media Adaptation and Personalization*; SMA: Zakynthos, Greece, 2020; pp. 1–6. [CrossRef]
19. Ridge, M. From tagging to theorizing: Deepening engagement with cultural heritage through crowdsourcing. *Curator Mus. J.* **2013**, *56*, 435–445. [CrossRef]
20. Navarrete, T. Crowdsourcing the digital transformation of heritage. In *Digital Transformation in the Cultural and Creative Industries*; Massi, M., Vecco, M., Lin, Y., Eds.; Routledge: London, UK, 2020; pp. 99–116.
21. Van Hyning, V. Curating Crowds: A Review of Crowdsourcing Our Cultural Heritage. In *DHQ: Digital Humanities Quarterly 2019*; Alliance of Digital Humanities Organizations: Daejeon, Republic of Korea, 2019; Volume 13. Available online: http://www.digitalhumanities.org/dhq/vol/13/1/000410/000410.pdf (accessed on 20 February 2026).
22. Terras, M. Crowdsourcing in the digital humanities. In *A New Companion to Digital Humanities*; Schreibman, S., Siemens, R., Unsworth, J., Eds.; Wiley-Blackwell: Hoboken, NJ, USA, 2016; pp. 420–439.
23. Cardellicchio, A.; Ruggieri, S.; Leggieri, V.; Uva, G. ViewVULMA: Data Set for Training a Machine-Learning Tool for a Fast Vulnerability Analysis of Existing Buildings. *Data* **2022**, *7*, 4. [CrossRef]
24. Kaldeli, E.; Bekiaris, S.; Menis-Mastromichalakis, O.; Ralli, M.; Tzouvaras, V.; Stamou, G. CrowdHeritage: Crowdsourcing for Improving the Quality of Cultural Heritage Metadata. *Information* **2021**, *12*, 64. [CrossRef]
25. Federal Emergency Management Agency. *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook*, 3rd ed.; FEMA P-154; Federal Emergency Management Agency: Washington, DC, USA, 2015.
26. Federal Emergency Management Agency. *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook*, 3rd ed.; FEMA P-155; Homeland Security Dept, Federal Emergency Management Agency: Washington, DC, USA, 2015.
27. Federal Emergency Management Agency. *Rapid Visual Screening of Buildings for Potential Seismic Hazards: Supporting Documentation (FEMA, 2015)*; FEMA P-155 report; Federal Emergency Management Agency: Washington, DC, USA, 2015.
28. Calò, M.; Ruggieri, S.; Nettis, A.; Uva, G. A MTInSAR-Based Early Warning System to Appraise Deformations in Simply Supported Concrete Girder Bridges. *Struct. Control Health Monit.* **2024**, *27*, 8978782. [CrossRef]
29. Zhu, M.; Yu, X.; Tan, H.; Yuan, J. Integrated high-precision monitoring method for surface subsidence in mining areas using D-InSAR, SBAS, and UAV technologies. *Sci. Rep.* **2024**, *14*, 12445. [CrossRef] [PubMed]
30. Boardman, C.; Bryan, P.; McDougall, L.; Reuter, T.; Payne, E.; Moitinho, V.; Rodgers, T.; Honkova, J.; O'Connor, L.; Blockley, C.; et al. *3D Laser Scanning for Heritage: Advice and Guidance on the Use of Laser Scanning in Archaeology and Architecture*; Historic England: Swindon, England, 2018.
31. Xystouris, K.; Apostolidou, E.; Kylili, A.; Fokaides, P.A. The effect of climate change on weathering: Evidences from heritage buildings under subtropical conditions. *J. Sustain. Archit. Civ. Eng.* **2021**, *29*, 232–245. [CrossRef]
32. Bektaş, N.; Kegyes-Brassai, O. A case study of seismic vulnerbility assessment of residential urm buildings based on Rapid Visual Screening in Györ, Hungary. In Proceedings of the Stipendium Hungaricum PhD Student Conference, Budapest, Hungary, 7 July 2022.
33. Haryanto, Y.; Hu, H.-T.; Widyaningrum, A.; Alfidiah, E.; Hidayat, B. FEMA 310 Tier 1 seismic evaluation of existing building: A case study of a 7-story academic RC building of Jenderal Soedirman University, Indonesia. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *982*, 012031. [CrossRef]
34. Van An Genechten, B.; Heine, E.; Lerma, J.L.; Santana Quintero, M.; Van Genechten, B.; Caner, H.; Poelman, R.; Reiner, H.; Biosca Taronger, J.M.; De Bruyne, M.; et al. *Theory and Practice on Terrestrial Laser Scanning: Training Material Based on Practical Applications*; Universidad Politecnica de Valencia Editorial: Valencia, Spain, 2008.
35. Yuan, C.; Tang, Y.; Tian, Y. Application of Terrestrial Laser Scanning (TLS) in the Architecture, Engineering and Construction (AEC) Industry. *Sensors* **2022**, *22*, 265. [CrossRef] [PubMed]
36. Haddad, N.A. From ground surveying to 3D laser scanner: A review of techniques used for spatial documentation of historic sites. *J. King Saud Univ.-Eng. Sci.* **2011**, *23*, 109–118. [CrossRef]
37. Harikumar, A. Advanced Methods for Tree Species Classification and Biophysical Parameter Estimation Using Crown Geometric Information in High Density LiDAR Data. Ph.D. Thesis, University of Toronto, Toronto, ON, Canada, 2020. [CrossRef]
38. Che, E.; Jung, J.; Olsen, M.J. Object Recognition, Segmentation, and Classification of Mobile Laser Scanning Point Clouds: A State of the Art Review. *Sensors* **2019**, *19*, 810. [CrossRef] [PubMed]
39. Suchocki, C.; Katzer, J. Terrestrial laser scanning harnessed for moisture detection in building materials—Problems and limitations. *Autom. Constr.* **2018**, *94*, 127–134. [CrossRef]
40. Kukko, A.; Kaartinen, H.; Hyyppä, J.; Chen, Y. Multiplatform mobile laser scanning: Usability and performance. *Sensors* **2012**, *12*, 11712–11733. [CrossRef]
41. Kaartinen, E.; Dunphy, K.; Sadhu, A. LiDAR-Based Structural Health Monitoring: Applications in Civil Infrastructure Systems. *Sensors* **2022**, *22*, 4610. [CrossRef] [PubMed] [PubMed Central]

42. Remondino, F. Heritage Recording and 3D Modelling with Photogrammetry and 3D Scanning. *Remote Sens.* **2011**, *3*, 1104–1138. [CrossRef]
43. Ding, J.; Liang, M.; Chen, W. Integration of BIM and Chinese architectural heritage: A bibliometric analysis research. *Buildings* **2023**, *13*, 593. [CrossRef]
44. Rashdi, R.; Martínez-Sánchez, J.; Arias, P.; Qiu, Z. Scanning Technologies to Building Information Modelling: A Review. *Infrastructures* **2022**, *7*, 49. [CrossRef]
45. Li, Y.; Zhao, L.; Chen, Y.; Zhang, N.; Fan, H.; Zhang, Z. 3D LiDAR and multi-technology collaboration for preservation of built heritage in China: A review. *Int. J. Appl. Earth Obs. Geoinf.* **2023**, *116*, 103156. [CrossRef]
46. Ascione, F.; Ceroni, F.; Rossi, F.; Pecce, M. Historical buildings: Multidisciplinary approach to structural/energy diagnosis and performance assessment. *Appl. Energy* **2015**, *185*, 1517–1528. [CrossRef]
47. Gomes, M.; Tomé, A. A digital and non-destructive integrated methodology for heritage modelling and deterioration mapping. The case study of the Moorish Castle in Sintra. *Dev. Built Environ.* **2023**, *14*, 100145. [CrossRef]
48. Skoutelis, N.; Providakis, C.; Stavroulaki, M.; Sari, E.; Mania, K.; Stavroulakis, G.E.; Kasabali, A.; Charalambidi, B.; Tairidis, G.; Ephorate of Antiquities of Chania (Eds.) *Research Investigation for the Restoration of Neoria*; Progress and Final Reports; Technical University of Crete: Chania, Greece; Municipality of Chania: Chania, Greece; Ephorate of Antiquities: Chania, Greece, 2021; pp. 2021–2024.
49. Charalambidi, B.; Koutsianitis, P.; Motsa, S.M.; Tairidis, G.; Kasampali, A.; Drosopoulos, G.; Stavroulaki, M.; Stavroulakis, G. Modelling, identification and structural damage investigation of the Neoria monument in Chania. *Dev. Built Environ.* **2022**, *10*, 10006. [CrossRef]
50. Stavroulaki, M.E.; Kasampali, A.; Charalambidi, B.; Motsa, S.M.; Drosopoulos, G.A.; Stavroulakis, G.E. Linear and nonlinear earthquake analysis for strength evaluation of masonry monument of Neoria. *Buildings* **2023**, *13*, 2204. [CrossRef]
51. Motsa, S.M.; Drosopoulos, G.A.; Stavroulaki, M.E.; Maravelakis, E.; Borg, R.P.; Galea, P.; D'amico, S.; Stavroulakis, G.E. Structural investigation of Mnajdra megalithic monument in Malta. *J. Cult. Herit.* **2020**, *41*, 96–105. [CrossRef]
52. Stavroulaki, M.E.; Drosopoulos, G.A.; Tavlopoulou, E.; Skoutelis, N.; Stavroulakis, G.E. Investigation of the structural behaviour of a masonry castle by considering the actual damage. *Int. J. Mason. Res.* **2018**, *3*, 1–33. [CrossRef]
53. Drosopoulos, G.A.; Stavroulakis, G.E. A computational homogenization approach for the study of localization of masonry structures using the XFEM. *Arch. Appl. Mech.* **2018**, *88*, 2135–2152. [CrossRef]
54. Gilbert, M.; Melbourne, C. Rigid-block analysis of masonry structures. *Struct. Eng.* **1994**, *72*, 356–361.
55. Evlogimenou, I. Venetian Neoria Chania: Static Solution and Intervention Proposal. Diploma Thesis, National Technical University of Athens, Athens, Greece, 2011.
56. Abbate, E.; Invernizzi, S.; Spanò, A. HBIM Parametric Modelling from Clouds to Perform Structural Analyses Based on Finite Elements: A Case Study on a Parabolic Concrete Vault. *Appl. Geomat.* **2022**, *14*, 79–96. [CrossRef]
57. Abdelalim, M. Heritage Preservation Using Laser Scanning: Architectural Digital Twins Using Al-Mu'izz Street as a Case Study. *Buildings* **2025**, *15*, 1480. [CrossRef]
58. Acar, D.; Acar, D.; Kurtca, G. Sustainable Restoration of a Historical Building in Ankara: A Case Study in Preservation and Conservation Using BIM. In *Advances in Science, Technology Innovation*; Gallo, P., Bibri, S.E., Alberti, F., Matamanda, A.R., Piselli, C., Rabiei, H., Romano, R., Ozcan-Buckley, A., Eds.; Springer Nature: Berlin/Heidelberg, Germany, 2025; pp. 253–269. [CrossRef]
59. Adami, A.; Fregonese, L.; Rosignoli, O.; Scala, B.; Taffurelli, L.; Treccani, D. Geometric Survey Data and Historical Sources Interpretation for Hbim Process: The Case of Mantua Cathedral Fąade. In *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Grimoldi, A., Previtali, M., Scaioni, M., Rinaudo, F., Brumana, R., Cantini, L., Pracchi, V., Eds.; Copernicus GmbH: Göttingen, Germany, 2019; Volume 42, pp. 29–35. [CrossRef]
60. Al-Bayari, O.; Shatnawi, N. Geomatics Techniques and Building Information Model for Historical Buildings Conservation and Restoration. *Egypt. J. Remote Sens. Space Sci.* **2022**, *25*, 563–568. [CrossRef]
61. Alghafis, M.F.; Altami, S.A. Digital Twins for Historic Mosque: A Digital Transformation Strategy for Heritage Preservation. In *Proceedings of the IEEE International Conference on E-Business Engineering*; Hussain, O.K., Alsaleem, S., Ma, S.-P., Lu, X., Chao, K.-M., Eds.; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2025; pp. 183–188. [CrossRef]
62. Almasoudi, A.; Bhatti, A.Q.; Alluqmani, A.E.; Alotaibi, A. Investigation of Enhancing Heritage Preservation Utilizing Heritage Building Information Modeling (HBIM). *J. Umm Al-Qura Univ. Eng. Archit.* **2025**, *16*, 414–442. [CrossRef]
63. Alshawabkeh, Y.; Baik, A.; Fallatah, A. As-Textured as-Built Bim Using Sensor Fusion, Zee Ain Historical Village as a Case Study. *Remote Sens.* **2021**, *13*, 5135. [CrossRef]
64. Andriasyan, M.; Moyano, J.; Nieto-Julián, J.E.; Antón, D. From Point Cloud Data to Building Information Modelling: An Automatic Parametric Workflow for Heritage. *Remote Sens.* **2020**, *12*, 1094. [CrossRef]
65. Angelini, M.G.; Baiocchi, V.; Costantino, D.; Garzia, F. Scan to BIM for 3D Reconstruction of the Papal Basilica of Saint Francis in Assisi In Italy. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Tucci, G., Bonora, V., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2017; Volume 42, pp. 47–54. [CrossRef]

66. Apollonio, F.I.; Gaiani, M.; Sun, Z. A Reality Integrated BIM for Architectural Heritage Conservation. In *Architecture and Design: Breakthroughs in Research and Practice*; Information Resources Management Association: Hershey, PA, USA, 2018; Volume 1–2, pp. 142–176. [CrossRef]
67. Apollonio, F.I.; Gaiani, M.; Sun, Z. A Reality Integrated BIM for Architectural Heritage Conservation. *Geospat. Intell. Concepts Methodol. Tools Appl.* **2019**, *2*, 900–934. [CrossRef]
68. Argasiński, K.; Marciniak, P.; Prałat, K. Challenges in Survey Methodology Workflows for Complex Geometry Structures. Case Study of the Church of Divine Mercy in Kalisz, Poland. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Shim, H., Choi, S., Lee, W., Rii, H.U., Kim, S., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2025; Volume 48, pp. 57–62. [CrossRef]
69. Argiolas, R.; Bagnolo, V.; Cera, S.; Sanna, G. Analytical representation of architectural built heritage. A sketch-to-bim approach. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Fregonese, L., Fassi, F., Remondino, F., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2022; Volume 46, pp. 33–40. [CrossRef]
70. Argiolas, R.; Bagnolo, V.; Cera, S.; Cuccu, S. Virtual environments to communicate built cultural heritage: A hbim based virtual tour. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Shults, R., Dlesk, A., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2022; Volume 46, pp. 21–29. [CrossRef]
71. Aricò, M.; Ferro, C.; La Guardia, M.; Lo Brutto, M.; Taranto, G.; Ventimiglia, G.M. Scan-to-BIM Process and Architectural Conservation: Towards an Effective Tool for the Thematic Mapping of Decay and Alteration Phenomena. *Heritage* **2024**, *7*, 6257–6281. [CrossRef]
72. Bac-Bronowicz, J.; Piech, I.; Wojciechowska, G. Integrated TLS-UAV Workflow for HBIM Generation in Heritage Documentation. *Remote Sens.* **2026**, *18*, 857. [CrossRef]
73. Badenko, V.; Fedotov, A.; Zotov, D.; Lytkin, S.; Lipatova, A.; Volgin, D. Features of Information Modeling of Cultural Heritage Objects. In *IOP Conference Series: Materials Science and Engineering*; Institute of Physics Publishing: Bristol, UK, 2020; Volume 890. [CrossRef]
74. Bagnolo, V.; Argiolas, R. Scan-to-BIM Process Versus 3D Procedural Modelling of Gothic Masonry Vaults. In *From Building Information Modelling to Mixed Reality*; Springer Tracts in Civil Engineering Series; Springer: Berlin/Heidelberg, Germany, 2021; pp. 17–31. [CrossRef]
75. Bagnolo, V.; Argiolas, R.; Cuccu, S.; Paba, N. Beyond Hbim: Serious Games And Procedural Modelling For Heritage Dissemination. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Truong-Hong, L., Che, E., Jia, F., Emamgholian, S., Laefer, D., Vo, A.V., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2021; Volume 46, pp. 55–60. [CrossRef]
76. Baik, A. A Comprehensive Heritage BIM Methodology for Digital Modelling and Conservation of Built Heritage: Application to Ghiqa Historical Market, Saudi Arabia. *Remote Sens.* **2024**, *16*, 2833. [CrossRef]
77. Baik, A. Najdi Architecture in HBIM for Sustainable Conservation. *J. Umm Al-Qura Univ. Eng. Archit.* **2026**, *17*, 148–168. [CrossRef]
78. Baik, A.; Yaagoubi, R.; Boehm, J. Integration of Jeddah Historical Bim and 3D GIS for Documentation and Restoration of Historical Monument. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Yen, Y.-N., Weng, K.-H., Cheng, H.-M., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2015; Volume 40, pp. 29–34. [CrossRef]
79. Balestrieri, M.; Valmori, I.; Montuori, M. UAS and TLS 3D Data Fusion for Built Cultural Heritage Assessment and the Application for St. Catherine Monastery in Ferrara, Italy. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Jabari, S., Shahbazi, M., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2024; Volume 48, pp. 9–16. [CrossRef]
80. Banfi, F. The Integration of a Scan-To-Hbim Process in Bim Application: The Development of an Add-in to Guide Users in Autodesk Revit. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Pracchi, V., Previtali, M., Brumana, R., Rinaudo, F., Grimoldi, A., Cantini, L., Scaioni, M., Eds.; Copernicus GmbH: Göttingen, Germany, 2019; Volume 42, pp. 141–148. [CrossRef]
81. Banfi, F.; Cazzani, A.; Liu, W. XR Technologies for Enhanced Cultural Engagement: From HBIM to a Comparative Analysis of VR and WebVR Development Tools. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Shim, H., Choi, S., Lee, W., Rii, H.U., Kim, S., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2025; Volume 48, pp. 95–102. [CrossRef]
82. Banihashemi, S.; Hajirasouli, A.; Golzad, H.; Taghavi, N.; Ireland, T. Digital Engineering for Heritage Conservation: Standards-Aligned UAV-TLS Workflow and Immersive Dissemination for Climate-Exposed Heritage Landscapes. *Digit. Appl. Archaeol. Cult. Herit.* **2026**, *41*, e00536. [CrossRef]
83. Bianconi, F.; Filippucci, M.; Amoruso, G.; Bertinelli, M. From the Integrated Survey of Historic Settlements to the Pattern Book Within the Bim. In *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Fassi, F., Cardaci, A., Remondino, F., Eds.; Copernicus GmbH: Göttingen, Germany, 2019; Volume 42, pp. 135–142. [CrossRef]

84. Bitelli, G.; Castellazzi, G.; D'Altri, A.M.; De Miranda, S.; Lambertini, A.; Selvaggi, I. On the Generation of Numerical Models from Point Clouds for the Analysis of Damaged Cultural Heritage. In *IOP Conference Series: Materials Science and Engineering*; Institute of Physics Publishing: Bristol, UK, 2018; Volume 364. [CrossRef]
85. Bitelli, G.; Dellapasqua, M.; Girelli, V.A.; Sanchini, E.; Tini, M.A. 3D Geomatics Techniques for an Integrated Approach to Cultural Heritage Knowledge: The Case of San Michele in Acerboli's Church in Santarcangelo Di Romagna. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Tucci, G., Bonora, V., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2017; Volume 42, pp. 291–296. [CrossRef]
86. Boit, B.; Oyuga, J.; Kedogo, J. Adoption of Digital Technologies for Heritage Conservation: The Case of Al-Busaidy Heritage Site, Mombasa County, Kenya. In Proceedings of the IEEE AFRICON Conference, Nairobi, Kenya, 20–22 September 2023. [CrossRef]
87. Borkowski, A.S.; Winiarska, W. The HBIM Model as a Source in the Building Reconstruction Process: A Case Study of the "Koprówka" in Celestynów, Poland. *Buildings* **2025**, *15*, 1442. [CrossRef]
88. Bounouioua, F.; Saffidine, D.R.; Korichi, A. An Enhanced Hbim Framework Integrating Advanced Technologies To Strengthen The Cultural Heritage. *J. Inf. Technol. Constr.* **2025**, *30*, 570–602. [CrossRef]
89. Buldo, M.; Agustín-Hernández, L.; Verdoscia, C. Semantic Enrichment of Architectural Heritage Point Clouds Using Artificial Intelligence: The Palacio de Sástago in Zaragoza, Spain. *Heritage* **2024**, *7*, 6938–6965. [CrossRef]
90. Carrión-Ruiz, B.; Blanco-Pons, S.; Duong, M.; Chartrand, J.; Li, M.; Prochnau, K.; Fai, S.; Lerma, J.L. Augmented Experience To Disseminate Cultural Heritage: House Of Commons Windows, Parliament Hill National Historic Site (Canada). In *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Cardaci, A., Fassi, F., Remondino, F., Eds.; Copernicus GmbH: Göttingen, Germany, 2019; Volume 42, pp. 243–247. [CrossRef]
91. Castagnetti, C.; Dubbini, M.; Ricci, P.C.; Rivola, R.; Giannini, M.; Capra, A. Critical Issues and Key Points from the Survey to the Creation of the Historical Building Information Model: The Case of Santo Stefano Basilica. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Tucci, G., Bonora, V., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2017; Volume 42, pp. 467–474. [CrossRef]
92. Çemrek, H.A.; Sönmez, S.; Işıkdağ, Ü. Mobile 3D LiDAR-Based Scan2BIM Process: A Comparison of Point Cloud Processing Tools. In *Proceedings of the 43rd Conference on Education and Research in Computer Aided Architectural Design in Europe, eCAADe 2025*; Sorguç, A.G., Yemişcioğlu, M.K., Erol, S.B., Bük, M.E., Güney, D., Sulayıcı, B.A., Akol, M., Eds.; Education and Research in Computer Aided Architectural Design in Europe: Ankara, Turkey, 2025; Volume 1, pp. 503–512.
93. Chai, C.S.; Xiong, Y.; Hanifa, A.N.; Suib, S.I.; Tatt, S.L. Tls and uav photogrammetry for the use of heritage building information modelling development: A case study of the sarawak islamic heritage museum. *J. Eng. Sci. Technol.* **2025**, *20*, 1–19.
94. Chen, J.; Zhong, J.; Ning, Q.; Xu, Z.; Fukuda, H. Heritage Conservation and Management of Traditional Anhui Dwellings Using 3D Digitization: A Case Study of the Architectural Heritage Clusters in Huangshan City. *Buildings* **2026**, *16*, 211. [CrossRef]
95. Chiabrando, F.; Lingua, A.; Spreafico, A.; Sammartano, G.; Matrone, F.; Borras, M.; Mendikute Garate, A.; Miller, A.; Ioannides, M.; Siegkas, P.; et al. HERITALISE. Project Insights and Initial Developments. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Shim, H., Choi, S., Lee, W., Rii, H.U., Kim, S., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2025; Volume 48, pp. 269–276. [CrossRef]
96. Chiabrando, F.; Lo Turco, M.; Santagati, C. Digital Invasions: From Point Clouds to Historical Building Object Modeling (h-BOM) of a Unesco WHL Site. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Remondino, F., Kersten, T., Georgopoulos, A., Stathopoulou, E., Aguilera, D., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2017; Volume 42, pp. 171–178. [CrossRef]
97. Chow, L.; Fai, S. Developing Verification Systems for Building Information Models of Heritage Buildings with Heterogeneous Datasets. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Ouimet, C., Fai, S., Hayes, J., Smith, L., Santana Quintero, M., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2017; Volume 42, pp. 125–128. [CrossRef]
98. Ciuffreda, A.L.; Trovatelli, F.; Meli, F.; Caselli, G.; Stramaccioni, C.; Coli, M.; Tanganelli, M. Historic Building Information Modeling for Conservation and Maintenance: San Niccolo's Tower Gate, Florence. *Heritage* **2024**, *7*, 1334–1356. [CrossRef]
99. Clini, P.; Mariotti, C.; Angeloni, R.; Ferretti, U. Combining HBIM and AR for Heritage Conservation. From Digital Survey to an Interactive Management Tool. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Quattrini, R., Pierdicca, R., Fassi, F., Remondino, F., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2026; Volume 48, pp. 97–104. [CrossRef]
100. Colace, F.; Ferrandino, F.; Lombardi, M.; Lorusso, A.; Valentino, C. Digital Twin and Predictive Maintenance in Cultural Heritage: A Multidisciplinary Educational Experience with HBIM and IoT. In *Proceedings of the Frontiers in Education Conference*; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2025. [CrossRef]
101. Costa-Jover, A.; Núñez-Andrés, M.A.; Buill Pozuelo, F. Advances in Geomatics Data Acquisition for Architectural Heritage: A Critical Review Toward Sustainable, Data-Driven Conservation. *Sustainability* **2026**, *18*, 3003. [CrossRef]

102. Costantino, D.; Pepe, M.; Restuccia, A.G. Scan-to-HBIM for Conservation and Preservation of Cultural Heritage Building: The Case Study of San Nicola in Montedoro Church (Italy). *Appl. Geomat.* **2023**, *15*, 607–621. [CrossRef]
103. Croce, V.; Caroti, G.; Piemonte, A.; Bevilacqua, M.G. From Survey to Semantic Representation for Cultural Heritage: The 3D Modelling of Recurring Architectural Elements. *Acta IMEKO* **2021**, *10*, 98–108. [CrossRef]
104. Cuperschmid, A.R.M.; Dias, M.S. Valuing and Sharing Contemporary Architectural Heritage: Exploring the Scan-to-HBIM-to-XR Process with Veneza Farm Chapel. In *Contemporary Heritage Lexicon*; Springer Tracts in Civil Engineering Series; Springer: Berlin/Heidelberg, Germany, 2024; Volume 1, pp. 109–127. [CrossRef]
105. Cuperschmid, A.R.M.; Fabricio, M.M.; Franco, J.C. Hbim Development of a Brazilian Modern Architecture Icon: Glass House by Lina Bo Bardi. *Heritage* **2019**, *2*, 1927–1940. [CrossRef]
106. D'Auria, S.; Franzese, A.; Nicolella, M.; D'Agostino, P. Integration of HBIM and Machine Learning Processes for Cultural Heritage Maintenance: A Case of Piazza d'Armi in the Aragonese Castle of Ischia. In *Lecture Notes in Civil Engineering*; Mazzolani, F.M., Landolfo, R., Faggiano, B., Eds.; Springer Science and Business Media Deutschland GmbH: Berlin/Heidelberg, Germany, 2025; Volume 595 LNCE, pp. 585–592. [CrossRef]
107. D'Urso, M.G.; Aldrighettoni, J. Geodatabase, Metric Reconstruction and a GIS Platform of Historical-Archaeological Sites in Aquino. *Acta IMEKO* **2024**, *13*, 1–14. [CrossRef]
108. Del Rio, I.; Cabaleiro, M.; Conde, B.; Riveiro, B.; Caamaño, J.C. Hbim Application to Historical Steel Structures: The Case Study of Lapela Bridge. In *World Congress on Civil, Structural, and Environmental Engineering*; El Naggar, H., Barros, J., Eds.; Avestia Publishing: Ottawa, ON, Canada, 2020; pp. 160–161. [CrossRef]
109. Donato, V.; Biagini, C.; Bertini, G.; Marsugli, F. Challenges and Opportunities for the Implementation of H-Bim with Regards to Historical Infrastructures: A Case Study of the Ponte Giorgini in Castiglione Della Pescaia (Grosseto—Italy). In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Tucci, G., Bonora, V., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2017; Volume 42, pp. 253–260. [CrossRef]
110. Dore, C.; Murphy, M. Integration of Historic Building Information Modeling (HBIM) and 3D GIS for Recording and Managing Cultural Heritage Sites. In *Proceedings of the International Conference on Virtual Systems and Multimedia*; IEEE: New York, NY, USA, 2012; pp. 369–376. [CrossRef]
111. Dore, C.; Murphy, M. Semi-Automatic Modelling of Building Façades with Shape Grammars Using Historic Building Information Modelling. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Boehm, J., Remondino, F., Kersten, T., Fuse, T., Gonzalez-Aguilera, D., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2013; Volume 40, pp. 57–64.
112. Dore, C.; Murphy, M. Semi-Automatic Techniques for as-Built BIM Façade Modeling of Historic Buildings. In *2013 Digital Heritage International Congress (DigitalHeritage)*; IEEE: New York, NY, USA, 2013; Volume 1, pp. 473–480. [CrossRef]
113. Dore, C.; Murphy, M.; McCarthy, S.; Brechin, F.; Casidy, C.; Dirix, E. Structural Simulations and Conservation Analysis-Historic Building Information Model (HBIM). In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Gonzalez-Aguilera, D., Remondino, F., Boehm, J., Kersten, T., Fuse, T., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2015; Volume 40, pp. 351–357. [CrossRef]
114. Dudzińska, E.M.; Borkowski, A.S. HBIM in the Digital Reconstruction of Historic Buildings Based on Point Clouds—A Case Study of the Manor House in Nużewo, Poland. *Bud Archit.* **2026**, *25*, 1–8. [CrossRef]
115. Dzwierzynska, J.; Prokop, A. Reconstruction of Historic Monuments—A Dual Approach. *Sustainability* **2022**, *14*, 14651. [CrossRef]
116. Ekba, S. Features of the Survey and Monitoring of the Technical Condition of Cultural Heritage Objects Based on the BIM Model. In *E3S Web Conference*; Kankhva, V., Ed.; EDP Sciences: Les Ulis, France, 2021; Volume 258. [CrossRef]
117. Esponda, M.; Piraino, F.; Stanga, C.; Mezzino, D. Log Houses in Les Laurentides. from Oral Tradition to an Integrated Digital Documentation Based on the Re-Discovery of the Traditional Constructive-Geographical €Repertoires' Through Digital BIM Data Archive. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Hayes, J., Ouimet, C., Quintero, S., Fai, M., Smith, S., Eds.; Copernicus GmbH: Göttingen, Germany, 2017; Volume 4, pp. 75–82. [CrossRef]
118. Fernandes Dionizio, R.; Murphy, M.; Dezen-Kempter, E. Multi-Scale Documentation of Modern Brazilian Architecture: An HBIM-HGIS Approach. *Int. J. Archit. Herit.* **2025**, *19*, 3307–3324. [CrossRef]
119. Fidan, Ş.; Ulvi, A.; Yiğit, A.Y.; Hamal, S.N.G.; Yakar, M. Combination of Terrestrial Laser Scanning and Unmanned Aerial Vehicle Photogrammetry for Heritage Building Information Modeling: A Case Study of Tarsus St. Paul Church. *Photogramm. Eng. Remote Sens.* **2023**, *89*, 753–760. [CrossRef]
120. Francisco, C.; Gonçalves, L.M.S.; Gonçalves, G.; Solla Carracelas, M.; Ivan, P.L.; Providência, P.; Rodrigues, H.; Gaspar, F. An Integrated Approach of Non-Destructive Methods for Inspection and Characterization of Cultural Heritage: Case Study of Monastery of Batalha, Portugal. In *Rehabend*; Lombillo, I., Blanco, H., Boffill, Y., Eds.; University of Cantabria—Building Technology R&D Group: Santander, Spain, 2020; pp. 936–943.

121. Fregonese, L.; Taffurelli, L.; Adami, A.; Chiarini, S.; Cremonesi, S.; Helder, J.; Spezzoni, A. Survey and Modelling for the Bim of Basilica of San Marco in Venice. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Rehabend, F., Kersten, T., Georgopoulos, A., Stathopoulou, E., Aguilera, D., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2017; Volume 42, pp. 303–310. [CrossRef]
122. Froner, Y.A.; de Barros Gonçalves, W.; Souza, L.A.C.; Costa, A.G.; Rosado, A.; Mizrahy Cuperschmid, A.R.; de Oliveira Walter, G.; Neves Miranda, A.C.; Michelin, G.; Montalvão, A.C.; 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. *Stud. Conserv.* **2024**, *69*, 98–107. [CrossRef]
123. Fryskowska, A. A Novel Approach of Laser Scanning Point Cloud Quality Assessment Using Wavelet Analysis. In *Proceedings of the Baltic Geodetic Congress (Geomatics)*; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2017; pp. 11–17. [CrossRef]
124. Garagnani, S. Building Information Modeling and Real World Knowledge: A Methodological Approach to Accurate Semantic Documentation for the Built Environment. In *Proceedings of the Digital Heritage International Congress*; Eurographics (EG) Digital Library: Online, 2013; Volume 1, pp. 489–496. [CrossRef]
125. Garagnani, S.; Manferdini, A.M. Parametric Accuracy: Building Information Modeling Process Applied to the Cultural Heritage Preservation. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Boehm, J., Remondino, F., Kersten, T., Fuse, T., Gonzalez-Aguilera, D., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2013; Volume 40, pp. 87–92. [CrossRef]
126. Garcia-Valldecabres, J.L.; Liu, J.; Willkens, D.S.; Escudero, P.A.; Lopez-Gonzalez, C.; Cortes Meseguer, L.; Orozco Carpio, P.R. Development of a Virtual Itinerary with Hbim and Gis. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Tucci, G., Balletti, C., Bonora, V., Fassi, F., Spano, A., Parisi, E.I., Previtali, M., Sammartano, G., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2023; Volume 48, pp. 645–652. [CrossRef]
127. Giannuzzi, V.; Bruno, S.; Fatiguso, F.; Nieto-Julián, E. Decay Assessment in Historic Buildings with Texture-Based Classification Techniques: From Digital Survey to Hbim. In *Rehabend*; Boffill, Y., Lombillo, I., Blanco, H., Eds.; University of Cantabria—Building Technology R&D Group: Santander, Spain, 2024; pp. 2448–2456.
128. Gil, A.; Arayici, Y.; Kumar, B.; Laing, R. Machine and Deep Learning Implementations for Heritage Building Information Modelling: A Critical Review of Theoretical and Applied Research. *J. Comput. Cult. Herit.* **2024**, *17*, 1–22. [CrossRef]
129. Giuffrida, D.; Nardo, V.M.; Neri, D.; Cucinotta, G.; Calabrò, I.V.; Pace, L.; Ponterio, R.C. A Multi-Analytical Study for the Enhancement and Accessibility of Archaeological Heritage: The Churches of San Nicola and San Basilio in Motta Sant'agata (Rc, Italy). *Remote Sens.* **2021**, *13*, 3738. [CrossRef]
130. Gómez-López, J.M.; Pérez-García, J.L.; Mozas-Calvache, A.T.; Vico-García, D. Documentation of cultural heritage through the fusion of geomatic techniques. case study of the cloister of "santo domingo" (Jaén, Spain). In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Tucci, G., Balletti, C., Bonora, V., Fassi, F., Spano, A., Parisi, E.I., Previtali, M., Sammartano, G., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2023; Volume 48, pp. 677–683. [CrossRef]
131. Gspurning, J.; Sulzer, W.; Held, D.; Landl, N. Surveying 3D Data as Basis of a HBIM for the Management of Cultural Heritage Objects. *Balt. J. Mod. Comput.* **2022**, *10*, 776–783. [CrossRef]
132. Imtiaz, S.; Arif, S.; Nawaz, A.; Shah, S.A.R. Conservation of Socio-Religious Historic Buildings: A Case Study of Shah Yousuf Gardez Shrine. *Buildings* **2024**, *14*, 2116. [CrossRef]
133. Ippolito, A.; Attenni, M.; Darwa, R. Hbim as a tool for heritage presentation of santa maria in trastevere. *SCIRES-IT* **2023**, *13*, 53–66. [CrossRef]
134. Kalinka, M.; Eriņš, I.; Vaivode, V.; Goldbergs, L.; Korna, I.; Smirnovs, R.; Gorovojs, K. 3D Data Life in cesis medieval castle in latvia. In *Environ. Engineering*; Čygas, D., Vaiškūnaitė, R., Eds.; Vilnius Gediminas Technical University: Vilnius, Lithuania, 2023. [CrossRef]
135. Karasaka, L.; Ulutas, N. Point Cloud-Based Historical Building Information Modeling (H-BIM) in Urban Heritage Documentation Studies. *Sustainability* **2023**, *15*, 10726. [CrossRef]
136. Khoshelham, K. Smart Heritage: Challenges in Digitisation and Spatial Information Modelling of Historical Buildings. In *CEUR Workshop Proceedings*; Migliorini, S., Hallot, P., Billen, R., Belussi, A., Eds.; CEUR-WS: Aachen, Germany, 2018; Volume 2230, pp. 7–12. [CrossRef]
137. Kovalchuk, I.; Ievsiukov, T.; Kutsenko, O.; Kozhemiako, M.; Kozhemiako, P. Application of Laser Scanning for Modeling Cultural Heritage Objects. In *International Conference of Young Professionals "GeoTerrace"*; European Association of Geoscientists and Engineers EAGE: Bunnik, The Netherlands, 2025. [CrossRef]
138. Kuruc, M.; Volařík, T.; Vystavěl, O.; Berková, A.; Chladil, M. Information Modelling of Historical Buildings of Selected Culture Heritage Objects in Moravia Region. *Inz. Miner.* **2024**, *53*, 329–336. [CrossRef]

139. Lenggogeni, L.; Ramadhan, M.A.; Purnomo, A.; Pratama, G.N.I.P.; Fadli, R. The Role of Digital Technologies in Heritage Building Maintenance: A Comprehensive Bibliometric Study. In *AIP Conference Proceedings*; Setiadi, B.R., Mustikaningtyas, A., Majid, A., Riyadi, A., Fatin, N.N., Dewi, A.S., Null, A., Eds.; American Institute of Physics: College Park, MD, USA, 2025; p. 3354. [CrossRef]
140. Li, B.; Willkens, D.S.; Alathamneh, S.; Park, S.C.; Liu, J. Digitally Decoding Heritage: Analyzing the Sellman Tenant House Through HBIM and Digital Documentation Techniques. *Virtual Worlds* **2025**, *4*, 10. [CrossRef]
141. Liu, J.; Bird, G.; Willkens, D.S.; Burt, R.A.; McGonagill, H. Preserving the history of african american education: Digital documentation of rosenwald schools-a case study on the tankersley school in hope hull, alabama, USA. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Tucci, G., Balletti, C., Bonora, V., Fassi, F., Spano, A., Parisi, E.I., Previtali, M., Sammartano, G., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2023; Volume 48, pp. 951–958. [CrossRef]
142. Liu, J.; Li, B. Heritage Building Information Modelling (HBIM): A Review of Published Case Studies. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Tang, X., Tommaselli, A.M.G., Zhang, T., Xie, J., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2024; Volume 48, pp. 387–393. [CrossRef]
143. Liu, J.; Willkens, D. Reexamining the old depot museum in selma, alabama, USA. In *Built Environment*; Long, C., Mahdjoubi, J.J., Galiano Garrigos, A., Eds.; WIT, Transactions; WIT Press: Billerica, MA, USA, 2021; Volume 205, pp. 171–186. [CrossRef]
144. Liu, J.; Willkens, D.; Gentry, R. Developing a Practice-Based Guide to Terrestrial Laser Scanning (TLS) for Heritage Documentation. *Heritage* **2025**, *8*, 313. [CrossRef]
145. Liu, J.; Willkens, D.; López, C.; Cortés-Meseguer, L.; García-Valldecabres, J.L.; Escudero, P.A.; Alathamneh, S. Comparative analysis of point clouds acquired from a tls survey and a 3d virtual tour for hbim development. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Tucci, G., Balletti, C., Bonora, V., Fassi, F., Spano, A., Parisi, E.I., Previtali, M., Sammartano, G., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2023; Volume 48, pp. 959–968. [CrossRef]
146. Martínez-Carricondo, P.; Carvajal-Ramírez, F.; Yero-Paneque, L.; Agüera-Vega, F. Combination of Nadiral and Oblique UAV Photogrammetry and HBIM for the Virtual Reconstruction of Cultural Heritage. Case Study of Cortijo Del Fraile in Níjar, Almería (Spain). *Build. Res. Inf.* **2020**, *48*, 140–159. [CrossRef]
147. Mazzetto, S. Integrating Emerging Technologies with Digital Twins for Heritage Building Conservation: An Interdisciplinary Approach with Expert Insights and Bibliometric Analysis. *Heritage* **2024**, *7*, 6432–6479. [CrossRef]
148. Morbidoni, C.; Pierdicca, R.; Paolanti, M.; Quattrini, R.; Mammoli, R. Learning from Synthetic Point Cloud Data for Historical Buildings Semantic Segmentation. *J. Comput. Cult. Herit.* **2020**, *13*, 1–16. [CrossRef]
149. Moyano, J.; Gil-Arizón, I.; Nieto-Julián, J.E.; Marín-García, D. Analysis and Management of Structural Deformations through Parametric Models and HBIM Workflow in Architectural Heritage. *J. Build. Eng.* **2022**, *45*, 103274. [CrossRef]
150. Moyano, J.; León, J.; Nieto-Julián, J.E.; Bruno, S. Semantic Interpretation of Architectural and Archaeological Geometries: Point Cloud Segmentation for HBIM Parameterisation. *Autom. Constr.* **2021**, *130*, 103856. [CrossRef]
151. Moyano, J.; Martínez, E.; Nieto-Julián, J.E.; Fernández-Alconchel, M. Integrating Wooden Altarpieces into H-BIM: Geometric Profiling, Complex Artworks, and Digital Heritage Mapping. *Autom. Constr.* **2025**, *175*, 106213. [CrossRef]
152. Moyano, J.; Nieto-Julián, J.E.; Bienvenido-Huertas, D.; Marín-García, D. Validation of Close-Range Photogrammetry for Architectural and Archaeological Heritage: Analysis of Point Density and 3d Mesh Geometry. *Remote Sens.* **2020**, *12*, 3571. [CrossRef]
153. Mulush, A.; Baik, A. Digital Architectural Heritage in Saudi Arabia: An Integrated Model for Documentation and Preservation. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Al Mansoori, S., Kaur, N., Haneef, M., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2025; Volume 48, pp. 1085–1093. [CrossRef]
154. Murphy, M.; Fai, S.; Chow, L.; Meegan, E.; Scandurra, S.; Pavia, S.; Corns, A.; Cahil, J. Virtual Historic Centers: Digital Representation of Archaeological Heritage. *Handb. Cult. Herit. Anal.* **2022**, *2*, 1497–1528. [CrossRef]
155. Murphy, M.; Pavia, S.; Cahill, J.; Lenihan, S.; Corns, A. An Initial Design Framework for Virtual Historic Dublin. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Grimoldi, A., Brumana, R., Cantini, L., Previtali, M., Pracchi, V., Scaioni, M., Rinaudo, F., Eds.; Copernicus GmbH: Göttingen, Germany, 2019; Volume 42, pp. 901–907. [CrossRef]
156. Nguyen, T.A.; Do, S.T.; Le-Hoai, L.; Nguyen, V.T.; Pham, T.-A. Practical Workflow for Cultural Heritage Digitalization and Management: A Case Study in Vietnam. *Int. J. Constr. Manag.* **2023**, *23*, 2305–2319. [CrossRef]
157. Nguyen, T.A.; Do, S.T.; Pham, T.-A.; Nguyen, D.H.; Tamura, H. Integration of H-BIM, Virtual Reality, and Augmented Reality in Digital Twin Era—A Case Study in Cultural Heritage. In *Lecture Notes in Civil Engineering*; Reddy, J.N., Wang, C.M., Luong, V.H., Le, A.T., Eds.; Springer Science and Business Media Deutschland GmbH: Berlin/Heidelberg, Germany, 2023; Volume 268, pp. 303–312. [CrossRef]
158. Nieto-Julián, E.; Bruno, S.; Moyano, J. An Efficient Process for the Management of the Deterioration and Conservation of Architectural Heritage: The HBIM Project of the Duomo of Molfetta (Italy). *Remote Sens.* **2024**, *16*, 4542. [CrossRef]

159. Nieto-Julián, E.; Moyano, J.; Pili, A.; Bruno, S. Data Interoperability Between Element Classifications and Semantics of Historic Buildings: Case Study of the Duomo of Molfetta (Italy). In *Advances in Science, Technology Innovation*; Teba, T., Di Raimo, A., Eds.; Springer Nature: Berlin/Heidelberg, Germany, 2025; pp. 175–188. [CrossRef]
160. Nieto-Julián, E.; Robador, M.D.; Moyano, J.; Bruno, S. Semantic HBIM for Heritage Conservation: A Methodology for Mapping Deterioration and Structural Deformation in Historic Envelopes. *Buildings* **2025**, *15*, 1990. [CrossRef]
161. Nieto-Julián, J.E.; Antón, D.; Moyano, J.J. Implementation and Management of Structural Deformations into Historic Building Information Models. *Int. J. Archit. Herit.* **2020**, *14*, 1384–1397. [CrossRef]
162. Nieto-Julián, J.E.; Farratell, J.; Bouzas Cavada, M.; Moyano, J. Collaborative Workflow in an HBIM Project for the Restoration and Conservation of Cultural Heritage. *Int. J. Archit. Herit.* **2023**, *17*, 1813–1832. [CrossRef]
163. Notarangelo, N.M.; Capece, N.; Manfredi, G.; Abate, N.; Masini, N.; Sole, A.; Erra, U. Terrestrial Laser Scanning for Surveying and 3D Modelling of Underground Built Heritage: A Case Study of Hypogea in the Sassi of Matera. In *CEUR Workshop Proceeding*; Terkaj, W., Poveda-Villalon, M., Pauwels, P., Eds.; CEUR-WS: Aachen, Germany, 2023; Volume 3633, pp. 189–200.
164. Nufaisa, R.P.; Nastiar, K.; Choirunnisa, F.; Affriani, A.R.; Nuraini, S.; Sugiyanto, F.A. Accuracy Assessment of Static and Mobile 3D Laser Scanning Systems: A Comparative Study. In *International Conference on Data Science and Geoinformatics*; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2025; pp. 129–134. [CrossRef]
165. Oreni, D.; Brumana, R.; Torre, S.D.; Banfi, F. Survey, HBIM and Conservation Plan of a Monumental Building Damaged by Earthquake. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Tucci, G., Ed.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2017; Volume 42, pp. 337–342. [CrossRef]
166. Palcak, M.; Kudela, P.; Fandakova, M.; Kordek, J. Utilization of 3D Digital Technologies in the Documentation of Cultural Heritage: A Case Study of the Kunerad Mansion (Slovakia). *Appl. Sci.* **2022**, *12*, 4376. [CrossRef]
167. Parrinello, S.; Pettineo, A. Traditional Architectures Along the Cultural Route of James I of Aragon in the Province of Valencia: Leveraging Laser Scanning and BIM for Heritage Management. In *Materials Research Proceedings*; Azrour, M., Pittaluga, D., Tilioua, A., Baba, K., Batan, A., EL Rhaffari, Y., Fratini, F., Gonzalez, F., Haddad, M., Ibnoussina, M., et al., Eds.; Association of American Publishers: Washington, DC, USA, 2024; Volume 40, pp. 350–357. [CrossRef]
168. Patrucco, G.; Chiabrando, F.; Dameri, A.; Teppati Losè, L. Geomatic contribution for the restoration project of the valentino castle green room. from data acquisition to integrated documentation. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Paparoditis, N., Mallet, C., Lafarge, F., Remondino, F., Toschi, I., Fuse, T., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2020; Volume 43, pp. 885–892. [CrossRef]
169. Patrucco, G.; Gómez, A.; Adineh, A.; Rahrig, M.; Lerma, J.L. 3D Data Fusion for Historical Analyses of Heritage Buildings Using Thermal Images: The Palacio de Colomina as a Case Study. *Remote Sens.* **2022**, *14*, 5699. [CrossRef]
170. Pavelka, K.; Kuzmanov, P.; Pavelka, K.; Rapuca, A. Different data joining as a basic model for hbIM—A case project st. pataleimon in skopje. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Shults, R., Dlesk, A., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2023; Volume 48, pp. 85–91. [CrossRef]
171. Pavelka, K.; Matoušková, E.; Pavelka, K. The Contribution of Geomatic Technologies to BIM. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; McDougall, K., Bhatta, G.P., Paudyal, D.R., Shrestha, R., Upadhyaya, P.S., Dahal, T.P., Ranjit, B., Shrestha, S., Thapa, L., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2019; Volume 42, pp. 85–89. [CrossRef]
172. Porcari, V.D.; Priore, A.; Porcari, S.; Fattore, C. Feature Extraction of Point Clouds for Cultural Heritage Monitoring and Conservation. In *Lecture Notes in Civil Engineering*; Albatici, R., Dalprà, M., Gatti, M.P., Maracchini, G., Torresin, S., Eds.; Springer Science and Business Media Deutschland GmbH: Berlin/Heidelberg, Germany, 2025; Volume 764 LNCE, pp. 524–541. [CrossRef]
173. Prizeman, O.; Jones, C.B.; Parisi, M.; Pezzica, C. How Can Century-Old Architectural Hierarchies for the Design of Public Libraries Be Re-Interpreted and Re-Used? *J. Cult. Herit. Manag. Sustain. Dev.* **2018**, *8*, 481–494. [CrossRef]
174. Rahim, S.A.A.; Ashaari, N.I.M.; Kamarudin, S.S.; Hashim, M.A.S.; Arjinan, S.; Chala, G.T.; Rahmat, S. The integration of historic building information modelling (hbim) for the traditional cultural heritage of rumah tukang kahar. *J. Eng. Sci. Technol.* **2024**, *19*, 249–260.
175. Rao, Z.; Wang, G. Smart Data-Enabled Conservation and Knowledge Generation for Architectural Heritage System. *Buildings* **2025**, *15*, 2122. [CrossRef]
176. Reina Ortiz, M.; Yang, C.; Weigert, A.; Dhanda, A.; Min, A.; Gyi, M.; Su, S.; Fai, S.; Santana Quintero, M. Integrating heterogeneous datasets in hbim of decorated surfaces. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Gonzalez-Aguilera, D., Remondino, F., Toschi, I., Rodriguez-Gonzalvez, P., Stathopoulou, E., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2019; Volume 42, pp. 981–988. [CrossRef]

177. Robador González, M.D.; Nieto-Julián, J.E.; Millán-Millán, P.M.; Galera-Rodríguez, A.; Bruno, S.; Debenedictis, D.; Moyano, J. Management Properties and Procedures in the Information Model of the Historic Building Hbim on Building Facades. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Tucci, G., Balletti, C., Bonora, V., Fassi, F., Spano, A., Parisi, E.I., Previtali, M., Sammartano, G., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2023; Volume 48, pp. 1323–1330. [CrossRef]
178. Rocha, J.H.A.; Gonzales, R.J.R.; Castro, N.C.R.; Rosas, M.H.; Campos, A.A.; Chileno, N.G.C.; Lordsleem Júnior, A.C. The Utilization of Unmanned Aerial Vehicles (UAVs) in Cultural Heritage Buildings: A Systematic Literature Review. *Iran. J. Sci. Tech. Trans. Civ. Eng.* **2025**, *49*, 2241–2256. [CrossRef]
179. Rolin, R.; Antaluca, E.; Batoz, J.-L.; Lamarque, F.; Lejeune, M. From Point Cloud Data to Structural Analysis through a Geometrical hBIM-Oriented Model. *J. Comput. Cult. Herit.* **2019**, *12*, 1–26. [CrossRef]
180. Román, J.; Lerones, P.M.; Llamas, J.; Zalama, E.; Gómez-García-Bermejo, J. Towards the automatic 3d parametrization of non-planar surfaces from point clouds in hbim applications. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Gonzalez-Aguilera, D., Remondino, F., Toschi, I., Rodriguez-Gonzalvez, P., Stathopoulou, E., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2019; Volume 42, pp. 1023–1030. [CrossRef]
181. Rossato, L.; Planu, F.; Montanari, G.; Rizzi, D. The Rocca Malatestiana of Verucchio SCAN to HBIM Process for the Digitisation of Cultural Site with Severe Topography Condition. *DISEGNARECON* **2023**, *16*, 2.1–2.12. [CrossRef]
182. Rossi, A.; Palmieri, U. From the Survey to the Digital Construction Site. In *Digital Modernism Heritage Lexicon*; Springer Tracts in Civil Engineering Series; Springer: Berlin/Heidelberg, Germany, 2022; pp. 947–967. [CrossRef]
183. Salah, R.; Károlyfi, K.A.; Szép, J.; Géczy, N. A Structured Framework for HBIM Standardization: Integrating Scan-to-BIM Methodologies and Heritage Conservation Standards. *Digit. Appl. Archaeol. Cult. Herit.* **2025**, *37*, e00420. [CrossRef]
184. Saleeb, N.; Marzouk, M.; Atteya, U. A Comparative Suitability Study between Classification Systems for Bim in Heritage. *Int. J. Sustain. Dev. Plan.* **2018**, *13*, 130–138. [CrossRef]
185. Santagati, C.; Laurini, C.R.; Sanfilippo, G.; Bakirtzis, N.; Papacharalambous, D.; Hermon, S. Hbim for the Surveying, Analysis and Restoration of the Saint John the Theologian Cathedral in Nicosia (Cyprus). In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Rinaudo, F., Scaioni, M., Brumana, R., Grimoldi, A., Cantini, L., Pracchi, V., Previtali, M., Eds.; Copernicus GmbH: Göttingen, Germany, 2019; Volume 42, pp. 1039–1046. [CrossRef]
186. Santagati, C.; Lo Turco, M.; Garozzo, R. Reverse Information Modeling for Historic Artefacts: Towards the Definition of a Level of Accuracy for Ruined Heritage. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Remondino, F., Toschi, I., Fuse, T., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2018; Volume 42, pp. 1007–1014. [CrossRef]
187. Santagati, C.; Papacharalambous, D.; Sanfilippo, G.; Bakirtzis, N.; Laurini, C.; Hermon, S. HBIM Approach for the Knowledge and Documentation of the St. John the Theologian Cathedral in Nicosia (Cyprus). *J. Archaeol. Sci. Rep.* **2021**, *36*, 102804. [CrossRef]
188. Santosa, H.; Yudono, A.; Adhitama, M.S. The Digital Management System of the Tangible Culture Heritage for Enhancing Historic Building Governance in Malang, Indonesia. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing Ltd.: Bristol, UK, 2021; Volume 738. [CrossRef]
189. Sarıcaoğlu, T.; Saygı, G. Data-driven conservation actions of heritage places curated with hbim. *Virtual Archaeol. Rev.* **2022**, *13*, 17–32. [CrossRef]
190. Satriawansyah, T.; Mulyadi, L.; Krismanto, A.U.; Erlinda, L.K.D.; Suhari, K.T. A Multi-Sensor LiDAR–Photogrammetry Workflow for 3D Documentation of Sumbawa Besar Heritage Sites Toward H-BIM Development. In *International Conference on Data Science and Geoinformatics*; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2025; pp. 208–212. [CrossRef]
191. Solla, M.; Gonçalves, L.M.S.; Gonçalves, G.; Francisco, C.; Puente, I.; Providência, P.; Gaspar, F.; Rodrigues, H. A Building Information Modeling Approach to Integrate Geomatic Data for the Documentation and Preservation of Cultural Heritage. *Remote Sens.* **2020**, *12*, 4028. [CrossRef]
192. Soonwald, E.S.; Wojnarowski, A.E.; Tikhonov, S.G.; Artemeva, O.V.; Tyurin, S.V. Building Information Modeling Applied to the Industrial Architectural Monuments Case Study of Saint Petersburg. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Safar, V., Seredovich, V., Vach, K., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2019; Volume 42, pp. 59–63. [CrossRef]
193. Sowder, A.M.; Issa, R.R.A. HBIM for Historic Concrete Buildings: Benefits of Documentation and Analysis for Historic Preservation. In *Lecture Notes in Civil Engineering*; Francis, A., Miresco, E., Melhado, S., Eds.; Springer Science and Business Media Deutschland GmbH: Berlin/Heidelberg, Germany, 2025; Volume 628 LNCE, pp. 365–371. [CrossRef]
194. Sridhar, M.; Paygude, A.; Pande, H.; Tiwari, P.S. 3DITA—A 3D Benchmark Dataset for Nagara-Style Indian Temple Architecture: India's First Point Cloud Dataset for Semantic Segmentation. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Shim, H., Choi, S., Lee, W., Rii, H.U., Kim, S., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2025; Volume 48, pp. 1435–1441. [CrossRef]

195. Stanga, C.; Hasníková, H.; Brumana, R.; Grimoldi, A.; Banfi, F. Geometric Primitives Assessing Italian-Czech Vault Construction Techniques in Baroque Period. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Cantini, L., Scaioni, M., Pracchi, V., Previtali, M., Brumana, R., Rinaudo, F., Grimoldi, A., Eds.; Copernicus GmbH: Göttingen, Germany, 2019; Volume 42, pp. 1081–1088. [CrossRef]
196. Sthapit, I.; Panthi, K. Integrating BIM and Laser Scanning Technologies for Efficient and Effective Restoration of Heritage Structures in the Context of Post-Disaster Recovery. In *International Conference on Construction in the 21st Century*; East Carolina University: Greenville, NC, USA, 2024.
197. Suhari, K.T.; Saptari, A.Y.; Abidin, H.Z.; Gunawan, P.H. Integrating Advanced Surveying Technologies and Indigenous Knowledge into 3D Building Information Modeling. *Civ. Engi. Arch.* **2024**, *12*, 2819–2831. [CrossRef]
198. Sun, Z.; Zhang, Y. Using Drones and 3D Modeling to Survey Tibetan Architectural Heritage: A Case Study with the Multi-Door Stupa. *Sustainability* **2018**, *10*, 2259. [CrossRef]
199. Svytytė, E.; Bocullo, V.; Seduikyte, L. Digital Tools for Sustainable Renovation of Heritage Buildings: From HBIM to Low-Carbon Material Selection. In *Lecture Notes in Civil Engineering*; Jurelionis, A., Fokaides, P.A., Mazzarella, L., Hartmann, T., Eds.; Springer Science and Business Media Deutschland GmbH: Berlin/Heidelberg, Germany, 2026; Volume 775 LNCE, pp. 111–122. [CrossRef]
200. Tortosa, J.A.H.; Fuentes, D.T.; Cereceda, M.L.; Berrio, Y.S. The Façade of the Church of Nuestra Señora de La Asunción in Biar (Spain): From Point Cloud to HBIM. *WIT Trans. Built Environ.* **2017**, *169*, 69–77. [CrossRef]
201. Trizio, I.; Marra, A.; Savini, F.; Fabbrocino, G. Survey methodologies and 3d modelling for conservation of historical masonry bridges. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Dang, A., Li, A., Hou, M., He, Y., Yan, H., Eds.; Copernicus GmbH: Göttingen, Germany, 2021; Volume 8, pp. 163–170. [CrossRef]
202. Turchetti, F.; Cuca, B.; Oreni, D.; Agapiou, A. Recording of Historic Buildings and Monuments for FEA: Current Practices and Future Directions. *Heritage* **2025**, *8*, 55. [CrossRef]
203. Turco, M.L.; Mattone, M.; Rinaudo, F. Metric Survey and Bim Technologies to Record Decay Conditions. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Tucci, G., Ed.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2017; Volume 42, pp. 261–268. [CrossRef]
204. Vieira, M.M.; Gonçalves, J.E.; Silva, D.M.d.O.; Mesquita, E.F.T.; Lima, J.M. Semi-Automatic Scan-to-BIM Procedure Applied to Architectural Ornaments of Nossa Senhora Do Rosário Church, Aracati-CE. *J. Build. Pathol. Rehabil.* **2024**, *9*, 75. [CrossRef]
205. Vieira, M.M.; Ribeiro, G.; Paulo, R.; Bessa, M.; Sousa, F.R.; Moreira, E.; Mesquita, E. Strategy for HBIM Implementation Using High-Resolution 3D Architectural Documentation Based on Laser Scanning and Photogrammetry of the José de Alencar Theatre. *Digit. Appl. Archaeol. Cult. Herit.* **2023**, *30*, e00287. [CrossRef]
206. Wang, S.; Guo, J.; Xu, Y.; Yang, R. Between Hybridity and Compatibility: Conservation and Adaptive Reuse of Allen Hall at Soochow University from the Perspective of Structural Technology. *Int. J. Archit. Herit.* **2025**, *19*, 2471–2487. [CrossRef]
207. Willkens, D.S.; Liu, J.; Alathamneh, S. A Case Study of Integrating Terrestrial Laser Scanning (TLS) and Building Information Modeling (BIM) in Heritage Bridge Documentation: The Edmund Pettus Bridge. *Buildings* **2024**, *14*, 1940. [CrossRef]
208. Xia, X.; Chen, Z.; Xu, Y. Digital Restoration and Feature Recognition of a Qing-Dynasty Vernacular Dwelling Based on Multimodal Data Fusion. *Sci. Rep.* **2026**, *16*, 1844. [CrossRef] [PubMed]
209. Yaagoubi, R.; Miky, Y. Developing a Combined Light Detecting and Ranging (LiDAR) and Building Information Modeling (BIM) Approach for Documentation and Deformation Assessment of Historical Buildings. In *MATEC Web Conference*; Brahim, A., Bahi, L., Khachani, L., Nounah, N., Saadi, A., Boukhari, M., Aride, A., Diouri, J., Eds.; EDP Sciences: Les Ulis, France, 2018; Volume 149. [CrossRef]
210. Yakar, M.; Yılmaz, H.M. The Use of Unmanned Aerial Vehicles in Cultural Heritage Documentation. *Int. J. Eng. Geosci.* **2025**, *11*, 496–509. [CrossRef]
211. Yang, X.; Koehl, M.; Grussenmeyer, P. Parametric Modelling of As-Built Beam Framed Structure in Bim Environment. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Remondino, F., Kersten, T., Georgopoulos, A., Stathopoulou, E., Aguilera, D., Eds.; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2017; Volume 42, pp. 651–657. [CrossRef]
212. Yu, Y.; Wang, Z.; van Oosterom, P.; Pottgiesser, U.; Verbree, E.; Peng, Y. Reframing the "H" in HBIM: From Systematic Review to UML-Based Conceptual Modeling. *Front. Archit. Res.* **2026**, *in press*. [CrossRef]
213. Zachos, A.; Anagnostopoulos, C.-N. Using TLS, UAV, and MR Methodologies for 3D Modelling and Historical Recreation of Religious Heritage Monuments. *J. Comput. Cult. Herit.* **2025**, *17*, 1–23. [CrossRef]
214. Zakharova, G.; Romanov, A. Technologies for Digital Twins of Historical Buildings in the Educational Process of Architects. In *Lecture Notes in Civil Engineering*; Ulrikh, D.V., Gasiyarov, V.R., Radionov, A.A., Eds.; Springer Science and Business Media Deutschland GmbH: Berlin/Heidelberg, Germany, 2025; Volume 565 LNCE, pp. 496–506. [CrossRef]
215. Zhang, X. Digital Preservation of Ancient Timber Structures Through Integrated TLS-UAV-BIM Reverse Modeling: A Case Study in Gansu Province, China. In *Proceedings of the International Conference on Big Data, Information and Computer Networking*; BDICN: Beijing, China, 2026; pp. 91–96. [CrossRef]

216. Zhao, J.; Hua, X.; Yang, J.; Yin, L.; Liu, Z.; Wang, X. A review of point cloud segmentation of architectural cultural heritage. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; El-Sheimy, N., Abdelbary, A.A., El-Bendary, N., Mohasseb, Y., Eds.; Copernicus Publications: Göttingen, Germany, 2023; Volume 10, pp. 247–254. [CrossRef]
217. Murphy, M.; Corns, A.; Cahill, J.; Eliashvili, K.; Chenau, A.; Pybus, C.; Shaw, R.; Devlin, G.; Deevy, A.; Truong-Hong, L. Developing Historic Building Information Modelling Guidelines and Procedures for Architectural Heritage in Ireland. *ISPRS-Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *XLII-2/W5*, 539–546. [CrossRef]
218. Murphy, M.; McGovern, E.; Pavia, S. Historic building information modelling (HBIM). *Struct. Surv.* **2009**, *27*, 311–327. [CrossRef]
219. Murphy, M.; McGovern, E.; Pavia, S. Historic Building Information Modelling—Adding intelligence to laser and image-based surveys of European classical architecture. *ISPRS J. Photogramm. Remote Sens.* **2013**, *76*, 89–102. [CrossRef]
220. López, F.J.; Lerones, P.M.; Llamas, J.; Gómez-García-Bermejo, J.; Zalama, E. A Review of Heritage Building Information Modeling (H-BIM). *Multimodal Technol. Interact.* **2018**, *2*, 21. [CrossRef]
221. Yang, X.; Grussenmeyer, P.; Koehl, M.; Macher, H.; Murtiyoso, A.; Landes, T. Review of built heritage modelling: Integration of HBIM and other information techniques. *J. Cult. Herit.* **2020**, *46*, 350–360. [CrossRef]
222. Puerto, A.; Castañeda, K.; Sanchez Rivera, O.; Peña Soto, C.; Gutiérrez, L.; Sáenz, P. Building Information Modeling and Complementary Technologies in Heritage Buildings: A Bibliometric Analysis. *Results Eng.* **2024**, *22*, 102192. [CrossRef]
223. Quattrini, R.; Malinverni, E.S.; Clini, P.; Nespeca, R.; Orlietti, E. From tls to hbim. high quality semantically-aware 3d modeling of complex architecture. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *XL-5/W4*, 367–374. [CrossRef]
224. Stober, D.; Žarnić, R.; Penava, D.; Turkalj Podmanicki, M.; Virgej-Đurašević, R. Application of HBIM as a Research Tool for Historical Building Assessment. *Civ. Eng. J.* **2018**, *4. 1565*. [CrossRef]
225. Moyano, J.; Nieto-Julián, J.E.; Lenin, L.M.; Bruno, S. Operability of Point Cloud Data in an Architectural Heritage Information Model. *Int. J. Arch. Herit.* **2021**, *16*, 1588–1607. [CrossRef]
226. Gordon, M.; von Zimmerman, L.; Haradhun, O.; Campanella, D.; Bräutigam, M.; De Wolf, C. Digitising Building Materials for Reuse with Reality Capture and Scan-to-BIM Technologies. In *A Circular Built Environment in the Digital Age Circular Economy and Sustainability*; De Wolf, C., Çetin, S., Bocken, N.M.P., Eds.; Springer: Cham, Switzerland, 2024. [CrossRef]
227. Franco, G.; Mauri, S. Reconciling Heritage Buildings' Preservation with Energy Transition Goals: Insights from an Italian Case Study. *Sustainability* **2024**, *16*, 712. [CrossRef]