FACULTY OF ARCHITECTURE AND THE BUILT ENVIRONMENT, DEPARTMENT OF ARCHITECTURAL ENGINEERING AND TECHNOLOGY

ARCHITECTURAL HERITAGE INFORMATION INFRASTRUCTURE BASED ON SMART POINT CLOUD

PHD RESEARCH PROPOSAL

YINGWEN YU

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TU Delft Delft University of Technology

Challenge the future

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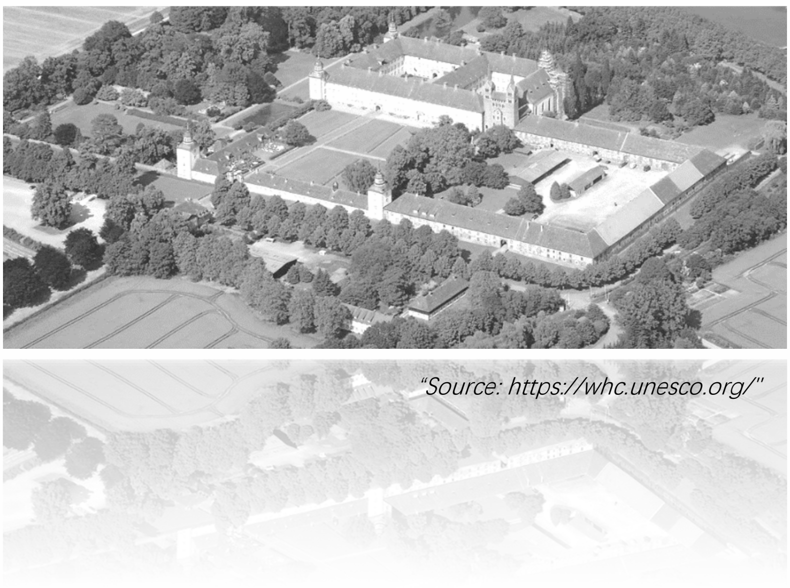

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Yingwen Yu
christinayu@tudelft.nl

Delft University of Technology
Faculty of Architecture and the Built Environment
Department of Architectural Engineering + Technology
Section of Heritage & Architecture / Section Digital Technologies

Supervisors
Prof.dr.ir. P.J.M. (Peter) van Oosterom
Prof. Dr.-Ing U. (Uta) Pottgiesser
Daily Supervisor
Ir. E. (Edward) Verbree

Committee Members
Chair: Prof. Dr.ing. S. (Steffen) Nijhuis
External Peer: Dr. H.T. (Hilde) Remoy
External Peer: Dr. Ir. S.C. (Stefan) van der Spek

TU Delft Delft University of Technology

Architectural Heritage Documentation Infrastructure based on Smart Point Cloud

ABSTRACT

This Ph.D. research project aims to design architectural heritage information infrastructure (AHII) based on point clouds using Heritage Building Information Modeling (HBIM) defined concepts for structuring and semantically enriching. The AHII has the following functions: 1. Collect digital data and information about architectural heritage (including 3D models, interactive maps, geo-location narratives, and audio-visual materials), 2. Structure the information according to international standards (partly to be developed), 3. Manage the information in the Heritage register/database, and 4. Disseminate (and Visualize) the architectural heritage via web services (view, download, process). The AHII encourages systematical and digital information archiving to support the long-term preservation and sustainable management of architectural heritage. Enabling the flexible and timely integration of various layers of information between communities, researchers, industry, and other architectural stakeholders will be demonstrated in multiple use cases. The AHII also evaluates the applicability of HBIM modeling in combination with different digital tools, standardizes the processing of digital tools for other applications of point clouds, and provides the public with rich information and virtual experience of these buildings.

KEYWORDS:

Architectural Heritage, Digital Infrastructure, Heritage Building Information Modeling, (Smart)Point Cloud

Table 1:

Some of the major abbreviations that appear in the PhD project

KEY ABBREVIATIONS	
AHII	*Architectural Heritage Information Infrastructure*
AR	*Augmented Reality*
BIM	*Building Information Modelling*
DBMS	*Database Management System*
DT	*Digital Twins*
HBIM	*Heritage Building Information Infrastructure*
LoD	*Level of Detail*
PC	*Point Cloud*
SPC	*Digital Twins Smart Point Cloud*
VR	*Virtual Reality*

CONTENTS

1. INTRODUCTION

1.1 Research motivation (State of questions)

Architectural heritage constitutes a vital component of human cultural heritage (Liang et al., 2023), playing a significant role in our collective identity and history (Panzera, 2022). They encompass the legacy of the past, the present, and the future, representing invaluable sources of life and inspiration (UNESCO, 2021), (Mekonnen et al., 2022; Noyes, 2011). Protecting these structures is crucial for preserving the tangible manifestations of our past and holds profound significance for humanity, providing insights into historical socio-cultural contexts and technological advancements (Nilson & Thorell, 2018).

One of many conservational approaches to safeguarding architectural heritage (**Table 2**)involves the utilization of digital technologies for data collection, data sharing, data specification, use of standards, and governance/organization (Crompvoets et al., 2018), which is also referred to as Architectural Heritage Information Infrastructure (AHII) (Candón Fernández et al.). Though these digital technologies have been widely applied in the preservation of architectural heritage for decades, the AHII applications still face challenges, including (Green et al., 2019):

Table 1:
Examples of architectural heritages are Italy, Germany, and the Netherlands.

Architectural Heritage (some examples) Definition: An architectural heritage can be interpreted as an “artifact” where its elements are witnesses of the cultures. Actors and events that occurred during the life of the building.		
Italy	Germany	Netherlands
		
Chiesa di Santo Stefano (Volterra)	Abbey Church Corvey (Germany, Carolingian)	Rietveld Schröder House (*Rietveld Schröderhuis*)

(a) High-quality 3D modeling: The need for such high-quality models is critical for preservation, study, and educational purposes, but the resources required to create these models can be prohibitive (Megahed, 2015). This includes the technological equipment necessary for precise data capture, such as advanced scanning and imaging technologies (Wang & Kim, 2019), and the human expertise needed for data processing, model creation, and validation (López et al., 2018).

(b) Financial affordability: The technology and expertise needed for high-quality 3D modeling and virtual reconstructions are often expensive. The cost barriers encompass a range of expenses, from the initial acquisition of sophisticated scanning and imaging equipment to the ongoing expenses related to software licenses, maintenance, and upgrades necessary to process and manage the data effectively (Masciotta et al., 2023).

(c) Community sharing and accessibility: There is a gap in the widespread sharing and accessibility of these 3D models within the heritage conservation community and the public. The challenges here involve the technical aspects of making these detailed digital representations widely available and legal, copyright, and privacy concerns that may restrict sharing (King et al., 2016).

(d) Integration with the existing archives and datasets: Ensuring compatibility and ease of access while maintaining the integrity and detail of the 3D models requires coordinated efforts and resources (Shafique et al., 2020).

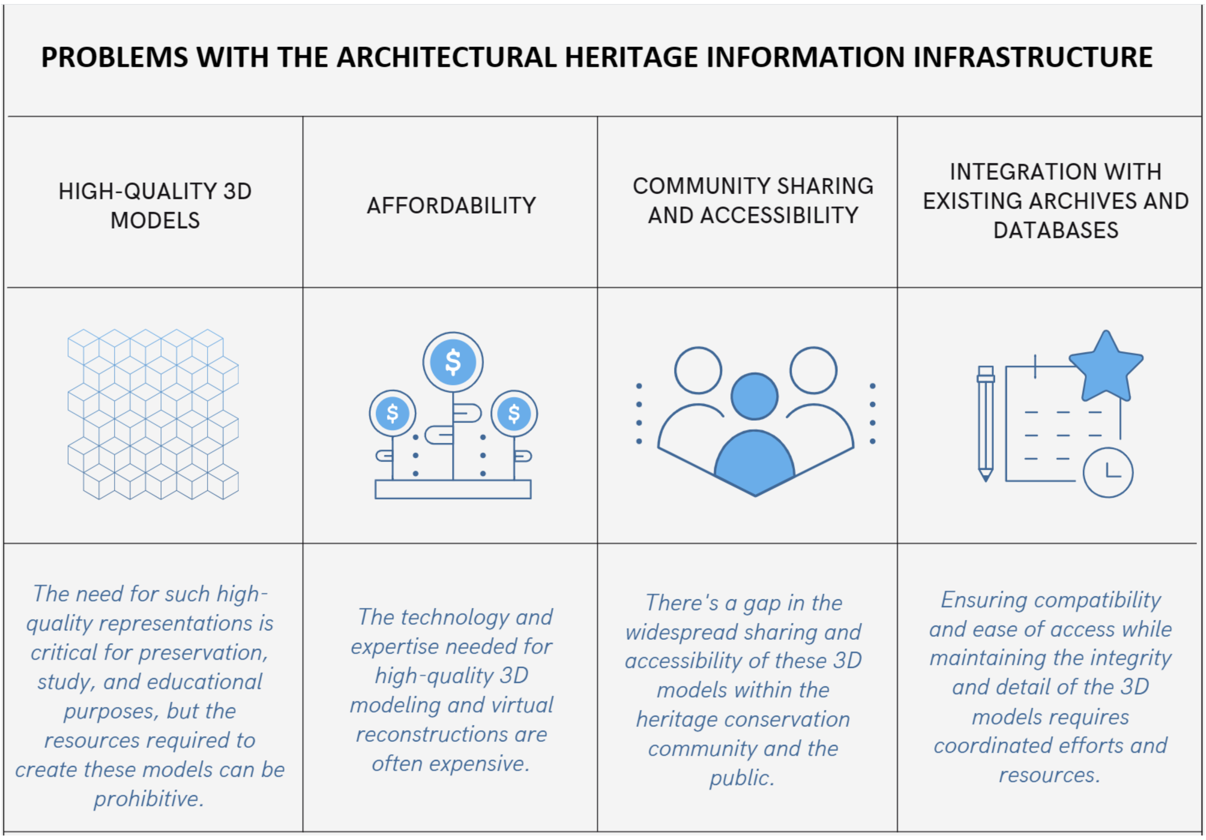


Fig. 1. The challenges for applying Architectural Heritage Information Infrastructure (Source: by author).

This doctoral project aims to utilize existing technological methods, combined with new digital technologies, to address the aforementioned issues as effectively as possible. The emergence of the point cloud (PC) (**Fig. 2**) technology presents a possibility for addressing the problems related to preserving architectural heritage (Ferro et al., 2023; Rodríguez-Moreno et al., 2018). Therefore, PC technology has become this project's central focus and technological approach.

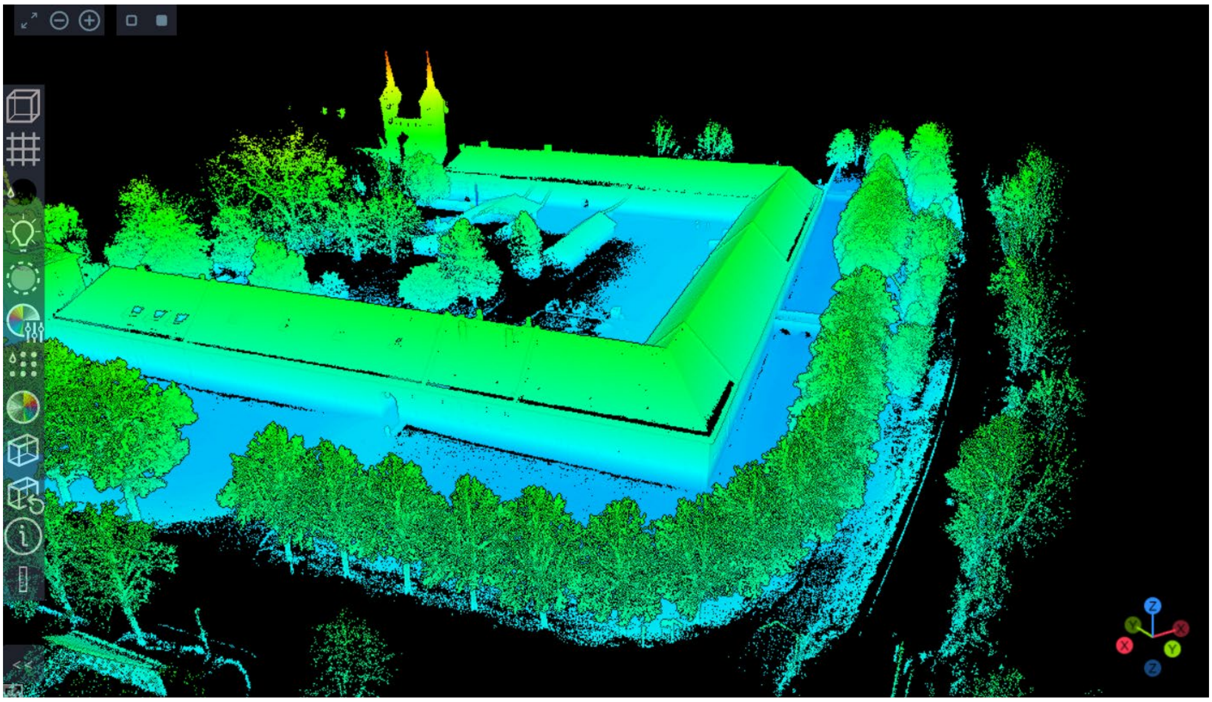


Fig. 2. Point Cloud in Faro Connect viewer (Source: by author)

1.2 AHII-SPC: Potential solution

AHII is a comprehensive digital system that supports architectural heritage management, research, and preservation. This infrastructure typically encompasses databases, digital archives, Geographic Information Systems (GIS), Building Information Modeling (BIM), and other digital tools and platforms. It aims to facilitate collecting, storing, analyzing, and sharing information regarding historic buildings, sites, and landscapes, contributing to their conservation and public awareness (Letellier & Eppich, 2015).

These processes are closely linked to the characteristics of the emerging PC technology, providing the possibility for integrating PC into the AHII as a geometric basis. With the advent of three-dimensional Light Detection and Ranging (LiDAR) scanning technology and dense matching of images, point clouds (PC) generated by LiDAR or dense matching have the potential to address these questions (mentioned in (**Fig. 1**.)) due to its high precision, superior detail fidelity, efficient site information acquisition, along with capabilities in disaster prediction, is significantly enhanced by "Time dimension, repeated scans forming the basis for monitoring" — which, in effect, creates a 4D point cloud for detailed analysis. (Bhatia et al., 2023). In addition, the emergence of smart point clouds (SPC), enriched with additional data and attributes, further enhances the potential application of SPC data in the conservation of architectural heritages (Bartolini et al., 2023).

However, research and practice on how to integrate SPC and AHII and utilize them for the sustainable preservation and management of architectural heritage remain relatively scarce (Bruno et al., 2018; Rossi & Bournas, 2023). Therefore, this doctoral research program is dedicated to creating an architectural heritage information infrastructure for architectural heritage conservation using HBIM and SPC technologies.

1.3 Research question

Focusing on the integration of point cloud technology with the conservation of architectural heritage, this project will explore how to incorporate an investigation of point cloud technology and its potential applications in heritage building preservation, including information collection, documentation, database creation, dissemination, and visualization for various purposes, incl. conservation. It will also discuss new insights that point cloud technology can bring to the protection of heritage buildings. Consequently, the primary research question and corresponding secondary research questions of this study have been defined as follows:

Main Research Question:

How to design the Architectural Heritage Information Infrastructure based on Smart Point Cloud?

Sub Research Questions:

SQ1: *What is the state of the art of smart point clouds and their application in a heritage context?*
SQ2: *What kind of tools are available for the structure and enhancement of point clouds (based on HBIM concepts)?*
SQ3: *For the dissemination method, what methods are most appropriate for what users? VR, AR, Web, DT?*
SQ4: *How to develop an information infrastructure for Architectural Heritage serving various applications?*
SQ5: *What is the added value of the Architectural Heritage Information Infrastructure for various use cases (with various actors)?*

1.4 Structure of the document

This document is organized into four main sections and three appendices, including **Chapter 1, Introduction:** This chapter introduces the origin of the research questions, focusing on point cloud technology and heritage buildings (as well as the relationship between them) and poses the corresponding research questions. **Chapter 2, Background:** This section delves into key concepts and research findings related to heritage buildings, Architectural Heritage Information Infrastructure, and smart point clouds. **Chapter 3, Research gaps:** It identifies knowledge gaps; thereby, **Chapter 4, Research objectives:** It clarifies the purpose and significance of this study. **Chapter 5, Methodology:** This chapter will describe the research methods, technological approaches, and case studies employed in this study (including some preliminary research results). **Chapter 6, Practical Aspects:** The final section outlines the tools, the supervision, the project timeline, and the doctoral educational plan.

2. BACKGROUND

Architectural heritage encompasses historically significant buildings, structures, and spaces embodying past generations' cultural, aesthetic, and historical values. Technologies based on AHII have always been an essential means for digitally preserving heritage buildings. In this chapter, we will provide a background introduction to the fundamental concepts involved in this research, including an overview of architectural heritage and their digital preservation standards (**2.1**), an examination of the technologies associated with AHII (**2.2**), a summary of the current applications and attempts of PC and SPC in heritage building preservation (**2.3**), and a review of the cutting-edge HBIM technologies based on PC (**2.4, 2.5**). Following this, we will review current research (**2.6**), including those related to SPC and HBIM technologies themselves, as well as the application of these technologies in heritage preservation.

2.1 Architectural Heritage

Architectural heritage is a testimony to socio-cultural and religious history, helping people acquire a sense of place and identity through a stable link to the past (Nilson & Thorell, 2018). Architectural Heritage is a term that refers to buildings or structures of historical or cultural importance, which are a vital part of the country's heritage and require conservation (UNESCO, 1972). Worldwide organizations and governments, including UNESCO and ICOMOS, have developed a series of regulations and standards for protecting architectural heritage. These regulations aim to ensure the protection, conservation, presentation, and transmission of cultural and natural heritage to future generations; see Table 1. What is missing is a standardized information model (IM) that provides the ontology (concepts: terms, definitions, and relationships) to document the various types of architectural heritage.

Table 2:

Necessary chapters/standards focus on architectural heritages.

Organization	Chapter/standards	Year	Topic and focus
UNESCO	World Heritage Convention	1972	Establishes the criteria for inscribing sites on the World Heritage List and outlines the obligations of State Parties to protect their heritage.
ICOMOS	Venice Charter	1964	The International Charter for the Conservation and Restoration of Monuments and Sites (Venice Charter) provides guidelines for conserving and restoring historic buildings.
ICOMOS	Charter on the Built Vernacular Heritage	1999	It focuses on protecting and preserving non-monumental buildings and landscapes with cultural significance.
ICOMOS	Florence Charter	1982	This charter addresses the preservation of historic gardens, emphasizing their recognition and protection as an integral part of the cultural heritage.
ICOMOS	Washington Charter	1987	Provides guidelines for preserving historic towns and urban areas' associated cultural and social values.
ICOMOS	Principles for the Analysis, Conservation, and Structural Restoration of Architectural Heritage	2003	Establishes principles for the structural restoration of historic buildings to preserve their authenticity and integrity.
ICOMOS	New Delhi Charter	1986	It focuses on conservation and restoration practices suitable for different cultures and regions.

ICOMOS	The Burra Charter	1979, 2013	Developed by Australia, this charter provides guidelines for conserving and managing places of cultural significance (also known as the Australian ICOMOS Charter for Places of Cultural Significance).

2.2 Digital Information Infrastructure of Architectural Heritage

Digital conservation is a method of comprehensively, accurately, and efficiently recording, analyzing, storing, managing, presenting, and disseminating information about architectural heritage using digital technologies such as three-dimensional (3D) scanning, modeling, visualization, and virtual reality (VR) (Germs et al., 1999; Li et al., 2023; Verbree et al., 1999). Focusing on architectural heritage conservation, the "Architectural Heritage Information Infrastructure" (AHII) refers to the comprehensive framework and set of technologies used to capture, store, manage, and disseminate digital data and information about architectural heritage sites (**Fig. 3**). Specifically, the workflow of AHII encompasses the following five key steps:

(a) Data Collecting: The data collection for architectural heritage primarily involves surveying, photographic documentation (Stylianidis, 2020), thermal imaging (Adamopoulos & Rinaudo, 2021), and various point cloud scanning technologies such as terrestrial scanning (Lemmens & Lemmens, 2011), mobile scanning (Che et al., 2019; Liu et al., 2022), and airborne methods (Kedzierski & Fryskowska, 2015). Among these, scanning-based techniques are becoming crucial for historical architectural data collection due to their efficiency and accuracy (Al-Bayari & Shatnawi, 2022).
(b) Data Processing: The methods of data processing are directly related to the type of data collected (Van de Vijver & Leung, 1997). Focusing on point cloud data, the main processes include data cleaning (noise reduction and outlier removal) (Rakotosaona et al., 2020), the fusion of multiple viewpoints and coordinates (Kundu et al., 2020), organizing in continuous levels of detail (van Oosterom et al., 2022), and downsampling (Zhang et al., 2018). Additionally, processing requirements also need to adhere to data standards (Dore & Murphy, 2012); however, literature on integrating data standards with relevant technologies is relatively scarce (Laakso & Kiviniemi, 2012).
(c) Data Storage: There are various methods for data storage, but BIM and HBIM have become among the mainstream approaches (Pezeshki & Ivari, 2018). HBIM is commonly used to establish 3D models containing various information types (Murphy et al., 2009). The collection of HBIM models must be organized in an archive and managed by a database management system (DBMS).
(d) Data Sharing: Sharing architectural heritage data is also essential (Bastem & Cekmis, 2022). Currently, the primary method of sharing is through online platforms such as DoCoMo Mo (Guillet, 2007; Pottgiesser & Dragutinovic, 2022). However, establishing a paradigm for sharing heritage architectural data, especially point cloud and smart point cloud data (3D representations), still requires further development (Stylianidis, 2020).
(e) Heritage Data Using: Although many practices exist for other data types, the Information Infrastructure approach for architectural heritage will be evaluated via various case studies (Wang et al., 2021).

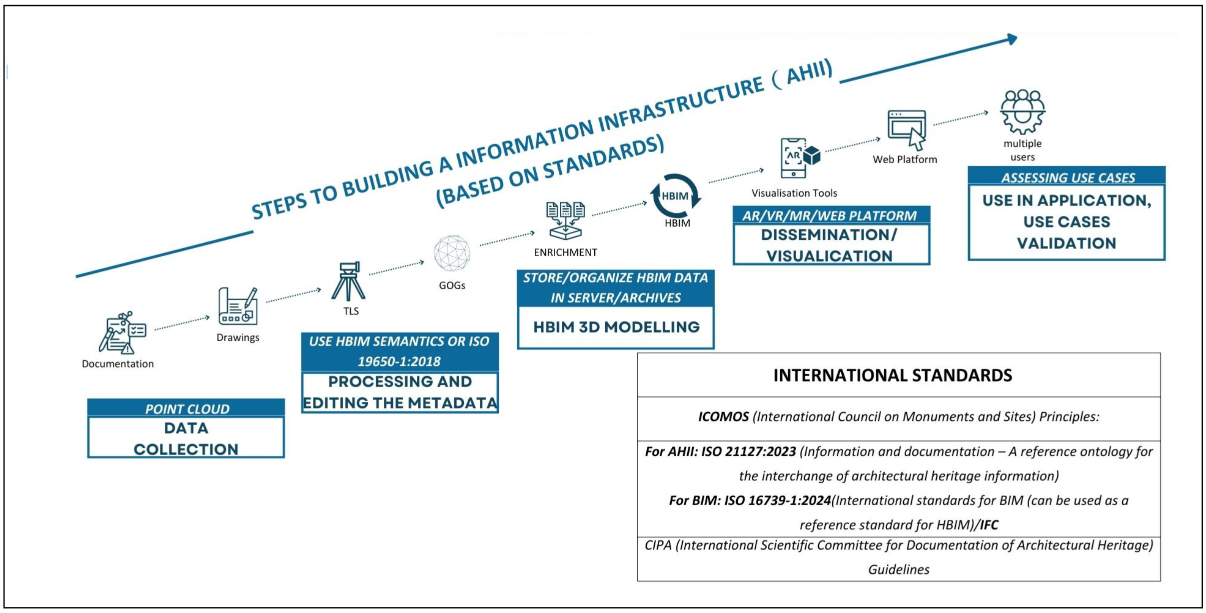


Fig. 3: Overview of Architectural Heritage Information Infrastructure (AHII); (Source: by author).

Nowadays, information/digital technology has become widespread across all industries and has also become an essential aid in preserving architectural heritage. The international standards/chapters related to the preservation of architectural heritage currently are described in **Table 3**.

Table 3:
Necessary chapters/standards focus on digital/information-based architectural heritage protection.

Organization	Chapter/standards	Year	Topic and focus
ISO 16739-1:2024	The London Charter for the Computer-based Visualization of Cultural Heritage	2023	This standard outlines a reference ontology, which serves as a model for the description and structuring of information that is common within the domain of architectural heritage. It is designed to facilitate the sharing, integration, and preservation of heritage data, enabling various stakeholders such as conservators, historians, and architects to communicate effectively and to ensure that information about heritage assets is accessible and usable over time.
ICOMOS	The Charter on the Digital Documentation of Cultural Heritage	2017	Also known as the Istanbul Principles, this charter emphasizes the importance of digital documentation in cultural heritage conservation, offering guidelines for high-quality digital recording.
ICOMOS	The Seville Principles: International Principles of Virtual Archaeology	2011	Provides a framework for applying virtual reality and digital reconstruction in archaeology, ensuring that digital techniques are used scientifically, transparently, and ethically.

ICOMOS	The Principles for the Recording of Monuments, Groups of Buildings, and Sites	1996	Although not solely focused on digital technologies, this document by ICOMOS offers guidance on recording techniques that are increasingly being applied through digital means, emphasizing the importance of comprehensive documentation for preservation and research.

2.3 From PC to SPC: Smart Point Cloud

Point cloud technology plays a crucial role in the digital documentation and preservation of architectural heritage. A “point” is a collection of data, collected by laser scanning or dense matching of overlapping camera images, containing thousands or millions of specifically located points that accurately represent the object's shape. Therefore, point cloud data primarily contains precise geospatial information, and in some cases, it also includes semantic segmentation information and color data such as RGB. Although the detail in point cloud data far exceeds that of traditional surveying and modeling, there are still challenges in further analysis and archiving, such as digitalizing architectural heritage information. This indicates that while point cloud technology represents a significant advancement over traditional methods in capturing detailed data, there remain gaps in its ability to fully address the complexities and multi-dimensional needs of architectural heritage digitalization.

Stephan Nebiker proposed the originally termed “Rich Point Cloud Paradigm” in 2009, which is a departure from traditional methods that emphasize explicit 3D vector geometric or image-based raster modeling (textures typically draped over meshes). Key elements of this new paradigm include treating 3D point clouds with radiometric and semantic properties as actual urban 3D models rather than merely input for traditional 3D modeling processes (Nebiker et al., 2010). The process of a point cloud becoming “smart” is often referred to as enrich structuring and semantic enrichment (Poux et al., 2016). In his research, he proposed an intelligent infrastructure for point clouds in which users can extract specific information based on semantic memory. Hereby, he also underlines the importance of structuring and semantics as essential in providing this added value (Baauw et al., 2019). The term Smart Point Cloud is also the preferred term in this PhD thesis project. Compared to traditional point cloud technologies, smart point clouds typically offer the following advantages:

(a) Enhanced Detail and Accuracy: SPC provides a highly detailed and accurate digital representation of architectural heritage, capturing not just the geometry but also the texture, color, and material properties of structures, which can be achieved with the integration of 3D laser scanning, photogrammetry, texture mapping, and machine learning. This level of detail is crucial for understanding the condition and characteristics of heritage sites.

(b) Improved Accessibility and Usability: By adding structure, integrating semantic data, and making the point clouds comprehensible, smart point clouds enhance the accessibility of digital heritage information. Researchers, conservationists, and the public can interact more intuitively with the data, aiding educational efforts and broader engagement with heritage preservation.

(c) Visualization: Smart point clouds enable visualization supporting virtual reconstruction for inaccessible sites or lost time. This not only aids in preservation efforts but also allows the public and scholars to explore and understand heritage sites in a virtual environment, bridging the gap between past and present.

(d) Facilitation of Conservation and Restoration: The detailed and enriched data provided by smart point clouds support conservation and restoration efforts. By understanding the materials, construction techniques, and historical context of heritage structures, professionals can make informed decisions about conservation practices that are respectful of the site's integrity and significance.

In summary, SPC has significant potential for application throughout the entire lifecycle as supported by AHII, including aspects such as data collecting, data structuring, data storage, data manipulation, visualization, and sharing. The structuring characteristic is related to BIM and HBIM, providing standardized concepts and terms, aiming for SPC's richer information and better usability.

2.4 From BIM to HBIM: Heritage Building Information Modeling

Scan-to-BIM uses 3D scanning technology to capture the physical features of an existing building and then create an accurate 3D model using the BIM structure and semantics, which is widely used in the construction industry for new construction or renovation projects (see ISO 16739-1: 2024). As BIM technology matures and spreads, experts and researchers are beginning to realize that traditional BIM tools and methods do not fully meet the specific needs of historic building conservation and management due to missing entities capturing the specific heritage values. Historic buildings often have unique structures and complex details requiring more meticulous documentation and analysis methods. HBIM is a further developed application of Scan-to-BIM in cultural heritage conservation and historic building restoration, focusing on documenting, preserving, and managing historic buildings. In short, HBIM is a specialized extension and application of Scan-to-BIM in historic buildings, the concept of which was introduced in 2009 by Murphy and McGovern (Murphy et al., 2013) and is defined as a methodology for documenting, managing, and analyzing historic buildings by using Building Information Modelling (BIM) technology, especially for historic building preservation and maintenance needs.

At the practical level, the main applications of HBIM include:

(a) Accurate recording and monitoring: HBIM can provide an accurate 3D digital record of historic buildings, sites, and especially the information of "time" (Diaz et al., 2023), also known as 3D+ or 4D, helping to monitor more pre-conditions and analyze changes and deterioration over time.

(b) Conservation and maintenance: By documenting every aspect of the architectural heritage in detail, HBIM helps experts develop more precise and effective conservation and maintenance strategies.

(c) Restoration support: HBIM models can be used to simulate the effects of restoration and consolidation measures, helping decision-makers choose the most appropriate methods.

(d) Enhanced public participation: Through 3D interactive web-applications (potree of WebVR), Virtual Reality (VR) and Augmented Reality (AR) technologies, HBIM can enable the public to experience historic buildings in an interactive (and immersive way), thus increasing public interest in architectural heritage and awareness of conservation.

(e) Education and research: HBIM provides a rich repository of resources that contributes to academic research and educational activities, facilitating the dissemination of knowledge on historic architectural heritage.

The application of this technology in architectural heritage also faces the following challenges:

(a) Complexity of data collection: 3D scanning and data collection of historic buildings is time- and resource-intensive, especially for complex or severely damaged buildings.

(b) Technical expertise: HBIM requires specialized technical knowledge to create and manage models, which may limit its wide application in historic building conservation.

(c) Standardization and compatibility issues: There may be compatibility issues between different HBIM software and tools, and standardization of data and models is also a challenge.

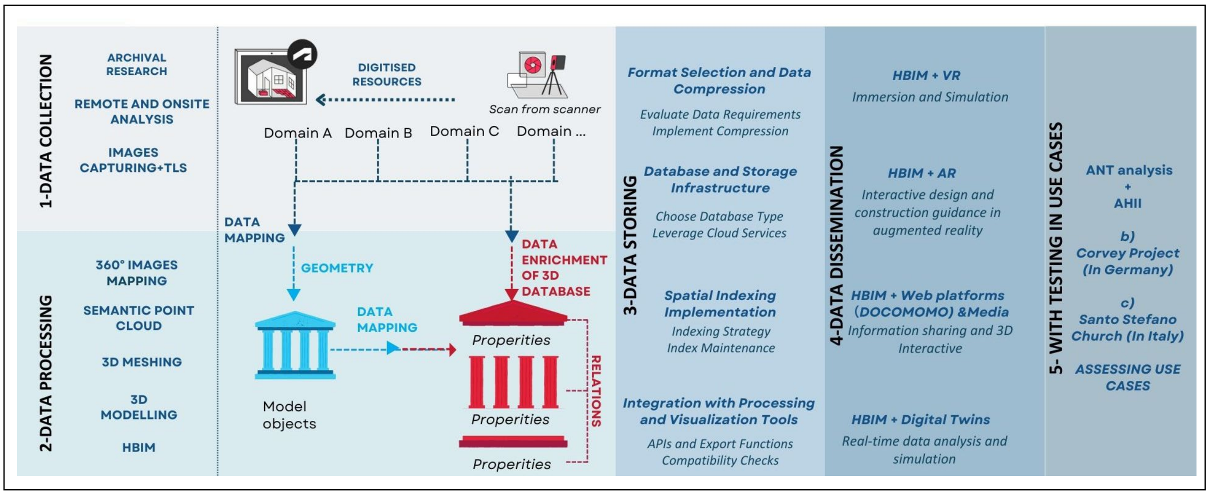


Fig. 4. Diagram of Definition of HBIM / Opportunities (Source: by author, adapted from (Calvano et al., 2022)).

2.4.1 Creating SPC based on HBIM

Realizing the Smart Point Clouds (SPC) based on the concepts and terms defined in Heritage Building Information Modeling (HBIM) is a process that evolves from capturing primarily geometric and visual data to developing a rich, semantically informed model. Initially, Point Clouds focuses on recording the exact physical form and surface characteristics of heritage structures. This stage is about precise data capture, including cleaning and registration, to ensure accuracy in representing the current state of the structure.

The leap to SPC based on HBIM involves integrating this detailed geometric data with extensive semantic information, such as historical context, material properties, and conservation measures. This process transforms the raw point cloud data into point cloud-based BIM models. These models are then augmented with layers of semantic data, which provide a much deeper understanding of the heritage assets. This integration is not merely about data collection; it requires a nuanced interpretation and integration of information, making it a more complex and multifaceted procedure. The end goal of HBIM is to manage and analyze this rich dataset for various purposes, including maintenance, decision-making, conservation, and presentation, ultimately supporting the comprehensive preservation of cultural heritage buildings.

SMART POINT CLOUD =	POINT CLOUD	+	HBIM
Data	*Primarily geometric and visual information.*	+	*Combines geometric models with extensive semantic information (e.g., history, materials, conservation measures).*
Purpose of Use	*To precisely record the physical form and surface characteristics of heritage structures.*	+	*To manage and analyze architectural heritage information for maintenance, decision-making, conservation, and presentation purposes.*
Application Focus	*Accurate documentation and visualization of the current state of heritage structures.*	+	*Creation of comprehensive information models to support the maintenance, management, and preservation of heritage buildings.*
Processing and Application	*Involves data capture, cleaning, and registration.*	+	*Involves converting point cloud data into parametric BIM models and augmenting them with semantic information, which is a more complex process requiring data interpretation and integration.*

Fig. 5. Point Clouds and HBIM together form the basis for SPC for Heritage (Source: by author).

2.4.2 Standards for HBIM

Currently, a suite of international standards exists that is designed to normalize the Building Information Modeling (BIM). These standards are twofold: firstly, those that establish norms for creating BIM frameworks, and secondly, those that govern data exchange, ensuring interoperability across various platforms and systems; see Table 3. What is missing is HBIM standards (on top of BIM standards) that support heritage concepts and values. Also, point Clouds are currently not supported by BIM standards. Here, the PhD research will contribute to standard proposals.

Table 4
Necessary chapters/standards focus on HBIM.

Organization	Chapter/standards	Year	Topic and focus
ISO	ISO 16739-1:2024	2024	The standard aims to facilitate interoperability and information exchange across different software platforms, enhancing collaboration and efficiency in construction and facility management projects.
IFC	Industry Foundation Classes (IFC)	2020	Industry Foundation Classes (IFC) are a fundamental part of BIM data exchange, covered by the ISO 16739 standard. While initially not heritage-specific, IFC is increasingly used for HBIM due to its ability to handle complex data models and ensure interoperability between different software platforms.

2.5 Integrating HBIM Concepts for SPC Structuring and Classification

The concepts of HBIM are extensively discussed in various studies regarding their application in the conservation, restoration, and management of cultural heritage buildings

(Bruno et al., 2018; López et al., 2018). These studies often focus on the integration of geometric and semantic data for improving workflows and decision-making processes in heritage studies. For example, HBIM's potential for enhancing data migration between different software solutions through the use of Industry Foundation Classes (IFC) open data exchange standards is noted, which can be crucial for the structuring and classification purposes in broader architectural and construction contexts. This indicates that while direct studies on the integration of HBIM concepts for SPC structuring and classification may not be widely documented, the foundational work on HBIM's applications and benefits in related fields provides a substantial basis for exploring this integration further. Despite the evident potential and applicability of HBIM for enhancing Spatial Planning and SPC through advanced structuring and classification, current exploration in this domain remains scant. This lack of engagement can primarily be attributed to the high complexity and resource-intensive nature of HBIM processes.

2.6 Literature research

After delving into the domains pertinent to the research background, a systematic organization of existing studies and scholarly articles has been undertaken. To facilitate this, the Web of Science database served as the primary resource for the preliminary retrieval of literature, employing specific search terms such as "Architectural Heritage," "HBIM" (Heritage Building Information Modeling), and "Point Cloud." This literature search analyzed a significant period, spanning from 1999 to 2023, ensuring a comprehensive coverage of the evolving discourse in these areas. In the ensuing discussion, the accumulated literature will be methodically presented, with a categorization scheme that emphasizes chronological progression and thematic focus, thereby offering a structured overview of the field's development and current trends.

2.6.1 Trend of publication

The two graphs presented here depict the publication trends related to the research themes of Architectural Heritage, Heritage Building Information Modeling (HBIM), and Point Clouds from 1999 through 2023. From the turn of the millennium, the interest in these research areas has shown a remarkable upward trajectory. Initially, the number of publications per year was relatively modest, indicating a niche field with limited academic output. However, starting from the mid-2000s, there has been a steady increase in the volume of published work, with a notable surge around the early 2010s. This period likely reflects a growing recognition of the importance of digital technologies in the conservation and documentation of architectural heritage. In conclusion, the publication trends reveal a robust and growing interest in the integration of digital methods within the realm of architectural heritage. The consistent rise in the number of papers illustrates an academic and professional domain that is not only thriving but is also likely to continue its expansion as new technologies emerge and interdisciplinary collaborations deepen.

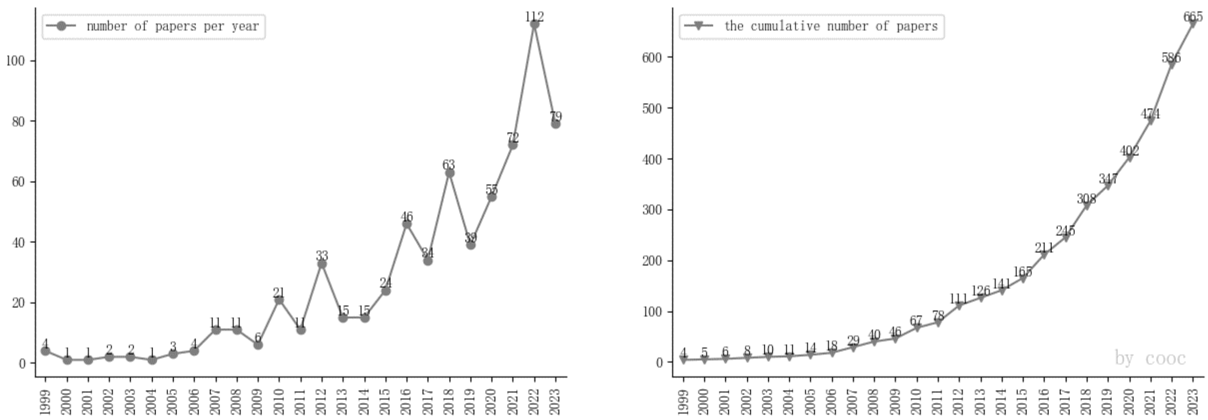


Fig. 6. The left graph (a) illustrates an annual count of published papers, and the right graph (b) shows the cumulative number of papers over the years mentioning Architectural Heritage, Point Clouds, and Conservation (Source: by author).

2.6.2 Review of the research focuses

The two diagrams in Figure 6 offer a comprehensive overview of the focus and evolution within the field of heritage documentation and digital reconstruction technologies. The radar charts encapsulate various dimensions of research, with the central spikes in certain domains indicating focal areas of interest. Initially, a strong emphasis is evident on '3D Laser Scanning', 'HBIM,' and 'Photogrammetry,' showcasing the reliance on these methodologies for data acquisition and modeling in architectural heritage. The consistent prominence of '3D Modeling' and '3D Laser Scanning Technology' across the charts suggests these remain core competencies within the field.

Over time, there has been an observable diversification in research interests, particularly with the integration of 'Virtual Reality,' 'Augmented Reality,' and 'Semantic Annotation,' reflecting a shift towards more immersive, interactive, and intelligent processing of heritage data. However, the charts also reveal a growing interest in 'UAV' (Unmanned Aerial Vehicle) use and 'IoT' (Internet of Things) (with the application of continuous sensors), which suggest an increasing adoption of newer, more agile data collection techniques and connected devices in heritage conservation.

The bar graph (**Fig. 6a**) extends this narrative, revealing the number of papers published in each sub-domain. 'HBIM' and '3D Laser Scanning' dominate, corroborating the radar chart insights, while 'Photogrammetry' and 'UAV' also show significant counts, underscoring their rising importance in recent research trends.

Together, these visual data representations illustrate a dynamic and evolving research landscape, marked by a foundational commitment to 3D data acquisition and modeling, enriched by emerging technologies that offer enhanced interaction with and interpretation of heritage data. This evolution signifies a paradigm shift in heritage conservation towards more integrated, technology-driven approaches that promise greater precision, engagement, and sustainability.

Fig. 7. Year-on-year keyword trends over the last 15 years (Source: by author).

3. RESEARCH GAPS

In the previous chapter, the primary technological methods involved in this study have been clarified. Through the analysis of existing research and practice, the following three research gaps can be identified: the first is the technological gap, specifically, the technical challenges arising from enriching point clouds using HBIM concepts; the second is the dilemma of data standardization and issues related to converting data across different software and platforms; and the third concerns data visualization and interaction.

3.1 Technology Gaps

Although the application prospects of HBIM based on SPC are broad, boasting advantages such as high accuracy and a variety of information types, two main challenges and technical gaps still exist in the process of converting SPC data into HBIM, including:

(a) Limitations of automation: Fully automated conversion of point cloud data into HBIM structured and semantic enriched objects is currently not feasible, especially for buildings with complex geometries and unique historical features. This is because automated tools struggle to accurately interpret and replicate these complex and detailed aspects. The main issues in the automatic semantic segmentation of architectural heritage include semantic consistency across multi-source point cloud data, semantic consistency at different spatial scales, and problems of over-segmentation.

(b) Challenges in segmenting semantic detail: The diversity and geometric complexity of architectural heritage pose challenges to the semantic segmentation of point clouds, though methods based on architectural intelligence or machine learning have already yielded substantial results in the automatic segmentation of geometric structures and damaged areas of architectural heritages. The loss of details still happens from time to time.

3.2 Interoperability Gaps

The workflow of Architectural Heritage Information Infrastructure (AHII) often involves interactions between different data sources, types of equipment, and software platforms. Therefore, it necessitates relevant data standards for unification, as well as corresponding technologies to integrate data across different software and platforms, in order to complete the Heritage Building Information Modeling (HBIM) model.

(a) Standardization: There is a lack of standardization across the board regarding how point cloud data is processed and integrated into HBIM models. This can lead to inconsistencies in how architectural heritage is documented and preserved digitally. Currently, there is a reliance on existing BIM standards; it is necessary to propose new international standards to regulate this process.

(b) Interoperability: Issues with interoperability between different software and platforms used in the process can complicate the integration of point cloud data into HBIM models. Ensuring data flow seamlessly from one process stage to another is crucial for efficient and accurate modeling.

3.3 Dissemination gaps

The global dissemination of digital information on architectural heritage is crucial for preserving, studying, and sharing the cultural and historical significance of heritage sites worldwide. Despite advancements in digital technologies and the growing recognition of the importance of heritage preservation, several gaps and challenges still hinder the effective global dissemination of this information, including:

(a) Difficulties in the visualization of AHII based on SPC: Though technologies like 3D interactive web, VR, and AR provide the new possibility to present SPC models, visualizing architectural heritages with SPC still faces challenges, including managing large, complex datasets, ensuring the accuracy of semantic enrichment, integrating multisource data, and achieving real-time rendering. Additional challenges include designing user-friendly interfaces for diverse audiences, preserving historical accuracy in visualizations, and maintaining data privacy and security. Addressing these issues demands interdisciplinary collaboration and advances in computer science, architecture, and visualization technologies. Balancing detail with performance and ensuring the authenticity and accessibility of visual representations are key to unlocking AHII's full potential.

(b) Lack of stakeholder engagement: The current engagement and utilization of digital heritage information by stakeholders, including researchers, conservationists, and the general public, remain notably low. This underutilization significantly impedes the broad dissemination and practical application of valuable digital heritage resources. The current situation stems from various factors, primarily due to a lack of adherence to the FAIR principles: Findability, Accessibility, Interoperability, and Reusability. Enhancing engagement levels is crucial for leveraging digital heritage information more effectively, thereby promoting its preservation, study, and appreciation on a wider scale.

(c) The usage for different users: Within the context of digital heritage and architectural information, there exists a pronounced disparity among users regarding their access to and capability to employ digital data effectively. This gap is evident across various demographics, with notable differences in digital literacy, technological resources, and geographic location contributing to unequal opportunities. As a result, not all individuals or communities are able to harness the full potential of this invaluable digital information, leading to a fragmentation in its utilization and benefits. Bridging this divide is essential for democratizing access to digital heritage resources, enhancing collective knowledge, and fostering inclusive cultural engagement.

3.4 Summary

In digital infrastructure construction for architectural heritage, focusing on point cloud-based HBIM combined with visualization tools involves integrating advanced scanning technologies like LiDAR with Building Information Modeling (BIM) tailored for historical structures. This integration allows for highly accurate digital representations that support preservation, analysis, and restoration efforts. Enhanced by visualization tools such as VR and AR, stakeholders can explore and interact with heritage sites in immersive environments, facilitating informed decision-making and public engagement. This approach is increasingly adopted worldwide to safeguard and manage cultural heritage digitally

This analysis delineates three principal research gaps in leveraging digital technologies for architectural heritage conservation, particularly through the integration of Semantic Point Clouds (SPC) into Heritage Building Information Modeling (HBIM). Initially, it underscores the technological hurdles in automating the transformation of point clouds to semantically enriched HBIM, exacerbated by the intricacies of architectural heritage's geometries and historical features. The challenge extends to accurately embedding semantic details, necessitating expert knowledge and manual effort. Furthermore, interoperability issues emerge due to the absence of uniform data standards and difficulties in harmonizing data across disparate software and platforms, which complicates the digital documentation and preservation processes. Lastly, the analysis points to dissemination challenges, highlighted by difficulties in visualizing AHII, low stakeholder engagement, and access disparities among users, reflecting a need for improved accessibility and user-friendly interfaces. Addressing these gaps necessitates the development of more sophisticated, user-centric tools and frameworks that enhance automation, standardization, and stakeholder engagement to fully realize the potential of digital heritage conservation.

4. RESEARCH OBJECTIVES

Following the identification of the research gaps outlined above, the objective of this doctoral project has become distinctly clear: it aims to construct a digital information infrastructure for architectural heritage. This infrastructure is intended to support the research community by facilitating the interpretation, conservation, documentation, innovation, and management of architectural heritage. The digital information infrastructure will include hardware and software solutions, data storage facilities, network resources, and standards and protocols for use and management. This comprehensive system ensures digital accessibility and longevity of architectural heritage data and supports a variety of user interactions through immersive experiences.

(a) Developing a digital platform focused on architectural heritage's scholarly exploration and preservation, leveraging HBIM combined with other visualization tools like AR, VR, MR, Digital Twins, and 3D (+time). This addition enables dynamic data collection over time, providing a deeper understanding of changes and developments in heritage sites. It enhances the platform's capability for analysis, enrichment, and presentation of architectural heritage, allowing for the exploration of historical evolution and facilitating the management of preservation efforts in a temporal context.

(b) Enabling the integration of various digital resources, including detailed 3D models based on point cloud data, interactive maps, geographically located narratives, and immersive technologies like VR, AR, and MR. These tools facilitate the dissemination and use of architectural heritage knowledge, allowing for broader public engagement, educational opportunities, and professional application, thereby fostering a deeper appreciation and awareness of historical contexts in a global audience.

(c) Establishing platform-specific standards to meet the demands of academic research and heritage conservation, ensuring architectural site quality, accuracy, and ethical representation. This includes setting guidelines for the application of point clouds, which offer a granular, data-rich 3D visualization critical for detailed analysis and digital preservation.

Additionally, it aims to incorporate a benchmarking framework to compare the effectiveness of point cloud data against vector graphics and other visualization forms. This would evaluate their respective advantages in different applications, such as the level of detail, scalability, and realism, to optimize the platform's use for academic and conservation work.

5. RESEARCH METHODOLOGY

The overall research methodology applied is Desing Science Research (DSR) as described by Hevner (Hevner et al., 2014); see Figure 6;

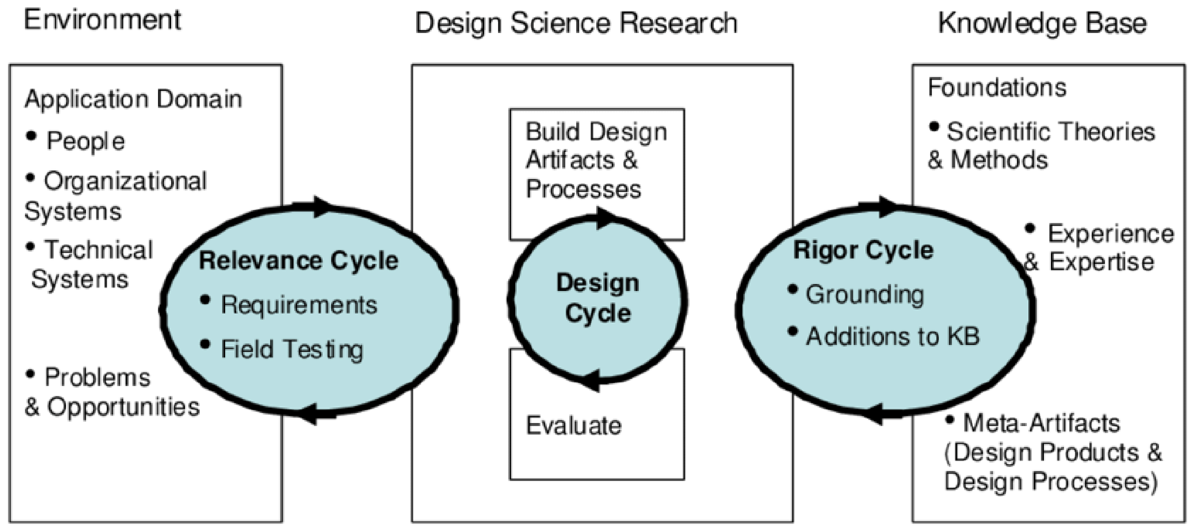


Fig. 8. Design science research framework (Source by Hevner).

The PhD project advocates an integrated approach based on intelligent point clouds to build an architectural heritage information infrastructure to further provide digital information sharing of architectural heritage to all populations, and is organized around five consecutive steps: i) compilation of data from technical and historical archives, point cloud files and site condition surveys; ii) creation of an HBIM model based on the collected data with reference to existing BIM international standards as well as other standard enriched/semantic/structure point clouds to create the HBIM model; iii) Storage and organization of the HBIM model data iv) Dissemination (linking with visualization tools, platforms) v) Data testing and updating of use cases. These five main strategies will be implemented through a series of activities.

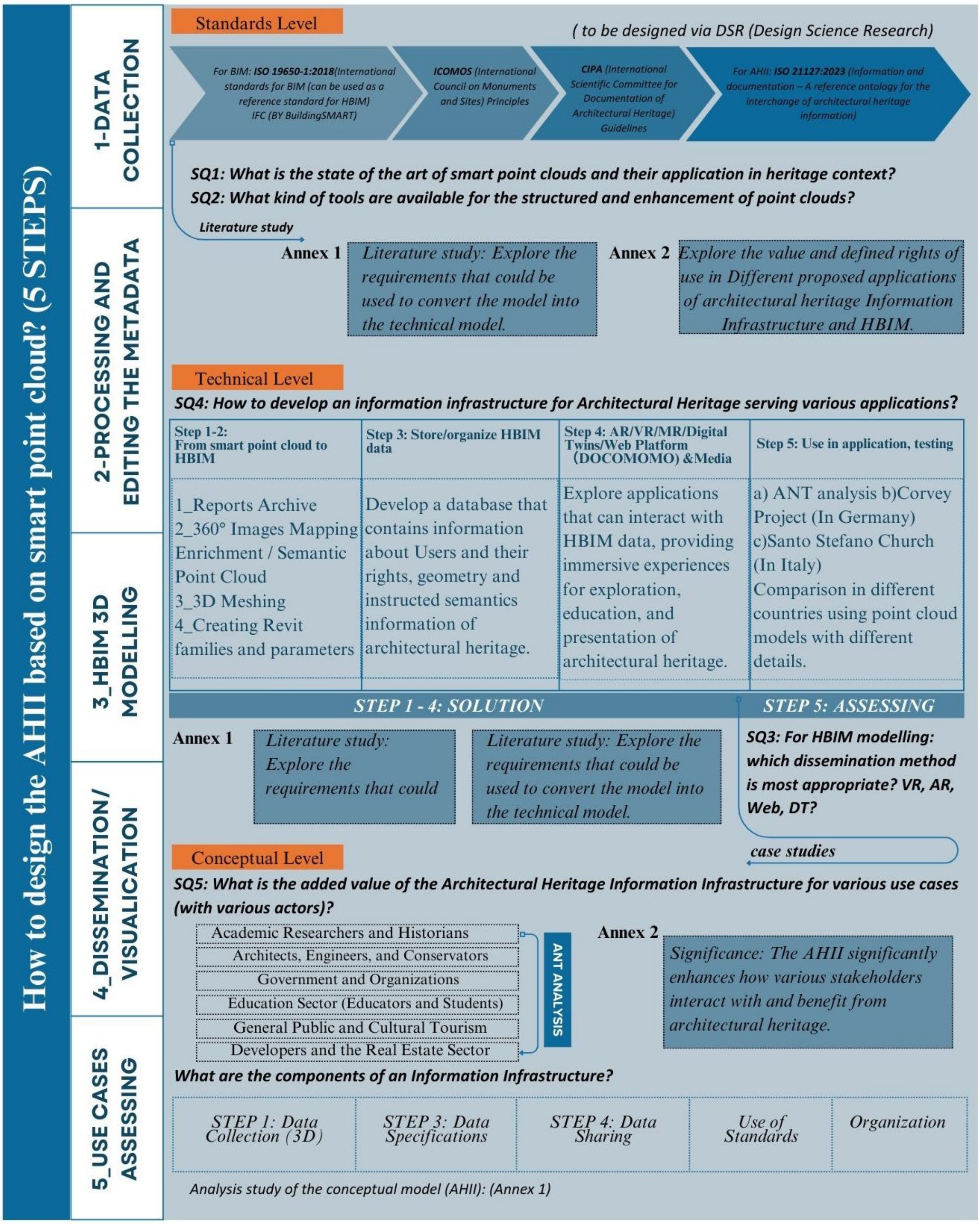


Fig. 9. Design Research Process

It will use smart point clouds as an information-gathering tool for historic buildings and construct HBIM for full-cycle monitoring and data collection. It will use several case studies (ANT analysis/ the church of Corvey in Germany/ Stefano Church in Italy) and adopt a mixed research methodology 1) using digital techniques and methods such as scanning, mapping, and field surveys to investigate the declared heritage values, caused by declines over time, outdated infrastructure/services and current use of stakeholder sites, e.g., Docomomo; 2) adopting participatory analysis methods such as participation, networking, storytelling, narrative recording, etc., to investigate analyses of various heritage users (e.g., professionals, indigenous and emerging residents, millennials and urban migrant workers, etc.), it helps to understand the complex web of relationships that influence the conservation and resilience of architectural heritage over time and the HBIM as an interactive technology can be better integrated into the design the AHII.

5.1 Detailed Research Components

The entire research methodology is divided into five components:

1. **Collect Data:** Data collection on historic buildings (capturing point clouds - comprehensive and detailed scanning of historic building information), also from stakeholders.

2. **Data Structuring/ Semantics**

    (a) **Data Cleaning**: Remove noise and irrelevant points using software like Cloud Compare or MeshLab.(FARO CONNECT VIEWER WITH IMAGES)

    (b) **Alignment**: Align different point cloud datasets into a coherent model through registration. (BOTH AUTOMATIC AND BY HAND)

    (c) **3D Modeling(Integration)**: Convert BIM MODEL BASE ON point clouds into 3D models(using software like Autodesk Revit or Bentley Systems for detailed analysis. (Incorporate the point cloud data into HBIM systems to manage historical information and facilitate conservation efforts—HBIM MODEL)SEMANTIC-ENRICHMENT THE POINT CLOUDS, AI/DL/ML

3. **Database with HBIM Model**(WITH THE SEMANTICS) Transformation, semantic enrichment of semantic classification 1-point clouds, by using an intelligent image recognition system to define the idea behind semantic enrichment (Tabkha et al., 2019) (**Fig. 10.**).

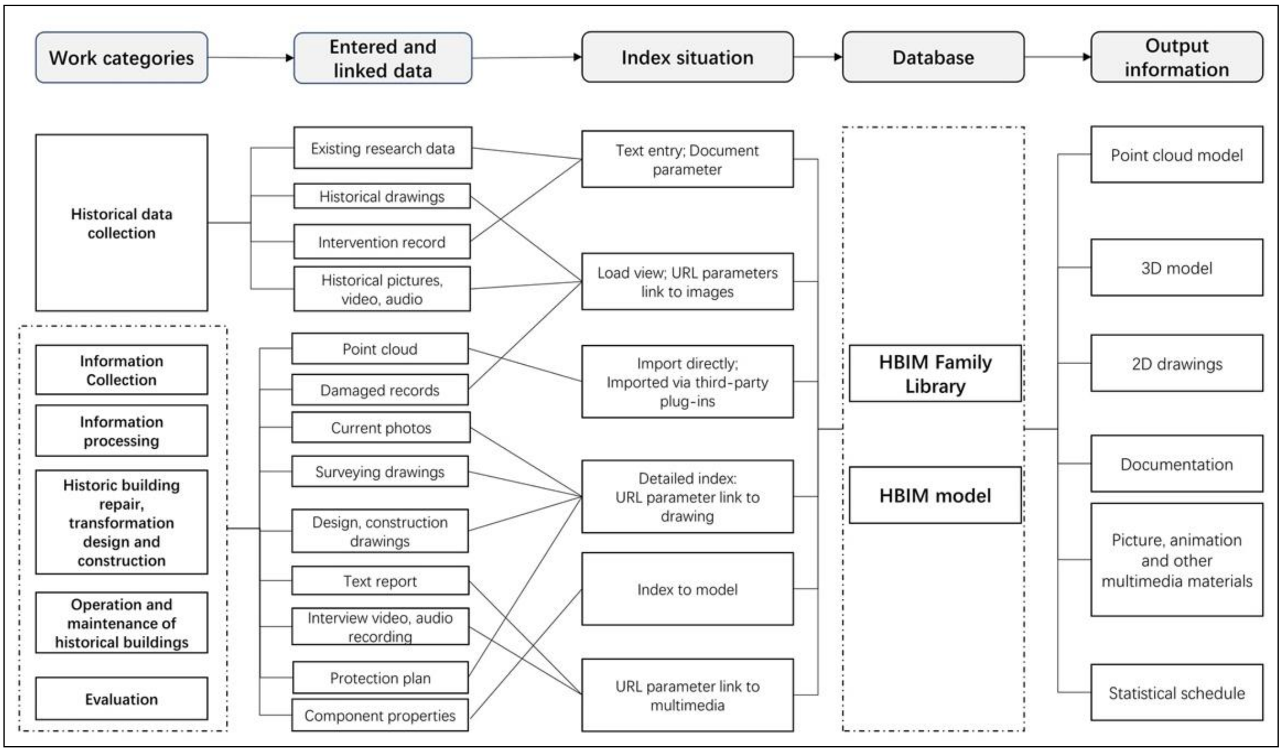


Fig. 10. Establishment of HBIM database (Source: by author).

4. **Sharing**: Share the modified point clouds with stakeholders for collaborative decision-making in conservation strategies.

5. **Use Cases Testing**

   a) ANT analysis
   b) Corvey Project (In Germany)
   c) Santo Stefano Church (In Italy)
   d) Dutch case (to be selected)

6. **Future Outlook:** The Gaussian Splatting technique can complete the 3D model by optimizing the rendering of the model's surface. By integrating Gaussian Splatting with AI/DL/ML technologies, the efficiency and quality of historic building information modeling can be significantly improved, providing robust technical support for the conservation and study of architectural heritage.

1- Gaussian Splatting (Basso et al., 2024) can visually enhance cleaned point cloud data, while Gaussian distributions can be semantically enriched in conjunction with AI.

2- AI techniques can recognize specific architectural elements in the point cloud, and Gaussian Splatting can enhance the visual representation of these elements, Storing/Organizing HBIM Data in serve/archives (Jiang et al., 2024).

6. PRACTICAL ASPECTS

6.1 Tools

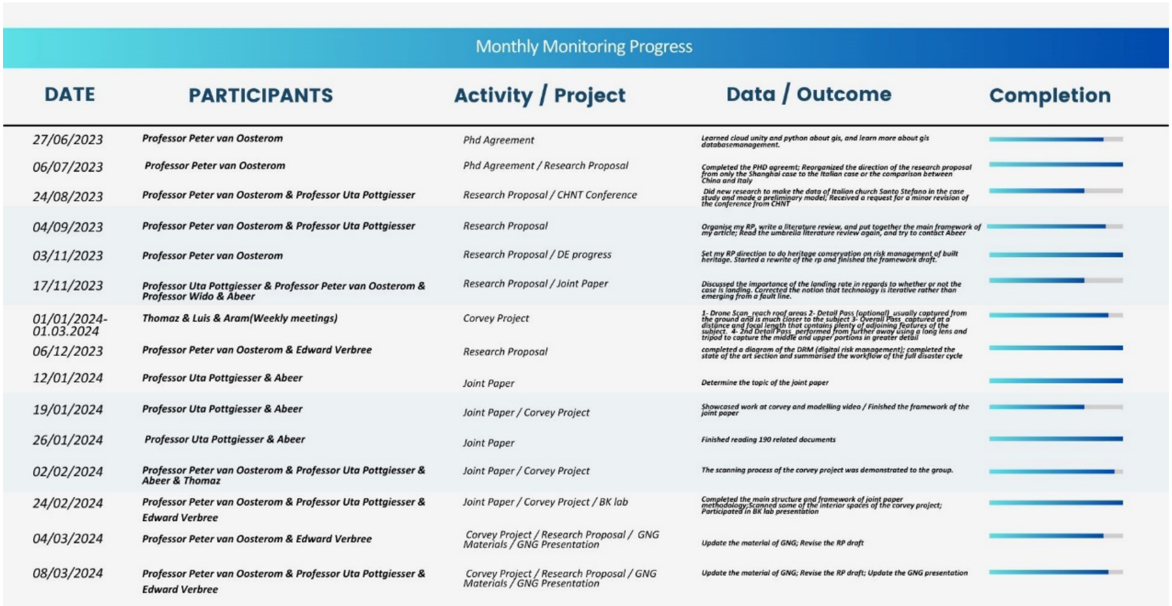
The following table illustrates the planned use of both hardware and software (Table 4).

Table 5:
Hardware and software required for the PhD project (Source from author).

TOOLS:	
HARDWARE	SOFTWARE
Drone Scanner(Mavic air 2)	*Faro Connect Viewer/ Faro Scene/Reality Capture*
Laser Scanner(Faro Focus M 70)	*Rhino 8/Cloudcompare*
GeoSLAM ZEB Horizon)	*Family reviser/PTGui*
Sony Alpha 7 iii	*Blender*
Phone/ Matterport	*Revit Families/*Revit Filter
Virtual reality headset	*Prospect by IrisVR*

6.2 Supervision

The following table illustrates the supervision agreements: every two weeks, meetings with all supervisors every four weeks, GISt PhD meetings, and ad hoc meetings when needed. Every 4 weeks, a progress monitor will be sent (as described in 'Mastering your PhD' by P. Gosling and B. Noordam, 2006).



Monthly Monitoring Progress

DATE	PARTICIPANTS	Activity / Project	Data / Outcome	Completion
27/06/2023	Professor Peter van Oosterom	Phd Agreement	Learned cloud unity and python about gis, and learn more about gis databasemanagement.	
06/07/2023	Professor Peter van Oosterom	Phd Agreement / Research Proposal	Completed the PHD agreemt; Reorganized the direction of the research proposal from only the Shanghai case to the Italian case or the comparison between China and Italy	
24/08/2023	Professor Peter van Oosterom & Professor Uta Pottgiesser	Research Proposal / CHNT Conference	Did new research to make the data of Italian church Santo Stefano in the case study and made a preliminary model; Received a request for a minor revision of the conference from CHNT	
04/09/2023	Professor Peter van Oosterom & Professor Uta Pottgiesser	Research Proposal	Organise my RP, write a literature review, and put together the main framework of my article; Read the umbrella literature review again, and try to contact Abeer	
03/11/2023	Professor Peter van Oosterom	Research Proposal / DE progress	Set my RP direction to do heritage conservation on risk management of built heritage. Started a rewrite of the rp and finished the framework draft.	
17/11/2023	Professor Uta Pottgiesser & Professor Peter van Oosterom & Professor Wido & Abeer	Research Proposal / Joint Paper	Discussed the importance of the landing rate in regards to whether or not the case is landing. Corrected the notion that technology is iterative rather than emerging from a fault line.	
01/01/2024-01.03.2024	Thomaz & Luis & Aram(Weekly meetings)	Corvey Project	1- Drone Scan reach roof areas 2- Detail Pass (optional) usually captured from the ground and is much closer to the subject 3- Overall Pass captured at a distance and focal length that contains plenty of adjoining features of the subject. 4- 2nd Detail Pass performed from further away using a long lens and tripod to capture the middle and upper portions in greater detail	
06/12/2023	Professor Peter van Oosterom & Edward Verbree	Research Proposal	completed a diagram of the DRM (digital risk management); completed the state of the art section and summarised the workflow of the full disaster cycle	
12/01/2024	Professor Uta Pottgiesser & Abeer	Joint Paper	Determine the topic of the joint paper	
19/01/2024	Professor Uta Pottgiesser & Abeer	Joint Paper / Corvey Project	Showcased work at corvey and modelling video / Finished the framework of the joint paper	
26/01/2024	Professor Uta Pottgiesser & Abeer	Joint Paper	Finished reading 190 related documents	
02/02/2024	Professor Peter van Oosterom & Professor Uta Pottgiesser & Abeer & Thomaz	Joint Paper / Corvey Project	The scanning process of the corvey project was demonstrated to the group.	
24/02/2024	Professor Peter van Oosterom & Professor Uta Pottgiesser & Edward Verbree	Joint Paper / Corvey Project / BK lab	Completed the main structure and framework of joint paper methodology;Scanned some of the interior spaces of the corvey project; Participated in BK lab presentation	
04/03/2024	Professor Peter van Oosterom & Edward Verbree	Corvey Project / Research Proposal / GNG Materials / GNG Presentation	Update the material of GNG; Revise the RP draft	
08/03/2024	Professor Peter van Oosterom & Professor Uta Pottgiesser & Edward Verbree	Corvey Project / Research Proposal / GNG Materials / GNG Presentation	Update the material of GNG; Revise the RP draft; Update the GNG presentation	

Fig. 11. Monthly Progress Monitoring (Source from author).

6.3 Time plan

The following table illustrates the timeline for the four years of the doctoral program as well as research activities and article publication plans.

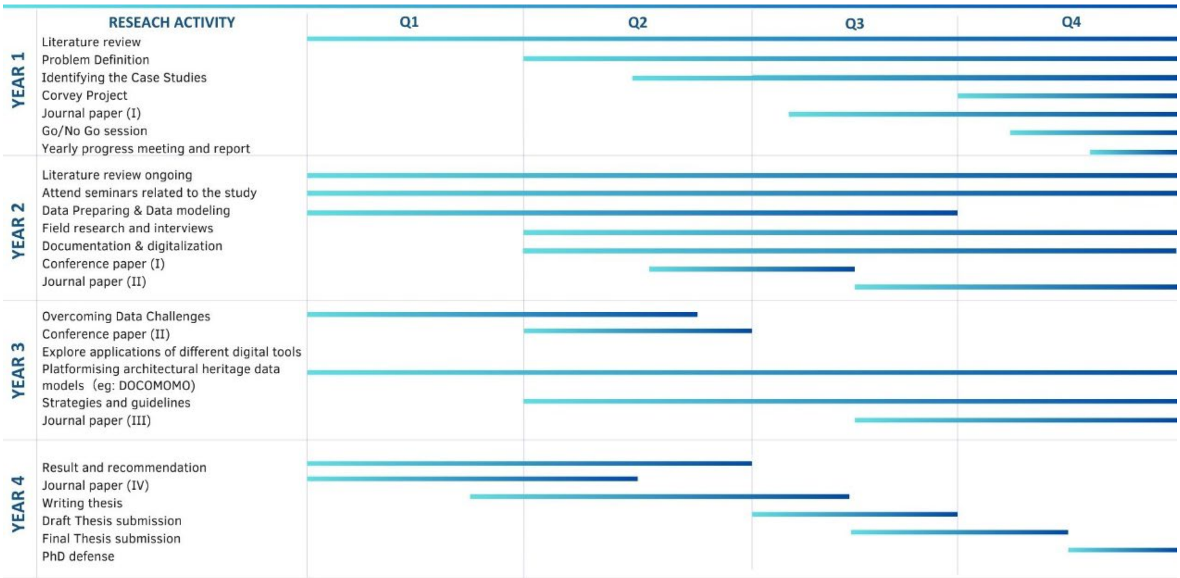


Fig. 12. Time plan for the four-year PhD program (Source: by author).

6.4 Publication Plans

Year 1: Journal paper (I): Digital tools in disaster management (heritage): a bibliometric qualitative analysis **(**to be submitted to Journal of Building Engineering see Annex B)

> **Abstract:** The aim of this paper is to fill this gap by conducting a systematic and robust review using a mixed-methods approach to show the progress of research on digital tools in architectural heritage risk management and to point out new directions for the future of architectural heritage conservation. The study included quantitative scientometric analyses and mapping as well as qualitative research. A combination of quantitative and qualitative tools was used to analyze 171 articles related to digital tools and architectural heritage (In draft).

Conference paper (I): Case Study 1/Italy (presented at NCG Symposium 2023) based on extended abstract / short paper

> **Abstract:** In the realm of Digital Disaster Management, the visualization of architectural cultural heritage presents a unique intersection of technology and historical inquiry, particularly through the lens of Actor-Network Theory (ANT) and the implementation of digital twins technology. This study employs Santo Stefano Church as a pivotal case study to explore the multifaceted relationships and networks that shape our understanding and preservation of architectural heritage. ANT serves as the theoretical foundation for this research, framing the church, its digital counterpart, researchers, technologies, and the broader community as co-acting agents in a dynamic network that continually influences the interpretation and valorization of architectural heritage.

This abstract emphasizes the use of ANT to understand the complex interactions between various actors involved in architectural heritage preservation and the digital twins' technology to achieve an immersive, detailed visualization and analysis of architectural heritage.

Year 2: Conference paper (II): Semantic preservation of architectural heritage (is overdevelopment also a hazard)

Journal paper (II): Application of digital technologies combined with ANT analyses for architectural heritage risk management (Corvey Project)

Year 3: Conference paper (III): The Phantomization Journey of Digital Architectural Heritage

Journal paper (III): A study of detail accuracy in architectural heritage modeling at different scales

Year 4: Journal paper (IV): Smart point cloud-based full-cycle monitoring and automated feedback for architectural heritage

6.5 Doctoral Education

Until now, it has been completed successfully with 15 GS credits obtained from transferable skills and research skills. The remaining 30 GS Credits will be obtained during the second, third, and early fourth year. Following is a breakdown of the progress of the Doctoral Education during the four years of the research project.

Table 6:

Doctoral Education plan

Year	Code	Course Name	GS Credits	Category	Status
1	T4.G1 - AI	PhD Startup Onboarding Module A & B	2	Transferable skills	Completed
	T2.D1	Teamwork, Leadership, and Group Dynamics	1.5	Transferable skills	Completed
	T4.B5	Project Management for PhD Candidates	2.5	Transferable skills	Completed
	T1.A7	Data visualizations - A practical approach	1	Transferable skills	Completed
	T1.A9	Scientific Text Processing with LaTeX	1.5	Transferable skills	Completed
	R2.B3	Data visualization as a tool for Scientific Research (using R)	1	Research skills	Completed
	T1.A7	Data visualizations - A practical approach	1	Transferable skills	Completed
	R1.C2	How to select-make a questionnaire and conduct an interview	2	Research skills	Completed
	R2.B1	Speedreading and Mindmapping	1.5	Research skills	Completed
	N/A	WORKSHOP	1	Discipline-related	Completed
	ABE 009	Research Proposal for Architecture and the Built Environment	4	Discipline-related	Scheduled
	T1.C1	Scientific Storytelling	2	Transferable skills	Scheduled
	R2.C1	Analysis of Interviews and other Unstructured Data General	2	Research skills	Scheduled
	R1.A2	The Informed Researcher - Information and Data Skills	1.5	Research skills	Scheduled
	TOTAL: 24.5				

3	LOJ	Writing the first conference paper	1	Research skills	Scheduled
	T4.G15	Mental Fitness Intervention Program	1	Transferable skills	Scheduled
	LOJ	Writing an international, peer-reviewed journal article	4	Research skills	Scheduled
	T4.G15	Mental Fitness Intervention Program - Available dates	1	Transferable skills	Scheduled
	GEO1007	Geoweb Technology	ECTS:5	Discipline-related	Planned
	GEO1006	Geo Database Management Systems	ECTS:5	Discipline-related	Planned
2	TOTAL: 7+ECTS10				
	N/A	WORKSHOP	1.5	Discipline-related	Planned
	LOJ	Supervising an MSc student/Bachelor project groups	2	Research skills	Planned
3	TOTAL: 3.5				
4	T1.B2	Presenting Scientific Research (PROM 2)	3	Transferable skills	Planned
	TOTAL: 3				

REFERENCES

Adamopoulos, E., & Rinaudo, F. (2021). Close-range sensing and data fusion for built heritage inspection and monitoring—a review. *Remote Sensing*, *13*(19), 3936.

Al-Bayari, O., & Shatnawi, N. (2022). Geomatics techniques and building information model for historical buildings conservation and restoration. *The Egyptian Journal of Remote Sensing and Space Science*, *25*(2), 563-568.

Bartolini, G., Giuliani, F., & De Falco, A. (2023). Proof of Concept for Methodological Framework Including Point Clouds in the Non-Destructive Diagnosis of Historical Masonry Structures. *International Journal of Architectural Heritage*, 1-24.

Basso, A., Condorelli, F., Giordano, A., Morena, S., & Perticarini, M. (2024). EVOLUTION OF RENDERING BASED ON RADIANCE FIELDS. THE PALERMO CASE STUDY FOR A COMPARISON BETWEEN NERF AND GAUSSIAN SPLATTING. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, *XLVIII-2/W4-2024*, 57-64. https://doi.org/10.5194/isprs-archives-XLVIII-2-W4-2024-57-2024

Bastem, S. S., & Cekmis, A. (2022). Development of historic building information modeling: A systematic literature review. *Building Research & Information*, *50*(5), 527-558.

Bhatia, M., Ahanger, T. A., & Manocha, A. (2023). Artificial intelligence based real-time earthquake prediction. *Engineering Applications of Artificial Intelligence*, *120*, 105856.

Bruno, S., De Fino, M., & Fatiguso, F. (2018). Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management. *Automation in Construction*, *86*, 256-276. https://doi.org/https://doi.org/10.1016/j.autcon.2017.11.009

Calvano, M., Martinelli, L., Calcerano, F., & Gigliarelli, E. (2022). Parametric processes for the implementation of HBIM—Visual programming language for the digitisation of the index of masonry quality. *ISPRS International Journal of Geo-Information*, *11*(2), 93.

Candón Fernández, E., Crespo-Márquez, A., Guillén López, A., & Hidalgo Fort, E. Model-based asset digitalization framework in the context of digital maintenance. An example using IoT platform and Asset Health Index model applied to civil infrastructures. *An example using IoT platform and Asset Health Index model applied to civil infrastructures*.

Che, E., Jung, J., & Olsen, M. J. (2019). Object recognition, segmentation, and classification of mobile laser scanning point clouds: A state of the art review. *Sensors*, *19*(4), 810.

Chiabrando, F., Sammartano, G., & Spanò, A. (2016). Historical buildings models and their handling via 3D survey: From points clouds to user-oriented HBIM. *the international archives of the photogrammetry, remote sensing and spatial information sciences*, *41*, 633-640.

Crompvoets, J., Vancauwenberghe, G., Ho, S., Masser, I., & De Vries, W. T. (2018). Governance of national spatial data infrastructures in Europe. *International Journal of Spatial Data Infrastructures Research*, *13*, 253-285.

Diaz, V., van Oosterom, P., Meijers, M., Verbree, E., Ahmed, N., & van Lankveld, T. (2023). Comparison of Cloud-to-Cloud Distance Calculation Methods-Is the Most Complex Always the Most Suitable? International 3D GeoInfo Conference,

Dore, C., & Murphy, M. (2012). Integration of Historic Building Information Modeling (HBIM) and 3D GIS for recording and managing cultural heritage sites. 2012 18th International conference on virtual systems and multimedia,

Germs, R., Van Maren, G., Verbree, E., & Jansen, F. W. (1999). A multi-view VR interface for 3D GIS. *Computers & Graphics*, *23*(4), 497-506. https://doi.org/https://doi.org/10.1016/S0097-8493(99)00069-2

Green, C., Verhagen, P., McKeague, P., Van'T Veer, R., Huvila, I., Moreau, A., Loup, B., Cooper, A., & Van Manen, N. (2019). Mapping our heritage: Towards a sustainable future for digital spatial information and technologies in European archaeological heritage management. *Journal of Computer Applications in Archaeology*, *2*(1).

Guillet, A.-L. (2007). Docomomo International. *Journal of Architectural Conservation*, *13*(2), 151-156. https://doi.org/10.1080/13556207.2007.10785002

Hevner, A. R., March, S., Park, J., & Ram, S. (2014). Design Science Research. In.

Jiang, P., Pandey, G., & Saripalli, S. (2024). 3DGS-ReLoc: 3D Gaussian Splatting for Map Representation and Visual ReLocalization. *arXiv preprint arXiv:2403.11367*.

Kedzierski, M., & Fryskowska, A. (2015). Methods of laser scanning point clouds integration in precise 3D building modelling. *Measurement*, *74*, 221-232.

King, L., Stark, J. F., & Cooke, P. (2016). Experiencing the digital world: The cultural value of digital engagement with heritage. *Heritage & Society*, *9*(1), 76-101.

Kundu, A., Yin, X., Fathi, A., Ross, D., Brewington, B., Funkhouser, T., & Pantofaru, C. (2020). Virtual multi-view fusion for 3d semantic segmentation. Computer Vision–ECCV 2020: 16th European Conference, Glasgow, UK, August 23–28, 2020, Proceedings, Part XXIV 16,

Laakso, M., & Kiviniemi, A. (2012). The IFC standard: A review of history, development, and standardization, information technology. *ITcon*, *17*(9).

Lemmens, M., & Lemmens, M. (2011). Terrestrial laser scanning. *Geo-information: technologies, applications and the environment*, 101-121.

Letellier, R., & Eppich, R. (2015). *Recording, documentation and information management for the conservation of heritage places*. Routledge.

Li, Y., Du, Y., Yang, M., Liang, J., Bai, H., Li, R., & Law, A. (2023). A review of the tools and techniques used in the digital preservation of architectural heritage within disaster cycles. *Heritage Science*, *11*(1),

199.
Liang, W., Ahmad, Y., & Mohidin, H. H. B. (2023). The development of the concept of architectural heritage conservation and its inspiration. *Built Heritage*, *7*(1), 21. https://doi.org/10.1186/s43238-023-00103-2
Liu, Z., van Oosterom, P., Balado, J., Swart, A., & Beers, B. (2022). Detection and reconstruction of static vehicle-related ground occlusions in point clouds from mobile laser scanning. *Automation in Construction*, *141*, 104461. https://doi.org/https://doi.org/10.1016/j.autcon.2022.104461
López, F. J., Lerones, P. M., Llamas, J., Gómez-García-Bermejo, J., & Zalama, E. (2018). A review of heritage building information modeling (H-BIM). *Multimodal Technologies and Interaction*, *2*(2), 21.
Masciotta, M. G., Sanchez-Aparicio, L. J., Oliveira, D. V., & Gonzalez-Aguilera, D. (2023). Integration of laser scanning technologies and 360º photography for the digital documentation and management of cultural heritage buildings. *International Journal of Architectural Heritage*, *17*(1), 56-75.
Megahed, N. A. (2015). Towards a theoretical framework for HBIM approach in historic preservation and management. *ArchNet-IJAR: International Journal of Architectural Research*, *9*(3), 130.
Mekonnen, H., Bires, Z., & Berhanu, K. (2022). Practices and challenges of cultural heritage conservation in historical and religious heritage sites: evidence from North Shoa Zone, Amhara Region, Ethiopia. *Heritage Science*, *10*(1), 172. https://doi.org/10.1186/s40494-022-00802-6
Murphy, M., McGovern, E., & Pavia, S. (2009). Historic building information modelling (HBIM). *Structural Survey*, *27*(4), 311-327.
Murphy, M., McGovern, E., & Pavia, S. (2013). Historic Building Information Modelling–Adding intelligence to laser and image based surveys of European classical architecture. *ISPRS journal of photogrammetry and remote sensing*, *76*, 89-102.
Nebiker, S., Bleisch, S., & Christen, M. (2010). Rich point clouds in virtual globes–A new paradigm in city modeling? *Computers, Environment and Urban Systems*, *34*(6), 508-517.
Nilson, T., & Thorell, K. (2018). Cultural heritage preservation: The past, the present and the future. In: Halmstad University Press.
Noardo, F., Arroyo Ohori, K., Krijnen, T., & Stoter, J. (2021). An inspection of IFC models from practice. *Applied Sciences*, *11*(5), 2232.
Noyes, J. E. (2011). The common heritage of mankind: past, present, and future. *Denv. J. Int'l L. & Pol'y*, *40*, 447.
Panzera, E. (2022). The Role of Cultural Heritage in Shaping Territorial Identities. In E. Panzera (Ed.), *Cultural Heritage and Territorial Identity: Synergies and Development Impact on European Regions* (pp. 117-143). Springer International Publishing. https://doi.org/10.1007/978-3-030-94468-1_5
Pezeshki, Z., & Ivari, S. A. S. (2018). Applications of BIM: a brief review and future outline. *Archives of Computational Methods in Engineering*, *25*, 273-312.
Pottgiesser, U., & Dragutinovic, A. (2022). ConCom and MoMove. Approaches to Industrial Heritage. In *MoMove Modern Movement and Industrial Heritage: Contributions to the Docomomo virtual exhibition-momove* (pp. 24-29). Technische Hochschule Ostwestfalen-Lippe.
Poux, F., Neuville, R., Hallot, P., & Billen, R. (2016). Smart point cloud: Definition and remaining challenges. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *4*(W1).
Rakotosaona, M. J., La Barbera, V., Guerrero, P., Mitra, N. J., & Ovsjanikov, M. (2020). Pointcleannet: Learning to denoise and remove outliers from dense point clouds. Computer graphics forum,
Rodríguez-Moreno, C., Reinoso-Gordo, J. F., Rivas-López, E., Gómez-Blanco, A., Ariza-López, F., & Ariza-López, I. (2018). From point cloud to BIM: An integrated workflow for documentation, research

and modelling of architectural heritage. *Survey Review*, *50*(360), 212-231.

Rossi, M., & Bournas, D. (2023). Structural health monitoring and management of cultural heritage structures: A state-of-the-art review. *Applied Sciences*, *13*(11), 6450.

Shafique, K., Khawaja, B. A., Sabir, F., Qazi, S., & Mustaqim, M. (2020). Internet of things (IoT) for next-generation smart systems: A review of current challenges, future trends and prospects for emerging 5G-IoT scenarios. *Ieee Access*, *8*, 23022-23040.

Stylianidis, E. (2020). *Photogrammetric survey for the recording and documentation of historic buildings*. Springer.

Tabkha, A., Hajji, R., Billen, R., & Poux, F. (2019). Semantic enrichment of point cloud by automatic extraction and enhancement of 360° panoramas. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*(W17).

Van de Vijver, F., & Leung, K. (1997). Methods and data analysis of comparative research. *Handbook of cross-cultural psychology*, *1*, 257-300.

van Oosterom, P., van Oosterom, S., Liu, H., Thompson, R., Meijers, M., & Verbree, E. (2022). Organizing and visualizing point clouds with continuous levels of detail. *ISPRS journal of photogrammetry and remote sensing*, *194*, 119-131. https://doi.org/https://doi.org/10.1016/j.isprsjprs.2022.10.004

Verbree, E., Maren, G. V., Germs, R., Jansen, F., & Kraak, M.-J. (1999). Interaction in virtual world views-linking 3D GIS with VR. *International Journal of Geographical Information Science*, *13*(4), 385-396. https://doi.org/10.1080/136588199241265

Wang, H., Zhao, Y., Gao, X., & Gao, B. (2021). Collaborative decision-making for urban regeneration: A literature review and bibliometric analysis. *Land Use Policy*, *107*, 105479.

Wang, Q., & Kim, M.-K. (2019). Applications of 3D point cloud data in the construction industry: A fifteen-year review from 2004 to 2018. *Advanced engineering informatics*, *39*, 306-319.

Zhang, R., Li, G., Li, M., & Wang, L. (2018). Fusion of images and point clouds for the semantic segmentation of large-scale 3D scenes based on deep learning. *ISPRS journal of photogrammetry and remote sensing*, *143*, 85-96.

Baauw, Marc. “Maintaining an up to Date Digital Twin by Direct Use of Point Cloud Data,” MScThesisMarcBaauw.pdf (gdmc.nl), 2024

ANNEX A. Self-reflection with 1st year

Reflecting on my first year as a PhD student has been an enriching journey filled with learning, discovery, and significant achievements. This year was dedicated to establishing a solid foundation for my research in architectural heritage protection, leveraging digital tools and technologies such as point clouds, HBIM (Historic Building Information Modelling), and various digital documentation methods. Here is a comprehensive overview of my progress, challenges, and insights gained during this period, as shown in the following figure.

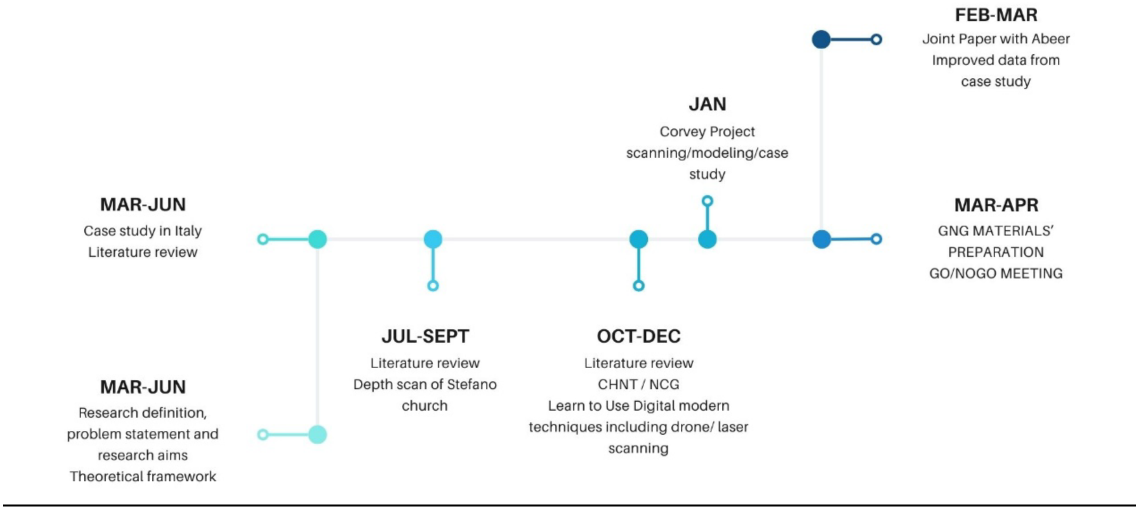


Fig.11. Implementation plan schedule for 1st year

Achievements and Learning

- Extensive Literature Review: My journey began with immersing myself in various scholarly articles and publications. This deep dive into the literature related to architectural heritage protection, point clouds, HBIM, digital tools, and methodologies for literature review was instrumental. It broadened my understanding and helped me formulate research hypotheses, identify research trends, and establish a knowledge base around heritage and its digital preservation. This clarity in research questions and methodologies is invaluable.
- Technical Proficiency: A significant part of my year was spent on acquiring and refining skills in using various hardware and software critical for digital documentation in heritage conservation. I have developed a robust skill set from mastering points cloud scanners like Geoslam ZEB Horizon RT Scanner and FARO Focus Laser Scanners to drones and mobile scanning apps such as Polycam and Kimi. I have also become proficient in software interacting with point cloud models, including FARO Scene, Rhino, Recap, and Revit, enhancing my ability to document and analyze architectural heritage digitally.

(a) Milestones

- **Enhanced Collaboration:** 1) Under the leadership of GIS Technology chair Peter van Oosterom, our engagement with the DT group improved significantly. Instituting monthly PhD GIS meetings has been a milestone, fostering better understanding and potential collaborations among peers. 2) Guided by Professor Uta's astute leadership within the Heritage department, our interaction with Abeer Abu Read. The initiation of weekly review meetings stands as a cornerstone achievement, facilitating a more profound exchange of progress updates and collaborative opportunities among team members.
- **Case Studies and International Experience:** Spending the initial months in Italy, where I also manage my design studio, allowed me to conduct valuable case studies on Italian heritage. This enriching experience sets the stage for comparative studies with other countries, offering diverse perspectives on architectural heritage.
- **Research Structure Development:** I outlined a comprehensive research structure covering the background, problem statement, research questions, objectives, methodology, and a predictive plan for the progression of my four-year PhD project.
- **Systematic Literature Review:** Employing tools like COOC, Vosviewer, and Citespace, I categorized the literature into three main areas: digital preservation assessment, risk management, and the integration of HBIM with point cloud technology. This systematic approach has been crucial in framing my research.
- **Conferences and Publications:** My participation in international conferences such as DOCOMOMO and NCG Symposium 2023 and the expected publication of my paper on "Digital technology in disaster management (heritage)" in 2024 are critical achievements in my academic journey.
- **Project Collaboration:** The collaboration on the Corvey project with OWL University, aiming to digitally document the new campus area and develop a BIM model, represents a significant step forward in my research and opens doors for longer-term collaborations.
- **Educational Progress:** Completing approximately 33% of my doctoral education (DE) courses has been both challenging and rewarding, providing a solid academic foundation for my research.

(b) Reflections and Looking Forward

This year has been a profound learning experience, both academically and in terms of personal growth. Navigating the complexities of digital documentation and heritage conservation, I have developed a deeper appreciation for the intricacies of preserving architectural heritage. Looking ahead, I am excited about the potential of my research to contribute meaningful insights and solutions in the field of heritage conservation. I anticipate the challenges and opportunities and am eager to continue this journey with the same zeal and dedication I have had in my first year.

ANNEX B. Literature paper

The Digital Frontier: A Review of Disaster Management Literature in the Age of Technology

Abstract: The preservation of architectural heritage is essential for maintaining cultural continuity, necessitating innovative approaches for its conservation. This paper examines the integration of digital tools in architectural heritage risk management (AHRM) over the past decade. Through a systematic literature review, we identify significant digital tool clusters such as Geospatial Analysis, 3D Documentation and Modeling, Data Management, Risk Analysis, and Digital Archiving. Each cluster contributes uniquely to AHRM, enhancing the precision and efficiency of conservation efforts. Our analysis reveals an increasing trend in the adoption of these technologies, underpinned by advancements in hardware, deep learning algorithms, and big data. The research demonstrates a strong correlation between scholarly attention and funding, particularly in tools like Heritage Building Information Modeling (HBIM), Geographic Information Systems (GIS), and Augmented Reality (AR). The paper underscores the potential of digital tools in risk management and highlights future research directions, emphasizing the need for technological integration and practical implementation strategies in the conservation of architectural heritage.
Keywords:
Digital tools, Digital Twins, HBIM, Architectural Heritage, Point Cloud, Disaster Assessment, Vosviewer

1. Introduction

Architectural heritage constitutes a significant part of human cultural heritage, embodying the essence of UNESCO's definition of human heritage (Labadi, 2013; Rouhi, 2017). Beyond its intrinsic cultural value, architectural heritage plays a pivotal role in fostering local identity (Graham, 2002; Munasinghe, 2005) and attracting tourists worldwide (Albourae et al., 2017; Alnafeesi, 2013). However, these invaluable assets often face multifaceted challenges stemming from both human and natural factors (Labadi et al., 2021; Pärn et al., 2017). Human-induced challenges include urban development pressures (Alnafeesi, 2013; Ashrafi et al., 2021; Kattel et al., 2013), neglect (Alnafeesi, 2013; Jigyasu et al., 2013; Vardopoulos, 2022), and vandalism (Bosher et al., 2020; Cunha Ferreira et al., 2023; Haddad et al., 2018), while natural factors encompass environmental degradation (Labadi et al., 2021; Stubbs, 2004) and climate change impacts such as flooding (Sabbioni et al., 2008; Sesana et al., 2020), earthquakes (Bankoff, 2015; Jorquera et al., 2017), and other disasters.

The management of disasters concerning architectural heritage is thus of paramount importance (Alnafeesi, 2013; Avramidou, 2003). Common disaster management strategies include risk assessment, preventive conservation, emergency planning, and restoration techniques that aim to mitigate damage and ensure the resilience of heritage structures (Coïsson & Ferrari, 2023; Jigyasu et al., 2013). In recent years, the emergence of digital technologies related to construction, inspection, management, and prediction has opened new possibilities for disaster management of architectural heritage (**Figure 1**) (Rouhani & Romão, 2023; Ruthven & Chowdhury, 2015; Wu & Zhu, 2022). The last decade has seen significant advancements in hardware capabilities (Chi et al., 2013; Perles et al., 2018), the development and maturation of deep learning algorithms (Galanakis et al., 2023; Wang, 2023), and the proliferation of big data technologies (Chen et al., 2014; Sun et al., 2016). Consequently, research and practice focusing on the application of digital technologies in the disaster management of heritage buildings have increasingly gained momentum (Münster et al., 2021; Trillo et al., 2020). This paper aims to conduct a systematic literature review for the period between 2013 and 2023, utilizing several generic literature analysis software platforms.

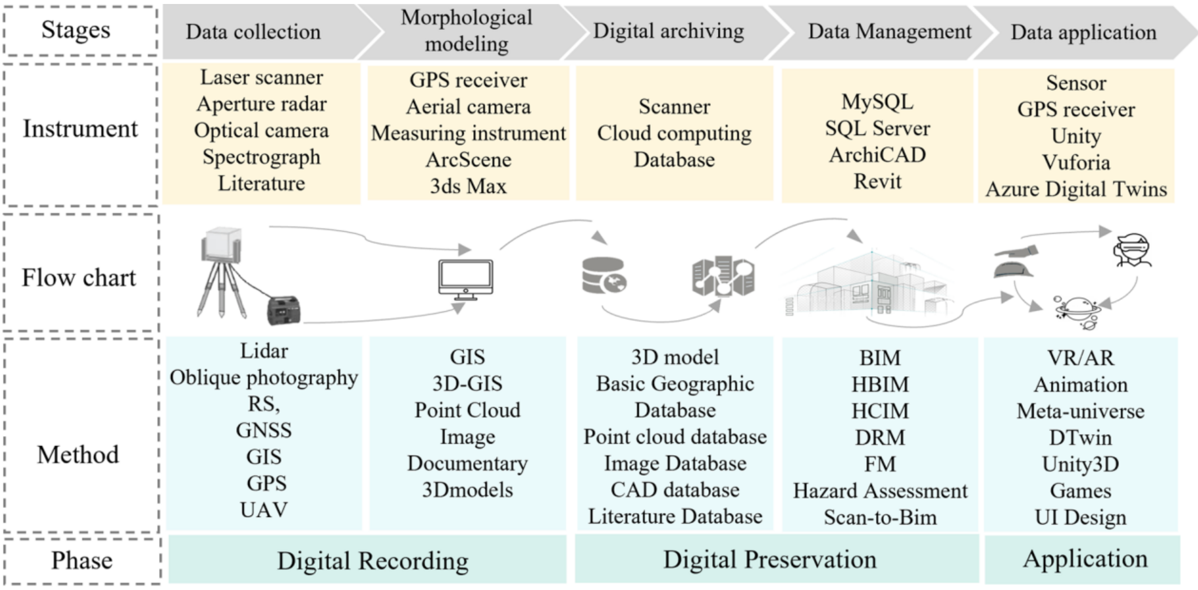


Fig. 1. Flowchart for the risk management of digital tools for architectural heritage
Source from (Li et al., 2023).

1.1 Architectural Heritage Risk Management

Risk management is the process of identifying, assessing, and controlling threats to an organization's capital and earnings (Hopkin, 2018; Nocco & Stulz, 2006). Focusing on architectural heritage management, architectural heritage risk management (AHRM) refers to the systematic process of identifying, assessing, controlling, and mitigating risks associated with the preservation, conservation, and management of architectural heritage sites (Fatorić & Seekamp, 2017; Paolini et al., 2012). This specialized field of risk management focuses on the unique challenges posed by historic structures and sites, which may include physical deterioration (Aven, 2016; Cardona, 2013), environmental impacts (Foster, 2020; Munarim & Ghisi, 2016), human activities (Mao et al., 2020; Thuestad et al., 2015), legal and regulatory changes (Mazzarella, 2015; Mualam & Alterman, 2020), and financial constraints (Khalid, 2022; Rossitti et al., 2021).

Specifically, the application of architectural heritage risk management primarily encompasses the following directions: (a) Identifying potential risks that could affect the integrity, authenticity, and accessibility of architectural heritage (Alberts & Hazen, 2010; Gullino & Larcher, 2013; Khalaf, 2022; Pendlebury et al., 2009); (b) Assessing the likelihood and potential impact of these risks on heritage sites (Ravankhah et al., 2019; Romão et al., 2016; Wignall et al., 2018); (c) Developing and implementing mitigation strategies to reduce or eliminate risks (Goklany, 2007; Majumdar et al., 2021; McGee et al., 2009); (d) Monitoring and reviewing the risk management plan regularly to ensure its effectiveness and adapt to new threats or changes in the heritage site's context (Ford et al., 2010; Heller & Zavaleta, 2009; Losada et al., 2019). Integrating digital tools with architectural heritage risk management applications significantly enhances conservation efforts' efficiency and effectiveness (Brahmi et al., 2022; Xiao et al., 2018).

1.2 Digital tools for AHRM

Due to their efficiency and other benefits, digital tools are increasingly being applied throughout the various stages of AHRM (Bose, 2003; Cresswell & Sheikh, 2013). Specifically, commonly utilized tools include Digital Twins, Heritage Building Information Modeling (HBIM), Geographic Information Systems (GIS), and Point Cloud (PC) technologies (P. Jouan & P. Hallot, 2019; Matrone et al., 2023; Xia et al., 2022). Each of these digital tools offers unique capabilities for the documentation, analysis, and preservation of architectural heritage. Digital Twins provide real-time monitoring and simulation capabilities (Ruppert & Abonyi, 2020; Schluse et al., 2018; Segovia & Garcia-Alfaro, 2022; Zipper, 2021), HBIM facilitates the detailed representation and management of heritage structures (Barontini et al., 2022; Jordan-Palomar et al., 2018; Martinelli et al., 2022; Yang et al., 2020), GIS enables spatial analysis and risk assessment across geographic areas (McMaster et al., 1997; Nyerges et al., 1997), and Point Cloud technology offers precise documentation of the physical conditions of heritage sites (Haddad, 2011; Jo & Hong, 2019; Moyano et al., 2022). Their applications encompass digital recording, preservation, and the broader scope of digital applications in heritage management (Haddad, 2011). These technologies enable stakeholders to create detailed and accurate records of heritage sites, implement strategies for their preservation, and apply digital tools in innovative ways to manage and mitigate risks.

Although these methods and technologies have matured, bridging the gaps between different technologies to achieve integration, identifying new research gaps and directions, and exploring application scenarios and potential remain areas requiring further review of current research and published articles. The evolving landscape of AHRM presents ongoing challenges and opportunities for innovation in digital applications, necessitating continuous examination and synthesis of recent scholarly work to harness the full potential of digital tools in the preservation and management of architectural heritage.

1.3 Literature review of the digital tools for architectural heritage applications

Currently, there is an abundance of literature reviews focusing on the application of various digital tools in the preservation of architectural and cultural heritage. These reviews often delve into specific technologies or categories of tools, such as the use of (Bortolini et al., 2022), the application of 3D point cloud technologies in architectural heritage (Yang et al., 2023), and the use of semantic segmentation and related services in heritage conservation (Guo et al., 2018). Additionally, some reviews focus on specific stages of digital preservation, including methods for initial data collection and subsequent preservation and application techniques (Pocobelli et al., 2018a). There are also comprehensive reviews covering the entire lifecycle of digital tools in the conservation of architectural heritage (Li et al., 2023). The majority of these publications are recent and cover various aspects and stages of digital technology in heritage conservation, including the publication countries and temporal trends. However, research gaps still exist:

(a) Queries for assessing technological integration barriers: Current reviews predominantly concentrate on discussing the application directions, scenarios, technological pathways, and challenges of different technologies individually. Although a few reviews mention the barriers to interaction between different technologies, there is a lack of in-depth exploration of the extent of connections and the levels of barriers between them.

(b) Demands for evaluating digital tools' practicality: Evaluating digital tools' practicality: Present reviews focus on the application of the technologies themselves, seldom investigating the feasibility and practicality of these technologies. Despite many technologies boasting high precision and detail fidelity, practical implementation often encounters issues such as high costs, significant manpower requirements, and difficulty in interaction. Therefore, a critical area that requires attention is the review of the feasibility of digital tools in the conservation of architectural heritage, addressing the urgent need for practical implementation strategies.

1.4 Research objective

Building on the identification of the aforementioned gaps, the purpose of this review has been clearly defined: to analyze publications from the past decade on the use of digital tools in the risk management of architectural heritage, revealing the interrelations, interaction difficulties, and practical implementation aspects of various technologies. This objective comprises three parts:

(a) Developing a methodology for the collection, screening, and systematic review of literature in the field of digital disaster control for architectural heritage;

(b) Uncovering the degree of connectivity between different tools involved in AHRM by organizing relationships among tools that appear together in various studies to analyze and understand the interaction challenges among different methodologies;

(c) Exploring the relationship between different tools used in AHRM and the practical projects and funding to indirectly assess the feasibility of project implementation.

This study could contribute to the field by offering a comprehensive overview of digital tool applications in architectural heritage risk management, highlighting critical areas for technological integration, and identifying actionable insights into enhancing practical deployment. By systematically evaluating the intersections and barriers among various digital approaches, this review aims to pave the way for more cohesive and practical strategies for preserving architectural heritage against risks.

2. Methods

2.1 Data collection

Web of Science (WOS) offers diverse, accessible databases for publications that explicitly articulate and use digital tools to manage the risks faced by architectural heritage from multiple disciplines. During the data collection phase, Web of Science (WOS) literature data was used to set the search strategy based on three keywords: disaster, architectural heritage, and digital tools (and their synonyms) as TS1 = (Heritage) AND TS2 = (“Build” OR “Building*” OR “Architecture* OR “Cultural”) AND TS3 = (Digital) AND TS4= (“Preservation” OR “Conservation” OR “Protection”) OR TS5 = (Heritage) AND TS6 = (“Build” OR “Building*”

OR “Architecture* OR “Cultural”) AND TS7 = (Risk OR “Risk management” OR “Risk assessment”).

2.2 Literature screening

According to the PRISMA statement (2020) (**Figure 2**) (Page et al., 2021) (Fig. 2), the results yielded 490 documents from the WOS, 17 duplicated papers, and three ineligible papers were removed before the screening. Overall, ten papers that were not recent 12 years and 20 non-English papers were excluded according to the PRISMA flow diagram, and one paper did not contain the main content. The second screening of the remaining studies (n = 441) and 33 articles were excluded due to their lack of focus on using risk management as the research subject. A further 348 papers were excluded because the literature did not address the application of the “digital tools” as a research method or tool or provide relevant workflows from an architectural heritage perspective, finally resulting in (n = 161) articles remaining as the final set of references used in this study.

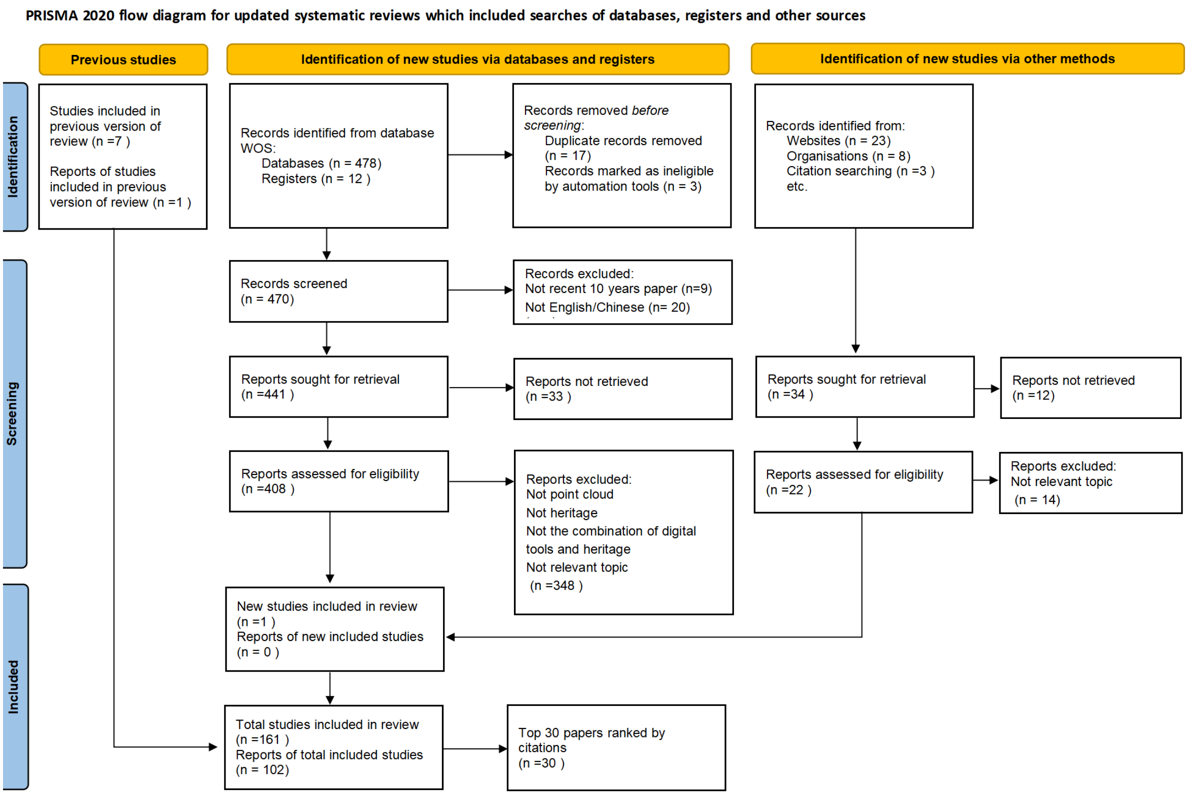


Fig. 2. For the architectural heritage/point cloud/digital technology-centered PRISMA framework

VOSviewer and Citespace are two leading software tools that were utilized in this research for bibliometric analysis and for the visualization of extensive linkages (clusters) among various documents. This approach was aimed at unveiling the inherent significance of the collection of papers studied. By analyzing how literature is co-cited, VOSviewer can help identify important literature and foundational work in a research area (Tomaszewski, 2023). To guarantee the formation of a comprehensive database for subsequent screening and analysis, it is crucial to gather as many relevant papers as possible.

Among them, the trend analysis and co-occurrence matrix analysis in Citespace are of great significance to this study: Citespace can identify thematic evolution paths and research frontiers within a specific research area, showing the evolution of keywords, topics, or technologies over time through a timeline view (Niazi, 2016). In addition, by analyzing the co-citation of literature, Citespace reveals the connections between different research efforts, helping to identify important literature and research foundations in the field (Synnestvedt et al., 2005).

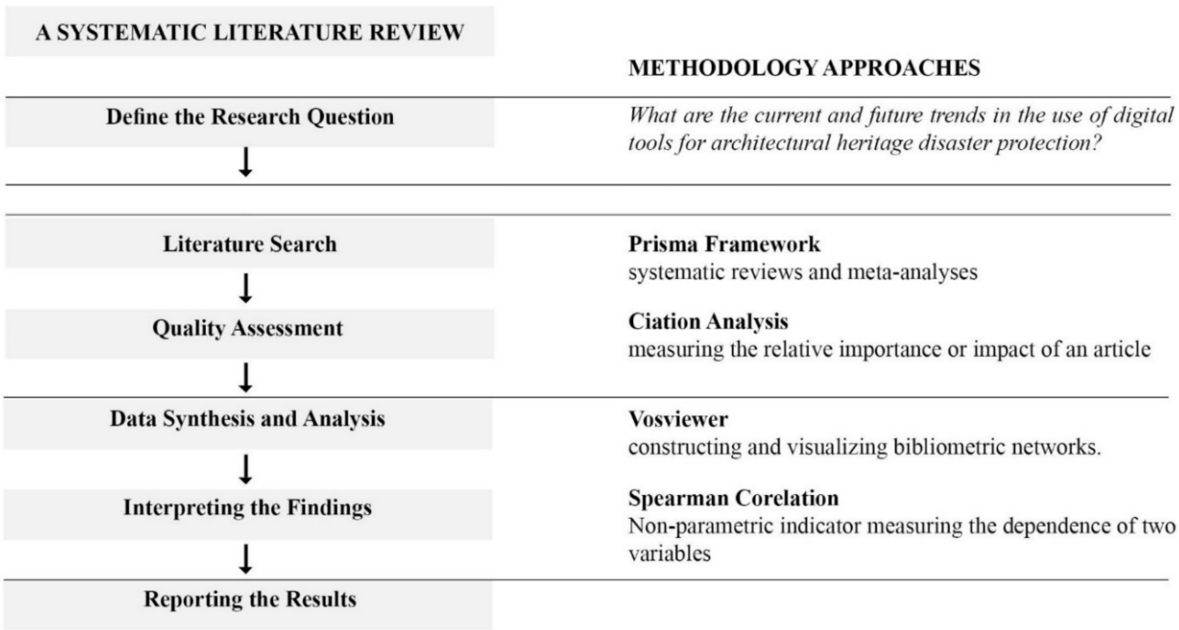


Fig. 3. The workflow for the systemic literature review.

This image is a visualization of keyword co-occurrence analysis created using VOSviewer, showing the relationship between different keywords and their importance over a specific time period (**Figure 3**). The size of the keywords represents how often they appear in the literature, while the lines indicate the strength of the association or co-occurrence between different keywords. Colors can represent changes over time, as shown by the color scale on the bottom timeline.

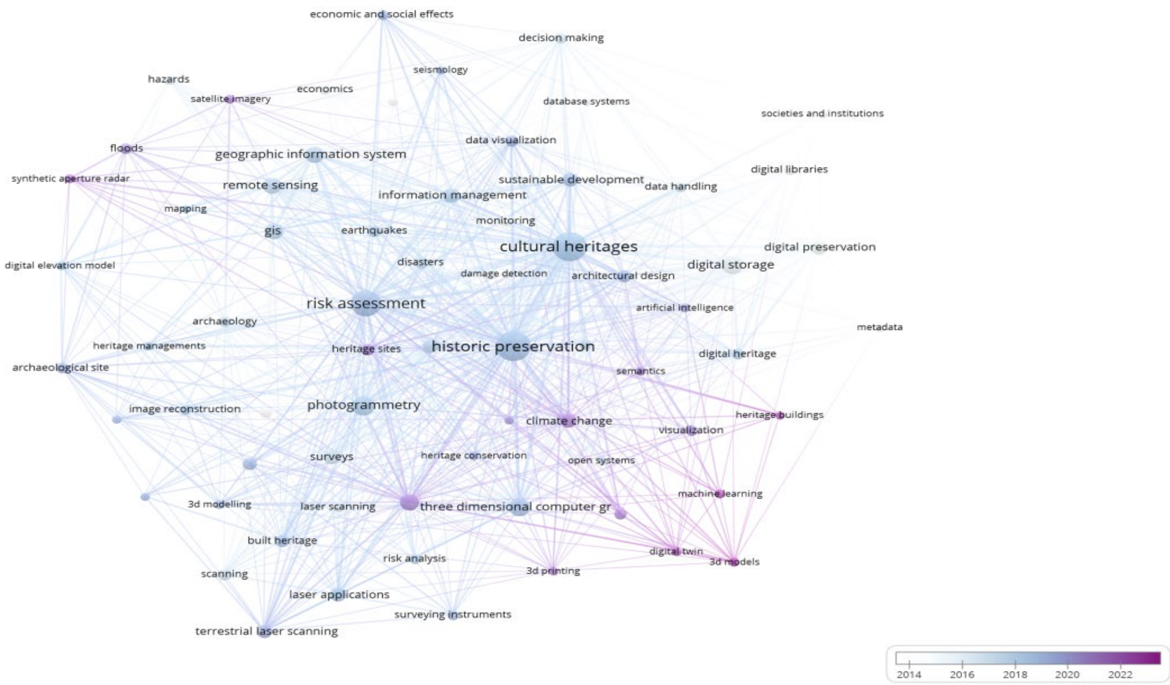


Fig. 4. VOSviewer software with modularity optimization and smart local moving algorithms.

From this visualization, we can infer that "architectural heritage preservation," "AR," and "HBIM" are the larger keywords, indicating that they are prominent research themes. The close association around these terms suggests that they are closely related to many other keywords. For example, "TLS" is clearly linked to "GIS," "UAV," and "SFM." There is a clear link between "TLS" and "GIS," "UAV" and "SFM."

Other keywords, such as "DEEP LEARNING," "MACHINE LEARNING," and "DIGITAL TWINS," highlight the fact that technological advances, such as digitization and automation, are being Technological advances such as digitization and automation are emerging as trends in the field of historical and cultural heritage conservation. Furthermore, the change in the timeline shows that these technologies and methods have become more critical in recent years...

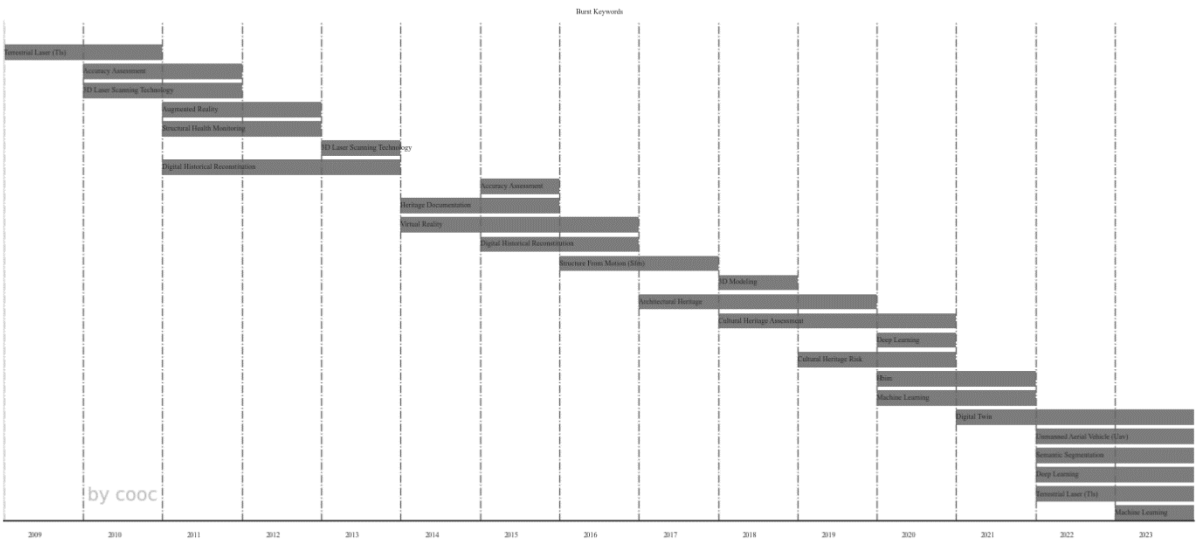


Fig. 5. VOSviewer Keyword co-occurrence analysis, keyword year-to-year trends

Derived from the data of the keyword co-occurrence analysis (**Figure 4**), we can observe that keywords vary in length and time of prominence. The overall visualization shows the changing research focus of digital tools for architectural heritage over time. There are keywords that gained prominence in specific years and may fade or continue to be in the spotlight in subsequent years. This type of analysis helps identify new trends, shifts in research focus, or gaps in the literature.

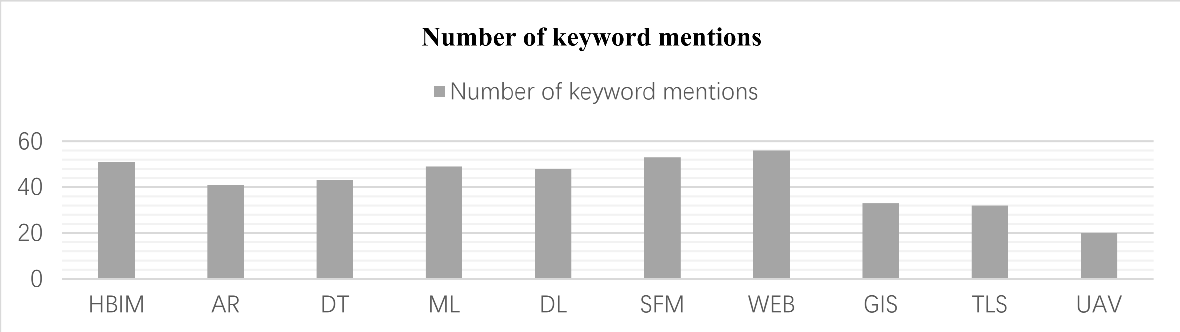


Fig. 6. Top 10 keyword trends and their frequency of use with VOSviewer software

Citation analysis is a bibliometric method for assessing the impact and frequency with which academic papers are cited in other works. When performing citation analysis on a set of articles, this paper tracks the number of times each article is cited by other papers. 161 articles were analyzed and ranked according to the number of citations, and the top 10 keywords represented the most influential or popular topics in that particular field of research(**Figure 5**).

3. Results

Spearman rank correlation coefficients between the number of mentions and the number of funded papers were calculated using HBIM as an example (Table 1)

Table 1:

Spearman's rank correlation coefficients using HBIM as an example

HBIM	2012		2015		2018		2021		2024	
Number of papers mentioned	*2*	*4*	*6*	*17*	*22*	*2*	*4*	*6*	*17*	*22*
RANK A	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
Number of literature funded	*0*	*5*	*2*	*11*	*17*	*0*	*5*	*2*	*11*	*17*
RANK B	*1*	*3*	*2*	*4*	*5*	*1*	*3*	*2*	*4*	*5*
☐ **Number of keyword mentions** ☐ **Number of project funds received**										
R（spearman）	0.900									
P-value	0.0374									

The Spearman correlation coefficient is 0.900, and the p-value of the correlation is 0.0374, which is below the commonly used significance level of 0.05. This suggests that the correlation observed is statistically significant, meaning we have sufficient evidence to believe that the correlation between these two indicators is not due to chance. In summary, the analysis results indicate that the "Number of papers mentioned" and the "Number of literature funded" have shown a consistent trend across the years examined, and this trend is statistically significant. This analysis demonstrates that HBIM (Heritage Building Information Modeling) has been gaining consistent attention and support in terms of academic mentions and funding over the years, highlighting its growing importance and recognition in the field.

Spearman's rank correlation coefficient for different digital tools between the number of mentions and the number of funded papers (Table 2)

Table 2:

Spearman rank correlation coefficients for different digital tools (correlation between mentions and fund acquisition rates)

	HBIM		AR		DT		ML		DL		SFM		WEB		GIS		TLS		UAV	
2024	*22*	*17*	*27*	*22*	*19*	*12*	*17*	*13*	*23*	*19*	*16*	*11*	*21*	*12*	*10*	*8*	*10*	*9*	*10*	*9*
☐ **Number of keyword mentions** ☐ **Number of project funds received**																				
R（spearman)	0.951																			
P-value	0.0000245																			

The Spearman correlation coefficient between the number of times various technologies are mentioned in literature and the number of documents funded for each technology is approximately 0.951. This high positive correlation suggests a strong association between the two sets of values. The p-value of approximately 2.45e-05 indicates that this correlation is statistically significant, meaning there is a very low chance that this strong correlation occurred by random chance. Based on the analysis, there is a very strong and statistically significant positive correlation between the frequency of mentions of various technologies in literature and the number of documents funded for each technology.

Spearman's rank correlation coefficient year-by-year between the number of mentions and the number of funded papers (Table 3)

Table 3:

Spearman rank correlation coefficients for year-by-year digital tools (correlation between year-by-year mention rates and Fund access rates)

	HBIM		AR		DT		ML		DL		SFM		WEB		GIS		TLS		UAV	
2012	*2*	*0*	*5*	*2*	*4*	*2*	*4*	*2*	*3*	*2*	*5*	*2*	*3*	*2*	*2*	*0*	*2*	*1*	*2*	*1*
2015	*4*	*0*	*4*	*1*	*4*	*1*	*5*	*2*	*5*	*1*	*3*	*1*	*6*	*2*	*4*	*1*	*3*	*0*	*3*	*0*
2018	*6*	*2*	*10*	*4*	*4*	*1*	*8*	*3*	*4*	*2*	*7*	*0*	*9*	*0*	*5*	*2*	*3*	*0*	*3*	*0*
2021	*17*	*11*	*24*	*13*	*12*	*5*	*15*	*10*	*13*	*7*	*22*	*13*	*17*	*13*	*13*	*11*	*14*	*10*	*14*	*10*
2024	*22*	*17*	*27*	*22*	*19*	*12*	*17*	*13*	*23*	*19*	*16*	*11*	*21*	*12*	*10*	*8*	*10*	*9*	*10*	*9*
☐ **Number of keywords mentioned Numb**☐**of project funds received**																				
R（spearman)	0.975		0.99		0.918		0.975		0.667		0.763		0.7		1		0.564		0.684	
P-value	0.0048		0.0001		0.028		0.0048		0.219		0.188		0.188		$1.4*1^{-25}$		0.322		0.203	

(a) Strong Correlation and Statistically Significant: Some technologies, like HBIM, AR, Digital Twins, and Machine Learning, showed very high Spearman rank correlation coefficients (close to or equal to 1.0) with extremely low P-values (far below 0.05). This indicates a very strong positive correlation between the number of mentions and the number of funded papers for these technologies, with this relationship being statistically significant.

(b)Moderate to Strong Correlation but Not Statistically Significant: Other technologies like SFM, Web technologies, GIS, TLS, and UAV exhibited moderate to strong correlations (Spearman coefficients around 0.7), but their P-values were above 0.05. This suggests that while a positive correlation was observed in the samples, the relationship is not statistically significant, making it uncertain if this correlation exists in a broader population. Deep Learning: The Deep Learning technology showed a moderate Spearman rank correlation coefficient (about 0.564), but its P-value (0.322) indicates that this correlation is not statistically significant.

These analyses reveal that among the technologies considered, certain ones have more significant correlations between the number of mentions in the literature and the number of funded papers. Especially, HBIM, AR, Digital Twins, and Machine Learning technologies receive more attention and funding in academic research, potentially reflecting the importance of research and current trends in these fields.

However, for those technologies with non-significant correlations, it doesn't mean they are less important or overlooked. It could be due to other factors such as sample size, the breadth of the research field, or specific criteria for funding allocation. Thus, these results should be seen as a preliminary understanding of current research and funding trends rather than an absolute assessment of the importance of each technology.

4. Discussions

4.1 Most-applied digital tool

The review delineates, predicated upon the relative magnitudes of P-values (with an inverse relationship between P-value size and the abundance of research), that Geographic Information Systems (GIS), Augmented Reality (AR), Machine Learning (ML), and Heritage Building Information Modeling (HBIM) are the technologies that boast the greatest number of scholarly publications.

GIS: In the scholarly discourse on technological applications within the realm of heritage conservation, Geographic Information Systems (GIS) command a notable preponderance in research volume. This prevalence is not uniformly escalating year over year, but a discernible growth trajectory is evident. Several factors underpin this phenomenon: Firstly, GIS technology has a more established history and widespread adoption, endowing a diverse array of researchers from various disciplines with proficient analytical skills. Secondly, the comprehensive support infrastructure of GIS, coupled with its interoperability with other software platforms, enhances its attractiveness for academic investigation. Finally, the versatility of GIS is unmatched, with applications spanning analysis, management, and modeling. Furthermore, its ability to support a multitude of data formats facilitates multifaceted and multi-scalar analyses, bolstering its utility and, consequently, the volume of research it generates.

AR: AR research stands as the runner-up in volume but exhibits a temporal trend distinct from GIS, with an incremental surge discernible in recent years. This surge is attributable to dual factors. Firstly, as an emergent technology, AR's uptake has escalated in contemporary research. Its nascent nature predicates a recent upswing in scholarly attention. Secondly, AR's utility in the management of disasters pertaining to architectural heritage is broad and multifaceted, encompassing applications such as risk assessment visualization, virtual restoration and reconstruction simulations, and the enhancement of public engagement and education through interactive experiences. These applications have bolstered AR's presence in academic research, reflecting its growing importance in the field.

ML: The field of Machine Learning (ML) is characterized by a substantial volume of publications. This proliferation is attributed to its expansive application across numerous domains, including predictive analytics in cultural heritage conservation, algorithmic enhancement in artifact restoration, and pattern recognition in historical data analysis. Furthermore, the revolutionary impact of ML has permeated various sectors, catalyzing transformative changes in data processing efficiency, decision-making automation, and the development of adaptive systems across disciplines, thereby significantly influencing research outputs and directions.

HBIM: This technology has become widely applied in the management of disasters affecting architectural heritage due to its comprehensive approach to preserving historical integrity while facilitating modern conservation efforts. By creating detailed digital twins of heritage structures, HBIM allows for the meticulous planning and simulation of restoration processes, enhancing the resilience of buildings against natural disasters and environmental decay. This methodology enables precise damage assessment, proactive maintenance planning, and the development of targeted restoration strategies that respect and preserve the original architectural features. Furthermore, HBIM's integration with Geographic Information Systems (GIS) and Augmented Reality (AR) technologies offers innovative solutions for risk management, allowing for the efficient allocation of resources in disaster-prone areas and the visualization of potential impact scenarios. Thus, HBIM stands as a pivotal tool in the intersection of technology and heritage conservation, ensuring that the legacy of the past is safeguarded for future generations.

The preceding discussion merely highlights the high frequency of use of the aforementioned tools in scholarly literature, indicating their prominence in academic discourse. However, it is crucial to note that the widespread application of these technologies in academic publications does not necessarily translate to their extensive practical application in real-world scenarios. Thus, it becomes imperative to conduct a nuanced analysis of their implementation. This entails examining factors such as technological accessibility, cost-effectiveness, ease of integration into existing conservation practices, and the readiness of stakeholders to adopt such innovations. Additionally, assessing the potential challenges and limitations these technologies may face in practical applications is essential for understanding their viability and effectiveness in actual heritage conservation efforts. Consequently, the subsequent analysis aims to bridge the gap between theoretical research and practical application, shedding light on the real-world applicability of these advanced digital tools in the conservation of architectural heritage.

4.2 Analysis of the Applicability

In the vast landscape of technological advancements, not all innovations are guaranteed practical applicability. The feasibility of technology deployment, often referred to as "grounding," can be correlated with the extent to which different technologies and projects receive funding. This relationship is quantifiable through the "R-value," which assesses the correlation between the use of various tools and their funding levels. As illustrated, in conjunction with the P-value, existing tools can be categorized into four distinct groups:

(a) high P-value, low R-value, indicating fewer publications and less funding;
(b) high R-value, low P-value, denoting a higher number of publications and more substantial funding;
(c) high P-value and R-value, suggesting fewer publications but more funding;
(d) low P-value and R-value, representing a high volume of publications with less funding.

Among the reviewed tools, only categories (a) and (b) were observed. Tools classified under category (a) include Heritage Building Information Modeling (HBIM), Augmented Reality (AR), Digital Twinning (DT), Machine Learning (ML), and Geographic Information Systems (GIS). Notably, GIS exhibits the most positive values in both metrics, not only being the most utilized but also the most likely to be funded, a phenomenon detailed in section 4.1.

Category (b) comprises Deep Learning (DL), Structure from Motion (SfM), Web Technologies (WEB), Terrestrial Laser Scanning (TLS), and Unmanned Aerial Vehicles (UAV), with TLS not only having the fewest studies but also the lowest probability of being funded. The primary reasons for this scenario may include the high cost of TLS equipment and the specialized training required to operate such technology, limiting its accessibility and applicability in broader research contexts. Additionally, the niche applications of TLS, while invaluable in precise topographical and architectural surveys, may not align with the funding priorities that favor more versatile or emergent technologies. This disparity in funding and publication volume underscores the complex interplay between technological innovation, academic interest, and practical utility. It reveals how funding priorities can shape the research landscape, elevating certain technologies over others based on perceived utility, applicability, and potential for groundbreaking contributions to the field. Thus, understanding these dynamics is crucial for researchers and practitioners aiming to navigate the ever-evolving terrain of technological applications in heritage conservation.

4.3 The clustering of different digital tools for AHRM

In the evolving field of AHRM, the advent and integration of digital tools have been pivotal. The network visualization provided delineates distinct clusters of these tools, each with specific functions and applications.

(a) At the core, Geospatial Analysis Tools such as GIS, remote sensing, and satellite imagery have become indispensable. These tools facilitate the extensive monitoring and mapping of heritage sites, providing a macroscopic view that aids in large-scale conservation planning. They enable specialists to detect and analyze changes over time, assess risks, and plan interventions without the need for physical contact, which is crucial for fragile sites.

(b) The 3D Documentation and Modeling Tools cluster, featuring laser scanning and photogrammetry, allows for the meticulous capture of the physical form of heritage structures. These tools create highly detailed digital surrogates that serve not only as records for posterity but also as a basis for restoration projects and virtual tours, enhancing public engagement and education.

(c) Data Management and Processing Tools like database systems are the backbone of heritage conservation in the digital age. They ensure that the vast quantities of data produced are systematically stored, processed, and easily retrievable for analysis and decision-making.

(d) Furthermore, Risk Analysis and Monitoring Tools draw upon advanced algorithms and simulation software to predict the impact of potential threats like natural disasters, facilitating preemptive measures to safeguard heritage assets.

(e)Lastly, the cluster of Digital Archiving and Presentation Tools underscores the role of digital libraries and metadata management in preserving the digital footprint of cultural heritages, ensuring that these treasures are archived and accessible to future generations.

The synergy between these digital tool clusters epitomizes a multi-faceted approach to heritage conservation. It encompasses risk assessment, structural analysis, and the democratization of access to cultural heritage, thereby reinforcing the resilience and sustainability of conservation efforts in the digital era.

5. Conclusion

In conclusion, the application of digital tools in AHRM represents a transformative evolution in the field of heritage conservation. Over the past decade, a discernible increase in scholarly attention and funding towards tools like GIS, HBIM, and AR indicates a recognition of their potential to enhance the preservation of architectural heritage. These technologies enable a granular understanding of heritage sites, foster predictive conservation strategies, and democratize the accessibility of cultural heritage. However, challenges remain in integrating these tools into cohesive workflows and translating academic research into practical applications. Future research should focus on bridging this gap, promoting interdisciplinary collaboration, and developing accessible, cost-effective solutions. The effective conservation of architectural heritage depends not only on technological innovation but also on the synergistic efforts of conservators, researchers, and policymakers to implement these digital tools in a manner that respects the past while embracing the future.

Reference:

Adamopoulos, E., & Rinaudo, F. (2021). Close-range sensing and data fusion for built heritage inspection and monitoring—a review. *Remote Sensing*, *13*(19), 3936.

Al-Allaf, E. H. (2014). Preventive conservation as a procedure for safeguarding mosul built heritage. *Diyala Journal of Engineering Sciences*, 98-129.

Al-Bayari, O., & Shatnawi, N. (2022). Geomatics techniques and building information model for historical buildings conservation and restoration. *The Egyptian Journal of Remote Sensing and Space Science*, *25*(2), 563-568.

Alberts, H. C., & Hazen, H. D. (2010). Maintaining Authenticity and Integrity at Cultural World Heritage Sites. *Geographical Review*, *100*(1), 56-73. https://doi.org/10.1111/j.1931-0846.2010.00006.x

Albourae, A., Armenakis, C., & Kyan, M. (2017). Architectural heritage visualization using interactive technologies. *The International Archives of the Photogrammetry, Remote Sensing and Spatial*

Information Sciences, *42*, 7-13.
Alnafeesi, A. M. (2013). The role & impact of preservation architectural heritage on domestic tourism.
Ariyachandra, M. M. F., & Wedawatta, G. (2023). Digital Twin Smart Cities for Disaster Risk Management: A Review of Evolving Concepts. *Sustainability*, *15*(15), 11910.
Ashrafi, B., Kloos, M., & Neugebauer, C. (2021). Heritage Impact Assessment, beyond an Assessment Tool: A comparative analysis of urban development impact on visual integrity in four UNESCO World Heritage Properties. *Journal of Cultural Heritage*, *47*, 199-207.
Aven, T. (2016). Risk assessment and risk management: Review of recent advances on their foundation. *European Journal of Operational Research*, *253*(1), 1–13. https://doi.org/https://doi.org/10.1016/j.ejor.2015.12.023
Avramidou, N. (2003). Vulnerability of cultural heritage to hazards and prevention measures. Proceeding of Advanced Research Workshops,
Bankoff, G. (2015). Design by disasters: Seismic architecture and cultural adaptation to earthquakes. In *Cultures and Disasters* (pp. 53-71). Routledge.
Barontini, A., Alarcon, C., Sousa, H. S., Oliveira, D. V., Masciotta, M. G., & Azenha, M. (2022). Development and Demonstration of an HBIM Framework for the Preventive Conservation of Cultural Heritage. *International Journal of Architectural Heritage*, *16*(10), 1451-1473. https://doi.org/10.1080/15583058.2021.1894502
Bartolini, G., Giuliani, F., & De Falco, A. (2023). Proof of Concept for Methodological Framework Including Point Clouds in the Non-Destructive Diagnosis of Historical Masonry Structures. *International Journal of Architectural Heritage*, 1-24.
Basso, A., Condorelli, F., Giordano, A., Morena, S., & Perticarini, M. (2024). EVOLUTION OF RENDERING BASED ON RADIANCE FIELDS. THE PALERMO CASE STUDY FOR A COMPARISON BETWEEN NERF AND GAUSSIAN SPLATTING. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, *XLVIII-2/W4-2024*, 57-64. https://doi.org/10.5194/isprs-archives-XLVIII-2-W4-2024-57-2024
Bastem, S. S., & Cekmis, A. (2022). Development of historic building information modelling: A systematic literature review. *Building Research & Information*, *50*(5), 527-558.
Bevilacqua, M. G., Russo, M., Giordano, A., & Spallone, R. (2022). 3D reconstruction, digital twinning, and virtual reality: Architectural heritage applications. 2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW),
Bhatia, M., Ahanger, T. A., & Manocha, A. (2023). Artificial intelligence based real-time earthquake prediction. *Engineering Applications of Artificial Intelligence*, *120*, 105856.
Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, *114*, 103179.
Bortolini, R., Rodrigues, R., Alavi, H., Vecchia, L. F. D., & Forcada, N. (2022). Digital Twins' Applications for Building Energy Efficiency: A Review. *Energies*, *15*(19), 7002. https://www.mdpi.com/1996-1073/15/19/7002
Bose, R. (2003). Knowledge management-enabled health care management systems: capabilities, infrastructure, and decision-support. *Expert Systems with Applications*, *24*(1), 59-71. https://doi.org/https://doi.org/10.1016/S0957-4174(02)00083-0
Bosher, L., Kim, D., Okubo, T., Chmutina, K., & Jigyasu, R. (2020). Dealing with multiple hazards and threats on cultural heritage sites: an assessment of 80 case studies. *Disaster Prevention and Management: An International Journal*, *29*(1), 109-128.
Boyes, H., & Watson, T. (2022). Digital twins: An analysis framework and open issues. *Computers in Industry*,

143, 103763.

Brahmi, B. F., Sassi Boudemagh, S., Kitouni, I., & Kamari, A. (2022). IPD and BIM-focussed methodology in renovation of heritage buildings. *Construction Management and Economics*, *40*(3), 186-206. https://doi.org/10.1080/01446193.2021.1933557

Bruno, S., De Fino, M., & Fatiguso, F. (2018). Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management. *Automation in Construction*, *86*, 256-276. https://doi.org/https://doi.org/10.1016/j.autcon.2017.11.009

Calvano, M., Martinelli, L., Calcerano, F., & Gigliarelli, E. (2022). Parametric processes for the implementation of HBIM—Visual programming language for the digitisation of the index of masonry quality. *ISPRS International Journal of Geo-Information*, *11*(2), 93.

Camuffo, D. (2019). *Microclimate for cultural heritage: Measurement, risk assessment, conservation, restoration, and maintenance of indoor and outdoor monuments*. Elsevier.

Candón Fernández, E., Crespo-Márquez, A., Guillén López, A., & Hidalgo Fort, E. Model-based asset digitalization framework in the context of digital maintenance. An example using IoT platform and Asset Health Index model applied to civil infrastructures. *An example using IoT platform and Asset Health Index model applied to civil infrastructures*.

Cardona, O. D. (2013). The need for rethinking the concepts of vulnerability and risk from a holistic perspective: a necessary review and criticism for effective risk management. In *Mapping vulnerability* (pp. 37-51). Routledge.

Che, E., Jung, J., & Olsen, M. J. (2019). Object recognition, segmentation, and classification of mobile laser scanning point clouds: A state of the art review. *Sensors*, *19*(4), 810.

Chen, M., Mao, S., Zhang, Y., & Leung, V. C. (2014). *Big data: related technologies, challenges and future prospects* (Vol. 100). Springer.

Chi, H.-L., Kang, S.-C., & Wang, X. (2013). Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. *Automation in construction*, *33*, 116-122.

Chiabrando, F., Sammartano, G., & Spanò, A. (2016). Historical buildings models and their handling via 3D survey: From points clouds to user-oriented HBIM. *the international archives of the photogrammetry, remote sensing and spatial information sciences*, *41*, 633-640.

Cinquepalmi, F., & Cumo, F. (2022). Using Digital Twin Models (DTM) for managing, protecting and restoring historical buildings. *Conservation Science in Cultural Heritage*, *22*, 425-445.

Coetzee, C., & Van Niekerk, D. (2012). Tracking the evolution of the disaster management cycle: A general system theory approach. *Jàmbá: Journal of Disaster Risk Studies*, *4*(1), 1-9.

Coïsson, E., & Ferrari, L. (2023). Emergency Response to Damaged Architectural Heritage: Time, Safety and Conservation. International Conference on Structural Analysis of Historical Constructions,

Cornia, M., Stefanini, M., Baraldi, L., Corsini, M., & Cucchiara, R. (2020). Explaining digital humanities by aligning images and textual descriptions. *Pattern Recognition Letters*, *129*, 166-172.

Cresswell, K., & Sheikh, A. (2013). Organizational issues in the implementation and adoption of health information technology innovations: An interpretative review. *International Journal of Medical Informatics*, *82*(5), e73-e86. https://doi.org/https://doi.org/10.1016/j.ijmedinf.2012.10.007

Crompvoets, J., Vancauwenberghe, G., Ho, S., Masser, I., & De Vries, W. T. (2018). Governance of national spatial data infrastructures in Europe. *International Journal of Spatial Data Infrastructures Research*, *13*, 253-285.

Cunha Ferreira, T., Romão, X., Freitas, P. M., & Mendonça, H. (2023). Risk Assessment and Vulnerability

Analysis of a Coastal Concrete Heritage Structure. *Heritage*, *6*(9), 6153-6171.

De Paoli, R. G., Di Miceli, E., & Giuliani, F. (2020). Disasters and Cultural Heritage: planning for prevention, emergency management and risk reduction. IOP Conference Series: Materials Science and Engineering,

Delgado, J. M. D., & Oyedele, L. (2021). Digital Twins for the built environment: learning from conceptual and process models in manufacturing. *Advanced engineering informatics*, *49*, 101332.

Diaz, V., van Oosterom, P., Meijers, M., Verbree, E., Ahmed, N., & van Lankveld, T. (2023). Comparison of Cloud-to-Cloud Distance Calculation Methods-Is the Most Complex Always the Most Suitable? International 3D GeoInfo Conference,

Dore, C., & Murphy, M. (2012). Integration of Historic Building Information Modeling (HBIM) and 3D GIS for recording and managing cultural heritage sites. 2012 18th International conference on virtual systems and multimedia,

Fatorić, S., & Seekamp, E. (2017). Securing the Future of Cultural Heritage by Identifying Barriers to and Strategizing Solutions for Preservation under Changing Climate Conditions. *Sustainability*, *9*(11), 2143. https://www.mdpi.com/2071-1050/9/11/2143

Fissore, V., Bovio, L., Perotti, L., Boccardo, P., & Borgogno-Mondino, E. (2023). Towards a Digital Twin Prototype of Alpine Glaciers: Proposal for a Possible Theoretical Framework. *Remote Sensing*, *15*(11), 2844.

Ford, J. D., Pearce, T., Duerden, F., Furgal, C., & Smit, B. (2010). Climate change policy responses for Canada's Inuit population: The importance of and opportunities for adaptation. *Global Environmental Change*, *20*(1), 177-191. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2009.10.008

Foster, C., & Thelen, K. (2023). Brandeis in Brussels? Bureaucratic discretion, social learning, and the development of regulated competition in the European Union. *Regulation & Governance*.

Foster, G. (2020). Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts. *Resources, Conservation and Recycling*, *152*, 104507. https://doi.org/https://doi.org/10.1016/j.resconrec.2019.104507

Fuchizaki, K., Wada, T., Naruta, H., Suzuki, A., & Irino, K. (2021). A unique multianvil 6–6 assembly for a cubic-type multianvil apparatus. *Review of Scientific Instruments*, *92*(2).

Galanakis, D., Maravelakis, E., Pocobelli, D. P., Vidakis, N., Petousis, M., Konstantaras, A., & Tsakoumaki, M. (2023). SVD-based point cloud 3D stone by stone segmentation for cultural heritage structural analysis–The case of the Apollo Temple at Delphi. *Journal of Cultural Heritage*, *61*, 177-187.

Germs, R., Van Maren, G., Verbree, E., & Jansen, F. W. (1999). A multi-view VR interface for 3D GIS. *Computers & Graphics*, *23*(4), 497-506. https://doi.org/https://doi.org/10.1016/S0097-8493(99)00069-2

Giaccardi, E. (2012). *Heritage and social media: Understanding heritage in a participatory culture*. Routledge.

Giuliani, F., De Falco, A., Cutini, V., & Di Sivo, M. (2021). A simplified methodology for risk analysis of historic centers: the world heritage site of San Gimignano, Italy. *International Journal of Disaster Resilience in the Built Environment*, *12*(3), 336-354.

Goklany, I. M. (2007). Integrated strategies to reduce vulnerability and advance adaptation, mitigation, and sustainable development. *Mitigation and Adaptation Strategies for Global Change*, *12*(5), 755-786. https://doi.org/10.1007/s11027-007-9098-1

Gomes, L., Bellon, O. R. P., & Silva, L. (2014). 3D reconstruction methods for digital preservation of cultural

heritage: A survey. *Pattern Recognition Letters*, *50*, 3-14.
Graham, B. (2002). Heritage as knowledge: capital or culture? *Urban studies*, *39*(5-6), 1003-1017.
Green, C., Verhagen, P., McKeague, P., Van'T Veer, R., Huvila, I., Moreau, A., Loup, B., Cooper, A., & Van Manen, N. (2019). Mapping our heritage: Towards a sustainable future for digital spatial information and technologies in European archaeological heritage management. *Journal of Computer Applications in Archaeology*, *2*(1).
Guillet, A.-L. (2007). Docomomo International. *Journal of Architectural Conservation*, *13*(2), 151-156. https://doi.org/10.1080/13556207.2007.10785002
Gullino, P., & Larcher, F. (2013). Integrity in UNESCO World Heritage Sites. A comparative study for rural landscapes. *Journal of Cultural Heritage*, *14*(5), 389-395. https://doi.org/https://doi.org/10.1016/j.culher.2012.10.005
Guo, Y., Liu, Y., Georgiou, T., & Lew, M. S. (2018). A review of semantic segmentation using deep neural networks. *International Journal of Multimedia Information Retrieval*, *7*(2), 87-93. https://doi.org/10.1007/s13735-017-0141-z
Haddad, N. A. (2011). From ground surveying to 3D laser scanner: A review of techniques used for spatial documentation of historic sites. *Journal of King Saud University - Engineering Sciences*, *23*(2), 109-118. https://doi.org/https://doi.org/10.1016/j.jksues.2011.03.001
Haddad, N. A., Fakhoury, L. A., & Akasheh, T. S. (2018). Notes on anthropogenic risks mitigation management and recovery of ancient theatres' heritage: Qualitative assessment and recommendations. *Journal of Cultural Heritage Management and Sustainable Development*, *8*(3), 222-256.
Hakiri, A., Gokhale, A., Yahia, S. B., & Mellouli, N. (2024). A comprehensive survey on digital twin for future networks and emerging Internet of Things industry. *Computer Networks*, 110350.
Halog, A., & Manik, Y. (2011). Advancing integrated systems modelling framework for life cycle sustainability assessment. *Sustainability*, *3*(2), 469-499.
Hammady, R., Ma, M., Strathern, C., & Mohamad, M. (2020). Design and development of a spatial mixed reality touring guide to the Egyptian museum. *Multimedia Tools and Applications*, *79*(5), 3465-3494.
Hayles, N. K. (2012). How we think: Transforming power and digital technologies. In *Understanding digital humanities* (pp. 42-66). Springer.
Heller, N. E., & Zavaleta, E. S. (2009). Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation*, *142*(1), 14-32. https://doi.org/https://doi.org/10.1016/j.biocon.2008.10.006
Hevner, A. R., March, S., Park, J., & Ram, S. (2014). Design Science Research. In.
Hopkin, P. (2018). *Fundamentals of risk management: understanding, evaluating and implementing effective risk management*. Kogan Page Publishers.
Illsley, W. R. (2022). Assembling the Historic Environment: Heritage in the Digital Making.
Jiang, P., Pandey, G., & Saripalli, S. (2024). 3DGS-ReLoc: 3D Gaussian Splatting for Map Representation and Visual ReLocalization. *arXiv preprint arXiv:2403.11367*.
Jigyasu, R., Murthy, M., Boccardi, G., Marrion, C., Douglas, D., King, J., O'Brien, G., Dolcemascolo, G., Kim, Y., & Albrito, P. (2013). Heritage and resilience: issues and opportunities for reducing disaster risks.
Jo, Y. H., & Hong, S. (2019). Three-Dimensional Digital Documentation of Cultural Heritage Site Based on the Convergence of Terrestrial Laser Scanning and Unmanned Aerial Vehicle Photogrammetry. *ISPRS International Journal of Geo-Information*, *8*(2), 53. https://www.mdpi.com/2220-

9964/8/2/53
Jordan-Palomar, I., Tzortzopoulos, P., García-Valldecabres, J., & Pellicer, E. (2018). Protocol to Manage Heritage-Building Interventions Using Heritage Building Information Modelling (HBIM). *Sustainability*, *10*(4), 908. https://www.mdpi.com/2071-1050/10/4/908
Jorquera, N., Vargas, J., Lobos Martínez, M. d. l. L., & Cortez, D. (2017). Revealing earthquake-resistant geometrical features in heritage masonry architecture in Santiago, Chile. *International Journal of Architectural Heritage*, *11*(4), 519-538.
Jouan, P., & Hallot, P. (2019). DIGITAL TWIN: A HBIM-BASED METHODOLOGY TO SUPPORT PREVENTIVE CONSERVATION OF HISTORIC ASSETS THROUGH HERITAGE SIGNIFICANCE AWARENESS. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, *XLII-2/W15*, 609-615. https://doi.org/10.5194/isprs-archives-XLII-2-W15-609-2019
Jouan, P., & Hallot, P. (2019). Digital twin: A HBIM-based methodology to support preventive conservation of historic assets through heritage significance awareness. *the international archives of the photogrammetry, remote sensing and spatial information sciences*, *42*, 609-615.
Jouan, P., & Hallot, P. (2020). Digital twin: Research framework to support preventive conservation policies. *ISPRS International Journal of Geo-Information*, *9*(4), 228.
Kattel, G. R., Elkadi, H., & Meikle, H. (2013). Developing a complementary framework for urban ecology. *Urban Forestry & Urban Greening*, *12*(4), 498-508.
Kedzierski, M., & Fryskowska, A. (2015). Methods of laser scanning point clouds integration in precise 3D building modelling. *Measurement*, *74*, 221-232.
Kelly, M. (2023). *The Representation of Interpretative Knowledge in Cultural Heritage Research* University of Brighton].
Khalaf, R. W. (2022). Integrity: Enabling a Future-Oriented Approach to Cultural Heritage. *The Historic Environment: Policy & Practice*, *13*(1), 5-27. https://doi.org/10.1080/17567505.2021.1981670
Khalid, A. (2022). Conservation Challenges and Emerging Trends of Digital Preservation for UNESCO Architectural Heritage, Pakistan. *Conservation*, *2*(1), 26-37. https://www.mdpi.com/2673-7159/2/1/3
King, L., Stark, J. F., & Cooke, P. (2016). Experiencing the digital world: The cultural value of digital engagement with heritage. *Heritage & Society*, *9*(1), 76-101.
Koller, D., Frischer, B., & Humphreys, G. (2010). Research challenges for digital archives of 3D cultural heritage models. *Journal on Computing and Cultural Heritage (JOCCH)*, *2*(3), 1-17.
Kundu, A., Yin, X., Fathi, A., Ross, D., Brewington, B., Funkhouser, T., & Pantofaru, C. (2020). Virtual multi-view fusion for 3d semantic segmentation. Computer Vision–ECCV 2020: 16th European Conference, Glasgow, UK, August 23–28, 2020, Proceedings, Part XXIV 16,
Laakso, M., & Kiviniemi, A. (2012). The IFC standard: A review of history, development, and standardization, information technology. *ITcon*, *17*(9).
Labadi, S. (2013). UNESCO, cultural heritage, and outstanding universal value: Value-based analyses of the World Heritage and Intangible Cultural Heritage Conventions.
Labadi, S., Giliberto, F., Rosetti, I., Shetabi, L., & Yildirim, E. (2021). Heritage and the sustainable development goals: Policy guidance for heritage and development actors. *International Journal of Heritage Studies*.
Latour, B., & Crawford, T. H. (1993). An interview with bruno latour. *Configurations*, *1*(2), 247-268.
Laužikas, R., Žižiūnas, T., & Fomin, V. (2022). Novel technologies as potential catalyst for democratizing urban heritage preservation practices: the case of 3D scanning and AI. *Information & media*, *93*,

93-115.
Lemmens, M., & Lemmens, M. (2011). Terrestrial laser scanning. *Geo-information: technologies, applications and the environment*, 101-121.
Letellier, R., & Eppich, R. (2015). *Recording, documentation and information management for the conservation of heritage places*. Routledge.
Li, S., Liu, L., & Peng, C. (2020). A review of performance-oriented architectural design and optimization in the context of sustainability: Dividends and challenges. *Sustainability*, *12*(4), 1427.
Li, X., Zhou, X., Weng, F., Ding, F., Wu, Y., & Yi, Z. (2024). Evolution of cultural landscape heritage layers and value assessment in urban countryside historic districts: the case of Jiufeng Sheshan, Shanghai, China. *Heritage Science*, *12*(1), 96.
Li, Y., Du, Y., Yang, M., Liang, J., Bai, H., Li, R., & Law, A. (2023). A review of the tools and techniques used in the digital preservation of architectural heritage within disaster cycles. *Heritage Science*, *11*(1), 199. https://doi.org/10.1186/s40494-023-01035-x
Liang, W., Ahmad, Y., & Mohidin, H. H. B. (2023). The development of the concept of architectural heritage conservation and its inspiration. *Built Heritage*, *7*(1), 21. https://doi.org/10.1186/s43238-023-00103-2
Liburd, J. J., & Becken, S. (2020). Values in nature conservation, tourism and UNESCO World Heritage Site stewardship. In *Protected areas, sustainable tourism and neo-liberal governance policies* (pp. 23-39). Routledge.
Lim, K. Y. H., Zheng, P., & Chen, C.-H. (2020). A state-of-the-art survey of Digital Twin: techniques, engineering product lifecycle management and business innovation perspectives. *Journal of Intelligent Manufacturing*, *31*(6), 1313-1337.
Liritzis, I., & Korka, E. (2019). Archaeometry's role in cultural heritage sustainability and development. *Sustainability*, *11*(7), 1972.
Liu, Z., van Oosterom, P., Balado, J., Swart, A., & Beers, B. (2022). Detection and reconstruction of static vehicle-related ground occlusions in point clouds from mobile laser scanning. *Automation in Construction*, *141*, 104461. https://doi.org/https://doi.org/10.1016/j.autcon.2022.104461
López, F. J., Lerones, P. M., Llamas, J., Gómez-García-Bermejo, J., & Zalama, E. (2018). A Review of Heritage Building Information Modeling (H-BIM). *Multimodal Technologies and Interaction*, *2*(2), 21. https://www.mdpi.com/2414-4088/2/2/21
Losada, I. J., Toimil, A., Muñoz, A., Garcia-Fletcher, A. P., & Diaz-Simal, P. (2019). A planning strategy for the adaptation of coastal areas to climate change: The Spanish case. *Ocean & Coastal Management*, *182*, 104983. https://doi.org/https://doi.org/10.1016/j.ocecoaman.2019.104983
Lowenthal, D. (1994). Identity, heritage, and history. *Commemorations: The politics of national identity*, 41-57.
Luther, W., Baloian, N., Biella, D., & Sacher, D. (2023). Digital twins and enabling technologies in museums and cultural heritage: An overview. *Sensors*, *23*(3), 1583.
Lysgaard, J. A., Bengtsson, S., & Laugesen, M. H.-L. (2019). *Dark pedagogy: Education, horror and the Anthropocene*. Springer.
Majumdar, A., Sinha, S. K., & Govindan, K. (2021). Prioritising risk mitigation strategies for environmentally sustainable clothing supply chains: Insights from selected organisational theories. *Sustainable Production and Consumption*, *28*, 543-555. https://doi.org/https://doi.org/10.1016/j.spc.2021.06.021
Mao, Y., Qi, J., & He, B.-J. (2020). Impact of the heritage building façade in small-scale public spaces on

human activity: Based on spatial analysis. *Environmental Impact Assessment Review*, *85*, 106457. https://doi.org/https://doi.org/10.1016/j.eiar.2020.106457

Martinelli, L., Calcerano, F., & Gigliarelli, E. (2022). Methodology for an HBIM workflow focused on the representation of construction systems of built heritage. *Journal of Cultural Heritage*, *55*, 277-289. https://doi.org/https://doi.org/10.1016/j.culher.2022.03.016

Masciotta, M. G., Sanchez-Aparicio, L. J., Oliveira, D. V., & Gonzalez-Aguilera, D. (2023). Integration of laser scanning technologies and 360º photography for the digital documentation and management of cultural heritage buildings. *International Journal of Architectural Heritage*, *17*(1), 56-75.

Matrone, F., Colucci, E., Iacono, E., & Ventura, G. M. (2023). The HBIM-GIS Main10ance Platform to Enhance the Maintenance and Conservation of Historical Built Heritage. *Sensors*, *23*(19), 8112. https://www.mdpi.com/1424-8220/23/19/8112

Mazzarella, L. (2015). Energy retrofit of historic and existing buildings. The legislative and regulatory point of view. *Energy and Buildings*, *95*, 23-31. https://doi.org/https://doi.org/10.1016/j.enbuild.2014.10.073

McGee, T. K., McFarlane, B. L., & Varghese, J. (2009). An Examination of the Influence of Hazard Experience on Wildfire Risk Perceptions and Adoption of Mitigation Measures. *Society & Natural Resources*, *22*(4), 308-323. https://doi.org/10.1080/08941920801910765

McMaster, R. B., Leitner, H., & Sheppard, E. (1997). GIS-based Environmental Equity and Risk Assessment: Methodological Problems and Prospects. *Cartography and Geographic Information Systems*, *24*(3), 172-189. https://doi.org/10.1559/152304097782476933

Megahed, N. A. (2015). Towards a theoretical framework for HBIM approach in historic preservation and management. *ArchNet-IJAR: International Journal of Architectural Research*, *9*(3), 130.

Mekonnen, H., Bires, Z., & Berhanu, K. (2022). Practices and challenges of cultural heritage conservation in historical and religious heritage sites: evidence from North Shoa Zone, Amhara Region, Ethiopia. *Heritage Science*, *10*(1), 172. https://doi.org/10.1186/s40494-022-00802-6

Messaoudi, T., Véron, P., Halin, G., & De Luca, L. (2018). An ontological model for the reality-based 3D annotation of heritage building conservation state. *Journal of Cultural Heritage*, *29*, 100-112.

Moyano, J., Nieto-Julián, J. E., Lenin, L. M., & Bruno, S. (2022). Operability of Point Cloud Data in an Architectural Heritage Information Model. *International Journal of Architectural Heritage*, *16*(10), 1588-1607. https://doi.org/10.1080/15583058.2021.1900951

Mualam, N., & Alterman, R. (2020). Architecture is not everything: a multi-faceted conceptual framework for evaluating heritage protection policies and disputes. *International Journal of Cultural Policy*, *26*(3), 291-311. https://doi.org/10.1080/10286632.2018.1518978

Muenster, S. (2022). Digital 3D technologies for humanities research and education: an overview. *Applied Sciences*, *12*(5), 2426.

Munarim, U., & Ghisi, E. (2016). Environmental feasibility of heritage buildings rehabilitation. *Renewable and Sustainable Energy Reviews*, *58*, 235-249. https://doi.org/https://doi.org/10.1016/j.rser.2015.12.334

Munasinghe, H. (2005). The politics of the past: constructing a national identity through heritage conservation. *International Journal of Heritage Studies*, *11*(3), 251-260.

Münster, S., Utescher, R., & Ulutas Aydogan, S. (2021). Digital topics on cultural heritage investigated: how can data-driven and data-guided methods support to identify current topics and trends in digital heritage? *Built Heritage*, *5*(1), 25. https://doi.org/10.1186/s43238-021-00045-7

Murdoch, J. (2001). Ecologising sociology: Actor-network theory, co-construction and the problem of human exemptionalism. *Sociology*, *35*(1), 111-133.

Murphy, M., McGovern, E., & Pavia, S. (2009). Historic building information modelling (HBIM). *Structural Survey*, *27*(4), 311-327.

Murphy, M., McGovern, E., & Pavia, S. (2013). Historic Building Information Modelling–Adding intelligence to laser and image based surveys of European classical architecture. *ISPRS journal of photogrammetry and remote sensing*, *76*, 89-102.

Nebiker, S., Bleisch, S., & Christen, M. (2010). Rich point clouds in virtual globes–A new paradigm in city modeling? *Computers, Environment and Urban Systems*, *34*(6), 508-517.

Niazi, M. A. (2016). Review of "CiteSpace: A Practical Guide For Mapping Scientific Literature" by Chaomei Chen. *Complex Adaptive Systems Modeling*, *4*(1), 23. https://doi.org/10.1186/s40294-016-0036-5

Nilson, T., & Thorell, K. (2018). Cultural heritage preservation: The past, the present and the future. In: Halmstad University Press.

Noardo, F., Arroyo Ohori, K., Krijnen, T., & Stoter, J. (2021). An inspection of IFC models from practice. *Applied Sciences*, *11*(5), 2232.

Nocco, B. W., & Stulz, R. M. (2006). Enterprise risk management: Theory and practice. *Journal of applied corporate finance*, *18*(4), 8-20.

Noyes, J. E. (2011). The common heritage of mankind: past, present, and future. *Denv. J. Int'l L. & Pol'y*, *40*, 447.

Nyerges, T., Robkin, M., & Moore, T. J. (1997). Geographic Information Systems for Risk Evaluation: Perspectives on Applications to Environmental Health. *Cartography and Geographic Information Systems*, *24*(3), 123-144. https://doi.org/10.1559/152304097782476960

Ogunsakin, R., Mehandjiev, N., & Marin, C. A. (2023). Towards adaptive digital twins architecture. *Computers in Industry*, *149*, 103920.

Panzera, E. (2022). The Role of Cultural Heritage in Shaping Territorial Identities. In E. Panzera (Ed.), *Cultural Heritage and Territorial Identity: Synergies and Development Impact on European Regions* (pp. 117-143). Springer International Publishing. https://doi.org/10.1007/978-3-030-94468-1_5

Paolini, A., Vafadari, A., Cesaro, G., Quintero, M. S., Van Balen, K., & Vileikis, O. (2012). *Risk management at heritage sites: A case study of the Petra world heritage site*. UNESCO.

Park, J. (2021). An Actor-Network Perspective on Collections Documentation and Data Practices at Museums. *Museum and Society*, *19*(2), 237-251.

Pärn, E. A., Edwards, D. J., & Sing, M. C. (2017). The building information modelling trajectory in facilities management: A review. *Automation in construction*, *75*, 45-55.

Pendlebury, J., Short, M., & While, A. (2009). Urban World Heritage Sites and the problem of authenticity. *Cities*, *26*(6), 349-358. https://doi.org/https://doi.org/10.1016/j.cities.2009.09.003

Perles, A., Pérez-Marín, E., Mercado, R., Segrelles, J. D., Blanquer, I., Zarzo, M., & Garcia-Diego, F. J. (2018). An energy-efficient internet of things (IoT) architecture for preventive conservation of cultural heritage. *Future Generation Computer Systems*, *81*, 566-581.

Pezeshki, Z., & Ivari, S. A. S. (2018). Applications of BIM: a brief review and future outline. *Archives of Computational Methods in Engineering*, *25*, 273-312.

Pocobelli, D. P., Boehm, J., Bryan, P., Still, J., & Grau-Bové, J. (2018a). BIM for heritage science: a review. *Heritage Science*, *6*(1), 1-15.

Pocobelli, D. P., Boehm, J., Bryan, P., Still, J., & Grau-Bové, J. (2018b). BIM for heritage science: a review. *Heritage Science*, *6*(1), 30. https://doi.org/10.1186/s40494-018-0191-4

Pottgiesser, U., & Dragutinovic, A. (2022). ConCom and MoMove. Approaches to Industrial Heritage. In *MoMove Modern Movement and Industrial Heritage: Contributions to the Docomomo virtual exhibition-momove* (pp. 24-29). Technische Hochschule Ostwestfalen-Lippe.

Poux, F., & Billen, R. (2019). A smart point cloud infrastructure for intelligent environments. In *Laser Scanning* (pp. 127-149). CRC Press.

Poux, F., Neuville, R., Hallot, P., & Billen, R. (2016). Smart point cloud: Definition and remaining challenges. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *4*(W1).

Poux, F., Neuville, R., Hallot, P., Van Wersch, L., Luczfalvy Jancsó, A., & Billen, R. (2017). Digital investigations of an archaeological smart point cloud: A real time web-based platform to manage the visualisation of semantical queries. GEOMATICS & RESTORATION 2017,

Rakotosaona, M. J., La Barbera, V., Guerrero, P., Mitra, N. J., & Ovsjanikov, M. (2020). Pointcleannet: Learning to denoise and remove outliers from dense point clouds. Computer graphics forum,

Rasheed, A., San, O., & Kvamsdal, T. (2019). Digital twin: Values, challenges and enablers. *arXiv preprint arXiv:1910.01719*.

Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital twin: Values, challenges and enablers from a modeling perspective. *Ieee Access*, *8*, 21980-22012.

Ravankhah, M., de Wit, R., Argyriou, A. V., Chliaoutakis, A., Revez, M. J., Birkmann, J., Žuvela-Aloise, M., Sarris, A., Tzigounaki, A., & Giapitsoglou, K. (2019). Integrated Assessment of Natural Hazards, Including Climate Change's Influences, for Cultural Heritage Sites: The Case of the Historic Centre of Rethymno in Greece. *International Journal of Disaster Risk Science*, *10*(3), 343-361. https://doi.org/10.1007/s13753-019-00235-z

Rodríguez-Moreno, C., Reinoso-Gordo, J. F., Rivas-López, E., Gómez-Blanco, A., Ariza-López, F., & Ariza-López, I. (2018). From point cloud to BIM: An integrated workflow for documentation, research and modelling of architectural heritage. *Survey Review*, *50*(360), 212-231.

Romão, X., Paupério, E., & Pereira, N. (2016). A framework for the simplified risk analysis of cultural heritage assets. *Journal of Cultural Heritage*, *20*, 696-708. https://doi.org/https://doi.org/10.1016/j.culher.2016.05.007

Rosenbaum, D. P. (2002). Evaluating multi-agency anti-crime partnerships: Theory, design, and measurement issues. *Crime prevention studies*, *14*, 171-225.

Rossi, M., & Bournas, D. (2023). Structural health monitoring and management of cultural heritage structures: A state-of-the-art review. *Applied Sciences*, *13*(11), 6450.

Rossitti, M., Oppio, A., & Torrieri, F. (2021). The Financial Sustainability of Cultural Heritage Reuse Projects: An Integrated Approach for the Historical Rural Landscape. *Sustainability*, *13*(23), 13130. https://www.mdpi.com/2071-1050/13/23/13130

Rouhani, B., & Romão, X. (2023). *Managing disaster risks to cultural heritage: from risk preparedness to recovery for immovable heritage*. Taylor & Francis.

Rouhi, J. (2017). Definition of cultural heritage properties and their valuesby the past. *Asian Journal of Science and Technology*, *8*(12), 7109-7114.

Ruppert, T., & Abonyi, J. (2020). Integration of real-time locating systems into digital twins. *Journal of Industrial Information Integration*, *20*, 100174. https://doi.org/https://doi.org/10.1016/j.jii.2020.100174

Ruthven, I., & Chowdhury, G. G. (2015). *Cultural heritage information: Access and management* (Vol. 1). Facet publishing.

Sabbioni, C., Cassar, M., Brimblecombe, P., & Lefevre, R.-A. (2008). Vulnerability of cultural heritage to climate change. *European and Mediterranean Major Hazards Agreement (EUR-OPA)*, 1-24.

Schluse, M., Priggemeyer, M., Atorf, L., & Rossmann, J. (2018). Experimentable Digital Twins—Streamlining Simulation-Based Systems Engineering for Industry 4.0. *IEEE Transactions on Industrial Informatics*, *14*(4), 1722-1731. https://doi.org/10.1109/TII.2018.2804917

Segovia, M., & Garcia-Alfaro, J. (2022). Design, Modeling and Implementation of Digital Twins. *Sensors*, *22*(14), 5396. https://www.mdpi.com/1424-8220/22/14/5396

Sesana, E., Gagnon, A. S., Bonazza, A., & Hughes, J. J. (2020). An integrated approach for assessing the vulnerability of World Heritage Sites to climate change impacts. *Journal of Cultural Heritage*, *41*, 211-224.

Shafique, K., Khawaja, B. A., Sabir, F., Qazi, S., & Mustaqim, M. (2020). Internet of things (IoT) for next-generation smart systems: A review of current challenges, future trends and prospects for emerging 5G-IoT scenarios. *Ieee Access*, *8*, 23022-23040.

Shahzad, M., Shafiq, M. T., Douglas, D., & Kassem, M. (2022). Digital twins in built environments: an investigation of the characteristics, applications, and challenges. *Buildings*, *12*(2), 120.

Stubbs, M. (2004). Heritage-sustainability: developing a methodology for the sustainable appraisal of the historic environment. *Planning Practice & Research*, *19*(3), 285-305.

Styliani, S., Fotis, L., Kostas, K., & Petros, P. (2009). Virtual museums, a survey and some issues for consideration. *Journal of Cultural Heritage*, *10*(4), 520-528.

Stylianidis, E. (2020). *Photogrammetric survey for the recording and documentation of historic buildings*. Springer.

Sun, Y., Song, H., Jara, A. J., & Bie, R. (2016). Internet of things and big data analytics for smart and connected communities. *IEEE access*, *4*, 766-773.

Synnestvedt, M. B., Chen, C., & Holmes, J. H. (2005). CiteSpace II: visualization and knowledge discovery in bibliographic databases. *AMIA Annu Symp Proc*, *2005*, 724-728.

Tabkha, A., Hajji, R., Billen, R., & Poux, F. (2019). Semantic enrichment of point cloud by automatic extraction and enhancement of 360° panoramas. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*(W17).

Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., Guo, Z., Lu, S. C.-Y., & Nee, A. Y. (2019). Digital twin-driven product design framework. *International Journal of Production Research*, *57*(12), 3935-3953.

Templin, T., & Popielarczyk, D. (2020). The use of low-cost unmanned aerial vehicles in the process of building models for cultural tourism, 3D web and augmented/mixed reality applications. *Sensors*, *20*(19), 5457.

Thuestad, A. E., Tømmervik, H., & Solbø, S. A. (2015). Assessing the impact of human activity on cultural heritage in Svalbard: a remote sensing study of London. *The Polar Journal*, *5*(2), 428-445. https://doi.org/10.1080/2154896X.2015.1068536

Tomaszewski, R. (2023). Visibility, impact, and applications of bibliometric software tools through citation analysis. *Scientometrics*, *128*(7), 4007-4028. https://doi.org/10.1007/s11192-023-04725-2

Trillo, C., Aburamadan, R., Mubaideen, S., Salameen, D., & Makore, B. C. N. (2020). Towards a Systematic Approach to Digital Technologies for Heritage Conservation. Insights from Jordan. *Preservation, Digital Technology & Culture*, *49*(4), 121-138. https://doi.org/doi:10.1515/pdtc-2020-0023

Udeaja, C., Trillo, C., Awuah, K. G., Makore, B. C., Patel, D. A., Mansuri, L. E., & Jha, K. N. (2020). Urban heritage conservation and rapid urbanization: Insights from Surat, India. *Sustainability*, *12*(6), 2172.

Uhlenkamp, J.-F., Hauge, J. B., Broda, E., Lütjen, M., Freitag, M., & Thoben, K.-D. (2022). Digital twins: A maturity model for their classification and evaluation. *Ieee Access*, *10*, 69605-69635.

Van de Vijver, F., & Leung, K. (1997). Methods and data analysis of comparative research. *Handbook of cross-cultural psychology*, *1*, 257-300.

van Oosterom, P., van Oosterom, S., Liu, H., Thompson, R., Meijers, M., & Verbree, E. (2022). Organizing and visualizing point clouds with continuous levels of detail. *ISPRS journal of photogrammetry and remote sensing*, *194*, 119-131.

Vardopoulos, I. (2022). Industrial building adaptive reuse for museum. Factors affecting visitors' perceptions of the sustainable urban development potential. *Building and Environment*, *222*, 109391.

Verbree, E., Maren, G. V., Germs, R., Jansen, F., & Kraak, M.-J. (1999). Interaction in virtual world views-linking 3D GIS with VR. *International Journal of Geographical Information Science*, *13*(4), 385-396. https://doi.org/10.1080/136588199241265

Verschuuren, B., Mallarach, J.-M., Bernbaum, E., Spoon, J., Brown, S., Borde, R., Brown, J., Calamia, M., Mitchell, N. J., & Infield, M. (2021). *Cultural and spiritual significance of nature: Guidance for protected and conserved area governance and management* (Vol. 32). IUCN, International Union for Conservation of Nature and Natural Resour.

Vuoto, A., Funari, M. F., & Lourenço, P. B. (2023a). On the use of the digital twin concept for the structural integrity protection of architectural heritage. *Infrastructures*, *8*(5), 86.

Vuoto, A., Funari, M. F., & Lourenço, P. B. (2023b). Shaping digital twin concept for built cultural heritage conservation: A systematic literature review. *International Journal of Architectural Heritage*, 1-34.

Wang, H., Zhao, Y., Gao, X., & Gao, B. (2021). Collaborative decision-making for urban regeneration: A literature review and bibliometric analysis. *Land Use Policy*, *107*, 105479.

Wang, Q., & Kim, M.-K. (2019). Applications of 3D point cloud data in the construction industry: A fifteen-year review from 2004 to 2018. *Advanced engineering informatics*, *39*, 306-319.

Wang, S. (2023). Application of computer-aided CAD in urban planning heritage protection. *Soft Computing*, 1-10.

Wignall, R. M. L., Gordon, J. E., Brazier, V., MacFadyen, C. C. J., & Everett, N. S. (2018). A qualitative risk assessment for the impacts of climate change on nationally and internationally important geoheritage sites in Scotland. *Proceedings of the Geologists' Association*, *129*(2), 120-134. https://doi.org/https://doi.org/10.1016/j.pgeola.2017.11.003

Wu, Y., & Zhu, H. (2022). Intelligent Protection and Inheritance Method of the Historic Centre of Macao Based on BIM+ Concept——A Case Study of Mandarin's House. International Conference on Green Building, Civil Engineering and Smart City,

Xia, H., Liu, Z., Efremochkina, M., Liu, X., & Lin, C. (2022). Study on city digital twin technologies for sustainable smart city design: A review and bibliometric analysis of geographic information system and building information modeling integration. *Sustainable Cities and Society*, *84*, 104009. https://doi.org/https://doi.org/10.1016/j.scs.2022.104009

Xiao, W., Mills, J., Guidi, G., Rodríguez-Gonzálvez, P., Gonizzi Barsanti, S., & González-Aguilera, D. (2018). Geoinformatics for the conservation and promotion of cultural heritage in support of the UN Sustainable Development Goals. *ISPRS Journal of Photogrammetry and Remote Sensing*, *142*, 389-406. https://doi.org/https://doi.org/10.1016/j.isprsjprs.2018.01.001

Yang, S., Hou, M., & Li, S. (2023). Three-Dimensional Point Cloud Semantic Segmentation for Cultural Heritage: A Comprehensive Review. *Remote Sensing*, *15*(3), 548. https://www.mdpi.com/2072-4292/15/3/548

Yang, X., Grussenmeyer, P., Koehl, M., Macher, H., Murtiyoso, A., & Landes, T. (2020). Review of built heritage modelling: Integration of HBIM and other information techniques. *Journal of Cultural*

Heritage, *46*, 350-360.

Yaqoob, L., Ahmed Khan, N., & Subhan, F. (2014). An overview of existing decision support systems for disasters management. *Sci Int (Lahore)*, *26*, 1765-1776.

YARAŞAN, H., & VATAN, M. (2020). Disaster Risk Management of Cultural Heritage in Urban Areas: The Case of Turkey. *A+ Arch Design International Journal of Architecture and Design*, *6*(2), 115-136.

Zappia, D. (2017). *An Augmented Reality Application to Perform a Virtual Tourist Guide* Politecnico di Torino].

Zhang, R., Li, G., Li, M., & Wang, L. (2018). Fusion of images and point clouds for the semantic segmentation of large-scale 3D scenes based on deep learning. *ISPRS journal of photogrammetry and remote sensing*, *143*, 85-96.

Zipper, H. (2021). Real-Time-Capable Synchronization of Digital Twins. *IFAC-PapersOnLine*, *54*(4), 147-152. https://doi.org/https://doi.org/10.1016/j.ifacol.2021.10.025

ANNEX C. Case Study 1/Italy (presented at NCG Symposium 2023)

Visualisation of Architectural Cultural Heritage in a Digital Disaster Management Perspective, with Santo Stefano Church as a Case Study.

Abstract: In the realm of Digital Disaster Management, the visualization of architectural cultural heritage presents a unique intersection of technology and historical inquiry, particularly through the lens of Actor-Network Theory (ANT) and the implementation of digital twins technology. This study employs Santo Stefano Church as a pivotal case study to explore the multifaceted relationships and networks that shape our understanding and preservation of architectural heritage. ANT serves as the theoretical foundation for this research, framing the church, its digital counterpart, researchers, technologies, and the broader community as co-acting agents in a dynamic network that continually influences the interpretation and valorization of architectural heritage. This abstract emphasizes using ANT to understand the complex interactions between various actors involved in architectural heritage preservation and the digital twins' technology to achieve an immersive, detailed visualisation and analysis of architectural heritage.

Keywords: disaster management, digital twins, ANT analysis, architectural heritage

1. Introduction

Due to anthropogenic and natural damages(Figure 1[1]), Italy's architectural heritage faces multiple threats (Alnafeesi, 2013; Camuffo, 2019). This paper advocates the application of the Digital Twin (DT) principle, using point clouds as digital replicas, to ensure technical support for the digital management protection of heritage sites (Camuffo, 2019; Jouan & Hallot, 2020; Luther et al., 2023). An extensive literature review proposes an integrated framework to incorporate DT into protecting the disaster management planning process for architectural heritage (Jouan & Hallot, 2020; Vuoto et al., 2023a). It advocates stakeholder collaboration through ANT theoretical analyses as part of a comprehensive validation and validation assessment throughout the entire DT lifecycle (Halog & Manik, 2011; Li et al., 2020; Rosenbaum, 2002).

[1] Map showing the distribution of the Italian architectural heritage in terms of quantity and the three most important hazards (earthquakes, floods, landslides)(ISTAT).

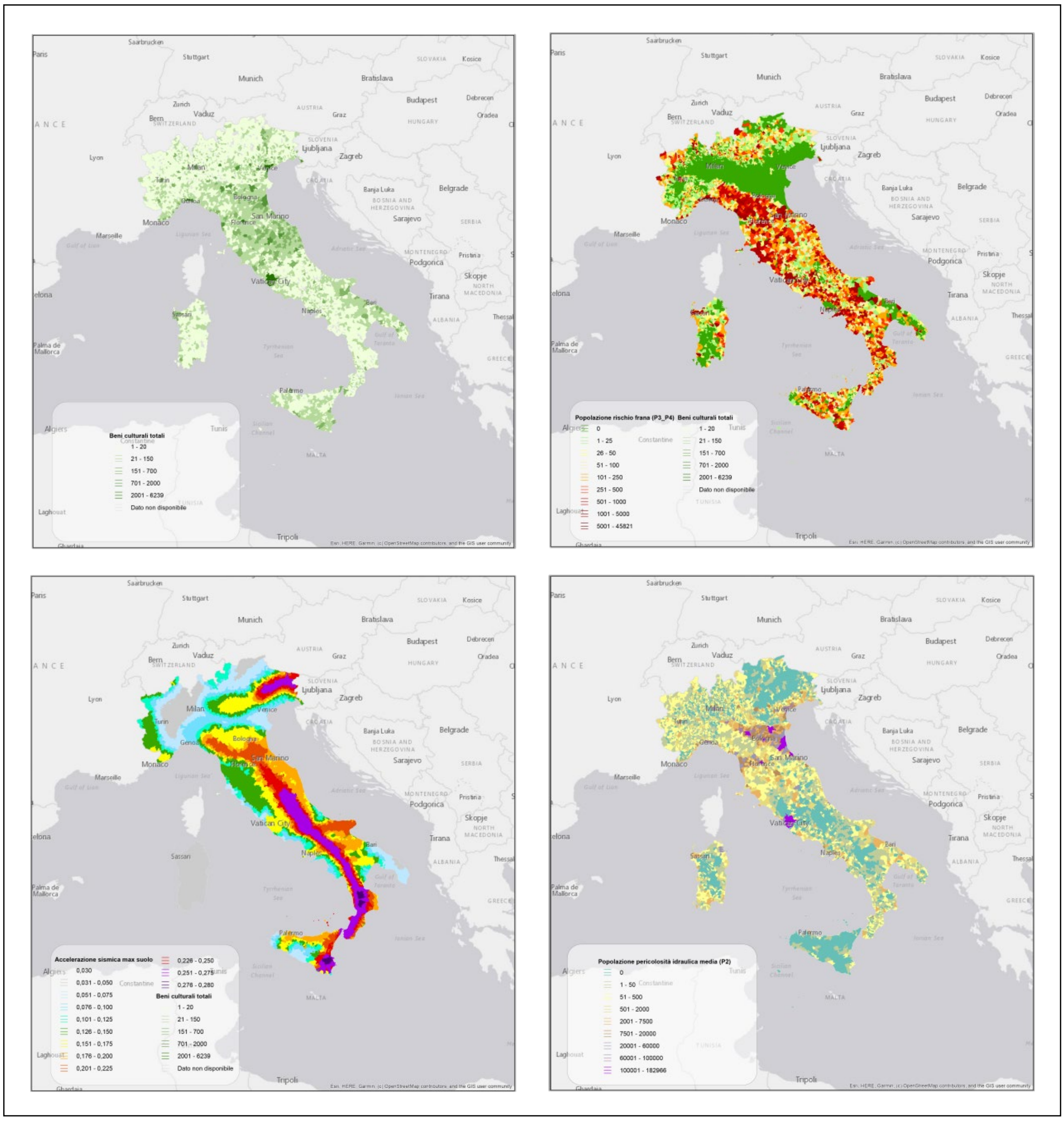


Fig.1. Analysis of the Italian Landslide Hazard Index/ Statistics on the total architectural heritage of Italy/ Analysis of the Italian seismic index/ Analysis of flood disaster areas in Italy (by author)

This study provides a new theoretical reference and practical guidance for architectural heritage conservation.

Typified by Santo Stefano Church, several important health management components are specifically analyzed, such as the digital twin's five-dimensional model, the digital twin, the data interaction process of the digital twin, and disaster identification and assessment. In particular, the process of preventive protection against disasters based on digital twins is described in detail (Cinquepalmi & Cumo, 2022; Hakiri et al., 2024; Li et al., 2023). The methodology provides a basis for future full-cycle disaster assessment of architectural heritage. It is of great significance for the application of digital twin technology in the conservation of architectural heritage, especially in disaster-concentrated areas (Bevilacqua et al., 2022; Pierre Jouan & Pierre Hallot, 2019; Jouan & Hallot, 2020; Vuoto et al., 2023b).

1.1 Digital Disaster Management (in the field of architectural heritage conservation)

Disaster management in the field of architectural heritage conservation refers to the planning (Al-Allaf, 2014; YARAŞAN & VATAN, 2020), organizing, and implementing of measures and strategies designed to protect, preserve, and restore buildings, structures, and sites of historical, cultural, or architectural significance from the impacts of natural or human-made disasters.

1.2 Digital Twins

Digital twins mean a virtual recreation of the entire life cycle of an object or system (Luther et al., 2023; Uhlenkamp et al., 2022).

Three features characterize digital disaster management through digital twin technology. Firstly, it is non-destructive, which means that the disaster of harm from physical damage to architectural heritage caused by digital methods can be minimized. At the same time, their accessibility and visibility can be improved, and they can be easily monitored and maintained (Gomes et al., 2014; Rossi & Bournas, 2023).

As shown through Citepsace and Vosviewer[2] data (Figure 1), using digital tools has become crucial in the construction industry, including heritage conservation (Liburd & Becken, 2020; Pocobelli et al., 2018b; Udeaja et al., 2020). In particular, the frequency of digital twin (DT) being mentioned in architectural heritage conservation and its association with other keywords is significantly higher, as analyzed by keyword co-occurrence, which is becoming increasingly valued in the conservation and analysis of architectural heritage.

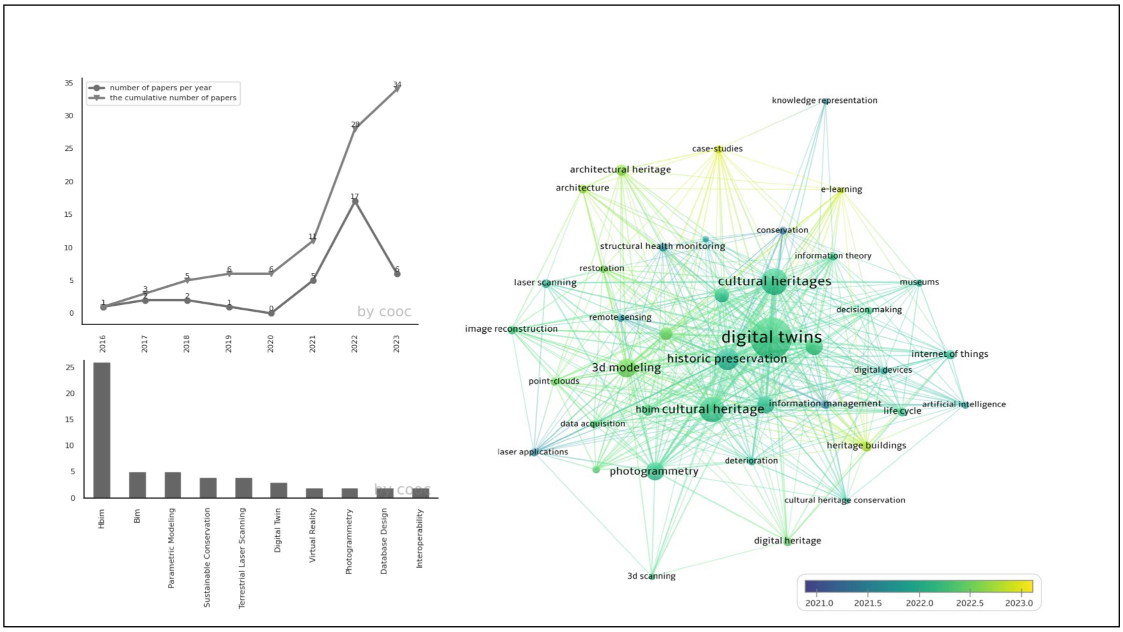


Fig.2. Variation of publication number per year and co-occurrence of keywords in research (154) by author.

In the domain of Digital disaster management, the concept of "digital twin" typically refers to the creation of high-precision digital replicas of cultural and historical assets for research,

2 VOSviewer software with modularity optimization and smart local moving algorithms.

conservation, exhibition, and educational purposes (Ariyachandra & Wedawatta, 2023; Fissore et al., 2023). These digital models accurately replicate architectural heritage's physical and functional attributes (Koller et al., 2010; Messaoudi et al., 2018; Yang et al., 2020), including their structure, materials, historical alterations, and interactions with their environment (Illsley, 2022; Koller et al., 2010). The current state of digital twins technology application in the context of architectural heritage conservation encompasses several key aspects (Table 1):

Table 1:

KEY ASPECTS	
3D Scanning and Modeling of Architectural Heritage	*Through laser scanning (Lidar), photogrammetry, and other high-precision measurement technologies, detailed three-dimensional digital models of architectural heritage are created* (Yin & Antonio, 2020).
Virtual Conservation and Restoration	*Digital twins technology allows for the testing of conservation and restoration measures in a virtual environment before any actual intervention* (Tzachor et al., 2023).
Simulation of Historical Changes	*Digital twins technology enables researchers to simulate changes in architectural heritage over its lifecycle* (Helbing & Sánchez-Vaquerizo, 2022)*, including damage due to natural aging, environmental changes, or human factors.*
Applications of Augmented and Virtual Reality	*Utilizing digital twin models, augmented reality (AR) and virtual reality (VR) technologies offer immersive experiences to the public and educators* (Kopec et al., 2022).
Disaster Management and Monitoring	*Digital twin technology can promptly monitor architectural heritage's condition through real-time data collection and analysis, identifying potential disasters and damages* (Jouan & Hallot, 2020).

1.3 ANT analysis

Actor–network theory (ANT) is a theoretical and methodological approach to social theory where everything in the social and natural worlds exists in constantly shifting networks of relationships (Latour & Crawford, 1993).

Digital investigations are changing the way cultural heritage researchers, archaeologists, and curators work and collaborate to progressively aggregate expertise through one common platform (Poux et al., 2017).

Applying Actor-Network Theory (ANT) analysis to digital humanities, especially in the context of architectural heritage, allows researchers and practitioners to understand the intricate web of relationships, power dynamics, and interactions that shape the creation, dissemination, and preservation of digital cultural artifacts (Giaccardi, 2012; Styliani et al., 2009). This approach underscores the necessity of acknowledging both human and non-human actors in the network to effectively manage and enhance the digital preservation and interpretation of architectural heritage (Kelly, 2023; Park, 2021; Verschuuren et al., 2021).

In digital disaster management, ANT facilitates a holistic view of the ecosystem surrounding digital cultural heritage projects. By treating technologies, digital platforms, archival materials, users, and creators as equally significant actors, ANT reveals how these elements collaboratively contribute to the success or challenges of digital projects. For instance, the development and application of digital twins technology in architectural heritage are not merely technical tasks but involve a network of interactions among software developers, historians, architects, digital humanities scholars, and the digital models themselves (Hayles, 2012; Muenster, 2022).

The burgeoning integration of digital technologies, especially digital twins, in the engineering domain for preserving and conserving architectural heritage underscores a pivotal shift towards more dynamic and interactive methodologies with the passage of time (Foster & Thelen, 2023). Digital twin technology, characterized by its capacity to evolve and simulate developmental outcomes through the replication of a physical entity and its encompassing environment, offers real-time monitoring advantages. This ensures that analysis results continually reflect the most current conditions (Tao et al., 2019). The sophistication of digital twins is increasingly supported by detailed architectural spatial data, enhanced by advances in laser scanning, total station measurements, and other high-precision techniques (Fuchizaki et al., 2021). As the technical challenges associated with spatial representation are progressively mitigated (Ogunsakin et al., 2023), a critical observation has emerged: an overemphasis on the technical and behavioural dimensions may neglect the essential process aspects of derivation and support (Boyes & Watson, 2022). This oversight is particularly evident in the monitoring and preservation of historic heritage buildings, where the emphasis on cultural, social, and historical contexts remains inadequately addressed (Lowenthal, 1994).

Incorporating Actor-Network Theory (ANT) analysis into this discourse provides a comprehensive framework that acknowledges the complex interplay of human and non-human actors involved in creating, preserving, and interpreting architectural heritage (Murdoch, 2001). ANT posits that material (technologies, artifacts) and immaterial (texts, concepts) entities act as agents within a network, influencing and shaping heritage conservation outcomes (Laužikas et al., 2022). This perspective highlights the significance of considering the processes by which digital twins are developed and supported, not merely as technical endeavors but as socio-technical systems that encapsulate the interactions among architects, engineers, technologies, historical narratives, and buildings (Delgado & Oyedele, 2021; Rasheed et al., 2019, 2020).

This integrated approach exemplifies the evolution of digital humanities techniques, extending beyond digital archives to embrace new methodologies like machine learning for combining abstract pattern semantics with textual descriptions (Cornia et al., 2020). By amalgamating textual archives that describe culture, society, and history with 3D and 2D images, digital humanities offer a promising avenue to overcome the limitations of digital twin technology in capturing the full spectrum of cultural aspects of architectural sites (Lysgaard et al., 2019). Thus, through the lens of ANT, the digital disaster management perspective not only enhances the accuracy of cultural context collection using digital twin technology but also fosters a more holistic understanding of architectural heritage conservation as a network of interacting agents. This approach ensures that the development and application of digital twins in architectural heritage are grounded in a rich tapestry of cultural, social, and historical dimensions, thereby broadening the scope and depth of conservation practices (Liritzis & Korka, 2019).

3. Research Questions

RQ: How can digital twins and ANT analysis be combined for architectural heritage disaster protection from a digital humanities perspective?

SQ1: How do these engagements(digital technologies and ANT) affect heritage interpretation, value, and understanding (in Italy)?

SQ2: How can ANT stakeholders be coordinated to participate in it?

4. Research Gap

Although current research has demonstrated the potential of digital twins, there remain many unexplored areas and potential developments in this field, including high costs, technical complexity, and integration issues with existing conservation practices.

While ANT provides a robust framework for understanding the complex interactions and networks within which architectural heritage exists, its application to digital twins technology in cultural heritage preservation is relatively unexplored. A research gap exists in developing a comprehensive theoretical model that integrates ANT's focus on actor networks with the technological capabilities of digital twins.

Researchers in the field of cultural heritage have used digital technologies to preserve historical architectural heritage, thus making them timeless in time. Most of these attempts are seen as autonomous and rarely organized. One of the digital tools from the field of product lifecycle management is the digital twin, which is defined as a digital representation of a physical product (Lim et al., 2020). Whether cultural heritage can be risk managed from a digital twin perspective and whether the application of the digital twin concept can be sustainable in risk management of cultural heritage environments has been debated (Boje et al., 2020; Pierre Jouan & Pierre Hallot, 2019; Jouan & Hallot, 2020; Shahzad et al., 2022), and the research framework on digital twins in the risk management cycle of architectural heritage is still incomplete, and there is a lack of discussion on the link between technology and stakeholders. The level of detail, the frequency of updates, and the integration of information remain a challenge in the reconstruction of architectural heritage.

5. Methodology

1) **Data collection on historic buildings (capturing point clouds - comprehensive and detailed scanning of historic building information), also from stakeholders.**

Several technologies were combined during the data acquisition procedure. The goal of the survey was to create a dataset that enables deriving architectural 2D products (views, layouts, sections) and detailed 3D models for virtual reality presentations as well. To complete my data

collection. I need to use the data acquisition equipment as follows:
Nodal Ninja 4 + Canon EOS 700D
DJI OSMO POCKET + DJI Phantom unmanned aerial vehicle equipped with GoPro Hero3 (UAV)
Z+F IMAGER® 5010C, 3D laser scanner
Faro terrestrial laser scanners (TLS)
Geoslam horizon scanner

Due to the historic building's complex geometry (uneven wall surfaces, irregular shapes) and size, multiple surveying techniques have been applied. The gate, the near environment of the building, and the rooms have been mapped by terrestrial laser scanning, while structured light scanners have been used to capture the fine details of small objects. Aerial images have been taken by UAV to acquire information on the tall parts of the building. The high-density point cloud supports virtual/augmented reality applications; both experts and tourists can take a virtual walk in the building (Templin & Popielarczyk, 2020; Zappia, 2017).

2) **Transform**

a) 1-3D point cloud data describes our physical world spatially. Knowledge discovery processes, including semantic segmentation and classification, are a great way to complement this information by leveraging analytic or domain knowledge to extract semantics. Combining this information efficiently opens intelligent environments and deep automation (Poux & Billen, 2019). Moreover, according to Tabkha et al. (2019), it is very important to obtain a rigorous characterization for use in the classification of a point cloud. Especially because there is a huge variety of 3D point cloud domain applications. In recent years, deep learning algorithms have become very effective tools for label and multi-label classification, and various implementations of these algorithms have been published for developers as Application Programming Interfaces (APIs) (Tabkha et al., 2019). It uses accurate, dense point clouds to support the creation of virtual models that can be used in VR/AR environments. The state-of-the-art spatial surveying technologies can support heritage protection, and by merging multiple types of data, the results can be used in virtual/augmented reality applications. The goal of the survey was to create a dataset that enables deriving architectural 2D products (views, layouts, sections) and detailed 3D models for virtual reality presentations.
b) Special hardware must be utilized to fully experience the surroundings in 3D and on the right scale. There are many ready-to-use technologies to display virtual content in development. The HMD (Head Mounted Display) technology can seamlessly involve visitors in visual scenarios (Hammady et al., 2020). A great graphics card is also needed for VR experiences, such as NVIDIA's GeForce RTX™ GPU, which is compatible with all advanced headset devices.

3）Show it to the public

It will test this technique in a historical building in Italy(such as by using WebXR Device API (Sites can be provided with simple 3D visualisation via WebXR)) for participators to get maximum public reach). Storytelling, narrative, animation, documentary, and other means to complete a story construction can make more people participate in immersive interaction and experience to achieve the purpose of heritage**.**

6. Case Study

As a country with a large architectural heritage, the specificity of Italy's architectural heritage lies in its individual structures and in synthesizing historical periods, regional differences, and artistic expressions that together form a rich and multifaceted heritage. Many of its assets are listed as national heritage or World Heritage Sites (WHS) (De Paoli et al., 2020; Giuliani et al., 2021).

Several significant factors contribute to the vulnerability of Italy's architectural treasures: 1. Natural disasters: Italy is prone to earthquakes due to its location along the seismically active Apennines. Earthquakes can cause serious damage to historic buildings and monuments. Efforts have been made to retrofit and strengthen structures. However, many are still at disaster.2. Climate change: Rising temperatures, extreme weather events, and rising sea levels associated with climate change threaten Italy's built heritage. Coastal areas with historic sites are particularly vulnerable to erosion and flooding.3. Urbanization and development: Uncontrolled urbanization and development may encroach on historic sites, leading to their degradation or destruction. Balancing the needs of a growing population with the preservation of cultural heritage is an ongoing challenge (**Figure 3**). Establishing a digital full-cycle disaster management is a must to protect built heritage.

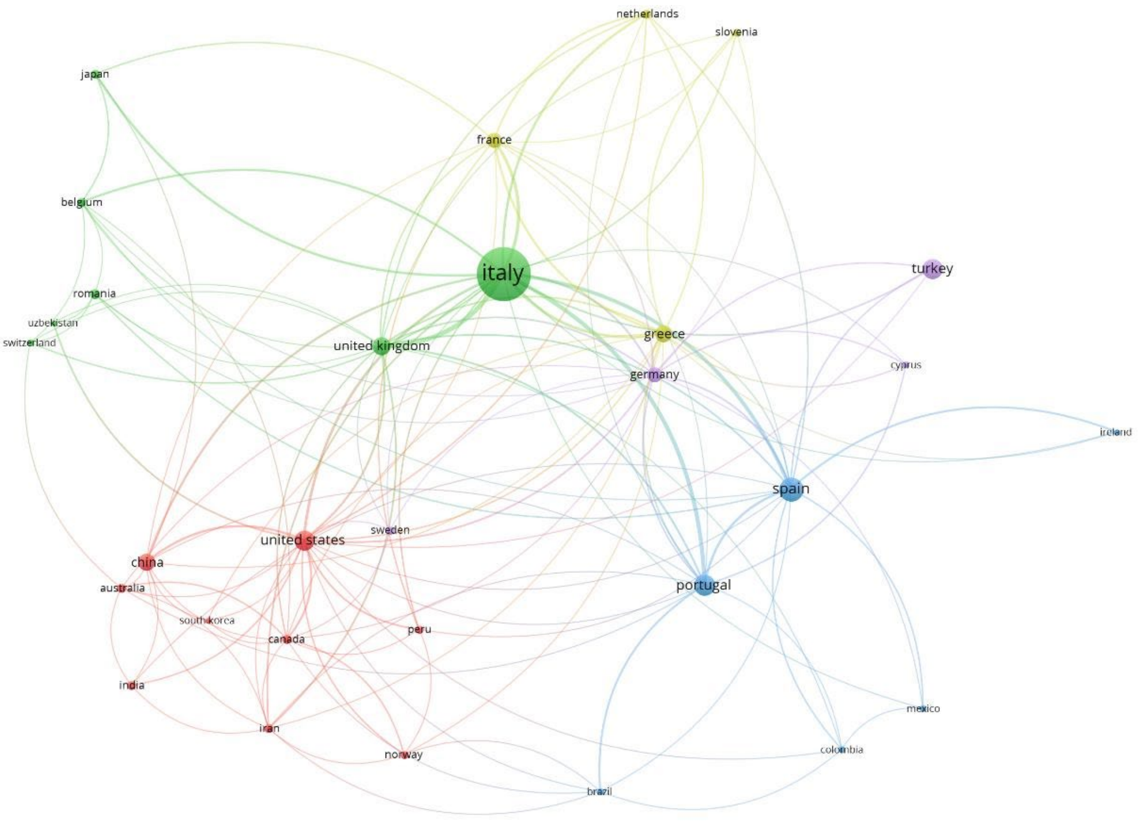


Fig.3. Distribution and number of countries in the architectural heritage and disaster literature with Vosviewer.

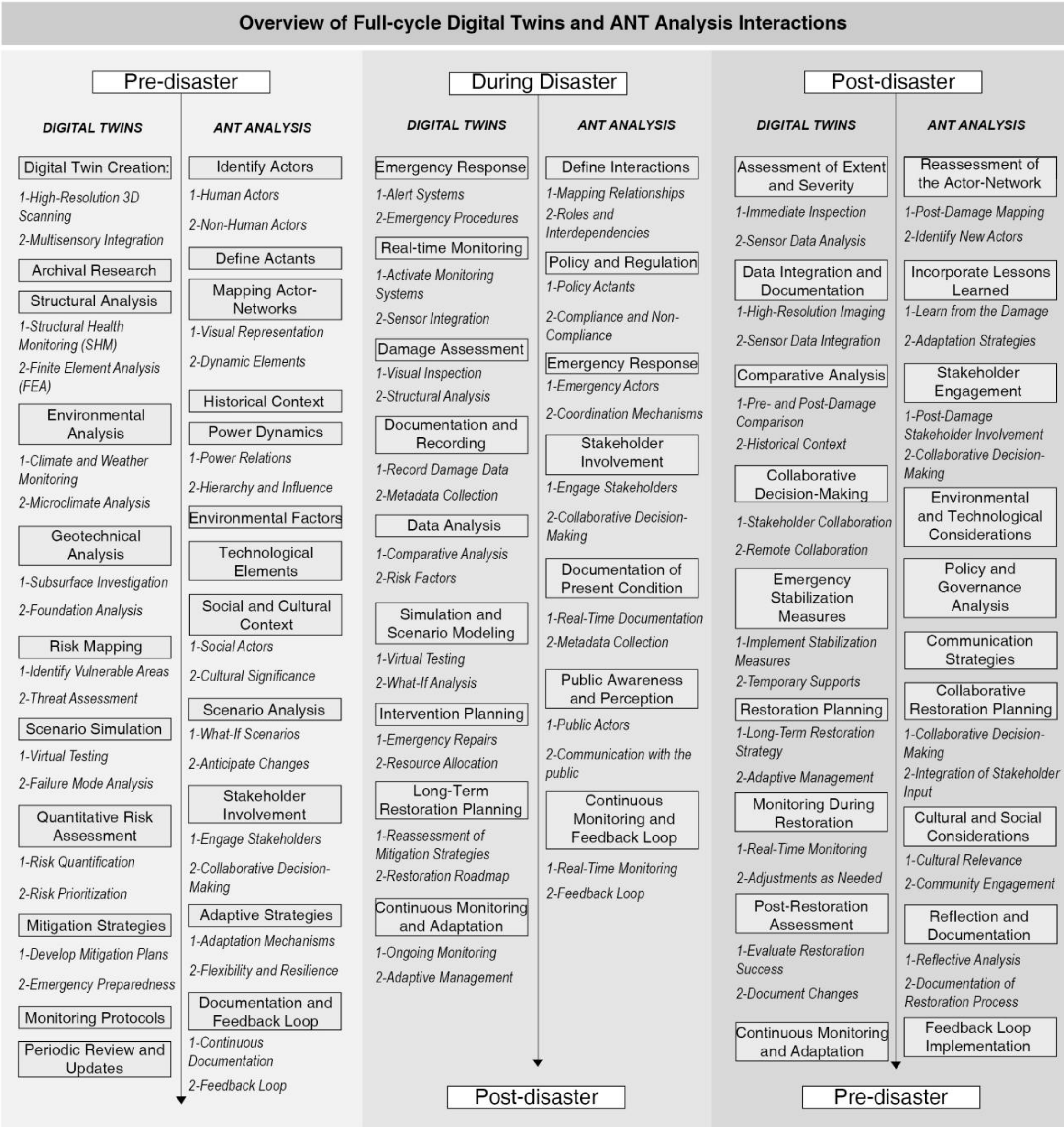


Fig.4. Overview of Full-cycle Digital Twins and ANT Analysis Interactions (by author)

A full life-cycle conservation approach can help reduce losses by employing different strategies before, during, and after a disaster. This approach follows the concept of the disaster cycle, which was first introduced by Baird et al. (1975) (Coetzee & Van Niekerk, 2012; Li et al., 2023)and later refined by Khan et al. into three phases: pre-disaster, during disaster and post-disaster (Yaqoob et al., 2014). Each phase has different needs, challenges, tools, strategies, and resources（**Figure 4**）.

In Volterra, in the province of Pisa, 700 meters from Piazza dei Priori, in the Borgata S. Stefano, the Church of Santo Stefano, dating back to 1161 but now completely in ruins, the lower part of the façade with three portals has been preserved, of which the central one, the largest, the church shows the Romanesque style, in particular with the modest traces that remain of the decorations above the side portals, lacking a roof, the interior has become a garden (**Figure 5**).

Fig.4. The Church of Santo Stefano (Volterra, Italy)

Address: Borgata S. Stefano, 91, 56048 Volterra, Italy
Province: Pisa
Architectural style: Romanesque

Fig. 5. Point cloud data for the Church of Santo Stefano (Volterra, Italy)

Elements of a Digital Twin

6.1 From point cloud to digital twins:
a) Data collection and integration
1-Data Modeling
2-System integration and management
3-Reality capture, for example, with drones or point clouds
4-Create objects
b) Real-time and visualization
Use real-time information to make better decisions, discover new patterns, or gain new insights Dashboards and reports.
1-Real-time IoT (Internet of Things) integration
2-Insights and analytics
3-Advanced visualization
c) Analyzing and predicting: Analyze and make accurate predictions with powerful statistics, Machine Learning (ML), Deep Learning (DL), and Artificial Intelligence (AI) tools.
1-Automation (AI/ML/DL)
2-Notebooks and Modeling
3-Simulation and scenario modelling
4-To predict
6.2 Result
TO BE CONTINUE……

7. Research Significance

In 2003, the United Nations Educational, Scientific and Cultural Organization (UNESCO) issued the Charter on the Preservation of Digital Heritage, which defines digital preservation as the process of using digital technologies (DTech) to record, preserve, and access the cultural and historical values of historic buildings and sites (Li et al., 2024). Notably, the digital twin combines real-time and historical data to support highly integrated analytics that facilitate rapid planning and forecasting; thus, in addition to saving time and facilitating monitoring, it helps to continually improve performance and eliminate anomalies throughout the project's lifecycle.

This study aims to provide new theoretical and practical perspectives on the field by exploring the application of digital bijoux technologies and other digitisation methods in conserving heritage buildings. Our objectives include 1) analysing the main current threats to heritage buildings in Italy, 2) exploring and evaluating the effectiveness of the application of digital technologies in disaster management and heritage conservation, and 3) demonstrating the practical application of these technologies through case studies. This study adopts the methods of literature review, case study analysis, and keyword extraction to provide a comprehensive analysis of the application of digital technologies in the conservation of heritage buildings in Italy based on relevant literature and practical cases from the last fifteen years.

Through this study, we expect to provide more effective digital solutions for conserving and restoring heritage buildings and simultaneously provide references and lessons for related policy formulation and practice.

By constructing a digital twin of Santo Stefano Church, we engage in a detailed analysis of the architectural features, historical narratives, and cultural significances embedded within its physical and digital existence. This process not only democratizes access to cultural heritage through digital means but also fosters a deeper engagement with the socio-technical networks that constitute our cultural memory. The digital twin, acting as both a mirror and a window, enables a comprehensive exploration of the church's architectural details, historical evolution, and interconnectedness with the socio-cultural landscape. Through this integrative approach, the research highlights the potential of digital twins technology as a tool for enhancing the visualization, analysis, and preservation of architectural cultural heritage. It underscores the importance of considering the entanglements of human and non-human actors in the study and preservation of cultural heritage, offering insights into how digital humanities can contribute to the sustainable stewardship of our architectural past.

8. Conclusion

In the context of case studies such as the case of St Stefano's Church, it can be seen that improving the accuracy of the model is, on the one hand, and the other hand, strengthening the humanistic perspective and integrating the cultural dimensions is crucial in blending the technological and cultural contexts.

Deligiorgi et al. (2021) and Hasan et al. (2022) point out that the integration of humanities methods and perspectives into the application of digital twins can enrich the digitalisation of heritage buildings beyond the reproduction of physical attributes. The added cultural dimension through the review of historical and social events surrounding the building helps to deepen the understanding and interpretation of heritage values, thus making the digital model not just a cold dataset but a medium of cultural communication full of life and stories.

In conclusion, the effective application of digital twin technology in the preservation of architectural cultural heritage can be ensured by strengthening humanistic perspectives, integrating cultural dimensions, and synergising technological orientations that work together to improve model accuracy.

9. Reference

Ćosović, M., & Maksimović, M. (n.d.). *Application of the digital twin concept in cultural heritage*.

Helbing, D., & Sánchez-Vaquerizo, J. A. (2022). *Digital Twins: Potentials, Ethical Issues, and Limitations*.

Jouan, P., & Hallot, P. (2020). Digital Twin: Research Framework to Support Preventive Conservation Policies. *ISPRS International Journal of Geo-Information*, *9*(4), 228. https://doi.org/10.3390/ijgi9040228

Kopec, J., Pekarčíková, M., Lachvajderová, L., & Trebuňa, M. (n.d.). *DIGITAL TWIN, VIRTUAL REALITY AND AUGMENTED REALITY AND THEIR USE*.

Tzachor, A., Hendel, O., & Richards, C. E. (2023). Digital twins: A stepping stone to achieve ocean sustainability? *Npj Ocean Sustainability*, *2*(1), 16. https://doi.org/10.1038/s44183-023-00023-9

Yin, Y., & Antonio, J. (2020). Application of 3D laser scanning technology for image data processing in the protection of ancient building sites through deep learning. *Image and Vision Computing*, *102*, 103969. https://doi.org/10.1016/j.imavis.2020.103969

Adamopoulos, E., & Rinaudo, F. (2021). Close-Range Sensing and Data Fusion for Built Heritage Inspection and Monitoring—A Review. Remote Sensing, 13(19), 3936. https://doi.org/10.3390/rs13193936

Adegoriola et al. - 2021—Heritage building maintenance management (HBMM) A.pdf. (n.d.).

Adegoriola, M. I., Lai, J. H. K., Chan, E. H., & Darko, A. (2021). Heritage building maintenance management (HBMM): A bibliometric-qualitative analysis of literature. Journal of Building Engineering, 42, 102416. https://doi.org/10.1016/j.jobe.2021.102416

Allen, T. R., McLeod, G., Richter, H., & Nielsen, A. (2022). Digitally Twinning Coastal Resilience Via Multsensor Imagery, in Situ Sensors, and Geospatial Analysis. IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium, 4739–4742. https://doi.org/10.1109/IGARSS46834.2022.9883133

Antón, D., Medjdoub, B., Shrahily, R., & Moyano, J. (2018). Accuracy evaluation of the semi-automatic 3D modeling for historical building information models. International Journal of Architectural Heritage, 12(5), 790–805. https://doi.org/10.1080/15583058.2017.1415391

Argiolas, R., Bagnolo, V., Cera, S., & Cuccu, S. (2022). VIRTUAL ENVIRONMENTS TO COMMUNICATE BUILT CULTURAL HERITAGE: A HBIM BASED VIRTUAL TOUR. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVI-5/W1-2022, 21–29. https://doi.org/10.5194/isprs-archives-XLVI-5-W1-2022-21-2022

Bastem, S. S., & Cekmis, A. (2022). Development of historic building information modelling: A systematic literature review. Building Research & Information, 50(5), 527–558. https://doi.org/10.1080/09613218.2021.1983754

Belhi, A., Ahmed, H. O., Alfaqheri, T., Bouras, A., Sadka, A. H., & Foufou, S. (2023). An integrated framework for the interaction and 3D visualization of cultural heritage. Multimedia Tools and Applications. https://doi.org/10.1007/s11042-023-14341-0

Benavides López, J. A., Martín Civantos, J. M., & Rouco Collazo, J. (2020). Levantamiento arquitectónico y análisis arqueológico del castillo de Píñar como punto de partida para su conservación. Virtual Archaeology Review, 11(22), 95. https://doi.org/10.4995/var.2020.12397

Benkari, N. (2022). The built heritage as a resource for architectural education: Documentation of the vernacular settlements and architecture in Oman. Journal of Cultural Heritage Management and Sustainable Development. https://doi.org/10.1108/JCHMSD-12-2021-0211

Brumana, R., Oreni, D., Barazzetti, L., Cuca, B., Previtali, M., & Banfi, F. (2020). Survey and Scan to BIM Model for the Knowledge of Built Heritage and the Management of

Conservation Activities. In B. Daniotti, M. Gianinetto, & S. Della Torre (Eds.), Digital Transformation of the Design, Construction and Management Processes of the Built Environment (pp. 391–400). Springer International Publishing. https://doi.org/10.1007/978-3-030-33570-0_35

Bruno, S., Musicco, A., Fatiguso, F., & Dell'Osso, G. R. (2021). The Role of 4D Historic Building Information Modelling and Management in the Analysis of Constructive Evolution and Decay Condition within the Refurbishment Process. International Journal of Architectural Heritage, 15(9), 1250–1266. https://doi.org/10.1080/15583058.2019.1668494

Cardinali, V., Ciuffreda, A. L., Coli, M., De Stefano, M., Meli, F., Tanganelli, M., & Trovatelli, F. (2023). An Oriented H-BIM Approach for the Seismic Assessment of Cultural Heritage Buildings: Palazzo Vecchio in Florence. Buildings, 13(4), 913. https://doi.org/10.3390/buildings13040913

Cinquepalmi, F. (n.d.). USING DIGITAL TWIN MODELS (DTM) FOR MANAGING, PROTECTING AND RESTORING HISTORICAL BUILDINGS.

Ćosović, M., & Maksimović, M. (n.d.). Application of the digital twin concept in cultural heritage.

Croce, V., Caroti, G., De Luca, L., Jacquot, K., Piemonte, A., & Véron, P. (2021). From the Semantic Point Cloud to Heritage-Building Information Modeling: A Semiautomatic Approach Exploiting Machine Learning. Remote Sensing, 13(3), 461. https://doi.org/10.3390/rs13030461

Currà, E., D'Amico, A., & Angelosanti, M. (2022). HBIM between Antiquity and Industrial Archaeology: Former Segrè Papermill and Sanctuary of Hercules in Tivoli. Sustainability, 14(3), 1329. https://doi.org/10.3390/su14031329

DAmico_From-TSL-survey_2018.pdf. (n.d.).

De Fino, M., Bruno, S., & Fatiguso, F. (2022). Dissemination, assessment and management of historic buildings by thematic virtual tours and 3D models. Virtual Archaeology Review, 13(26), 88–102. https://doi.org/10.4995/var.2022.15426

Domínguez-Ruíz, V., Rey-Pérez, J., & Rivero-Lamela, G. (2020). Contribution to the Knowledge of Cultural Heritage via a Heritage Information System (HIS). The Case of "La Cultura del Agua" in Valverde de Burguillos, Badajoz (Spain). Sustainability, 12(3), 1141. https://doi.org/10.3390/su12031141

Ec_rtd_candidate-list-european-partnerships-for-CH.pdf. (n.d.).

El-Din Fawzy, H. (2019). 3D laser scanning and close-range photogrammetry for buildings documentation: A hybrid technique towards a better accuracy. Alexandria Engineering Journal, 58(4), 1191–1204. https://doi.org/10.1016/j.aej.2019.10.003

Adamopoulos, E., & Rinaudo, F. (2021). Close-range sensing and data fusion for built heritage inspection and monitoring—a review. *Remote Sensing*, *13*(19), 3936.

Al-Allaf, E. H. (2014). Preventive conservation as a procedure for safeguarding mosul built heritage. *Diyala Journal of Engineering Sciences*, 98-129.

Al-Bayari, O., & Shatnawi, N. (2022). Geomatics techniques and building information model for historical buildings conservation and restoration. *The Egyptian Journal of Remote Sensing and Space Science*, *25*(2), 563-568.

Alberts, H. C., & Hazen, H. D. (2010). Maintaining Authenticity and Integrity at Cultural World Heritage Sites.

Geographical Review, *100*(1), 56-73. https://doi.org/10.1111/j.1931-0846.2010.00006.x

Albourae, A., Armenakis, C., & Kyan, M. (2017). Architectural heritage visualization using interactive technologies. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*, 7-13.

Alnafeesi, A. M. (2013). The role & impact of preservation architectural heritage on domestic tourism.

Ariyachandra, M. M. F., & Wedawatta, G. (2023). Digital Twin Smart Cities for Disaster Risk Management: A Review of Evolving Concepts. *Sustainability*, *15*(15), 11910.

Ashrafi, B., Kloos, M., & Neugebauer, C. (2021). Heritage Impact Assessment, beyond an Assessment Tool: A comparative analysis of urban development impact on visual integrity in four UNESCO World Heritage Properties. *Journal of Cultural Heritage*, *47*, 199-207.

Aven, T. (2016). Risk assessment and risk management: Review of recent advances on their foundation. *European Journal of Operational Research*, *253*(1), 1-13. https://doi.org/https://doi.org/10.1016/j.ejor.2015.12.023

Avramidou, N. (2003). Vulnerability of cultural heritage to hazards and prevention measures. Proceeding of Advanced Research Workshops,

Bankoff, G. (2015). Design by disasters: Seismic architecture and cultural adaptation to earthquakes. In *Cultures and Disasters* (pp. 53-71). Routledge.

Barontini, A., Alarcon, C., Sousa, H. S., Oliveira, D. V., Masciotta, M. G., & Azenha, M. (2022). Development and Demonstration of an HBIM Framework for the Preventive Conservation of Cultural Heritage. *International Journal of Architectural Heritage*, *16*(10), 1451-1473. https://doi.org/10.1080/15583058.2021.1894502

Bartolini, G., Giuliani, F., & De Falco, A. (2023). Proof of Concept for Methodological Framework Including Point Clouds in the Non-Destructive Diagnosis of Historical Masonry Structures. *International Journal of Architectural Heritage*, 1-24.

Basso, A., Condorelli, F., Giordano, A., Morena, S., & Perticarini, M. (2024). EVOLUTION OF RENDERING BASED ON RADIANCE FIELDS. THE PALERMO CASE STUDY FOR A COMPARISON BETWEEN NERF AND GAUSSIAN SPLATTING. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, *XLVIII-2/W4-2024*, 57-64. https://doi.org/10.5194/isprs-archives-XLVIII-2-W4-2024-57-2024

Bastem, S. S., & Cekmis, A. (2022). Development of historic building information modelling: A systematic literature review. *Building Research & Information*, *50*(5), 527-558.

Bevilacqua, M. G., Russo, M., Giordano, A., & Spallone, R. (2022). 3D reconstruction, digital twinning, and virtual reality: Architectural heritage applications. 2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW),

Bhatia, M., Ahanger, T. A., & Manocha, A. (2023). Artificial intelligence based real-time earthquake prediction. *Engineering Applications of Artificial Intelligence*, *120*, 105856.

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, *114*, 103179.

Bortolini, R., Rodrigues, R., Alavi, H., Vecchia, L. F. D., & Forcada, N. (2022). Digital Twins' Applications for Building Energy Efficiency: A Review. *Energies*, *15*(19), 7002. https://www.mdpi.com/1996-1073/15/19/7002

Bose, R. (2003). Knowledge management-enabled health care management systems: capabilities, infrastructure, and decision-support. *Expert Systems with Applications*, *24*(1), 59-71. https://doi.org/https://doi.org/10.1016/S0957-4174(02)00083-0

Bosher, L., Kim, D., Okubo, T., Chmutina, K., & Jigyasu, R. (2020). Dealing with multiple hazards and threats on cultural heritage sites: an assessment of 80 case studies. *Disaster Prevention and Management: An International Journal*, *29*(1), 109-128.

Boyes, H., & Watson, T. (2022). Digital twins: An analysis framework and open issues. *Computers in Industry*, *143*, 103763.

Brahmi, B. F., Sassi Boudemagh, S., Kitouni, I., & Kamari, A. (2022). IPD and BIM-focussed methodology in renovation of heritage buildings. *Construction Management and Economics*, *40*(3), 186-206. https://doi.org/10.1080/01446193.2021.1933557

Bruno, S., De Fino, M., & Fatiguso, F. (2018). Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management. *Automation in Construction*, *86*, 256-276. https://doi.org/https://doi.org/10.1016/j.autcon.2017.11.009

Calvano, M., Martinelli, L., Calcerano, F., & Gigliarelli, E. (2022). Parametric processes for the implementation of HBIM—Visual programming language for the digitisation of the index of masonry quality. *ISPRS International Journal of Geo-Information*, *11*(2), 93.

Camuffo, D. (2019). *Microclimate for cultural heritage: Measurement, risk assessment, conservation, restoration, and maintenance of indoor and outdoor monuments*. Elsevier.

Candón Fernández, E., Crespo-Márquez, A., Guillén López, A., & Hidalgo Fort, E. Model-based asset digitalization framework in the context of digital maintenance. An example using IoT platform and Asset Health Index model applied to civil infrastructures. *An example using IoT platform and Asset Health Index model applied to civil infrastructures*.

Cardona, O. D. (2013). The need for rethinking the concepts of vulnerability and risk from a holistic perspective: a necessary review and criticism for effective risk management. In *Mapping vulnerability* (pp. 37-51). Routledge.

Che, E., Jung, J., & Olsen, M. J. (2019). Object recognition, segmentation, and classification of mobile laser scanning point clouds: A state of the art review. *Sensors*, *19*(4), 810.

Chen, M., Mao, S., Zhang, Y., & Leung, V. C. (2014). *Big data: related technologies, challenges and future prospects* (Vol. 100). Springer.

Chi, H.-L., Kang, S.-C., & Wang, X. (2013). Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. *Automation in construction*, *33*, 116-122.

Cinquepalmi, F., & Cumo, F. (2022). Using Digital Twin Models (DTM) for managing, protecting and restoring historical buildings. *Conservation Science in Cultural Heritage*, *22*, 425-445.

Coetzee, C., & Van Niekerk, D. (2012). Tracking the evolution of the disaster management cycle: A general system theory approach. *Jàmbá: Journal of Disaster Risk Studies*, *4*(1), 1-9.

Coïsson, E., & Ferrari, L. (2023). Emergency Response to Damaged Architectural Heritage: Time, Safety and Conservation. International Conference on Structural Analysis of Historical Constructions,

Cornia, M., Stefanini, M., Baraldi, L., Corsini, M., & Cucchiara, R. (2020). Explaining digital humanities by aligning images and textual descriptions. *Pattern Recognition Letters*, *129*, 166-172.

Cresswell, K., & Sheikh, A. (2013). Organizational issues in the implementation and adoption of health information technology innovations: An interpretative review. *International Journal of Medical Informatics*, *82*(5), e73-e86. https://doi.org/https://doi.org/10.1016/j.ijmedinf.2012.10.007

Crompvoets, J., Vancauwenberghe, G., Ho, S., Masser, I., & De Vries, W. T. (2018). Governance of national spatial data infrastructures in Europe. *International Journal of Spatial Data Infrastructures Research*, *13*, 253-285.

Cunha Ferreira, T., Romão, X., Freitas, P. M., & Mendonça, H. (2023). Risk Assessment and Vulnerability

Analysis of a Coastal Concrete Heritage Structure. *Heritage*, *6*(9), 6153-6171.

De Paoli, R. G., Di Miceli, E., & Giuliani, F. (2020). Disasters and Cultural Heritage: planning for prevention, emergency management and risk reduction. IOP Conference Series: Materials Science and Engineering,

Delgado, J. M. D., & Oyedele, L. (2021). Digital Twins for the built environment: learning from conceptual and process models in manufacturing. *Advanced engineering informatics*, *49*, 101332.

Diaz, V., van Oosterom, P., Meijers, M., Verbree, E., Ahmed, N., & van Lankveld, T. (2023). Comparison of Cloud-to-Cloud Distance Calculation Methods-Is the Most Complex Always the Most Suitable? International 3D GeoInfo Conference,

Dore, C., & Murphy, M. (2012). Integration of Historic Building Information Modeling (HBIM) and 3D GIS for recording and managing cultural heritage sites. 2012 18th International conference on virtual systems and multimedia,

Fatorić, S., & Seekamp, E. (2017). Securing the Future of Cultural Heritage by Identifying Barriers to and Strategizing Solutions for Preservation under Changing Climate Conditions. *Sustainability*, *9*(11), 2143. https://www.mdpi.com/2071-1050/9/11/2143

Ferro, A., Lo Brutto, M., & Ventimiglia, G. M. (2023). A SCAN-TO-BIM PROCESS FOR THE MONITORING AND CONSERVATION OF THE ARCHITECTURAL HERITAGE: INTEGRATION OF THEMATIC INFORMATION IN A HBIM MODEL. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, *XLVIII-M-2-2023*, 549-556. https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-549-2023

Fissore, V., Bovio, L., Perotti, L., Boccardo, P., & Borgogno-Mondino, E. (2023). Towards a Digital Twin Prototype of Alpine Glaciers: Proposal for a Possible Theoretical Framework. *Remote Sensing*, *15*(11), 2844.

Ford, J. D., Pearce, T., Duerden, F., Furgal, C., & Smit, B. (2010). Climate change policy responses for Canada's Inuit population: The importance of and opportunities for adaptation. *Global Environmental Change*, *20*(1), 177-191. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2009.10.008

Foster, C., & Thelen, K. (2023). Brandeis in Brussels? Bureaucratic discretion, social learning, and the development of regulated competition in the European Union. *Regulation & Governance*.

Foster, G. (2020). Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts. *Resources, Conservation and Recycling*, *152*, 104507. https://doi.org/https://doi.org/10.1016/j.resconrec.2019.104507

Fuchizaki, K., Wada, T., Naruta, H., Suzuki, A., & Irino, K. (2021). A unique multianvil 6–6 assembly for a cubic-type multianvil apparatus. *Review of Scientific Instruments*, *92*(2).

Galanakis, D., Maravelakis, E., Pocobelli, D. P., Vidakis, N., Petousis, M., Konstantaras, A., & Tsakoumaki, M. (2023). SVD-based point cloud 3D stone by stone segmentation for cultural heritage structural analysis–The case of the Apollo Temple at Delphi. *Journal of Cultural Heritage*, *61*, 177-187.

Germs, R., Van Maren, G., Verbree, E., & Jansen, F. W. (1999). A multi-view VR interface for 3D GIS. *Computers & Graphics*, *23*(4), 497-506. https://doi.org/https://doi.org/10.1016/S0097-8493(99)00069-2

Giaccardi, E. (2012). *Heritage and social media: Understanding heritage in a participatory culture*. Routledge.

Giuliani, F., De Falco, A., Cutini, V., & Di Sivo, M. (2021). A simplified methodology for risk analysis of historic centers: the world heritage site of San Gimignano, Italy. *International Journal of Disaster Resilience in the Built Environment*, *12*(3), 336-354.

Goklany, I. M. (2007). Integrated strategies to reduce vulnerability and advance adaptation, mitigation, and sustainable development. *Mitigation and Adaptation Strategies for Global Change*, *12*(5), 755-786. https://doi.org/10.1007/s11027-007-9098-1

Gomes, L., Bellon, O. R. P., & Silva, L. (2014). 3D reconstruction methods for digital preservation of cultural heritage: A survey. *Pattern Recognition Letters*, *50*, 3-14.

Graham, B. (2002). Heritage as knowledge: capital or culture? *Urban studies*, *39*(5-6), 1003-1017.

Green, C., Verhagen, P., McKeague, P., Van'T Veer, R., Huvila, I., Moreau, A., Loup, B., Cooper, A., & Van Manen, N. (2019). Mapping our heritage: Towards a sustainable future for digital spatial information and technologies in European archaeological heritage management. *Journal of Computer Applications in Archaeology*, *2*(1).

Guillet, A.-L. (2007). Docomomo International. *Journal of Architectural Conservation*, *13*(2), 151-156. https://doi.org/10.1080/13556207.2007.10785002

Gullino, P., & Larcher, F. (2013). Integrity in UNESCO World Heritage Sites. A comparative study for rural landscapes. *Journal of Cultural Heritage*, *14*(5), 389-395. https://doi.org/https://doi.org/10.1016/j.culher.2012.10.005

Guo, Y., Liu, Y., Georgiou, T., & Lew, M. S. (2018). A review of semantic segmentation using deep neural networks. *International Journal of Multimedia Information Retrieval*, *7*(2), 87-93. https://doi.org/10.1007/s13735-017-0141-z

Haddad, N. A. (2011). From ground surveying to 3D laser scanner: A review of techniques used for spatial documentation of historic sites. *Journal of King Saud University - Engineering Sciences*, *23*(2), 109-118. https://doi.org/https://doi.org/10.1016/j.jksues.2011.03.001

Haddad, N. A., Fakhoury, L. A., & Akasheh, T. S. (2018). Notes on anthropogenic risks mitigation management and recovery of ancient theatres' heritage: Qualitative assessment and recommendations. *Journal of Cultural Heritage Management and Sustainable Development*, *8*(3), 222-256.

Hakiri, A., Gokhale, A., Yahia, S. B., & Mellouli, N. (2024). A comprehensive survey on digital twin for future networks and emerging Internet of Things industry. *Computer Networks*, 110350.

Halog, A., & Manik, Y. (2011). Advancing integrated systems modelling framework for life cycle sustainability assessment. *Sustainability*, *3*(2), 469-499.

Hammady, R., Ma, M., Strathern, C., & Mohamad, M. (2020). Design and development of a spatial mixed reality touring guide to the Egyptian museum. *Multimedia Tools and Applications*, *79*(5), 3465-3494.

Hayles, N. K. (2012). How we think: Transforming power and digital technologies. In *Understanding digital humanities* (pp. 42-66). Springer.

Heller, N. E., & Zavaleta, E. S. (2009). Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation*, *142*(1), 14-32. https://doi.org/https://doi.org/10.1016/j.biocon.2008.10.006

Hevner, A. R., March, S., Park, J., & Ram, S. (2014). Design Science Research. In.

Hopkin, P. (2018). *Fundamentals of risk management: understanding, evaluating and implementing effective risk management*. Kogan Page Publishers.

Illsley, W. R. (2022). Assembling the Historic Environment: Heritage in the Digital Making.

Jiang, P., Pandey, G., & Saripalli, S. (2024). 3DGS-ReLoc: 3D Gaussian Splatting for Map Representation and Visual ReLocalization. *arXiv preprint arXiv:2403.11367*.

Jigyasu, R., Murthy, M., Boccardi, G., Marrion, C., Douglas, D., King, J., O'Brien, G., Dolcemascolo, G., Kim, Y., & Albrito, P. (2013). Heritage and resilience: issues and opportunities for reducing disaster risks.

Jo, Y. H., & Hong, S. (2019). Three-Dimensional Digital Documentation of Cultural Heritage Site Based on the Convergence of Terrestrial Laser Scanning and Unmanned Aerial Vehicle Photogrammetry. *ISPRS International Journal of Geo-Information*, *8*(2), 53. https://www.mdpi.com/2220-9964/8/2/53

Jordan-Palomar, I., Tzortzopoulos, P., García-Valldecabres, J., & Pellicer, E. (2018). Protocol to Manage Heritage-Building Interventions Using Heritage Building Information Modelling (HBIM). *Sustainability*, *10*(4), 908. https://www.mdpi.com/2071-1050/10/4/908

Jorquera, N., Vargas, J., Lobos Martínez, M. d. l. L., & Cortez, D. (2017). Revealing earthquake-resistant geometrical features in heritage masonry architecture in Santiago, Chile. *International Journal of Architectural Heritage*, *11*(4), 519-538.

Jouan, P., & Hallot, P. (2019). Digital twin: A HBIM-based methodology to support preventive conservation of historic assets through heritage significance awareness. *the international archives of the photogrammetry, remote sensing and spatial information sciences*, *42*, 609-615.

Jouan, P., & Hallot, P. (2019). DIGITAL TWIN: A HBIM-BASED METHODOLOGY TO SUPPORT PREVENTIVE CONSERVATION OF HISTORIC ASSETS THROUGH HERITAGE SIGNIFICANCE AWARENESS. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, *XLII-2/W15*, 609-615. https://doi.org/10.5194/isprs-archives-XLII-2-W15-609-2019

Jouan, P., & Hallot, P. (2020). Digital twin: Research framework to support preventive conservation policies. *ISPRS International Journal of Geo-Information*, *9*(4), 228.

Kattel, G. R., Elkadi, H., & Meikle, H. (2013). Developing a complementary framework for urban ecology. *Urban Forestry & Urban Greening*, *12*(4), 498-508.

Kedzierski, M., & Fryskowska, A. (2015). Methods of laser scanning point clouds integration in precise 3D building modelling. *Measurement*, *74*, 221-232.

Kelly, M. (2023). *The Representation of Interpretative Knowledge in Cultural Heritage Research* University of Brighton].

Khalaf, R. W. (2022). Integrity: Enabling a Future-Oriented Approach to Cultural Heritage. *The Historic Environment: Policy & Practice*, *13*(1), 5-27. https://doi.org/10.1080/17567505.2021.1981670

Khalid, A. (2022). Conservation Challenges and Emerging Trends of Digital Preservation for UNESCO Architectural Heritage, Pakistan. *Conservation*, *2*(1), 26-37. https://www.mdpi.com/2673-7159/2/1/3

King, L., Stark, J. F., & Cooke, P. (2016). Experiencing the digital world: The cultural value of digital engagement with heritage. *Heritage & Society*, *9*(1), 76-101.

Koller, D., Frischer, B., & Humphreys, G. (2010). Research challenges for digital archives of 3D cultural heritage models. *Journal on Computing and Cultural Heritage (JOCCH)*, *2*(3), 1-17.

Kundu, A., Yin, X., Fathi, A., Ross, D., Brewington, B., Funkhouser, T., & Pantofaru, C. (2020). Virtual multi-view fusion for 3d semantic segmentation. Computer Vision–ECCV 2020: 16th European Conference, Glasgow, UK, August 23–28, 2020, Proceedings, Part XXIV 16,

Laakso, M., & Kiviniemi, A. (2012). The IFC standard: A review of history, development, and standardization, information technology. *ITcon*, *17*(9).

Labadi, S. (2013). UNESCO, cultural heritage, and outstanding universal value: Value-based analyses of the World Heritage and Intangible Cultural Heritage Conventions.

Labadi, S., Giliberto, F., Rosetti, I., Shetabi, L., & Yildirim, E. (2021). Heritage and the sustainable development goals: Policy guidance for heritage and development actors. *International Journal of*

Heritage Studies.
Latour, B., & Crawford, T. H. (1993). An interview with bruno latour. *Configurations*, *1*(2), 247-268.
Laužikas, R., Žižiūnas, T., & Fomin, V. (2022). Novel technologies as potential catalyst for democratizing urban heritage preservation practices: the case of 3D scanning and AI. *Information & media*, *93*, 93-115.
Lemmens, M., & Lemmens, M. (2011). Terrestrial laser scanning. *Geo-information: technologies, applications and the environment*, 101-121.
Letellier, R., & Eppich, R. (2015). *Recording, documentation and information management for the conservation of heritage places*. Routledge.
Li, S., Liu, L., & Peng, C. (2020). A review of performance-oriented architectural design and optimization in the context of sustainability: Dividends and challenges. *Sustainability*, *12*(4), 1427.
Li, X., Zhou, X., Weng, F., Ding, F., Wu, Y., & Yi, Z. (2024). Evolution of cultural landscape heritage layers and value assessment in urban countryside historic districts: the case of Jiufeng Sheshan, Shanghai, China. *Heritage Science*, *12*(1), 96.
Li, Y., Du, Y., Yang, M., Liang, J., Bai, H., Li, R., & Law, A. (2023). A review of the tools and techniques used in the digital preservation of architectural heritage within disaster cycles. *Heritage Science*, *11*(1), 199.
Liang, W., Ahmad, Y., & Mohidin, H. H. B. (2023). The development of the concept of architectural heritage conservation and its inspiration. *Built Heritage*, *7*(1), 21. https://doi.org/10.1186/s43238-023-00103-2
Liburd, J. J., & Becken, S. (2020). Values in nature conservation, tourism and UNESCO World Heritage Site stewardship. In *Protected areas, sustainable tourism and neo-liberal governance policies* (pp. 23-39). Routledge.
Lim, K. Y. H., Zheng, P., & Chen, C.-H. (2020). A state-of-the-art survey of Digital Twin: techniques, engineering product lifecycle management and business innovation perspectives. *Journal of Intelligent Manufacturing*, *31*(6), 1313-1337.
Liritzis, I., & Korka, E. (2019). Archaeometry's role in cultural heritage sustainability and development. *Sustainability*, *11*(7), 1972.
Liu, Z., van Oosterom, P., Balado, J., Swart, A., & Beers, B. (2022). Detection and reconstruction of static vehicle-related ground occlusions in point clouds from mobile laser scanning. *Automation in Construction*, *141*, 104461. https://doi.org/https://doi.org/10.1016/j.autcon.2022.104461
López, F. J., Lerones, P. M., Llamas, J., Gómez-García-Bermejo, J., & Zalama, E. (2018). A Review of Heritage Building Information Modeling (H-BIM). *Multimodal Technologies and Interaction*, *2*(2), 21. https://www.mdpi.com/2414-4088/2/2/21
Losada, I. J., Toimil, A., Muñoz, A., Garcia-Fletcher, A. P., & Diaz-Simal, P. (2019). A planning strategy for the adaptation of coastal areas to climate change: The Spanish case. *Ocean & Coastal Management*, *182*, 104983. https://doi.org/https://doi.org/10.1016/j.ocecoaman.2019.104983
Lowenthal, D. (1994). Identity, heritage, and history. *Commemorations: The politics of national identity*, 41-57.
Luther, W., Baloian, N., Biella, D., & Sacher, D. (2023). Digital twins and enabling technologies in museums and cultural heritage: An overview. *Sensors*, *23*(3), 1583.
Lysgaard, J. A., Bengtsson, S., & Laugesen, M. H.-L. (2019). *Dark pedagogy: Education, horror and the Anthropocene*. Springer.
Majumdar, A., Sinha, S. K., & Govindan, K. (2021). Prioritising risk mitigation strategies for environmentally

sustainable clothing supply chains: Insights from selected organisational theories. *Sustainable Production and Consumption*, *28*, 543-555. https://doi.org/https://doi.org/10.1016/j.spc.2021.06.021

Mao, Y., Qi, J., & He, B.-J. (2020). Impact of the heritage building façade in small-scale public spaces on human activity: Based on spatial analysis. *Environmental Impact Assessment Review*, *85*, 106457. https://doi.org/https://doi.org/10.1016/j.eiar.2020.106457

Martinelli, L., Calcerano, F., & Gigliarelli, E. (2022). Methodology for an HBIM workflow focused on the representation of construction systems of built heritage. *Journal of Cultural Heritage*, *55*, 277-289. https://doi.org/https://doi.org/10.1016/j.culher.2022.03.016

Masciotta, M. G., Sanchez-Aparicio, L. J., Oliveira, D. V., & Gonzalez-Aguilera, D. (2023). Integration of laser scanning technologies and 360º photography for the digital documentation and management of cultural heritage buildings. *International Journal of Architectural Heritage*, *17*(1), 56-75.

Matrone, F., Colucci, E., Iacono, E., & Ventura, G. M. (2023). The HBIM-GIS Main10ance Platform to Enhance the Maintenance and Conservation of Historical Built Heritage. *Sensors*, *23*(19), 8112. https://www.mdpi.com/1424-8220/23/19/8112

Mazzarella, L. (2015). Energy retrofit of historic and existing buildings. The legislative and regulatory point of view. *Energy and Buildings*, *95*, 23-31. https://doi.org/https://doi.org/10.1016/j.enbuild.2014.10.073

McGee, T. K., McFarlane, B. L., & Varghese, J. (2009). An Examination of the Influence of Hazard Experience on Wildfire Risk Perceptions and Adoption of Mitigation Measures. *Society & Natural Resources*, *22*(4), 308-323. https://doi.org/10.1080/08941920801910765

McMaster, R. B., Leitner, H., & Sheppard, E. (1997). GIS-based Environmental Equity and Risk Assessment: Methodological Problems and Prospects. *Cartography and Geographic Information Systems*, *24*(3), 172-189. https://doi.org/10.1559/152304097782476933

Megahed, N. A. (2015). Towards a theoretical framework for HBIM approach in historic preservation and management. *ArchNet-IJAR: International Journal of Architectural Research*, *9*(3), 130.

Mekonnen, H., Bires, Z., & Berhanu, K. (2022). Practices and challenges of cultural heritage conservation in historical and religious heritage sites: evidence from North Shoa Zone, Amhara Region, Ethiopia. *Heritage Science*, *10*(1), 172. https://doi.org/10.1186/s40494-022-00802-6

Messaoudi, T., Véron, P., Halin, G., & De Luca, L. (2018). An ontological model for the reality-based 3D annotation of heritage building conservation state. *Journal of Cultural Heritage*, *29*, 100-112.

Moyano, J., Nieto-Julián, J. E., Lenin, L. M., & Bruno, S. (2022). Operability of Point Cloud Data in an Architectural Heritage Information Model. *International Journal of Architectural Heritage*, *16*(10), 1588-1607. https://doi.org/10.1080/15583058.2021.1900951

Mualam, N., & Alterman, R. (2020). Architecture is not everything: a multi-faceted conceptual framework for evaluating heritage protection policies and disputes. *International Journal of Cultural Policy*, *26*(3), 291-311. https://doi.org/10.1080/10286632.2018.1518978

Muenster, S. (2022). Digital 3D technologies for humanities research and education: an overview. *Applied Sciences*, *12*(5), 2426.

Munarim, U., & Ghisi, E. (2016). Environmental feasibility of heritage buildings rehabilitation. *Renewable and Sustainable Energy Reviews*, *58*, 235-249. https://doi.org/https://doi.org/10.1016/j.rser.2015.12.334

Munasinghe, H. (2005). The politics of the past: constructing a national identity through heritage conservation. *International Journal of Heritage Studies*, *11*(3), 251-260.

Münster, S., Utescher, R., & Ulutas Aydogan, S. (2021). Digital topics on cultural heritage investigated: how can data-driven and data-guided methods support to identify current topics and trends in digital heritage? *Built Heritage*, *5*(1), 25. https://doi.org/10.1186/s43238-021-00045-7

Murdoch, J. (2001). Ecologising sociology: Actor-network theory, co-construction and the problem of human exemptionalism. *Sociology*, *35*(1), 111-133.

Murphy, M., McGovern, E., & Pavia, S. (2009). Historic building information modelling (HBIM). *Structural Survey*, *27*(4), 311-327.

Murphy, M., McGovern, E., & Pavia, S. (2013). Historic Building Information Modelling–Adding intelligence to laser and image based surveys of European classical architecture. *ISPRS journal of photogrammetry and remote sensing*, *76*, 89-102.

Nebiker, S., Bleisch, S., & Christen, M. (2010). Rich point clouds in virtual globes–A new paradigm in city modeling? *Computers, Environment and Urban Systems*, *34*(6), 508-517.

Niazi, M. A. (2016). Review of "CiteSpace: A Practical Guide For Mapping Scientific Literature" by Chaomei Chen. *Complex Adaptive Systems Modeling*, *4*(1), 23. https://doi.org/10.1186/s40294-016-0036-5

Nilson, T., & Thorell, K. (2018). Cultural heritage preservation: The past, the present and the future. In: Halmstad University Press.

Noardo, F., Arroyo Ohori, K., Krijnen, T., & Stoter, J. (2021). An inspection of IFC models from practice. *Applied Sciences*, *11*(5), 2232.

Nocco, B. W., & Stulz, R. M. (2006). Enterprise risk management: Theory and practice. *Journal of applied corporate finance*, *18*(4), 8-20.

Noyes, J. E. (2011). The common heritage of mankind: past, present, and future. *Denv. J. Int'l L. & Pol'y*, *40*, 447.

Nyerges, T., Robkin, M., & Moore, T. J. (1997). Geographic Information Systems for Risk Evaluation: Perspectives on Applications to Environmental Health. *Cartography and Geographic Information Systems*, *24*(3), 123-144. https://doi.org/10.1559/152304097782476960

Ogunsakin, R., Mehandjiev, N., & Marin, C. A. (2023). Towards adaptive digital twins architecture. *Computers in Industry*, *149*, 103920.

Panzera, E. (2022). The Role of Cultural Heritage in Shaping Territorial Identities. In E. Panzera (Ed.), *Cultural Heritage and Territorial Identity: Synergies and Development Impact on European Regions* (pp. 117-143). Springer International Publishing. https://doi.org/10.1007/978-3-030-94468-1_5

Paolini, A., Vafadari, A., Cesaro, G., Quintero, M. S., Van Balen, K., & Vileikis, O. (2012). *Risk management at heritage sites: A case study of the Petra world heritage site*. UNESCO.

Park, J. (2021). An Actor-Network Perspective on Collections Documentation and Data Practices at Museums. *Museum and Society*, *19*(2), 237-251.

Pärn, E. A., Edwards, D. J., & Sing, M. C. (2017). The building information modelling trajectory in facilities management: A review. *Automation in construction*, *75*, 45-55.

Pendlebury, J., Short, M., & While, A. (2009). Urban World Heritage Sites and the problem of authenticity. *Cities*, *26*(6), 349-358. https://doi.org/https://doi.org/10.1016/j.cities.2009.09.003

Perles, A., Pérez-Marín, E., Mercado, R., Segrelles, J. D., Blanquer, I., Zarzo, M., & Garcia-Diego, F. J. (2018). An energy-efficient internet of things (IoT) architecture for preventive conservation of cultural heritage. *Future Generation Computer Systems*, *81*, 566-581.

Pezeshki, Z., & Ivari, S. A. S. (2018). Applications of BIM: a brief review and future outline. *Archives of Computational Methods in Engineering*, *25*, 273-312.

Pocobelli, D. P., Boehm, J., Bryan, P., Still, J., & Grau-Bové, J. (2018a). BIM for heritage science: a review. *Heritage Science*, *6*(1), 30. https://doi.org/10.1186/s40494-018-0191-4

Pocobelli, D. P., Boehm, J., Bryan, P., Still, J., & Grau-Bové, J. (2018b). BIM for heritage science: a review. *Heritage Science*, *6*(1), 1-15.

Pottgiesser, U., & Dragutinovic, A. (2022). ConCom and MoMove. Approaches to Industrial Heritage. In *MoMove Modern Movement and Industrial Heritage: Contributions to the Docomomo virtual exhibition-momove* (pp. 24-29). Technische Hochschule Ostwestfalen-Lippe.

Poux, F., & Billen, R. (2019). A smart point cloud infrastructure for intelligent environments. In *Laser Scanning* (pp. 127-149). CRC Press.

Poux, F., Neuville, R., Hallot, P., & Billen, R. (2016). Smart point cloud: Definition and remaining challenges. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *4*(W1).

Poux, F., Neuville, R., Hallot, P., Van Wersch, L., Luczfalvy Jancsó, A., & Billen, R. (2017). Digital investigations of an archaeological smart point cloud: A real time web-based platform to manage the visualisation of semantical queries. GEOMATICS & RESTORATION 2017,

Rakotosaona, M. J., La Barbera, V., Guerrero, P., Mitra, N. J., & Ovsjanikov, M. (2020). Pointcleannet: Learning to denoise and remove outliers from dense point clouds. Computer graphics forum,

Rasheed, A., San, O., & Kvamsdal, T. (2019). Digital twin: Values, challenges and enablers. *arXiv preprint arXiv:1910.01719*.

Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital twin: Values, challenges and enablers from a modeling perspective. *Ieee Access*, *8*, 21980-22012.

Ravankhah, M., de Wit, R., Argyriou, A. V., Chliaoutakis, A., Revez, M. J., Birkmann, J., Žuvela-Aloise, M., Sarris, A., Tzigounaki, A., & Giapitsoglou, K. (2019). Integrated Assessment of Natural Hazards, Including Climate Change's Influences, for Cultural Heritage Sites: The Case of the Historic Centre of Rethymno in Greece. *International Journal of Disaster Risk Science*, *10*(3), 343-361. https://doi.org/10.1007/s13753-019-00235-z

Rodríguez-Moreno, C., Reinoso-Gordo, J. F., Rivas-López, E., Gómez-Blanco, A., Ariza-López, F., & Ariza-López, I. (2018). From point cloud to BIM: An integrated workflow for documentation, research and modelling of architectural heritage. *Survey Review*, *50*(360), 212-231.

Romão, X., Paupério, E., & Pereira, N. (2016). A framework for the simplified risk analysis of cultural heritage assets. *Journal of Cultural Heritage*, *20*, 696-708. https://doi.org/https://doi.org/10.1016/j.culher.2016.05.007

Rosenbaum, D. P. (2002). Evaluating multi-agency anti-crime partnerships: Theory, design, and measurement issues. *Crime prevention studies*, *14*, 171-225.

Rossi, M., & Bournas, D. (2023). Structural health monitoring and management of cultural heritage structures: A state-of-the-art review. *Applied Sciences*, *13*(11), 6450.

Rossitti, M., Oppio, A., & Torrieri, F. (2021). The Financial Sustainability of Cultural Heritage Reuse Projects: An Integrated Approach for the Historical Rural Landscape. *Sustainability*, *13*(23), 13130. https://www.mdpi.com/2071-1050/13/23/13130

Rouhani, B., & Romão, X. (2023). *Managing disaster risks to cultural heritage: from risk preparedness to recovery for immovable heritage*. Taylor & Francis.

Rouhi, J. (2017). Definition of cultural heritage properties and their valuesby the past. *Asian Journal of Science and Technology*, *8*(12), 7109-7114.

Ruppert, T., & Abonyi, J. (2020). Integration of real-time locating systems into digital twins. *Journal of Industrial Information Integration*, *20*, 100174.

https://doi.org/https://doi.org/10.1016/j.jii.2020.100174
Ruthven, I., & Chowdhury, G. G. (2015). *Cultural heritage information: Access and management* (Vol. 1). Facet publishing.
Sabbioni, C., Cassar, M., Brimblecombe, P., & Lefevre, R.-A. (2008). Vulnerability of cultural heritage to climate change. *European and Mediterranean Major Hazards Agreement (EUR-OPA)*, 1-24.
Schluse, M., Priggemeyer, M., Atorf, L., & Rossmann, J. (2018). Experimentable Digital Twins—Streamlining Simulation-Based Systems Engineering for Industry 4.0. *IEEE Transactions on Industrial Informatics*, *14*(4), 1722-1731. https://doi.org/10.1109/TII.2018.2804917
Segovia, M., & Garcia-Alfaro, J. (2022). Design, Modeling and Implementation of Digital Twins. *Sensors*, *22*(14), 5396. https://www.mdpi.com/1424-8220/22/14/5396
Sesana, E., Gagnon, A. S., Bonazza, A., & Hughes, J. J. (2020). An integrated approach for assessing the vulnerability of World Heritage Sites to climate change impacts. *Journal of Cultural Heritage*, *41*, 211-224.
Shafique, K., Khawaja, B. A., Sabir, F., Qazi, S., & Mustaqim, M. (2020). Internet of things (IoT) for next-generation smart systems: A review of current challenges, future trends and prospects for emerging 5G-IoT scenarios. *Ieee Access*, *8*, 23022-23040.
Shahzad, M., Shafiq, M. T., Douglas, D., & Kassem, M. (2022). Digital twins in built environments: an investigation of the characteristics, applications, and challenges. *Buildings*, *12*(2), 120.
Stubbs, M. (2004). Heritage-sustainability: developing a methodology for the sustainable appraisal of the historic environment. *Planning Practice & Research*, *19*(3), 285-305.
Styliani, S., Fotis, L., Kostas, K., & Petros, P. (2009). Virtual museums, a survey and some issues for consideration. *Journal of Cultural Heritage*, *10*(4), 520-528.
Stylianidis, E. (2020). *Photogrammetric survey for the recording and documentation of historic buildings*. Springer.
Sun, Y., Song, H., Jara, A. J., & Bie, R. (2016). Internet of things and big data analytics for smart and connected communities. *IEEE access*, *4*, 766-773.
Synnestvedt, M. B., Chen, C., & Holmes, J. H. (2005). CiteSpace II: visualization and knowledge discovery in bibliographic databases. *AMIA Annu Symp Proc*, *2005*, 724-728.
Tabkha, A., Hajji, R., Billen, R., & Poux, F. (2019). Semantic enrichment of point cloud by automatic extraction and enhancement of 360° panoramas. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*(W17).
Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., Guo, Z., Lu, S. C.-Y., & Nee, A. Y. (2019). Digital twin-driven product design framework. *International Journal of Production Research*, *57*(12), 3935-3953.
Templin, T., & Popielarczyk, D. (2020). The use of low-cost unmanned aerial vehicles in the process of building models for cultural tourism, 3D web and augmented/mixed reality applications. *Sensors*, *20*(19), 5457.
Thuestad, A. E., Tømmervik, H., & Solbø, S. A. (2015). Assessing the impact of human activity on cultural heritage in Svalbard: a remote sensing study of London. *The Polar Journal*, *5*(2), 428-445. https://doi.org/10.1080/2154896X.2015.1068536
Tomaszewski, R. (2023). Visibility, impact, and applications of bibliometric software tools through citation analysis. *Scientometrics*, *128*(7), 4007-4028. https://doi.org/10.1007/s11192-023-04725-2
Trillo, C., Aburamadan, R., Mubaideen, S., Salameen, D., & Makore, B. C. N. (2020). Towards a Systematic Approach to Digital Technologies for Heritage Conservation. Insights from Jordan. *Preservation, Digital Technology & Culture*, *49*(4), 121-138. https://doi.org/doi:10.1515/pdtc-2020-0023

Udeaja, C., Trillo, C., Awuah, K. G., Makore, B. C., Patel, D. A., Mansuri, L. E., & Jha, K. N. (2020). Urban heritage conservation and rapid urbanization: Insights from Surat, India. *Sustainability*, *12*(6), 2172.

Uhlenkamp, J.-F., Hauge, J. B., Broda, E., Lütjen, M., Freitag, M., & Thoben, K.-D. (2022). Digital twins: A maturity model for their classification and evaluation. *Ieee Access*, *10*, 69605-69635.

Van de Vijver, F., & Leung, K. (1997). Methods and data analysis of comparative research. *Handbook of cross-cultural psychology*, *1*, 257-300.

van Oosterom, P., van Oosterom, S., Liu, H., Thompson, R., Meijers, M., & Verbree, E. (2022). Organizing and visualizing point clouds with continuous levels of detail. *ISPRS journal of photogrammetry and remote sensing*, *194*, 119-131. https://doi.org/https://doi.org/10.1016/j.isprsjprs.2022.10.004

Vardopoulos, I. (2022). Industrial building adaptive reuse for museum. Factors affecting visitors' perceptions of the sustainable urban development potential. *Building and Environment*, *222*, 109391.

Verbree, E., Maren, G. V., Germs, R., Jansen, F., & Kraak, M.-J. (1999). Interaction in virtual world views-linking 3D GIS with VR. *International Journal of Geographical Information Science*, *13*(4), 385-396. https://doi.org/10.1080/136588199241265

Verschuuren, B., Mallarach, J.-M., Bernbaum, E., Spoon, J., Brown, S., Borde, R., Brown, J., Calamia, M., Mitchell, N. J., & Infield, M. (2021). *Cultural and spiritual significance of nature: Guidance for protected and conserved area governance and management* (Vol. 32). IUCN, International Union for Conservation of Nature and Natural Resour.

Vuoto, A., Funari, M. F., & Lourenço, P. B. (2023a). On the use of the digital twin concept for the structural integrity protection of architectural heritage. *Infrastructures*, *8*(5), 86.

Vuoto, A., Funari, M. F., & Lourenço, P. B. (2023b). Shaping digital twin concept for built cultural heritage conservation: A systematic literature review. *International Journal of Architectural Heritage*, 1-34.

Wang, H., Zhao, Y., Gao, X., & Gao, B. (2021). Collaborative decision-making for urban regeneration: A literature review and bibliometric analysis. *Land Use Policy*, *107*, 105479.

Wang, Q., & Kim, M.-K. (2019). Applications of 3D point cloud data in the construction industry: A fifteen-year review from 2004 to 2018. *Advanced engineering informatics*, *39*, 306-319.

Wang, S. (2023). Application of computer-aided CAD in urban planning heritage protection. *Soft Computing*, 1-10.

Wignall, R. M. L., Gordon, J. E., Brazier, V., MacFadyen, C. C. J., & Everett, N. S. (2018). A qualitative risk assessment for the impacts of climate change on nationally and internationally important geoheritage sites in Scotland. *Proceedings of the Geologists' Association*, *129*(2), 120-134. https://doi.org/https://doi.org/10.1016/j.pgeola.2017.11.003

Wu, Y., & Zhu, H. (2022). Intelligent Protection and Inheritance Method of the Historic Centre of Macao Based on BIM+ Concept——A Case Study of Mandarin's House. International Conference on Green Building, Civil Engineering and Smart City,

Xia, H., Liu, Z., Efremochkina, M., Liu, X., & Lin, C. (2022). Study on city digital twin technologies for sustainable smart city design: A review and bibliometric analysis of geographic information system and building information modeling integration. *Sustainable Cities and Society*, *84*, 104009. https://doi.org/https://doi.org/10.1016/j.scs.2022.104009

Xiao, W., Mills, J., Guidi, G., Rodríguez-Gonzálvez, P., Gonizzi Barsanti, S., & González-Aguilera, D. (2018). Geoinformatics for the conservation and promotion of cultural heritage in support of the UN Sustainable Development Goals. *ISPRS Journal of Photogrammetry and Remote Sensing*, *142*, 389-406. https://doi.org/https://doi.org/10.1016/j.isprsjprs.2018.01.001

Yang, S., Hou, M., & Li, S. (2023). Three-Dimensional Point Cloud Semantic Segmentation for Cultural

Heritage: A Comprehensive Review. *Remote Sensing*, *15*(3), 548. https://www.mdpi.com/2072-4292/15/3/548

Yang, X., Grussenmeyer, P., Koehl, M., Macher, H., Murtiyoso, A., & Landes, T. (2020). Review of built heritage modelling: Integration of HBIM and other information techniques. *Journal of Cultural Heritage*, *46*, 350-360.

Yaqoob, L., Ahmed Khan, N., & Subhan, F. (2014). An overview of existing decision support systems for disasters management. *Sci Int (Lahore)*, *26*, 1765-1776.

YARAŞAN, H., & VATAN, M. (2020). Disaster Risk Management of Cultural Heritage in Urban Areas: The Case of Turkey. *A+ Arch Design International Journal of Architecture and Design*, *6*(2), 115-136.

Zappia, D. (2017). *An Augmented Reality Application to Perform a Virtual Tourist Guide* Politecnico di Torino].

Zhang, R., Li, G., Li, M., & Wang, L. (2018). Fusion of images and point clouds for the semantic segmentation of large-scale 3D scenes based on deep learning. *ISPRS journal of photogrammetry and remote sensing*, *143*, 85-96.

Zipper, H. (2021). Real-Time-Capable Synchronization of Digital Twins. *IFAC-PapersOnLine*, *54*(4), 147-152. https://doi.org/https://doi.org/10.1016/j.ifacol.2021.10.025

ANNEX D. Case Study 2/Corvey

As a result, a comprehensive framework is proposed to incorporate HBIM + visualization digital technologies into the process of architectural heritage information dissemination, advocating stakeholder collaboration through ANT theoretical analyses as a basis for providing digital information assistance to different groups of people.

The research provides theoretical references and practical guidance for architectural heritage conservation. Several essential components of the digital workflow are specifically analyzed, as represented by the Corvey project, such as the modelling process of HBIM and the data interaction process with the platform.

An HBIM model of Carolingian Westwork and Civitas Corvey

WORKFLOW:

Data collection

(1) reality capture (e.g., point cloud, drones, photogrammetry, or drawings/sketches); (1) 2D map/system or 3D model (e.g., object-based, with no metadata or BIM); (2) connect model to persistent (static) data, metadata, and BIM Stage 2 (e.g., documents, drawings, and asset management systems); (3) enrich with real-time data (e.g., from IoT sensors); (4) two-way data integration and interaction; and (5) autonomous operations and maintenance.

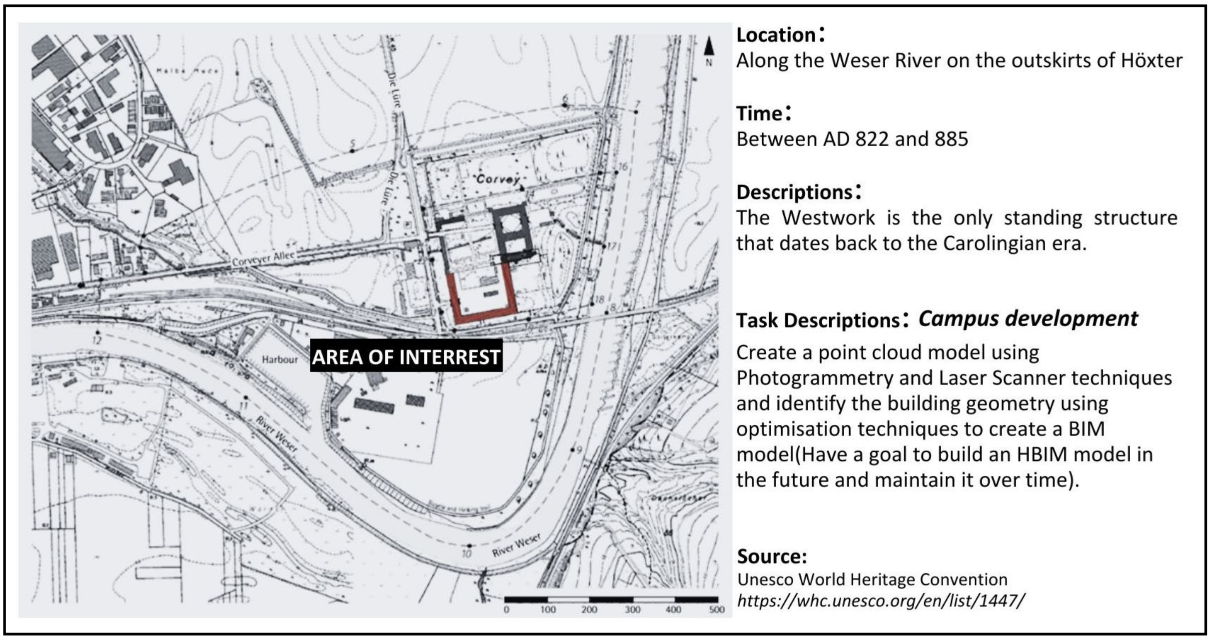


Fig. 1. Case Study: Site Background (in Germany) (Source: by author).

The Heritage building model was developed using multidisciplinary information from various sources, including building geometry, material data, orthophotos, historical documentation, high-definition surveys, and other relevant data. All this information was incorporated into the HBIM model (**Fig. 2**).

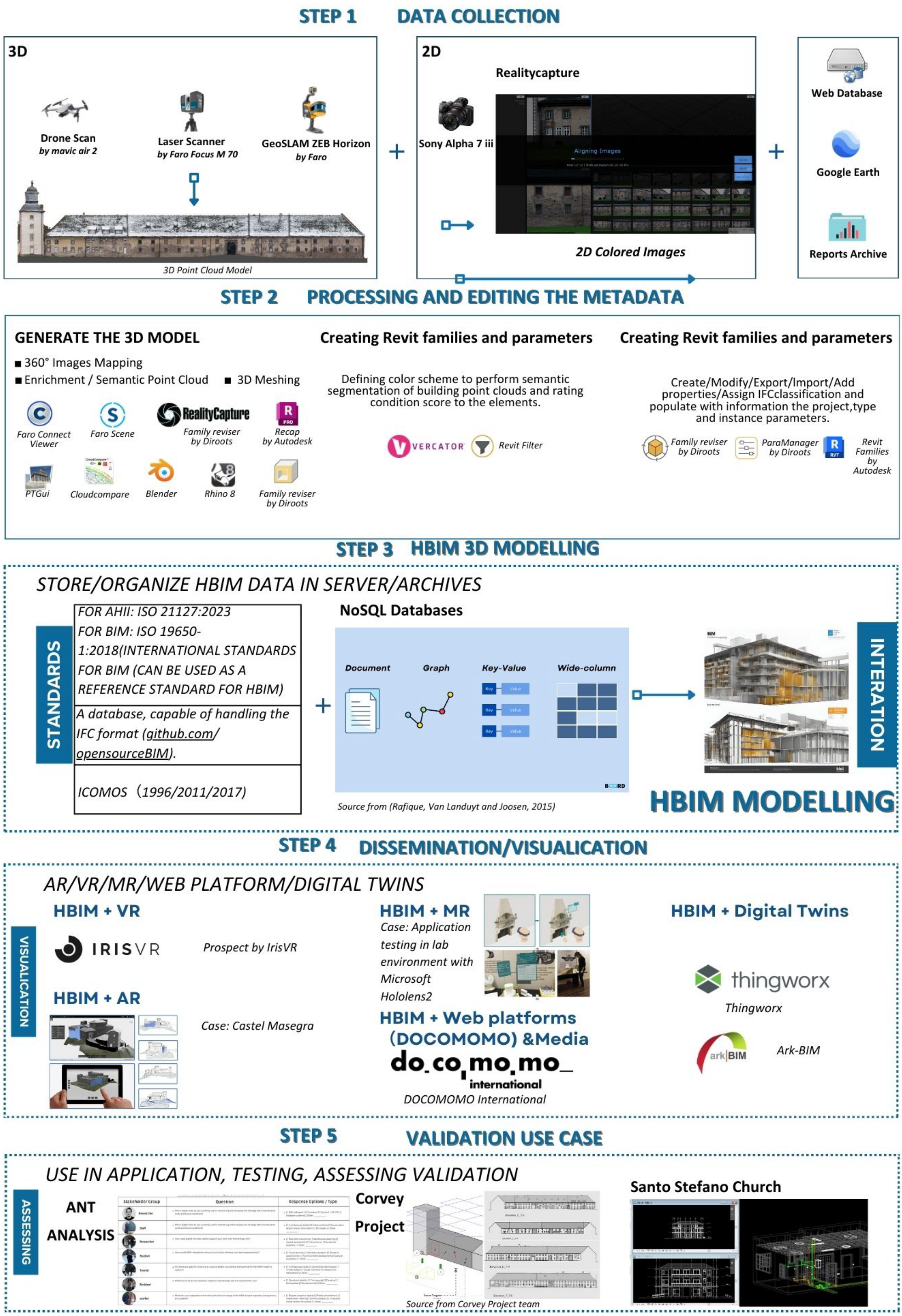


Fig.2. Sketch of a possible solution for reliable 3D representation of Heritage (with high quality and relatively low cost) (Source: by the author (adapted from (Noardo et al., 2021))

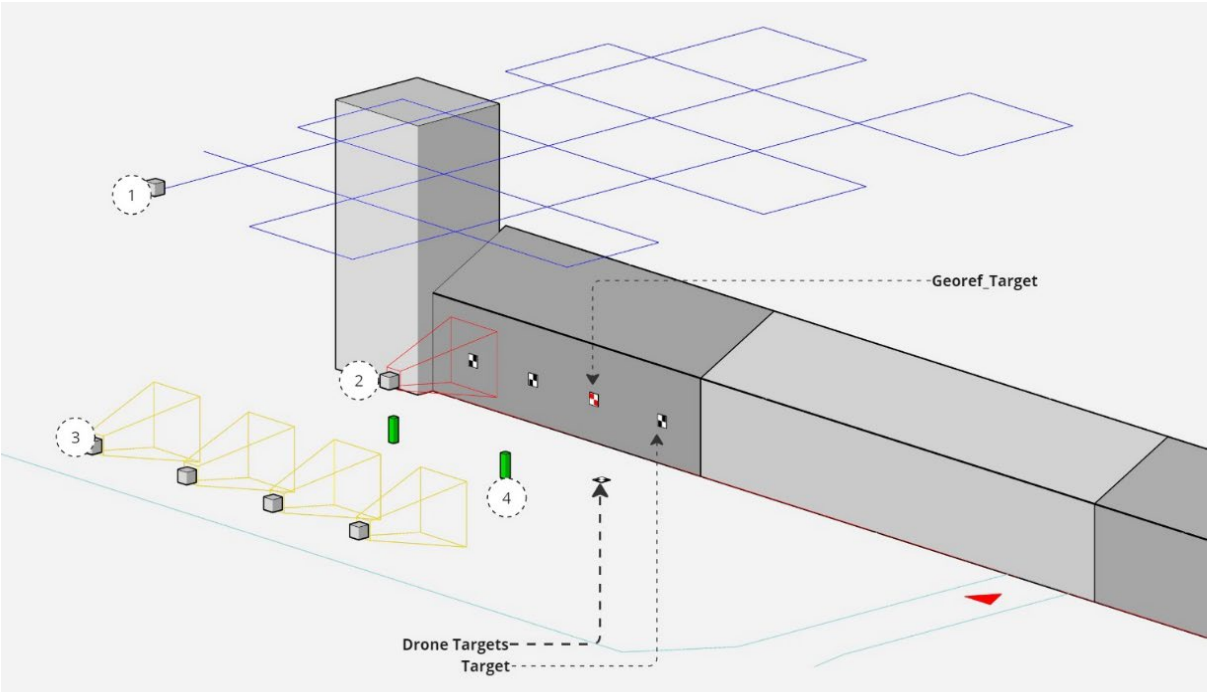
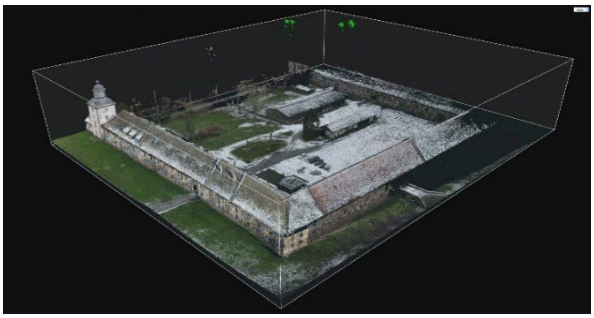


Fig. 3. Process Modelling for Scanning (Source: own figure (adapted from Thomaz et al.)

Required Equipments:

1- Drone Scan (Mavic Air 2)
2- Detail Pass (Sony Alpha 7 iii, Mavic Air 2)
3- Overall Pass (Sony alpha seven iii)
4- 2nd Detail Pass (FARO Focus M 70)
5- Internal composition (Geoslam ZEB Horizon RT, FARO Focus M 70)

Fig. 4. Point cloud data of sections 1-4((Source: by author, adapted from Thomaz et al.).



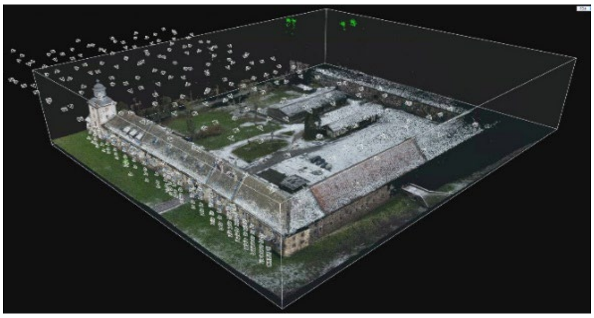


Fig. 5. Point cloud data from the drone((Source: by author, adapted from Thomaz et al.)

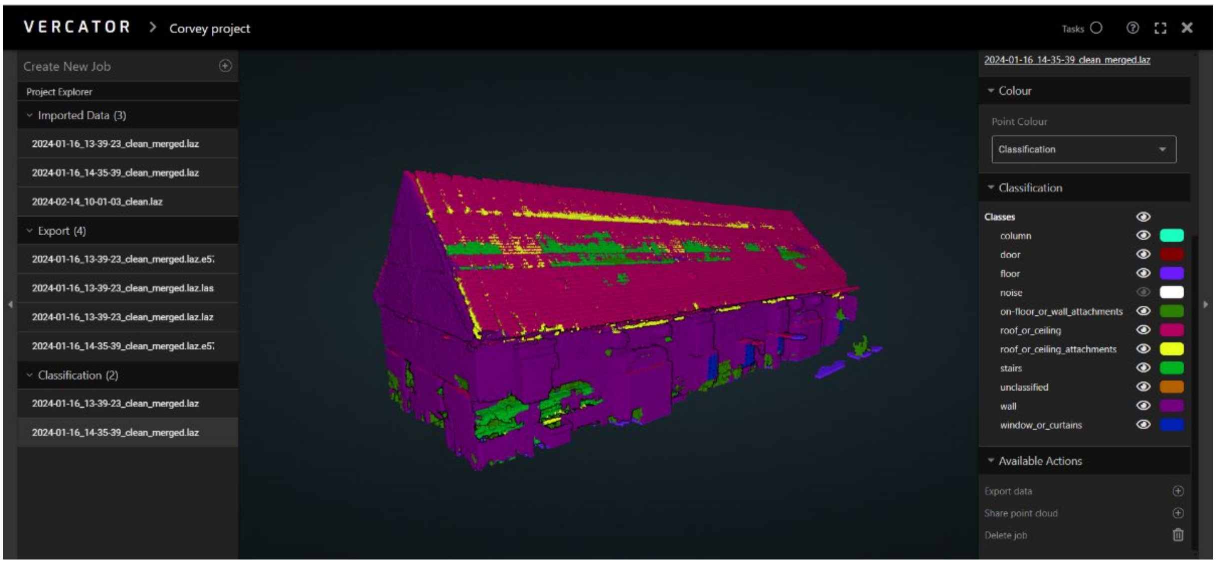


Fig. 6. Point cloud semantic process (Source: by author, https://vercator.cloud/web/new/projects/799557?jobId=6f6d4058-704e-43ff-a6b5)

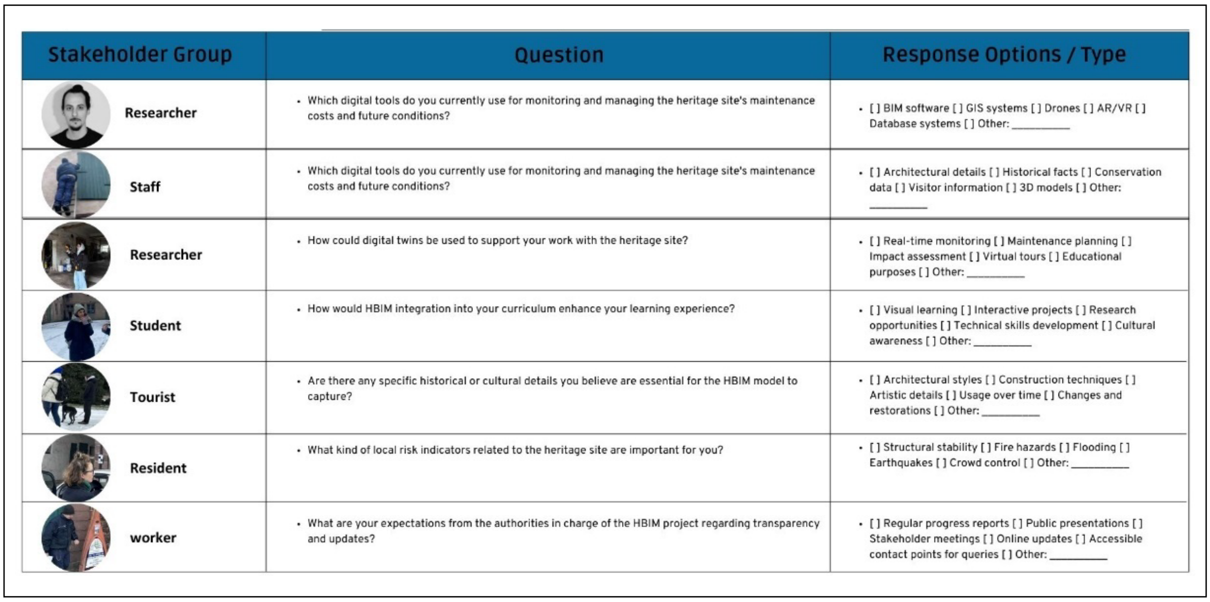
Fig. 7. HBIM MODELLING PROCESS (Source: by author, adapted from Thomaz et al.)

In conclusion, the significance of utilizing HBIM and smart point clouds for digital archiving and protection of heritage sites has been underscored through the inclusion of the Corvey Project case study from Germany. This case study demonstrates the potential to establish a digital information infrastructure on our proposed scholarly platform, allowing the dissemination of architectural heritage like that of Corvey to a wider audience. This initiative not only enhances access to digital heritage resources but also fosters a collaborative environment for scholars, researchers, and the general public, contributing to the preservation and appreciation of global architectural heritage.

ANNEX E. ANT

1. ANT Analysis(Actor Network Theory)

Actor–network theory (ANT) is a theoretical and methodological approach to social theory where everything in the social and natural worlds exists in constantly shifting networks of relationships (Latour, 1996). Applying ANT analysis to architectural heritage information infrastructure at present allows stakeholders to understand the complex web of relationships, power dynamics, and interactions that influence responses to the changing messages on architectural heritage (Figure 7).



Stakeholder Group	Question	Response Options / Type
Researcher	• Which digital tools do you currently use for monitoring and managing the heritage site's maintenance costs and future conditions?	• [ ] BIM software [ ] GIS systems [ ] Drones [ ] AR/VR [ ] Database systems [ ] Other: ________
Staff	• Which digital tools do you currently use for monitoring and managing the heritage site's maintenance costs and future conditions?	• [ ] Architectural details [ ] Historical facts [ ] Conservation data [ ] Visitor information [ ] 3D models [ ] Other: ________
Researcher	• How could digital twins be used to support your work with the heritage site?	• [ ] Real-time monitoring [ ] Maintenance planning [ ] Impact assessment [ ] Virtual tours [ ] Educational purposes [ ] Other: ________
Student	• How would HBIM integration into your curriculum enhance your learning experience?	• [ ] Visual learning [ ] Interactive projects [ ] Research opportunities [ ] Technical skills development [ ] Cultural awareness [ ] Other: ________
Tourist	• Are there any specific historical or cultural details you believe are essential for the HBIM model to capture?	• [ ] Architectural styles [ ] Construction techniques [ ] Artistic details [ ] Usage over time [ ] Changes and restorations [ ] Other: ________
Resident	• What kind of local risk indicators related to the heritage site are important for you?	• [ ] Structural stability [ ] Fire hazards [ ] Flooding [ ] Earthquakes [ ] Crowd control [ ] Other: ________
worker	• What are your expectations from the authorities in charge of the HBIM project regarding transparency and updates?	• [ ] Regular progress reports [ ] Public presentations [ ] Stakeholder meetings [ ] Online updates [ ] Accessible contact points for queries [ ] Other: ________

Fig. 7: ANT analysis on HBIM digital censer Point cloud to HBIM technology salvation participants (Source: own figure)

The PhD project uses fieldwork, questionnaires, and interviews to collect the information needed for ANT analysis, with questionnaires using Qualtrics[3], some of the relevant questions shown below, to be placed on an online platform to collect information about the needs and recommendations of different stakeholders.

Table 1:

Some of the questions used in the questionnaire on Qualtrics

Stakeholder group	Questions/Response Options/Type
a) Government and Regulatory Agencies	Q1. How do you currently engage with the heritage site? A. Through guided tours B. Via interactive apps or websites C. By attending educational workshops or lectures D. Through personal research E. Other: ___________

[3] Qualtrics: An American software company that provides online survey software as a service, widely used in market research, customer satisfaction surveys, employee engagement surveys, and many other areas.

b) Cultural Heritage Protection Agencies c) Research and Educational Institutions d) Architects and planners e) Owners and investors f) Community and public g) Culture and Tourism Sector h) technology provider i) Residents and pets	Q2. What tools and technologies does your organization use in the collection and management of architectural heritage information? A. Traditional documentation methods (e.g., written records, photography) B. Digital documentation tools (e.g., 3D scanning, digital mapping) C. Database and information management systems D. Social media and digital platforms for public engagement E. Other (please specify): ___________
	Q3. What type of information would you like to see included in the HBIM system for the heritage site? A. Architectural details and historical significance B. Information on materials and construction techniques C. Stories and background of people associated with the site D. Conservation and restoration efforts history E. Other: ___________
	Q4. Would you use an augmented reality (AR) tool to enhance your visit to the heritage site if it were available? A. Definitely yes B. Probably yes C. Maybe D. Probably not E. Definitely not
	Q5. How could digital twins be used to support your work with the heritage site? A. For real-time monitoring and maintenance B. To simulate the impact of environmental changes C. For virtual restoration experiments D. As an educational tool to engage the public E. Other: ___________
	Q7. Which digital tools do you currently use for monitoring and managing the heritage site's maintenance costs and future conditions? A. HBIM software B. GIS mapping tools C. Digital documentation archives D. Maintenance management systems E. Other: ___________
	Q8. Are there any specific historical or cultural details you believe are essential for the HBIM model to capture? A. Artistic features (e.g., frescoes, sculptures) B. Construction techniques and materials C. Historical events associated with the site D. Cultural practices and ceremonies E. Other: ___________
	Q9. What are your expectations from the authorities in charge of the HBIM project regarding transparency and updates? A. Regular progress reports B. Public access to non-sensitive data C. Stakeholder meetings and feedback sessions D. Transparency on budget and expenditures E. Other: ___________
	Q10. How important is community involvement in the HBIM process for you, and how should it be facilitated? A. Extremely important; through workshops and public consultations B. Important; by inviting feedback via digital platforms C. Somewhat important: through public exhibitions and displays D. Not very important; limited to information sessions E. Other: ___________
	Q11. How would HBIM integration into your curriculum enhance your learning experience?

	A. By providing practical case studies B. Through access to detailed digital models for analysis C. By facilitating remote learning opportunities D. By enabling collaboration on real-world projects E. Other: __________
	Q12. What technological or collaboration challenges have you encountered in cultural heritage projects? A. Difficulty in integrating different types of data and formats B. Challenges in ensuring the long-term preservation of digital data C. Limited access to advanced technological tools due to budget constraints D. Collaboration challenges with other organizations or stakeholders E. Other (please specify): __________
……	……

2. Practical Applications HBIM & ANT analysis

Although HBIM (Historic Building Information Modeling) has been widely discussed and applied as a digital tool in architectural heritage conservation and management, providing powerful 3D modelling(Lovell et al., 2023), information management and documentation capabilities, ANT (Actor-Network Theory) analysis Theory tools are effectively combined with HBIM to create a digital infrastructure platform where information is available to all users for in-depth practical applications when combined with visualization applications is still a large gap area in academia and practice.

The application of ANT theory to the development of information infrastructures for built heritage requires interdisciplinary knowledge and skills, including sociology, architecture, and information science. Currently, mechanisms and platforms to facilitate such interdisciplinary collaboration are not sufficiently developed.

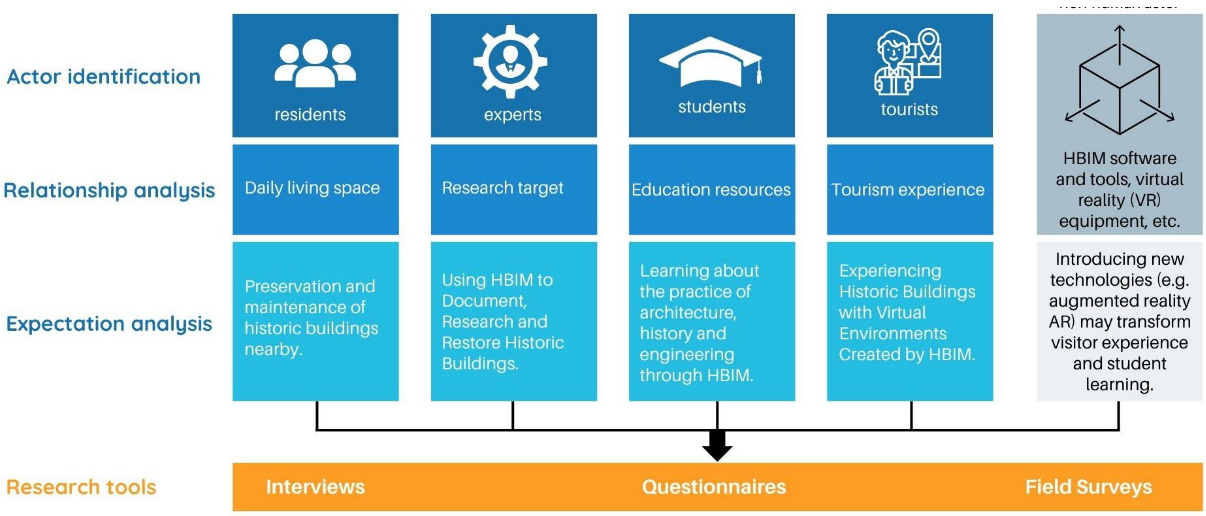


Fig. 8. ANT analysis on HBIM digital conservation participants

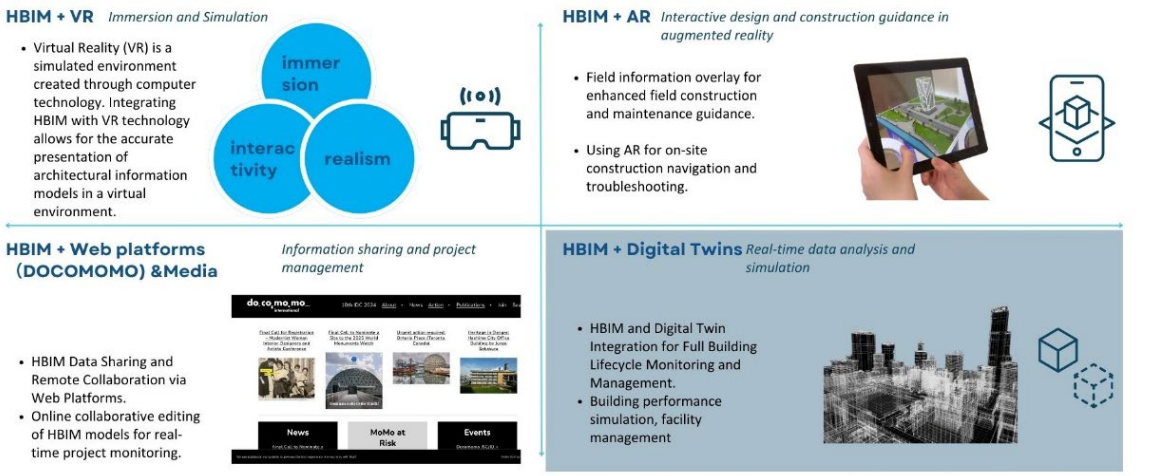


Fig. 18: The Future Collaboration of HBIM and Visualization Tools (Source: own figure)

The research highlights the significance of employing HBIM (Historic Building Information Modeling) and smart point clouds for the digital archiving and protection of heritage sites. Conducting a comprehensive literature review establishes standards for point cloud specifications across different applications and benchmarks the integration of point clouds with vector graphics and other forms of visualization. This includes addressing scattered historical metadata, the absence of dedicated object libraries, and standardization challenges. A comprehensive framework is proposed, incorporating HBIM and digital visualization technologies into the architectural heritage information dissemination process. This advocates for stakeholder collaboration through Actor-Network Theory (ANT) analysis, laying the foundation for providing digital information access to diverse audiences, thus enhancing education, research, and physical preservation planning of heritage sites.

Using this information for ANT analyses helps to understand the complex web of relationships that influence the conservation and resilience of built heritage over time, and the HBIM as an interactive technology can be better integrated into the design of the AHII.