infrastructures

Review

An Investigation of Historic Transportation Infrastructure Preservation and Improvement through Historic Building Information Modeling

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Abstract: Historical transportation infrastructures (HTIs) like railways and bridges are essential to our cultural heritage. However, the preservation and enhancement of these structures pose significant challenges due to their complex nature and the need for modern upgrades. Historic building information modeling (HBIM) has emerged as a solution, facilitating the documentation, restoration, and maintenance of historic transportation assets. The purpose of the proposed work is to provide a systematic review of research findings on the application of HBIM in historic transportation infrastructure, highlighting its role in capturing intricate architectural details and supporting decision making for preservation efforts. A series of case studies in which HBIM has been instrumental in preserving historic transportation infrastructure are investigated and analyzed using a comprehensive literature review method. Furthermore, future directions in HBIM research are proposed, identifying potential applications and recommending areas for further investigation. Additionally, this paper suggests HBIM's potential to balance modernization demands with the conservation needs of historic transportation infrastructure, providing policymakers and stakeholders with insightful strategies for sustainable heritage management.

Keywords: historic building information modeling (HBIM); historic transport infrastructure (HTI); preservation; heritage conservation; infrastructures

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1. Introduction

Maintaining our historical landmarks, particularly those related to historic transport infrastructure (HTI), is vital today. The growing need for efficient transport systems can strain the preservation of historical transport structures, such as railways, bridges, tunnels, and old roads. These enduring structures are not only symbols of past engineering accomplishments but also serve current transportation needs and contribute to regional economic growth. This dual role highlights their importance in both our shared heritage and today's society. However, the increasing challenges associated with preserving these historically significant, yet vulnerable infrastructures call for the development and implementation of innovative and flexible conservation strategies. Studies show that a large portion of the world's HTI is at risk due to ignorance, inadequate funding, and inappropriate development methods. These issues threaten not only our cultural heritage but also have significant economic and functional impacts on the communities they serve [1–3]. Therefore, the protection and preservation of these assets extend beyond cultural obligations and become a vital economic necessity. Each investment in maintenance and rehabilitation can help avoid substantial future reconstruction costs. In essence, conserving cultural heritage is more than a show of pride or adherence to tradition; it is a strategic investment aimed at achieving significant long-term cost savings [4–7].

The preservation of HTI poses a unique challenge as structures must strike a balance between operational standards and historical significance. In the study of Bezgin [8], seven historical transportation structures along with their conservation in modern urban networks and their integration into new urban environments were examined. Loren-Méndez et al. [9] introduced a multidisciplinary approach to evaluate the preservation of roadways, with a specific emphasis on the examination of natural, cultural, and historical characteristics. Furthermore, Olga et al. [10] developed a framework to evaluate the deformations of historical transport infrastructure objects in which the proposed approach involved constructing a model that consists of a polygonal mesh of three-dimensional triangles positioned between deformation marks.

The complexity of these structures has led to the use of historical building information modeling (HBIM) as a tool. HBIM provides a digital platform for detailed analyses and management of these structures, addressing current conservation limitations. Traditionally used in heritage building conservation, HBIM is now being applied more broadly. This shift has been explored in various studies, demonstrating HBIM's effectiveness in documenting, analyzing, and managing complex historical data. Integrating HBIM into preservation practices has been shown to streamline data management processes and facilitate informed decision making in conservation projects [11–13]. Building information modelling (BIM) was implemented in the management of constructed heritage in a study by Charlton et al. [14], in which they implemented a developed application of BIM at a heritage site, which enhanced their comprehension of the obstacles and motivators influencing the adoption of HBIM throughout the heritage industry. Giudice and Osello [15] conducted an investigation by utilizing a case study for the transformation of the approach to revitalizing cultural heritage within the building industry. An investigation of the application of BIM in conservation projects was presented by Pocobelli et al. [16] to study the preliminary stages of BIM implementation in conservation projects. Therefore, a concise overview of the modeling phase and the primary BIM methodologies devised for built heritage were discussed.

The intersection of HBIM and HTI has garnered significant attention in recent research. Studies have explored how HBIM can bridge the gap between heritage conservation and modern engineering practices, facilitating the preservation of transportation heritage while accommodating contemporary needs [17–20]. Recently, several case studies were investigated in the case of the integration of HBIM in HTI. For instance, Gómez et al. [21] examined the historical development of Gothic bridges through the utilization of HBIM technology, which involved parametric 3D modeling and terrestrial laser scanning. For preserving the surviving elements while reconstructing the obscured and vanished sections of the Chinese Eastern Railway, Xu et al. [22] utilized HBIM to analyze structural characteristics derived from fieldwork and original drawings.

This study builds upon previous research by demonstrating the practical application of HBIM in various HTI projects. We present case studies to which HBIM has been applied to showcase the practical implementation of HBIM and to illuminate its effectiveness in real-world conservation projects and provide suggested case studies to which it can be applied, as well as a comprehensive overview of conservation challenges and opportunities. Furthermore, future interdisciplinary research initiatives that will foster a new era of historic transportation infrastructure conservation practice are discussed, providing synthesized findings that will contribute to the evolving discourse on heritage conservation and practical insights for future applications of HBIM in heritage protection.

The layout of the rest of this paper is constructed as follows: Section 2 presents a comprehensive analysis of historical infrastructure, emphasizing its significance and the challenges it poses. Following that, Section 3 presents HBIM as a competent tool for the preservation of cultural assets. The details of implementing HBIM in HTI are presented in Section 4. Section 5 includes the practical case studies that are investigated in this work. The methodologies of how HBIM might further enhance HTI and a further discussion about the integration of HBIM into HTI are included in Section 6. Finally, Section 7 presents the main conclusions of the proposed work and our final remarks.

2. Methodology

To ensure the investigation is representative, a comprehensive literature review on the application of HBIM in HTI was conducted. We performed a thorough search of academic databases covering recent years, using keywords such as “HBIM”, “historic transportation infrastructure”, “preservation”, “heritage conservation”, and “case studies”. Our search focused on peer-reviewed journal articles, conference papers, and relevant books.

To ensure relevance and comprehensiveness, we employed specific criteria for selecting case studies featured within the literature. Studies were prioritized if they (1) directly addressed the application of HBIM in HTI, (2) provided detailed methodological descriptions, and (3) demonstrated notable outcomes of and insights into HBIM practices. From the selected studies, we extracted key information, including the type of infrastructure studied, HBIM techniques and tools employed, the process, and study outcomes.

This extracted data were then systematically analyzed to identify common themes and best practices in current HBIM research within the HTI context. Our analysis focused on understanding how HBIM contributes to HTI preservation, the benefits it offers, and the challenges it addresses. Six case studies, representing diverse HBIM applications across different types of HTI, were chosen to exemplify these themes and provide a comprehensive overview of HBIM methodologies, outcomes, and challenges. This synthesis of the literature and analysis of representative case studies form the basis for the discussion and conclusions presented in this paper.

3. Historic Transportation Infrastructure

3.1. An Overview

HTI contains the foundational structures that facilitate movement and connection between cities. This comprehensive category includes railways, airports, roads, bridges, and tunnels, all of which have played a significant role in the progression of commerce, communication, and travel across different periods, serving as symbols of the historical significance of the locations where they are placed. Combining the designs, materials, and methods that were employed during their construction, these structures mirror the technological and engineering progress of their era [8,23].

Roads, the earliest form of transport infrastructure, have been essential in the development of civilizations, allowing the exchange of goods, ideas, and cultures. They represent the routes taken by pioneers and traders and have often evolved from simple paths to complex highway networks. Bridges and tunnels, feats of civil engineering, have traditionally conquered natural barriers like rivers and mountains, improving accessibility and fostering regional integration [24]. The inception of railway systems revolutionized the 19th and early 20th centuries by introducing a rapid and reliable means of long-distance travel and freight transport. They became the arteries of industrial nations, spurring urbanization and playing key roles in historical events. Many railway stations are architectural masterpieces, reflecting the prosperity and aspirations of the societies that built them [22]. Each type of historic transportation infrastructure presents unique characteristics, and their preservation offers numerous opportunities to understand their layers of human development. They bear witness to the evolution of technology and socioeconomic standards and are invaluable in interpreting the historical context of landscapes and nations. Preservation work on these infrastructures is crucial not only for maintaining their heritage and educational value but also for sustaining their functionality in today’s ever-expanding transportation network [22,24].

Infrastructure assessment throughout the years has been the subject of numerous case studies. For instance, Mimeur et al. [25] developed a historical geographic information system to document the progression of a railway network from 1860 to 1910, in which they described the effect of the expansion of the network on structures. Also, McKay et al. [26] analyzed historical transportation trends spanning a significant period of time through the comparison of transport studies that were conducted between 1975 and 2003, illustrating implications, trends, and patterns derived from observed transportation policies and practices.

3.2. Significance and Preservation Challenges

HTIs hold significant cultural and historical value, serving as tangible representations of past societies' advancements in technology, economic development, and societal progress. Railways, bridges, and tunnels are not just functional structures but also symbols of human ingenuity and the interconnectedness of communities. These infrastructures embody the identity and history of the regions they serve, acting as monuments that reflect cultural and architectural heritage. The preservation of these structures is crucial to maintaining a tangible link to the past and fostering an appreciation for history [22,27]. On the other hand, the preservation of HTI faces various challenges, primarily stemming from natural deterioration, aging, and exposure to environmental factors. The need to balance preservation efforts with modern safety standards and usability requirements poses a significant challenge. Maintaining historical accuracy while adapting structures for contemporary use adds complexity to preservation endeavors, especially considering the scarcity of original construction documentation and the unique characteristics of these infrastructures. These challenges highlight the importance of developing effective preservation strategies that ensure the longevity and safety of historic transportation structures while respecting their cultural significance [27,28]. The critical need for effective preservation lies in their dual roles as cultural heritage sites and active components of modern networks. Keeping these structures in service requires an approach that respects their historical significance while ensuring their reliability and safety for current users. Preservation sustains a tangible connection to our past and contributes to our understanding and appreciation of history [28]. Additionally, many historic transportation structures are part of vital networks, and their maintenance is crucial for regional connectivity and the economy. Thus, the preservation of historic transportation infrastructures is an endeavor of both reverence for the past and responsibility towards the future.

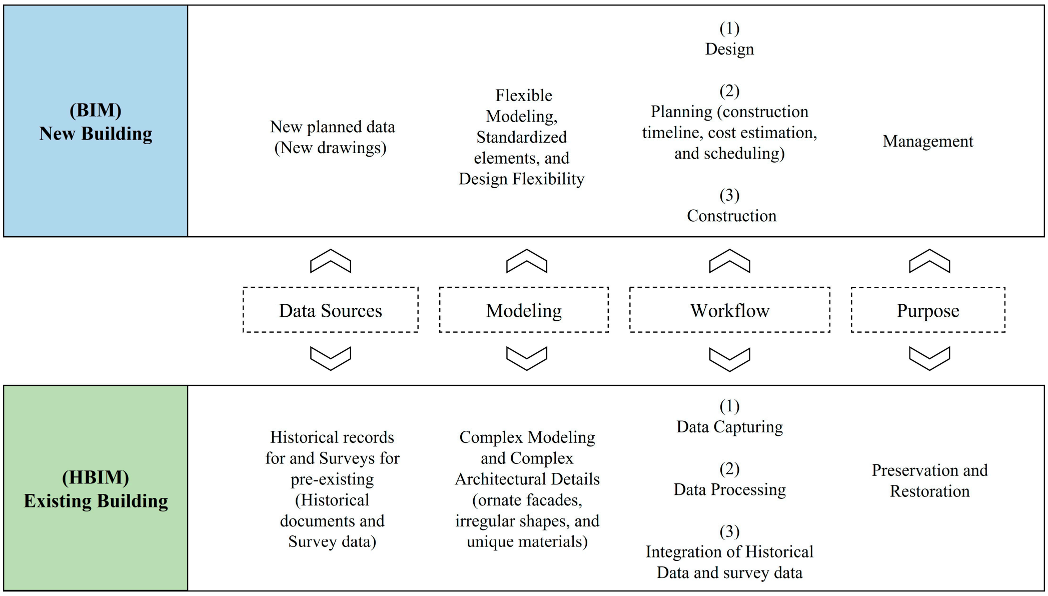
4. HBIM: Foundations and Applications in Heritage Conservation

4.1. Overview of HBIM and Its Inception

HBIM is a specialized subset of BIM that focuses on incorporating the conservation of cultural heritage into the digital planning domain, as first proposed by Murphy [11]. HBIM emerged as a response to the need of generating precise digital models of historical structures and locations. These models must capture the distinctive architectural elements and materials of these buildings with great accuracy, necessitating more nuanced and precise data [29].

The evolution of HBIM builds upon traditional methods of architectural conservation and documentation, now greatly enhanced by advances in three-dimensional scanning and modeling technologies. A crucial aspect of HBIM involves deciding whether to utilize historic plans from archives or to conduct measurements on the actual building. Historic designs are particularly valuable in restoration efforts following damage, as they provide comprehensive information on design, materials, and construction methods, facilitating precise restoration. However, in cases in which original blueprints are unavailable or inadequate or when the building has undergone significant alterations over time, modern measurement techniques such as laser scanning and photogrammetry become indispensable. These methods accurately capture the current condition of the structure, enabling informed decisions throughout the preservation and restoration phases.

By leveraging these digital techniques, HBIM creates parametric libraries based on historic architectural data and manuscripts, from Vitruvius to 18th-century pattern books; this allows for a more profound understanding and recreation of historical architecture within a digital environment. HBIM distinguishes itself from regular BIM through its specialized focus on heritage assets. While standard BIM processes are designed to optimize the planning, design, construction, and management of new buildings, HBIM is tailored to capture and maintain the intricate details of existing heritage structures [11,30]. When applied to heritage infrastructure, HBIM goes beyond the creation of digital models for new construction projects. It is a tool for reverse-engineering historical buildings by collecting detailed survey data, through methods such as laser scanning and photogrammetry, which are then used to build an information-rich model that documents the structure's current state and assists in its conservation (Figure 1). The level of detail required for these models is typically much higher than that of standard BIM, as it must encapsulate elements that have both cultural significance and intricate craftsmanship [31]. Moreover, HBIM models serve as digital twins for heritage sites, embodying the as-built condition of a structure and providing a platform for analysis, restoration, and educational purposes. This includes the ability to visualize changes over time, simulate the effects of potential interventions before they occur, and generate detailed documentation for conservation efforts [32].



	Data Sources	Modeling	Workflow	Purpose
(BIM) **New Building**	New planned data (New drawings)	Flexible Modeling, Standardized elements, and Design Flexibility	(1) Design (2) Planning (construction timeline, cost estimation, and scheduling) (3) Construction	Management
(HBIM) **Existing Building**	Historical records for and Surveys for pre-existing (Historical documents and Survey data)	Complex Modeling and Complex Architectural Details (ornate facades, irregular shapes, and unique materials)	(1) Data Capturing (2) Data Processing (3) Integration of Historical Data and survey data	Preservation and Restoration

Figure 1. Comparison of BIM for new buildings and HBIM for existing buildings, highlighting the data sources, modeling, workflow, and purpose for each.

By virtue of this distinct approach, HBIM adapts the principles and technology of BIM to the preservation and management of historical structures, ensuring that these cultural monuments are not only remembered but also kept in a state that allows them to be actively appreciated by future generations.

4.2. HBIM Methodology

HBIM methodology is a comprehensive process that involves capturing intricate details of historic structures and transforming these data into interactive digital models for conservation and management purposes (Figure 2). The methodology comprises several stages, integrating key technologies at each step to ensure the accuracy and fidelity of the digital models [33]. The initial phase of the HBIM methodology involves data collection, in which advanced techniques such as terrestrial laser scanning and photogrammetry are utilized to gather detailed information from the historic site. Terrestrial laser scanning creates point clouds that capture precise measurements of physical structures in three dimensions, while photogrammetry converts overlapping photographs into point clouds and comprehensive three-dimensional models, providing the geometric and textural information that is essential for HBIM [34]. Subsequently, the collected data undergo processing using software tools to create a coherent representation of the existing structure. This step involves managing and manipulating vast datasets to ensure the alignment and integration of disparate data sources, preparing the groundwork for the modeling phase [35].

The model creation stage utilizes advanced BIM software to construct detailed architectural elements through various modeling approaches. Custom objects are often required for historic structures due to their unique architectural features, which differ from those of contemporary buildings [36,37]. A distinguishing feature of HBIM is the integration of rich historical information into the digital model, including material composition, construction techniques, historical timelines, and documented restorations. This integration provides a holistic view of the structure as both a physical entity and a historical document, enabling preservationists, researchers, and stakeholders to understand the context, significance, and evolution of a historic building for informed decision-making processes [38].

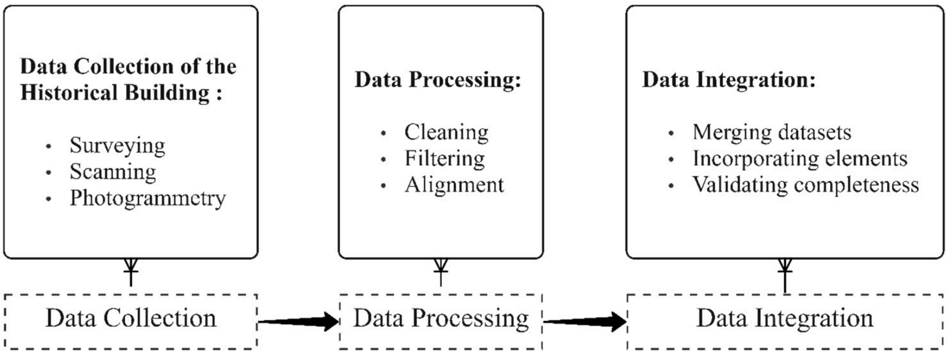


Figure 2. HBIM methodology [39].

4.3. Core Functions of HBIM

Heritage building preservation and maintenance are significantly impacted by HBIM. It functions as an encompassing documentation tool, capturing the rich architectural and historical data of these structures. This is illustrated through case studies. For example, at the Copper Coast Geopark in Ireland, Dore et al. [40] demonstrated the efficacy of detailed HBIM in conserving complex structures for study, analysis, and historical research.

In the area of maintenance and rehabilitation, HBIM provides a structured and detail-oriented framework for the care of heritage structures. It aids in identifying areas in need of repair, planning restoration interventions with precision, and tracking rehabilitation progress. Based on a review of recent works, Sousa et al. [41] developed a framework for using HBIM in rehabilitation and assessment based on a study of current studies. This framework aims to enhance the knowledge of how HBIM may be used to effectively manage important and necessary structures. Brumana et al. [42] reported the findings of their continuing research and efforts focused on surveying and undertaking HBIM of historical structures.

For operational management, HBIM is invaluable in the day-to-day maintenance of heritage sites. It integrates detailed models with current operational data, assisting in managing a site’s physical fabric, visitor movements, and daily maintenance tasks. A novel HBIM framework to manage heritage buildings, enabling integrated three-dimensional digital documentation for conservation and restoration planning, along with supporting facility management activities, was developed by Khan et al. [43]. Regular updates to the HBIM model ensure stakeholders have current data to make informed decisions regarding the maintenance and ongoing use of buildings. The functions mentioned above, each in its distinctive manner, emphasize the appropriateness of employing HBIM within the framework of historical infrastructure. HBIM, an advanced digital representation tool, possesses the ideal capabilities to efficiently represent and document the complicated historical details and complex geometries that are intrinsic to these structures.

5. Transition to Historic Transportation Infrastructure

The transition to applying HBIM in historic transportation infrastructure signifies a paradigm shift in heritage conservation practices. Recent research has highlighted its potential in an area often neglected in heritage conservation—transportation infrastructure. Like buildings, transportation infrastructures possess unique stories and complexities that require specific conservation strategies. HBIM, with its ability to capture detailed records of infrastructure components, enables the smooth integration of historical data with current operational needs.

The flexibility of HBIM is emphasized, showcasing its ability to create comprehensive and manipulable records of complex structures. Focusing on the utility of HBIM in the context of transportation, it underscores its capacity to support crucial analysis and decision-making processes for preservation efforts [44].

The application of HBIM to historic transportation infrastructure allows for a nuanced approach to preservation, in which the detailed digitization of physical assets enhances our understanding and management of their historical and current states [45]. HBIM provides a forward-thinking perspective on the conservation and enhancement of transportation heritage, ensuring these infrastructures continue to fulfill their purpose while preserving history.

The integration of new design solutions, while respecting and retaining heritage value, is crucial in managing the delicate balance between conservation and contemporary operational demands. Innovative strategies for incorporating modern materials and techniques through HBIM ensure the continued functionality of historic transportation structures within modern networks. Empirical evidence from case studies demonstrates successful applications of HBIM in railway preservation, maintaining both the aesthetic and functional aspects of these structures according to Ewart and Zuecco [45]. HBIM extends its utility beyond conventional building structures, proving indispensable in the analysis and management of transportation infrastructure. Its versatility allows it to be used throughout various aspects of infrastructure stewardship, including in risk assessments, structural analyses, and retrofitting and rehabilitation.

- Risk Assessments: HBIM serves as a preemptive tool for assessing risks associated with transportation infrastructure. Through its capacity for detailed modeling, HBIM allows for the simulation of potential impacts due to environmental and human factors, aiding in the development of risk mitigation strategies. International research, such as Barazzetti et al.'s investigation into seismic risk assessments of historic structures in Italy, utilizes HBIM to simulate weaknesses and develop suitable reinforcement approaches [36].
- Structural Analyses: Critical to HBIM applications, structural analyses provide insights into the current state and historical evolution of transportation infrastructure. By employing advanced modeling techniques, HBIM furnishes a comprehensive understanding of structural behavior, material degradation, and the effects of loads over time. For instance, a historical church and a masonry bridge were the subjects of an examination by Pepe et al. [46] in a cultural heritage setting. Their model is used for various objectives, such as performing a structural analysis and parameterizing rheological and geometric data for individual components of the structure to evaluate its structural integrity and conservation requirements.
- Retrofitting and Rehabilitation: HBIM plays a crucial role in planning and executing retrofitting and rehabilitation projects for transportation infrastructure. It allows for the precise modeling of existing conditions and the integration of new design elements in a cohesive digital environment. By utilizing previously recovered damage information that aids in the rehabilitation process through monitoring and classification, Polania et al. [47] established a damage database for the demolished structures of the Largo Grosseto bridge using HBIM methodologies. This study introduced a new standard procedure for infrastructure observation processes.

Through these applications, HBIM emerges as a vital tool in the management and preservation of heritage transportation infrastructures worldwide, striking a balance between conservation and contemporary demands. It provides decision makers with a detailed and accurate basis for maintaining and enhancing infrastructure while offering insights into its historical evolution.

6. HBIM Solutions for Preserving Heritage Transportation Infrastructures: Case Studies

This section presents case studies demonstrating the adoption of HBIM in HTI. These studies illustrate HBIM's practical application and effectiveness in preserving and managing transportation heritage sites.

6.1. Iron Bridges of Italian Railways

The 19th century marked a significant period in Italy's infrastructural development, particularly with the construction of railway bridges over the River Po between 1863 and 1892 (Figure 3). These iron lattice truss bridges, a technological advancement imported from the United States and later adopted in Europe, played a crucial role in the development of the national infrastructure system, especially following the country's unification. However, due to changing needs of railway traffic and bombings during World War II, these bridges were eventually demolished. Despite their loss, Donato et al. [19] emphasized that modern three-dimensional tools can comprehensively explore and allow one to appreciate the historical and technological significance of these bridges.

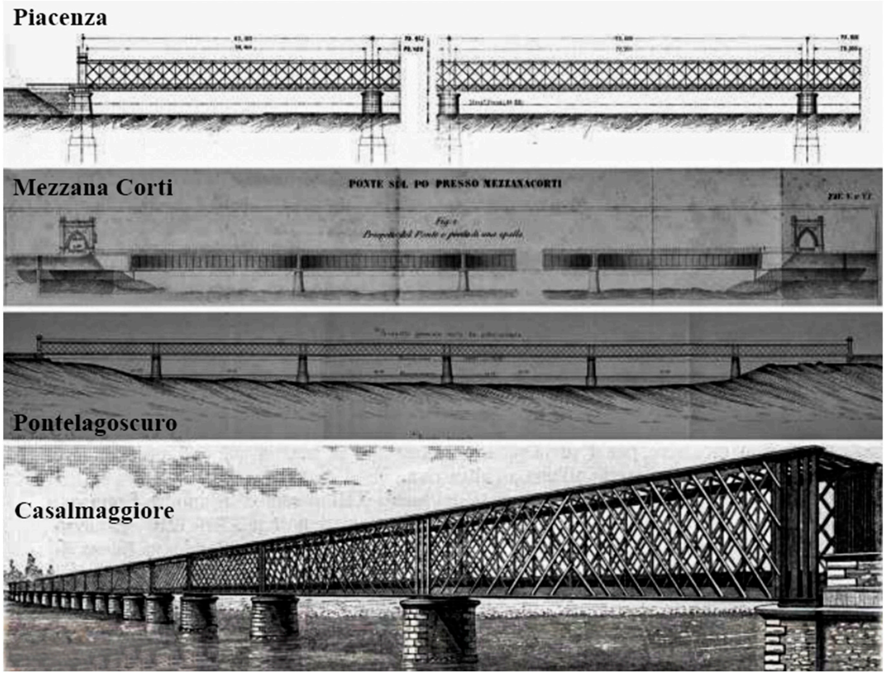


Figure 3. Railway bridges over the River Po [19].

The use of three-dimensional software with visual programming language (VPL) allows for the creation of modeling tools that enhance the historical value of these lost railway bridges through three-dimensional modeling and virtual representation. By combining traditional historical research with advanced three-dimensional modeling techniques, the study aimed to shed light on the architectural features, construction techniques, and structural innovations that characterized these iconic bridges and their impact on the landscape of the Po Valley. The best practices of the HBIM methodology were followed, and the use of HBIM as a viable methodology for the comprehensive documentation and representation of the bridges' geometric and structural features was introduced. Unlike traditional HBIM methodologies, this study faced unique challenges due to the demolition of the bridges several decades ago, necessitating the development of specialized tools to model the intricate iron and steel components used in these structures (Figures 4 and 5). Through the development of a VPL algorithm, the work aimed to provide a comprehensive and accurate representation of the railway bridges over the Po River. The outcomes of the research highlighted the architectural features of the railway bridges and their role in the development of the unified state's infrastructure system. The results showed that the VPL algorithm is flexible enough to handle a wide range of geometric and structural features. Through the application of the HBIM methodology, the work contributed to the preservation and documentation of Italy's industrial heritage, emphasizing the importance of integrating technology with historical research.

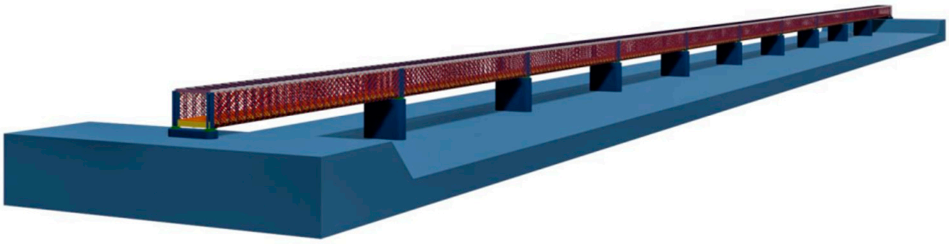


Figure 4. A general representation of the bridge in Mezzana Corti [19].

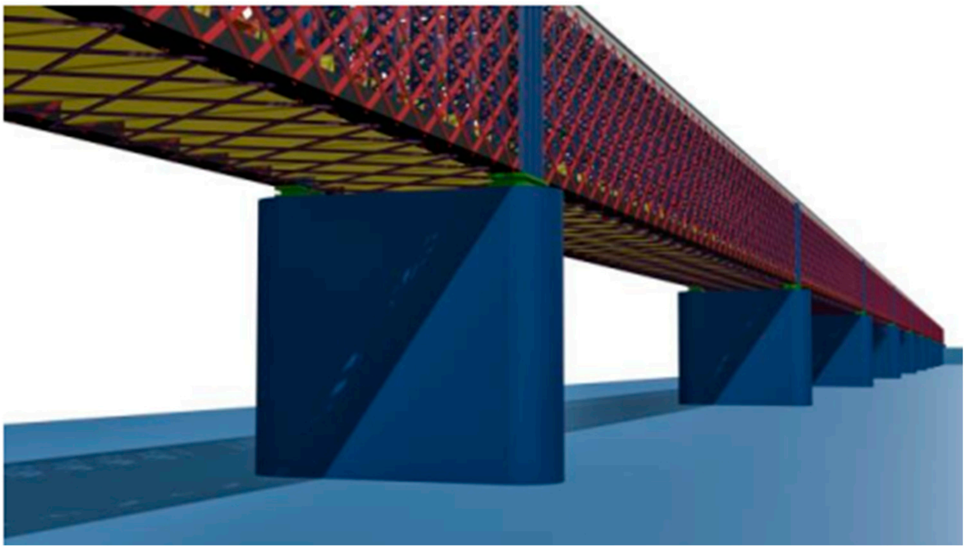


Figure 5. Bottom view of the bridge in Mezzana Corti [19].

The adaptation of HBIM to iron architecture highlighted a lesser-explored facet of heritage conservation. By merging traditional historical research with advanced three-dimensional modeling tools, the study highlighted the intricate relationships inherent in the construction of these bridges. This innovative approach represented a significant step in preserving and understanding Italy's industrial heritage, emphasizing the synergy between historical knowledge and cutting-edge technology.

6.2. Narrating Serranos Bridge

Valencia, Spain, situated on the Turia River, has a history marked by periodic flooding, necessitating the construction and maintenance of bridges. Among these, the Serranos Bridge stands out as a significant architectural landmark (Figures 6 and 7), recognized for its historical and cultural significance. Despite being the oldest bridge in the city, it has not been the subject of comprehensive study compared to other bridges. Gómez et al. [21] explored the evolution of the Serranos Bridge over time using HBIM techniques, combining remote sensing data, scan-to-HBIM workflows, and parametric three-dimensional modeling. Historical documents, including maps and views dating back to the 16th century, are integrated into the HBIM project to recreate the bridge's architectural features and volumetric changes. This approach allowed for a detailed examination of the bridge's evolution, shedding light on its historical importance within the urban landscape of Valencia [21].

Figure 6. The Serranos Bridge in 2023 [21].

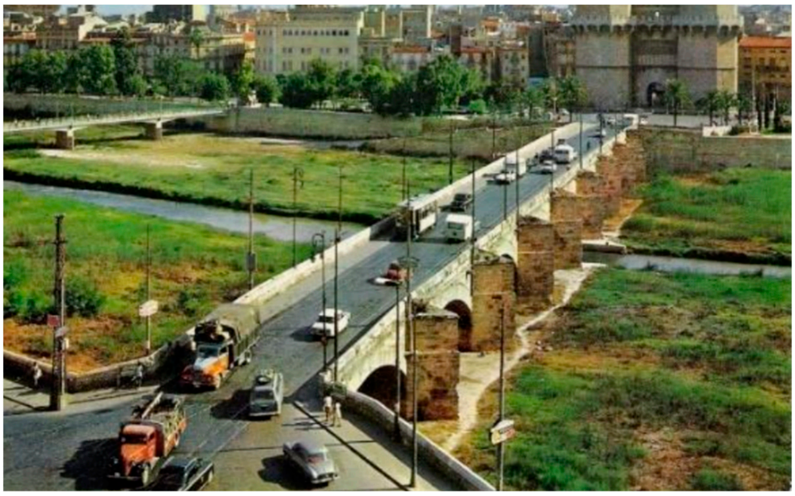


Figure 7. The Serranos Bridge in 1960 [21].

HBIM technology was utilized to meticulously document and recreate the evolution of the Serranos Bridge. Drawing from diverse sources such as historical documents, photographs, architectural drawings, and physical measurements, the case study provided insights into the bridge's original design and subsequent modifications. Advanced scanning technologies, including laser scanning, were employed to capture detailed and accurate data of the bridge, which were subsequently processed and enriched using BIM software to generate a digital twin. By harnessing HBIM's capabilities, Gómez et al. were able to individually model components, define distinct phases, and integrate historical data seamlessly, providing a holistic view of the bridge's evolution. This multifaceted HBIM workflow encompassed data acquisition, three-dimensional modeling, documentation, an analysis, and a reconstruction of the bridge's various historical periods.

The Serranos Bridge was successfully reconstructed using HBIM, revealing its evolution over time with detailed three-dimensional models (Figure 8). This integration streamlined the workflow, efficiently capturing its architectural nuances and restoration efforts. The HBIM reconstruction provided insights into changes in its architectural features and volumetric shifts. However, it also highlighted oversights in its restoration, such as the neglect of certain historical elements, like stone seats.

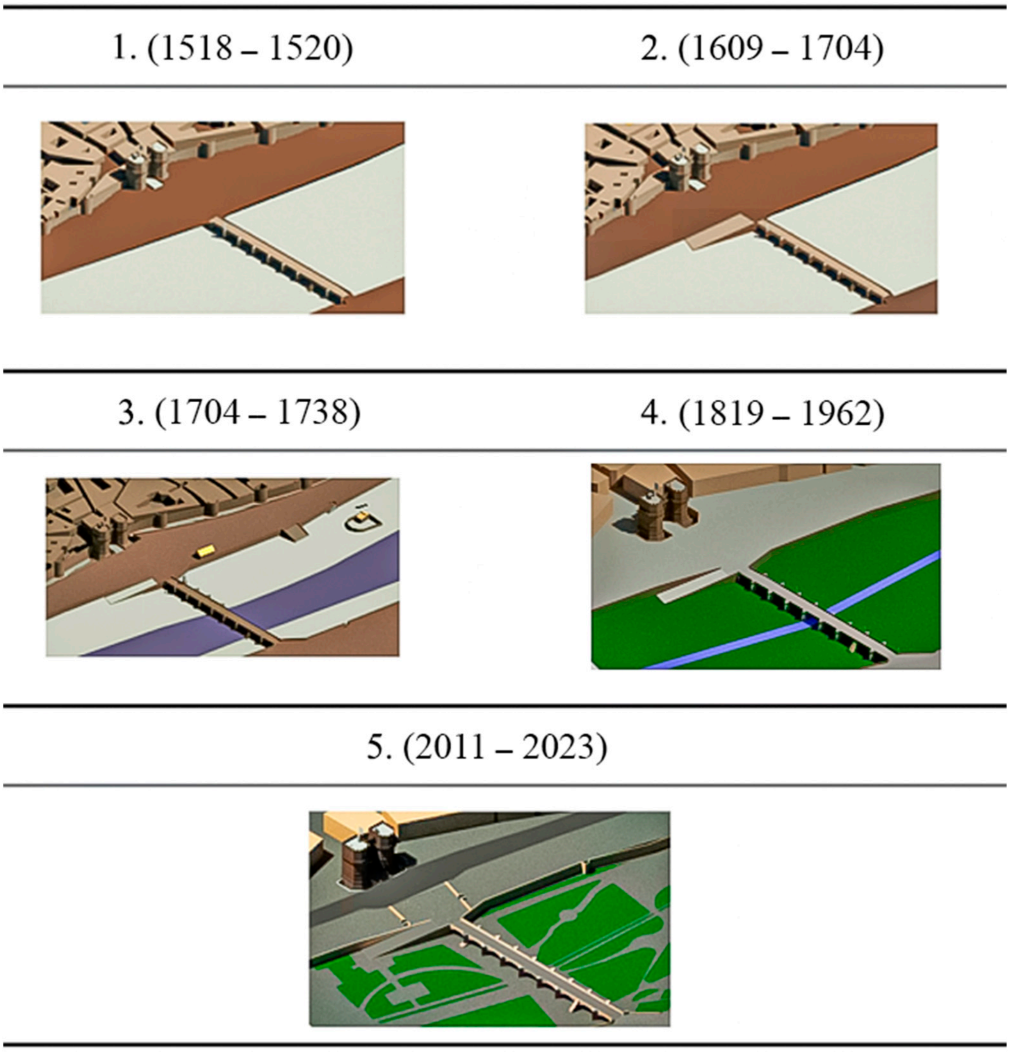


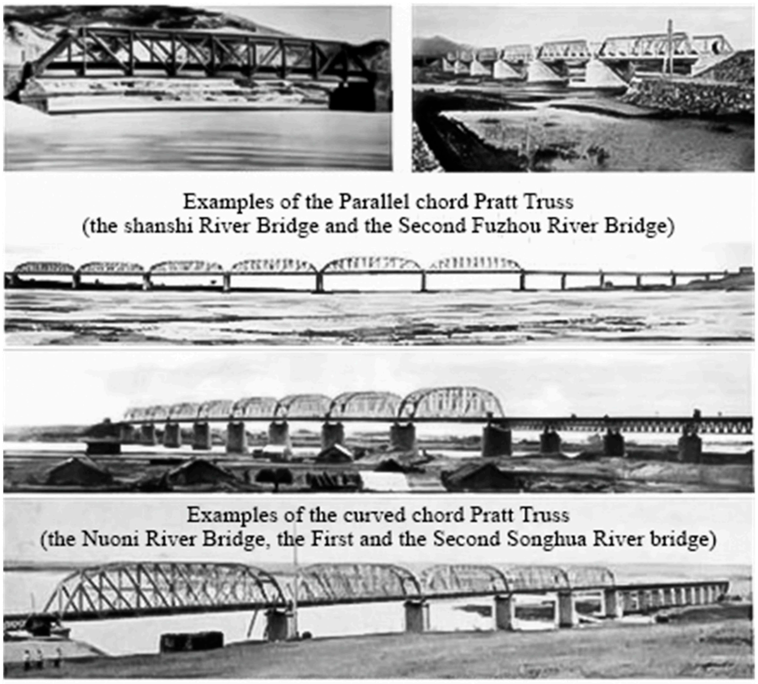
Figure 8. Serrano Bridge result, representing its evolution over time [21].

The importance of HBIM, historical data, and geomatics are highlighted in comprehending the complex evolution of historical structures like the Serranos Bridge. By integrating advanced technology with historical research, the work vividly brought to life the rich history of the bridge, offering valuable insights into its architectural development. The comprehensive virtual representation created through HBIM served as a valuable tool for its preservation, research, and cultural appreciation. In conclusion, HBIM technology has played a crucial role in documenting and understanding the dynamic changes that have shaped the Serranos Bridge over the centuries, facilitating its study and preservation as an important cultural heritage site.

6.3. The Chinese Eastern Railway

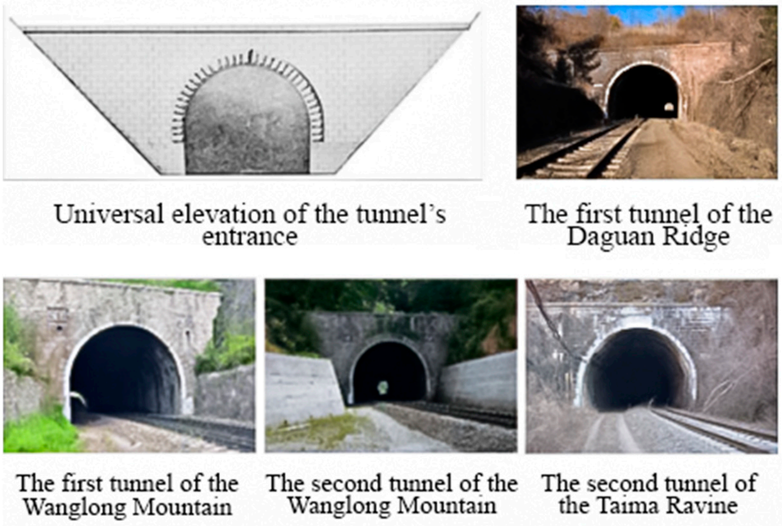
The Chinese Eastern Railway (CER), built between 1897 and 1903, is a prime example of heritage railways that connect remote regions with ancient cultures to contemporary society through exceptional infrastructure engineering. It links Russia with Northeastern

China, navigating challenging terrain through the construction of bridges, culverts, tunnels, and spiral lines (Figures 9 and 10). Despite its historical importance, infrastructure heritage along railway routes, including the CER, has often been overlooked in China, receiving less attention compared to architectural heritage. Xu et al. [22] discussed the integration of HBIM and Geographic Information System (GIS) data to preserve the infrastructure heritage along the CER, which is considered a symbol of the highest standard of technical construction and design methodologies. The infrastructure heritage of the CER represents the pinnacle of technical achievement and is a vital component of its cultural legacy [22].


Examples of the Parallel chord Pratt Truss
(the shanshi River Bridge and the Second Fuzhou River Bridge)

Examples of the curved chord Pratt Truss
(the Nuoni River Bridge, the First and the Second Songhua River bridge)

Figure 9. Some examples of CER bridges [22].


Universal elevation of the tunnel's entrance

The first tunnel of the Daguan Ridge

The first tunnel of the Wanglong Mountain

The second tunnel of the Wanglong Mountain

The second tunnel of the Taima Ravine

Figure 10. Some examples of CER tunnels [22].

Despite facing threats from urban expansion and natural degradation, the study aims to reconstruct the vanished and invisible parts of the CER by analyzing structural features based on original drawings and fieldwork. By integrating HBIM and GIS technologies, the work endeavored to document, analyze, and preserve the diverse elements of the CER's infrastructure, ensuring their longevity and cultural significance for future generations.

HBIM is instrumental in conserving the surviving elements of CER by enabling the precise reconstruction and modeling of its heritage components. By integrating historic data and contemporary research into a digital database, HBIM supports holistic preservation efforts. Additionally, the integration of HBIM with GIS enhances preservation efforts by creating dynamic databases that incorporate historical and current data, facilitating the effective management and conservation of infrastructure heritage. This synergy ensures the longevity and cultural significance of the CER for future generations.

The integration of HBIM and GIS technologies has yielded significant progress in documenting and analyzing the infrastructure heritage along the CER. Through fieldwork and data collection, a detailed database was created, providing essential information for heritage management and conservation planning. This database, which includes geographic coordinates, structural details, and historical information, serves as a valuable resource for government agencies, conservation organizations, and the public. By leveraging the capabilities of HBIM and GIS, the study demonstrates effective methods for preserving and valorizing cultural heritage in a sustainable manner. Furthermore, this offered a sustainable approach to preserving the cultural heritage of the CER infrastructure. This study emphasized the need for interdisciplinary cooperation, geographic data collection, and the creation of a database for efficient heritage management. Support from funding bodies, fieldwork contributions, and collaborative efforts are acknowledged to advance heritage conservation practices.

6.4. The Carlo III Bridge

The Carlo III Bridge (Figure 11), part of the Carolino Aqueduct in Moiano, Italy, is a significant historical structure built in the 18th century. Despite its historical importance, it has suffered from neglect and unauthorized interventions, leading to significant deterioration. To address these challenges, Conti et al. [17] applied historic building information modeling (HBIM) to provide comprehensive documentation and a maintenance plan [17].

Figure 11. Carlo III Bridge [17].

HBIM, which involves creating a parametric digital representation of existing structures, was used to accurately model the bridge's geometric and spatial data, including semantic content related to materials, degradation, and conservation interventions. The HBIM model served as a "smart repository", integrating GIS and HBIM data for comprehensive conservation and maintenance databases. This model, created using advanced survey techniques like laser scanning and photogrammetry, served as a reliable foundation for preservation and restoration efforts, establishing a common data environment for informed decision making in maintenance projects. The application of HBIM to the Carlo III Bridge yielded comprehensive and accurate HBIM (Figure 12), incorporating both graphical and non-graphical data. This model served as a valuable tool for maintenance, restoration, and conservation planning. By utilizing integrated three-dimensional survey data, the HBIM model allowed for the real-time monitoring of the bridge's condition and facilitated decision-making processes. The dynamic database of the HBIM model streamlines traditional manual operations and enhances the effectiveness of conservation interventions and future maintenance efforts.

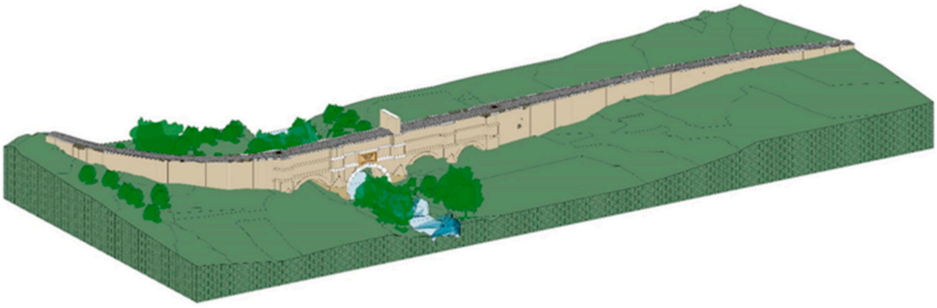


Figure 12. The HBIM of Carlo III Bridge [17].

The application of HBIM to the Carlo III Bridge exemplified the potential of digital technologies in heritage preservation. Despite challenges in adapting traditional BIM tools for historic structures, this study emphasized the need for further research and collaboration to enhance HBIM's utilization in cultural heritage preservation. The models made from combined three-dimensional surveys not only accurately showed the shape of the bridge but also linked parts of it to information about materials, damages, and conservation efforts, providing a complete way to manage its heritage. HBIM served as an operational tool for managing existing information and guiding future interventions, ensuring the sustainable conservation of historical structures.

6.5. The Giorgini Bridge

The Giorgini Bridge (Figure 13), located in Castiglione della Pescaia, Italy, is a significant historical structure that played a crucial role in the reclamation of the Maremma area. The bridge, with a width of 26 m and a height of 12 m, features two lateral shoulders, lowered round arches, and pylons housing three floodgates essential for marshland management. These floodgates, which could be operated manually or automatically, regulated the ingress and egress of seawater during tidal cycles, preventing marshland inundation. Donato et al. [20] explored the challenges and opportunities associated with implementing HBIM for historical infrastructure. They examined the difficulties in accurately capturing the bridge's complex geometry using structure from motion (SfM), terrestrial laser scanners (TLSs), and unmanned aerial vehicles (UAVs). Despite these challenges, HBIM emerged as a promising solution for the conservation and restoration of architectural heritage [20].

In the preservation of historical infrastructure, HBIM provided solutions for data management and decision-making support. However, converting geometrical survey data to parametric elements presented a significant obstacle. To conserve essential geometric details, this procedure required careful consideration regarding accuracy, simplification levels, and interoperability. The research established a 'lean' HBIM methodology and enhanced its workflow velocity. Implementing HBIM for historical infrastructure required meticulous survey techniques and semantic parsing to accurately represent building elements. The study explored the transition from point cloud data to HBIM models (Figure 14), emphasizing accuracy and fidelity in representing historical structures. The integration of diagnostic investigations enhanced the utility of restoration and conservation efforts, facilitating decision making, comparisons, and strategic planning for heritage site management.

Figure 13. The Giorgini Bridge [20].

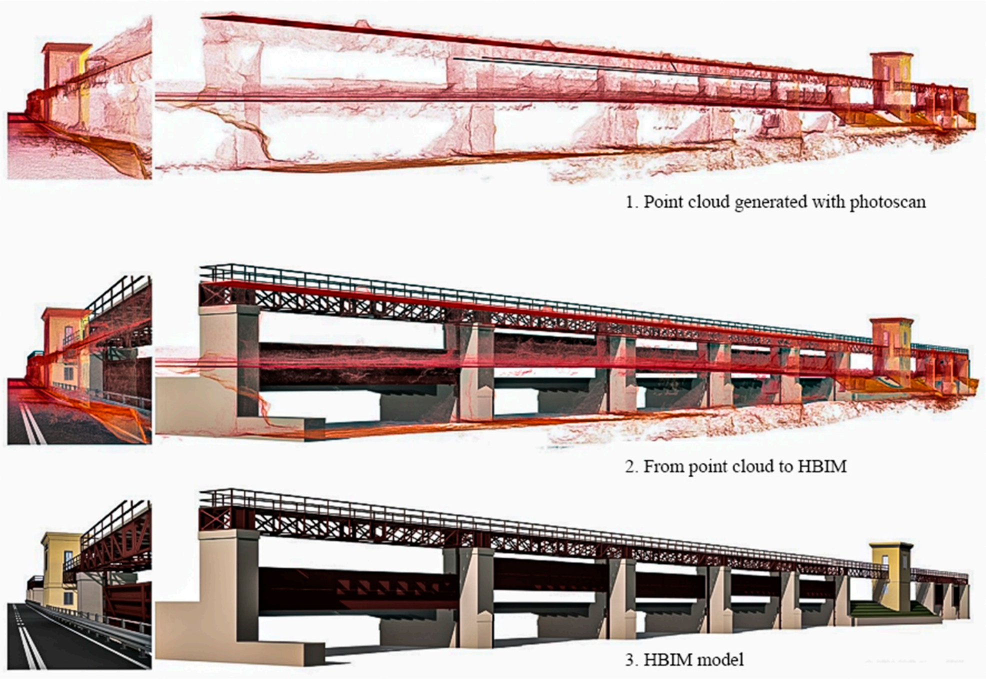


Figure 14. The process from point cloud to HBIM [20].

Through a detailed examination, the advantages and limitations of implementing HBIM for historical infrastructures were revealed. Despite the complexity of geometric data acquisition, the need for accurate building object models (BOMs), and the challenges of preserving original survey data, HBIM showed significant potential for facilitating the restoration and maintenance of historical infrastructure. The optimization of the workflow of information for existing artifacts led to 'lean' HBIM, showcasing the potential for improved efficiency and effectiveness in managing and preserving historical infrastructure. Ensuring the accuracy of digital models and effectively converting information into parametric elements are vital considerations within HBIM. Additionally, the establishment of a comprehensive glossary about historic materials and building elements is imperative for successful BIM modeling in the field of historical heritage. As HBIM continues to progress, future research will focus on incorporating additional diagnostic data into HBIM models and enhancing data interoperability. Collaborative efforts with organizations provide invaluable insights and resources for advancing HBIM implementation in cultural heritage conservation. By addressing these challenges and leveraging technological advancements, HBIM emerges as a promising tool for preserving and safeguarding historical infrastructure for future generations.

6.6. HBIM Applied to a Stone Bridge

The study by León-Robles et al. [18] introduced "Historical Bridge Information Modelling" (HBrIM), or HBIM, a novel approach for preserving historical bridges like the Ízbor Bridge in Granada, Spain (Figure 15). This bridge, built in the late 18th century, is significant for its historical and engineering value. The study used HBIM to document and analyze the bridge, emphasizing its construction details and conservation status. Laser scanning and BIM were utilized to generate a comprehensive model of the bridge, constructed in 1860, allowing a deeper understanding of its materials, geometry, and preservation requirements.

Figure 15. Ízbor bridge [48].

Despite the absence of parametric elements tailored for historical heritage in commercial BIM software, new parametric families were developed to accurately represent similar historical constructions. This process involved recording essential features of historical monuments, including their geometry, materials, and textures, while establishing relationships between the elements within the BIM model. The analysis of the Ízbor Bridge through HBIM revealed crucial insights into its structural condition and conservation needs. Significant changes and deformations spanning 158 years were identified, emphasizing the importance of ongoing monitoring and maintenance. The temporal data captured by the HBIM model provided a valuable foundation for planning future conservation measures, helping to prevent potential pathologies and ensure the bridge's long-term preservation. The HBIM model served as a valuable reference for similar heritage monuments and can aid government planning and conservation agencies in devising effective preservation strategies (Figure 16).

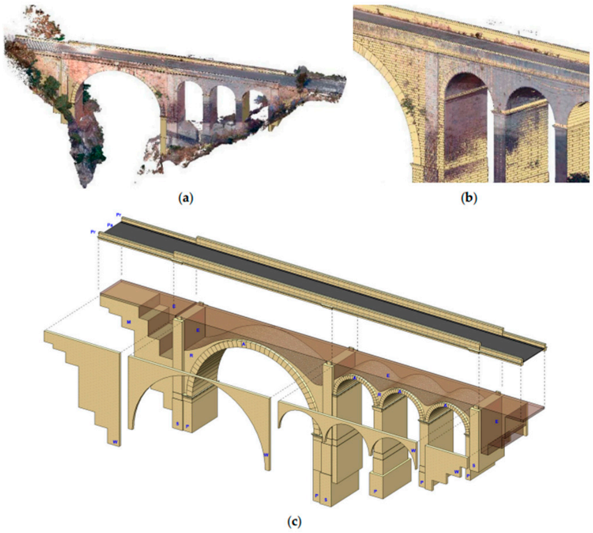


Figure 16. (**a**,**b**) Ízbor Bridge PC (point cloud) and BIM (building information modeling); and (**c**) exploded view of Ízbor Bridge BIM [18].

The efficacy of HBIM in comprehensively documenting and managing historic structures was demonstrated, laying the groundwork for continued conservation efforts and cultural heritage appreciation.

7. Discussions: Comprehensive Examination of HBIM for HTI

After a comprehensive examination of HBIM for HTI through a series of case studies spanning various geographical locations and historical periods, it is evident that the HBIM approach is utilized for both infrastructure and buildings. Each study outlined the model creation process, the uses of the digital model, and the LOD employed (Table 1). The primary goal of HBIM is to effectively preserve, maintain, and manage historical structures.

Table 1. Case studies' analysis.

Case Study		Year of Construction	The Model Creation Process	Digital Model Uses	The LOD Used
[19]	Italian railway bridges during the late 19th century varied in size, with lengths ranging from 65 to 81 m and column numbers from 6 to 17. The bridges were made of iron and featured a tubular truss design with straight trusses, a lattice iron structure, and masonry piers sunk in the riverbed with tubular pneumatic foundations. The iron lattice used for the construction varied in design and composition based on the specific bridge.	(1863–1892)	- Data Capturing: Research historical documentation and define the typological characteristics of truss structures. - Modeling Process: Establish a taxonomic classification, develop a library of geometric configurations, define operations to design a 1D model, and create a 3D model. The following are used: Blender with geometry nodes for parametric design and modeling operations; - Grasshopper and Dynamo for parametric design tools and VPL within proprietary BIM or 3D Cad software; - Freecad for parametric designs and integration of software with Dynamo and Pyflow for experimental use.	- Visualization and virtual representation; - Documentation and preservation; - Design and construction tracking; - Operational workflow and heritage information management.	Not defined, but based on description, the use of advanced modeling techniques like VPL suggests a potential for high LOD.

Table 1. *Cont.*

Case Study		Year of Construction	The Model Creation Process	Digital Model Uses	The LOD Used
[21]	The Serranos Bridge, originally built in the 16th century, no longer serves as a bridge over the river but has been transformed into a walkway. The bridge goes over a garden with 10 km length and 160 m width.The primary material was stone.	1518	- Data capture: Using Trimble TX8 laser scanning and Canon EOS-1Ds Mark III - Modeling process: Importing the point cloud data into Autodesk Revit software, adjusting the LOD based on the purpose, using higher LODs for detailed visualizations and lower LODs for analysis, and modeling the bridge based on historic maps, details, traces, and features to reconstruct a virtual representation of the structure.	- Visualization and documentation; - Structural analysis; - -Historical reconstruction; - Urban planning.	A high LOD was employed.The LODs were managed to ensure that the historical development of the bridge across different periods was represented as accurately as possible.
[22]	The Chinese Eastern Railway (CER)'s infrastructure, including its bridges, tunnels, and other structures, varied in size, with standardized designs for smaller structures like bridges spanning small-scale rivers, ravines, and valleys, as well as large-scale bridges.The materials used in building these heritage structures included timber for temporary bridges, stone for stone arch bridges, and steel for truss bridges.	(1897–1902)	- Data capture: Utilized Global Navigation Satellite System (GNSS) records and Google Earth® for collecting geographical coordinates of heritage items. Analyzed structural features based on original drawings and fieldwork. - Data analysis: Database was created by integrating HBIM and GIS (Geographic Information System), including historical data, status quo, material, and structure details. The HBIM software is used for accurate recording and documentation, and the GIS software, such as ArcGIS®, is used for managing spatial data.	- Reconstructing and conservation. - Documenting and gathering historical data. - A database integrating HBIM and GIS for planning purposes and public information.	Not defined, but the comprehensive and detailed approach taken in the process indicates to a high LOD.
[17]	The Carlo III bridge was built to cross the aqueduct over the river Isclero and served as part of the Carolino Aqueduct. It is approximately 150 m long above ground and almost 7 m high. It consists of four round arches separated by buttresses and two gradually entering "shoulders". The structure is divided into lower, intermediate, and upper levels, with the internal duct being across the second and third levels. The structure is predominantly made of local yellow tuff.	18th century	- Data capture: Utilized an integrated survey approach combining laser scanning, terrestrial photogrammetry, UAV photogrammetry, and survey constraints - Modeling process: Data alignment, manual processing, and integration of data into BIM software (Revit Autodesk).	- Digital visualization; - Database construction; - Framework establishment for monitoring; - Maintenance plan management.	Not defined, but it utilized a high LOD, regarding the following: - Laser scanning with a 3 mm resolution capturing detailed information, UAV survey generating a map with a 9 mm GSD for high-resolution imagery, and alignment and merging of data to achieve a 3 mm mean distance between point clouds.

Table 1. *Cont.*

Case Study		Year of Construction	The Model Creation Process	Digital Model Uses	The LOD Used
[20]	The Giorgini Bridge was built to cross the Bruna River and to prevent the water of the river from mixing with the salty sea water. It is 26 m wide, 12 m high, and composed of two lateral shoulders, lowered round arches, and pylons. The bridge was made of reinforced concrete structures and lattice steel structures. The floodgates were made of wood encased in metal frames.	1827	- Data capture: 1. Conduct a survey campaign to gather data using total station, GPS survey, and drone photogrammetry. 2. Use laser scanning and photogrammetry for data acquisition with tools like Terrestrial Laser Scanner (TLS), Structure from Motion (SfM), and UAV and software like CloudCompare and Agisoft PhotoScan - Modeling process: Convert acquired data into building object models (BOMs) and develop a detailed BIM model based on the historical data using Revit Autodesk.	- Visualization and documentation; - Structural analysis; - Diagnosis of deterioration and maintenance planning; - Interoperability for information exchange	Not defined, but based on the result, it shows a high LOD
[18]	The Ízbor Bridge was a civil engineering structure that provided a passageway for goods and source materials for over 150 years. Its dimensions are as follows: - Length: 80 m - Width: 6.80 m - Height of piers: 10.54 m - Height of highest abutment: 13.53 m - Thickness of piers and abutments: 6.80 m The construction materials are stonemasonry for piers, abutments, and arches, as well as stone and earth fillings.	1860	- Data Capture: Utilized different instruments for point cloud capture, including a Leica GPS 1200, a TLS Leica C10, and TLS BLK 360 - Modeling Process: Revit was used to create several families for modeling non-conventional bridge elements. The modeling required 12 levels to be defined for different elements.	- Government planning and conservation agencies; - Reference for similar heritage monuments; - Management and maintenance; - Documentation.	Utilized a high LOD for all the bridge elements according to the organization's BIMFORUM standards. The Level of Development used for the modeling process was 300 LOD.

The specific elements and details captured in the models differ based on the type of structure. For infrastructure like bridges, the focus is often on structural elements, material composition, and topographical features, while for buildings, the focus might extend to interior elements, decorative details, and building systems. The application of HBIM to infrastructure involves the use of a high LOD to capture intricate geometric and structural details. Various surveying methods are employed for this purpose, including laser scanning (terrestrial and aerial), photogrammetry (aerial and structure from motion), direct measurements (total station and GPS), archival research and historical documentation analyses, and ground-penetrating radar (GPR). The resulting models have diverse applications, such as in rehabilitation planning, conservation strategies, heritage tourism, research and education, and disaster risk management. These applications range from utilizing three-dimensional models to assess structural integrity and plan restoration works to creating virtual tours and interactive exhibits to showcase the historical significance of the bridges and using digital models for assessing their weaknesses and implementing mitigation measures.

The effectiveness of HBIM in infrastructure heritage conservation has been demonstrated through unique methodologies and outcomes. Precision scanning and photogrammetry are employed to capture accurate representations of existing sites, which are then integrated into HBIM systems, supplemented with historical records and specialized conservation notes. HBIM has proven to be instrumental in managing the challenging balance of maintaining routine operations while executing essential conservation initiatives, particularly for historical transportation networks that are still in active use. Furthermore, its role is crucial in addressing the dilemmas encountered in upgrading and utilizing infrastructure heritage. It enables comprehensive documentation, analyses, and intervention planning, allowing stakeholders to visualize potential changes, engage with the community, and make decisions that respect heritage while ensuring safety and functionality.

The integration of HTI with advanced technologies is essential for sustainable preservation and development. HBIM allows for the inclusion of modern solutions, such as innovative composite materials for structural support and non-invasive diagnostic tools for comprehensive evaluations. The updating of HBIM to incorporate modern design is gaining traction, enabling stakeholders to visualize, assess, and discuss interventions, ensuring that proposed designs respect heritage values while accommodating contemporary functionalities. Moreover, HBIM serves as a detailed archival tool, preserving the evolution and continuous improvement of transportation heritage. It records future alterations and advancements, making HBIM a chronicle of changes and ongoing preservation efforts within the transportation heritage sector. Despite the significant challenges presented by the implementation of HBIM, including technological integration, data quality and completeness, skill gaps and training, cost implications, resistance to change and adoption, management and collaboration, legal and regulatory barriers, and sustainability and upkeep, the benefits, opportunities, and innovations that HBIM offers are crucial for our responsibility to and ongoing use of these irreplaceable structures.

8. Conclusions and Remarks

This paper has examined the role of HBIM within the context of transportation heritage, revealing its essential role in the stewardship and evolution of historic infrastructure. As digital technologies advance, they enhance HBIM's capabilities, enhancing the application of new design solutions and conservation approaches. The case studies reflect successful applications of HBIM, demonstrating its versatility in various contexts and its ability to document, manage, and preserve heritage while incorporating necessary modern advancements. The field of HTI preservation is poised for a paradigm shift due to the ongoing evolution of digital technologies. The application of HBIM is poised to expand, becoming an even more integral part of the conservation toolkit. The intersection of HBIM with cutting-edge technologies offers promising avenues for enhancing the accuracy and efficiency of preservation initiatives. Researchers expect that in the future, HBIM will go beyond its present roles of documenting and maintaining infrastructure and will become a predictive tool for evaluating the resilience of infrastructure. To effectively use the capabilities of HBIM, attempts must be directed toward enhancing its usability for and accessibility to a wider range of professionals. There is a call for enhanced frameworks to facilitate a greater and more multidisciplinary implementation of HBIM, thereby ensuring that a variety of stakeholders can collaborate and make use of this technology. Furthermore, potential extensions of HBIM into domains such as public engagement highlight the importance of incorporating stakeholder input and community engagement in the preservation process. As building technologies evolve, there will be a need for regular updates to accurately represent new materials and construction techniques within HBIM systems. Regulatory and policy frameworks need to be adjusted to effectively incorporate HBIM into infrastructure projects, guaranteeing the preservation and safety of historical treasures in modern urban settings. Future research should focus on developing more advanced modeling techniques that integrate real-time data acquisition and analysis. Furthermore, the examination of applications of HBIM in a variety of climatic and environmental conditions could offer a more comprehensive understanding of the preservation requirements of various types of heritage infrastructure. To further improve HBIM methodologies and practices, it is also recommended that engineers, historians, and conservationists collaborate more effectively.

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