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The Future of Heritage: Digital Restoration and Intelligent Modeling Approaches in Historic Buildings[1]

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Abstract – Digital restoration is an innovative approach that brings together the possibilities offered by emerging technologies in the conservation and documentation of historic buildings. This study is literature-based research focusing on the integration of Historic Building Information Modeling (HBIM), Artificial Intelligence (AI), and Virtual Reality (VR) technologies. Historic structures are constantly threatened by natural disasters, human negligence, wars, and environmental degradation. Although traditional preservation methods remain valuable, they are often limited in terms of time efficiency, cost, and accessibility compared to today's digital capabilities. In this context, HBIM-based digital systems enable accurate documentation of historic structures, the simulation of environmental impacts in virtual environments, and the development of data-driven preservation strategies. Through a qualitative review of recent academic literature and case studies, this research identifies the application areas, advantages, and limitations of digital preservation approaches. The findings reveal that the integration of HBIM, Artificial Intelligence, and Virtual Reality significantly enhances the sustainability, accessibility, and effectiveness of cultural heritage conservation projects.

Keywords *– Intelligent Heritage Modeling; Artificial Intelligence Applications in Restoration; Virtual Reality Simulation; Digital Heritage Management; 3D Scanning and Modeling*

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I. INTRODUCTION

Historic buildings are invaluable cultural assets that must be protected against various threats such as natural disasters (earthquakes, floods, and fires), human-induced destruction, wars, neglect, and gradual physical deterioration over time. These structures are significant not only for their physical characteristics but also for their roles in shaping collective memory, cultural identity, and spatial continuity. Therefore, the preservation of historic buildings should not merely be considered a technical repair activity but a strategic responsibility for ensuring the sustainability of cultural heritage. The conservation of heritage structures requires accurate collection, processing, analysis, and documentation of large volumes of data. This necessity highlights the importance of an interdisciplinary approach, involving collaboration among experts in conservation, restoration, architecture, engineering, materials science, geographic information systems, and computer technologies. Ensuring data accuracy, spatial integrity, and temporal monitoring forms the foundation of an effective preservation strategy.

However, traditional preservation methods face significant limitations in today's rapidly digitalized information environment. Time-consuming documentation processes, high costs, dependence on manual labor, limited accessibility of physical archives, and difficulties in data transfer are among their major drawbacks [1].

Furthermore, the restricted capacity for data updating and sharing in conventional workflows often prevents preservation decisions from being based on holistic analyses. At this point, Building Information Modeling (BIM) has initiated a transformative shift in the field of conservation. BIM is an innovative information management system that encompasses the three-dimensional modeling, management, and analysis of buildings in a digital environment. Conceptually, it originated in the 1980s from object-based parametric modeling used in mechanical design. Today, it is widely applied across the architecture, engineering, and construction (AEC) sectors for lifecycle management, cost optimization, and data integration purposes [2].

BIM technology defines building components not only through geometric data but also by incorporating material properties, structural relationships, maintenance cycles, and energy performance parameters. Each component thus becomes an intelligent digital object that can be continuously updated throughout the project lifecycle. This multidimensional approach holds significant potential for the

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documentation, analysis, and restoration of historic structures. The United Kingdom is one of the leading countries in institutionalizing BIM practices. The Architecture, Engineering, and Construction (AEC) initiative launched in 2000 laid the groundwork for the development of standards in this field. In 2009, the integration of advanced BIM software and expert practitioners accelerated its adoption. The first BIM Protocol, published in November 2009, established the initial legal and technical framework for digital building management [3].

In the context of historic preservation, this approach has evolved into HBIM (Historic Building Information Modeling), which adapts traditional BIM infrastructure to the specific requirements of cultural heritage. HBIM combines processes such as documentation, analysis, monitoring of material decay, and simulation of restoration scenarios. The integration of Artificial Intelligence (AI) and Virtual Reality (VR) technologies within HBIM not only enhances technical efficiency but also transforms the fields of education, awareness, and virtual heritage experience.

This study comprehensively examines digital restoration practices aimed at the conservation of historic buildings, focusing particularly on the integration of HBIM, Artificial Intelligence, and Virtual Reality. Considering the constraints of traditional methods in terms of time, cost, accessibility, and data management, the research evaluates the opportunities provided by digital technologies. Through a qualitative literature review, the study investigates international BIM applications, with a particular focus on the United Kingdom, and analyzes developments in this field. The findings indicate that digital technologies facilitate interdisciplinary collaboration, strengthen data-driven decision-making processes, and make significant contributions to the documentation, analysis, and sustainable preservation of cultural heritage.

II. Materials and Method

This study is based on a qualitative analysis of the current academic literature on the digital restoration of historic buildings. During the data collection process, academic articles, reports, and official documents that examine the application of Historic Building Information Modeling (HBIM), artificial intelligence (AI), and virtual reality (VR) technologies in cultural heritage structures were reviewed. The literature review particularly focused on BIM implementations developed under the Architecture, Engineering, and Construction (AEC) initiative in the United Kingdom and sources published by institutions such as Historic England.

The data obtained were analyzed through a comparative evaluation of traditional and digital methods and interpreted in the context of their contributions to conservation processes. In this way, the effects of interdisciplinary approaches on digital restoration have been comprehensively revealed.

III. Literature Review

Perry (2014) distinguishes between digitization and digital preservation, emphasizing that digitization alone does not ensure long-term preservation. The article highlights key challenges in digital preservation, such as the rapid pace of technological change, lack of standards, insufficient training, and high costs. It also stresses the importance of metadata standards, software compatibility, and emulation techniques to ensure the long-term accessibility of digital objects. Perry argues that digital preservation is not only a technical task but also an ethical and managerial effort [4].

Digital preservation refers to the process of ensuring long-term accessibility and usability of content, whether born-digital or digitized from analog materials. According to Conway (2010), digitization is often equated with preservation, but they are distinct; digitization is merely a conversion process and does not guarantee permanence or authenticity [5].

Smith (2007) supports this view, stating that while digitization increases access, it does not ensure originality or sustainability [6]. Galloway (2009) asserts that digital records, like analog ones, must undergo archiving, processing, and preservation, though digital content is more complex and costly to preserve [7].

Fryskowska and Stachelek (2018) proposed a no-reference evaluation method for assessing the geometric quality of 3D models generated from laser scanning point clouds. This method is particularly valuable in HBIM applications, as it allows for the objective assessment of digital representations of buildings based on quantifiable criteria. Parameters such as point cloud density, surface smoothness, geometric complexity, and topological continuity are used to assess model quality. This approach offers a practical quality control mechanism, especially for documenting and conserving historic buildings, contributing significantly to improving data accuracy and modeling standards in HBIM workflows [8].

In the article Preserving our heritage: A photogrammetry-based digital twin framework for monitoring deteriorations of historic structures, Kong and Hucks introduce a digital twin framework based on photogrammetry for structural health monitoring of historic buildings. UAV-based high-resolution images taken at different time intervals are used to generate 3D point cloud models, which are then aligned using cloud-to-cloud (C2C) methods to detect time-dependent deformations and damage. The method was validated on a stone arch bridge and successfully identified simulated structural degradations.

The study outlines how digital twins can enable effective monitoring of historic structures, focusing on creating virtual models using photogrammetry and point cloud processing algorithms. These models are then aligned over time to detect structural changes due to deterioration [9].

In the article: The role of historic building information modeling in the cultural resistance of liberated city, the authors emphasize the significance of HBIM in preserving cultural heritage, particularly in reconstructing archaeological structures destroyed by war or natural disasters.

The study highlights the role of heritage in shaping collective memory and identity and argues that heritage preservation should be a priority during urban reconstruction. The research aims to model Khan Hamu Quddo in Mosul—destroyed during military operations in 2017—using Autodesk Revit 2021 and Lumion software. The resulting model serves as a tool for preserving memory, preventing cultural loss, and reconnecting society with its past [10].

The article Towards digital architecture, engineering, and construction (AEC) industry through virtual design and construction (VDC) and digital twin discusses major transformations in the architecture and construction industries

and the role of emerging technologies in shaping the sector's future. The authors explore how digital twins, when integrated with artificial intelligence, have the potential to automate and optimize human-centered decision-making processes, while also addressing future industry challenges [11].

In Digital Twin: A HBIM-Based Methodology to Support Preventive Conservation of Historic Assets Through Heritage Significance Awareness, the authors argue that HBIM provides a collaborative framework for managing data on existing heritage structures. The study emphasizes the necessity of information exchange among stakeholders and the potential of these processes to support effective conservation strategies. The paper proposes a comprehensive methodology for integrating tangible and intangible heritage values into HBIM models [12].

The article Modelling in HBIM to document materials decay by a thematic mapping to manage the cultural heritage: The case of "Chiesa della Pietà" in Fermo focuses on the church of Chiesa della Pietà in Fermo, Italy. Structural issues and significant wood decay were observed in the building. To monitor deterioration and guide potential restoration actions, the authors created a 3D model using HBIM software with multiple Levels of Detail (LOD). Based on a hierarchy of classes and subclasses, the study established a custom database that assigns unique ID codes to building components, enabling thematic mapping of material decay. This system serves as a preventive strategy to manage and mitigate degradation in heritage structures [13].

Murphy et al. (2009), in the article "Historic Building Information Modelling", explains that the HBIM process begins with the remote collection of data using a terrestrial laser scanner combined with digital photogrammetry. According to the authors, the outcome of HBIM is the creation of full 3D models containing detailed information about the construction techniques and material composition of the object. These models not only support the analysis and conservation of historic objects, buildings, and environments but also allow for the automatic generation of sections, details, schedules, orthographic projections, and 3D representations (either wireframe or textured) [14].

Rocha et al. (2020), in their study titled "A Scan-to-BIM Methodology Applied to Heritage Buildings", presents a comprehensive methodology for creating HBIM models of cultural heritage structures using 3D laser scanning and photogrammetry. The case study focuses on the Engine House of Paços Reais in Lisbon. The article first outlines the necessary considerations for carefully planning a scan-to-HBIM workflow. Second, it details the remote sensing campaign carried out to produce BIM outputs, including the steps of data alignment, cleaning, and merging. Finally, the paper describes the modeling stage based on point cloud data, offering insights into the transformation of raw scans into structured HBIM models [1]. Bruno and Roncella (2019), in the article "HBIM for Conservation: A New Proposal for Information Modeling," published in Remote Sensing, propose an HBIM framework designed to support documentation, management, and preventive conservation of historic buildings. The approach emphasizes the management of non-geometric historical data in a structured and coordinated manner. The system supports efficient data analysis, time management, flexibility, user accessibility, and information sharing. It is built around a customized database linked to a 3D model created with BIM software. Access to the system is provided via a desktop application that operates as a plug-in for BIM tools, and a web interface developed to facilitate data sharing and ease of use [15].

Traditional architectural heritage is shaped by the climatic conditions, social lifestyle, and construction techniques of its region, while also reflecting the cultural identity and sense of place unique to its context. Preserving the aesthetic, historical, and symbolic values embodied in these architectural fabrics is a complex and multidimensional process compared to other forms of tangible heritage.

However, the digital documentation and modeling of built heritage introduce a new perspective to the discipline of conservation, providing significant advantages in pre-intervention analysis, monitoring, and decision-making processes. In this context, Building Information Modeling (BIM)–based heritage management systems emerge as effective tools in the preventive conservation of historic buildings, contributing to a sustainable conservation approach supported by digital Technologies [16].

IV. Application and Findings

Evaluation of Traditional Historic Building Preservation Processes

The processes of survey (rölöve), restitution, and restoration of immovable cultural assets are carried out in accordance with the Conservation-Oriented Zoning Plan Regulation of the region in which the structures are located and based on the protection status of the buildings. During these processes, inspections are conducted by relevant departments of the Regional Boards for the Protection of Cultural Heritage. After the tender process, the contractor firm prepares the architectural drawings, which are then subjected to on-site inspections at various stages by the authorized representatives of the conservation board. These inspections cover compliance with regulations, design details, restoration planning, and implementation stages.

- However, these traditional methods involve several challenges:
- Loss of time due to the complexity of procedures.
- High margin of error in inspections.
- Difficulties in archiving physical data, leading to inadequate preservation of information for future generations.

Advanced technologies such as laser scanning are often limited to contractor possession and are not widely accessible, making future access to the data difficult and potentially requiring re-collection of data, which increases costs.

Digital Archiving Methods and HBIM Implementation

With the integration of technology into all aspects of life, digital data storage systems are becoming increasingly

common in archiving practices. The fundamental advantages of digital methods over traditional ones include:

- Time efficiency
- Cost-effectiveness
- Reduced labor requirements
- Prevention of data loss and increased accessibility

In this context, the use of digital information systems in the preservation of immovable cultural heritage allows for more effective storage and management of collected data.

Benefits of HBIM and Virtual Reality (VR) Technologies

The key innovations and advantages introduced by digital modeling include:

- Preservation of physical documentation of historic buildings in digital environments, thus preventing data loss.
- Secure access to all building-related information for authorized users via username/password systems.
- Reduced need for physical site inspections through the ability to update structural control processes via the HBIM platform, resulting in time savings.
- Promoting wider adoption of digitization in historic preservation practices in Turkey, in comparison to current traditional methods.

These innovations can be integrated with existing traditional preservation approaches in Turkey to enhance their effectiveness and sustainability. The integration of digital modeling (HBIM) and virtual reality (VR) technologies with conventional methods will improve both efficiency and quality of preservation processes.

CONCLUSION

Preservation and transmission of historic buildings to future generations is a multifaceted and interdisciplinary process that should not rely solely on physical interventions but should also be supported by the capabilities offered by digital technologies. Within the scope of this study, recent literature has been reviewed to examine the roles of innovative digital tools—such as Historic Building Information Modeling (HBIM), Artificial Intelligence (AI), Virtual Reality (VR), digital twin technologies, photogrammetry, laser scanning, and point cloud modeling—in the documentation, restoration, and sustainable conservation of historic structures. Based on the findings, a SWOT analysis has been conducted to comprehensively identify the strengths, weaknesses, opportunities, and threats associated with these technological approaches.

Among the strengths, HBIM offers a holistic digital representation that integrates the geometric, material, historical, and cultural layers of historic buildings. AI applications assist in identifying structural vulnerabilities, enabling more accurate planning of maintenance and repair processes, while VR-based simulations enhance decision-making and public engagement. Through this integrated framework, it becomes possible to digitize records, establish centralized digital archives, and manage conservation processes more effectively.

However, there are also some inherent weaknesses in the implementation of these technologies. Notably, HBIM is more complex than conventional BIM applications used in new construction projects. The challenges posed by irregular geometries, deteriorated structures, and diverse original materials necessitate greater financial investment, time, and expertise.

Furthermore, the lack of standardization and inadequate digital archive infrastructure in some countries present significant barriers to broader adoption and long-term efficiency (Table 1).

Table 1. SWOT Analysis of Digital Technologies in the Preservation of Historic Buildings

INTERNAL FACTORS	EXTERNAL FACTORS
Strengths	Opportunities
• HBIM enables detailed and holistic digital documentation of historic buildings. • AI optimizes damage detection, material selection, and maintenance planning. • VR integration supports decision-making through immersive simulations. • Multidisciplinary data integration: geometric, historical, material, and cultural layers.	• Virtual preservation and educational/touristic reuse of cultural heritage. • Eligibility for international funding and support from EU, UNESCO, etc. • Growing academic interest and evolving digital conservation standards. • Enhanced public engagement and awareness of cultural heritage.
Weaknesses	Threats
• HBIM is more complex than BIM for new constructions due to irregular geometries and decayed elements. • High cost and technical expertise required for advanced tools. • Lack of standardization in digitizing historical structures. • Limited digital archiving infrastructure in some countries like Turkey.	• Dependence on technology poses risks of software incompatibility and data loss. • Digital security and long-term sustainability challenges. • Inadequate legislation and inter-agency coordination. • Inaccurate modeling may lead to flawed restoration decisions.

HBIM, as an adaptation of the traditional Building Information Modeling (BIM) approach for historic buildings, is a system that integrates not only the physical attributes of a structure but also its historical, cultural, and artistic components into a comprehensive digital model. In this regard, HBIM facilitates information sharing in interdisciplinary conservation projects, enabling degradation monitoring, maintenance planning, and restoration decisions to be made in a more holistic and data-driven manner.

Digital twin technology, on the other hand, enables real-time monitoring of a building's physical condition through time-dependent 3D models generated via remote sensing techniques

such as photogrammetry and laser scanning. Methods like cloud-to-cloud (C2C) comparison allow for damage detection by comparing models of the same structure captured at different times, thus supporting the development of sustainable preventive maintenance strategies.

Artificial intelligence plays a crucial role in both data analysis and decision-support systems. AI algorithms help detect structural weaknesses, suggest optimal materials and intervention methods, and optimize time-cost planning. Moreover, through machine learning, insights from past conservation projects can be utilized to inform and improve future applications.

Virtual reality (VR) technology emerges as an effective tool for both visualizing restorations before-and-after scenarios and promoting cultural heritage through interactive presentations. This enables even non-expert users to experience the historical evolution of buildings, thereby enhancing public awareness and encouraging preservation efforts.

What unites all these technologies is their ability to support not only the protection of cultural heritage buildings but also their documentation, analysis, and dissemination through a comprehensive and integrated approach.

However, the successful implementation of these technologies also requires the establishment of necessary infrastructure, specialized expertise, and appropriate legal regulations. In conclusion, new-generation restoration methods empowered by digital technologies represent a paradigm shift in heritage conservation by ensuring the sustainability of both the physical presence and cultural significance of historic structures.

Authors'Contributions

The authors' contributions to the paper are equal.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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