Digital Approaches to the Rehabilitation of Built Heritage. Case Study of a Historic Residential Unit in Oradea, Romania

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Abstract. The following paper aims at providing a framework of how digital approaches can be used in the rehabilitation of residential built heritage for creating immersive spatial visualizations. Among these digital tools, Historic Building Information Modeling and Extended Reality facilitate an interdisciplinary collaboration and more effective strategies based on a clear assessment of the risks associated with the implementation process.

Keywords: Built Heritage Rehabilitation, HBIM, Digital Reconstruction, Virtual Reality, Immersive 3D Visualization.

1 Introduction

Built heritage is a dynamic and complex system of cultural, economic and social values that transcends its simple materiality. The preservation of the cultural identity of the built historical fund is threatened by natural factors, but also by anthropogenic activities. Heritage protection has become an increasingly important topic in contemporary research. The transition from remedial and emergency interventions to proactive and preventive approaches is supported by national and international policies and institutions, such as the International Council on Monuments and Sites (ICOMOS) (Chaves et al., 2024).

In the context of a digital era, characterized by an accelerated pace of technological development, protecting the cultural identity of historic urban spaces becomes a priority, as it is necessary to establish a balance between innovation and memory. The methods of conservation and protection are diverse, digitization is considered one of the main innovative directions (Vladimirova, 2012).

The case study, analyzed at a detailed scale, focuses on the integration of digital tools in the rehabilitation project of a small apartment located in a building with heritage value in the city of Oradea, Romania.

Digital Presentation and Preservation of Cultural and Scientific Heritage. Volume 16, pp. 387-396, 2026.
DOI: 10.55630/dipp.2026.16.32, ISSN 1314-4006, eISSN 2535-0366.

2 Digital Technologies in the Preservation of Built Heritage

2.1 Historic Building Information Modeling

Since 2009, Building Information Modeling (BIM), has fundamentally changed the way work is carried out throughout the construction process. It has enhanced interdisciplinary collaboration, execution planning, and cost reporting through the use of a synchronized and transparent system (Baik, 2025).

In recent years, the specialized literature has defined numerous solutions for the accuracy of constructing digital models of historic buildings. Documenting and managing the tangible and intangible values of built heritage using digital technologies plays an important role in the restoration process. Historic Building Information Modeling (HBIM) facilitates the organization of various types of information and integrates the management of all the specialized fields involved, in a collaborative digital project (Banfi et al., 2018).

HBIM is a digital system that facilitates interventions in heritage buildings. The concept has been extended to include the sphere of heritage, reflecting a complex set of historical values, but also the involvement of multiple actors and related disciplines. In addition to architects and engineers, the multidisciplinary team can be completed by surveyors, academic researchers, archaeologists, historians or specialists in historical materials (stone, wood, metal, etc.) (Ewart & Zuecco, 2019).

The HBIM process has three main steps: data collection, information processing for the generation of the initial 3D model, and the final form developed following the completion of the project (El Barhoumi & Hajji, 2024). Data collection includes 3D scanning, photogrammetry or manual measurements. Reality Capture technologies accelerate data collection and reduce the number of errors compared to manual methods (Bastem & Cekmis, 2022). The collected data are processed and used to generate the 3D model. The methods used for data collection are correlated according to the particularities and complexity of the building. In general, BIM software does not contain libraries with special elements for historical buildings, but by using Terrestrial Laser Scanners (TLS) and digital photogrammetry, special types of models can be defined for different categories of structures (Alshawabkeh et al., 2024).

Digital information is correlated with non-digital information, including historical documentation, resulting in a multidimensional model, namely HBIM. The physical layers, particularly the structure, installations, finishes, are digitally transposed and correlated with the historical layers identified analogically through documentation. Recent advances in the field of HBIM involve the integration of sensors into historic structures, which enable real-time monitoring. By continuously collecting data, long-term conservation strategies can be developed, supporting predictive maintenance (Baik, 2025). Regarding HBIM, the developed model is not limited to geometry; it also functions as an intelligent structure, which is able to integrate information regarding the authenticity of the constructive elements, but also of defining structural and functional relationships

between them (Bastem & Cekmis, 2022). Based on the HBIM methodology, the concept of Digital Twin is introduced, which not only presents the existing situation of the historic building, but also allows for simulations and analyses to be carried out to substantiate the decision regarding the restoration and preservation of the building (Chaves et al., 2024).

2.2 Extended Reality

Extended Reality (XR) is an integrative concept for technologies based on digital immersion:

- VR - Virtual Reality: the user is introduced into the created 3D digital space
- AR - Augmented Reality: digital elements are layered over the real environment.
- MR - Mixed Reality - Digital elements interact with the physical space in real time (El Barhoumi & Hajji, 2024).

The use of HBIM and XR concepts in design sets a new direction in the mediation of cultural heritage, facilitating immersive experiences and enhancing communication between specialists and the general public in the field of cultural heritage. The ability of XR technologies to enable interactive three-dimensional reconstructions represents a promising direction for mapping and valorizing historical aspects. Furthermore, it encourages the involvement of greater public engagement in the geospatial narrative of built heritage (El Barhoumi & Hajji, 2024).

Augmented reality and virtual reality help visualizing intervention proposals before implementing them. VR facilitates an interdisciplinary approach by defining a common digital environment for all those involved in the design process (Bastem & Cekmis, 2022).

Immersiveness and interactivity in virtual environments generate a strong sensation for the user of "being there", namely of being embodied in an autonomous and self-referential world (Pinotti, 2017). The tools related to digital immersion technology present a series of advantages in the design process, allowing the evaluation of various proposed compartmentalization solutions.

Virtual Reality also becomes a communication and visualization environment between all those involved in the project. Several teams can work on the virtual model at the same time, representing an efficient approach that reduces the time allocated to the project definition process (Hussain, 2025).

3 Digital Workflow in Heritage Rehabilitation

3.1 Data Acquisition and Documentation

In the restoration process, documentation, historical research, and interpretation of archival data represent the preliminary stages in understanding the evolution and history of the building under study.

The HBIM system facilitates coordination of the primary data sources, the tangible and tridimensional architectural and structural elements and the secondary data sources, which refer to semantic data, including historical drawings, archive data, physical properties, etc (Banfi et al., 2018). The main digital documentation techniques are three-dimensional laser scanning and photogrammetry, which contribute to the definition of the geometric configuration and visual architectural characteristics of the building and the development of three-dimensional BIM/HBIM models (Grămescu et al., 2025). The methods have various advantages and disadvantages, limitations, different levels of accuracy, and the potential ways in which they can be applied become particular for each type of intervention.

The digital geometric survey of the building is correlated with the intangible components in order to provide a broader understanding of the cultural and patrimonial value of the building. In national and international archives, important documents are found in physical format that present both written pieces and drawn parts, namely: plans, sections, facades, technical details. Current digital technologies allow information to be structured, reorganized, and interpreted. Documents in digital format allow for easier correlation, allowing you to view drawn parts at different levels of detail (zoom in/zoom out) and compare or overlay them (Feng et al., 2019).

3.2 HBIM Modelling and Semantic Structuring

The metric measurements taken with digital documentation techniques such as photogrammetry and Terrestrial Laser Scanner (TLS) facilitate the creation of 3D models with greater accuracy. The generated model integrates the structural and functional characteristics correlated with the semantic information (Bastem & Cekmis, 2022).

In the restoration process, the heritage is analyzed through social, technological, and cultural perspectives through integrated methods and diverse teams of specialists. The development of interdisciplinarity research is promoted (Ilieva & Vaptzarova, 2017).

Digital tools facilitate the creation of a three-dimensional support of the studied building, compatible with all specialists involved in the restoration process. This approach allows the integration of neglected information in a structured and correlated way, namely aspects related to improving energy efficiency, environmental aspects or the compatibility of proposed interventions with the principles of restoration and conservation (Oostwegel et al., 2022).

3.3 Visualizing Through XR Tools

Designing with the use of Virtual Reality emphasizes the experiential component, facilitating the user's understanding of the proposed project at a much deeper level through interaction with the virtual space (Huang et al., 2024). The 3D model can be completed with images to capture the proposed simulations, becoming an analysis tool for outlining the best intervention scenario within a building with heritage value. Visual communication of the digital outputs related to BIM are mostly static information. XR tools facilitate presenting the information to the expert and non-expert users through interactivity and immersion.

Using these digital tools in the cultural heritage sphere, risk management decisions are reduced (Bastem & Cekmis, 2022). Testing optimal intervention options on a digitally modeled structure and, through its immersive character, enables users to virtually enter the building to visualize the feasibility of the proposed interventions at real scale.

3.4 Evaluation of the Proposed Intervention

Architectural heritage, through its material specificity and history, generates certain challenges in the diagnostic and restoration process, limiting the application of current legislation and standards. Intervention solutions must be appropriate to the cultural context (International Council on Monuments and Sites [ICOMOS], 2003). The new technologies applied in the conservation and restoration of heritage buildings provide a range of tools that facilitate the development and testing of an optimal intervention scenario. Digitization is increasingly becoming an important pillar supporting the valorization of heritage. As an essential tool for protection and conservation, it contributes to preventing the loss of cultural and historical heritage, especially in the case of buildings at risk (Vladimirova, 2012).

The HBIM and XR digital approaches contribute to the decision-making process and evaluation of the intervention by correlating all the semantic and tangible layers of the study. Also, this workflow allows evaluating multiple scenarios and a comparison between the proposed interventions.

4 Case Study: Rehabilitation of a Studio Apartment Within a Heritage Building in Oradea, Romania

4.1 Concept

The presented case study is a 52 sqm apartment located in a heritage building in the city center of Oradea, situated in the western part of Romania. The historic center of Oradea is recognized for its architectural heritage, mostly built in the late 19th and early 20th centuries, strongly influenced by the Art Nouveau movement, absorbed mainly through the Budapest route (Novicov, 2011).

The building considered in this study, built in the early 1900s, is in a good state of preservation. From a structural point of view, no signs of degradation were identified. The intervention proposed through the project is mainly focused on the interior rehabilitation of the apartment. The apartment is accessed from the building's inner courtyard, with a linear layout of the interior spaces. In terms of functionality, the apartment was organized into three areas: a space that includes the entrance area and the kitchen, a bathroom and a room with a generous surface area, but without a clear functional definition.

The interior design approach follows two main directions, a balance between preserving the memory of the place and functional adaptation. The rehabilitation project proposes the restoration of valuable heritage elements found in the space: the carpentry

of the original exterior windows and the double interior door were restored. The original parquet flooring was refurbished, and the historic stove was preserved and reconditioned, becoming an accent element in the space, testimony to the past.

The functional layout organization of the spaces was conceived through non-invasive elements, namely through furniture elements. The main room was visually divided into two spaces (day/night) by a multifunctional furniture structure. The height of the proposed element is designed so as not to obstruct the access of natural light. The structure has several valences: a bookcase on the side facing the living area, wardrobe and a bedside table for the night area. Also, in the entrance area, the proposed interventions continue the concept of multifunctionality.

4.2 Integration of the Digital Workflow

The development of the project from the concept phase to implementation was carried out using digital tools. Data acquisition is supported by laser scanning and defining the general 3D model. The digital modeling process starts with the documentation of the historic building, correlated with the semantic information. The three-dimensional digital representation of the studied spaces facilitates the transmission and interoperability of information (Banfi et al., 2022).

After the three-dimensional generation of the space, concept development begins. The definition and overall visualization of the spatial configuration allow testing of various spatial intervention solutions. The 3D axonometry below represents the existing space prior to the intervention and the proposed scenario, which will be analyzed through immersive visualization methods (Fig. 1).

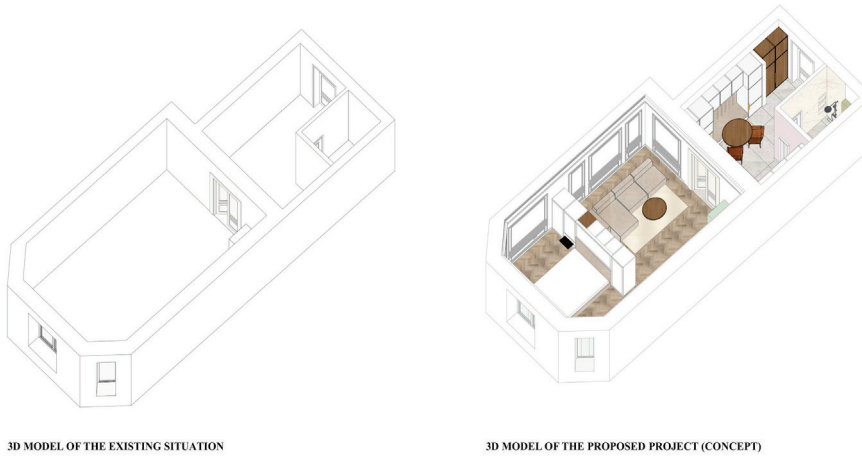

Fig. 1. 3D model of the existing situation/3D of the proposed project.

The XR technologies linked to the case study, have the main role to help the user and the project team to visualize the intervention proposals before implementing them.

The digital era defines the concept of interactive design, through digital tools, the user can interact with the proposals studied by the project (Wang, 2024). A significant step is the generation of realistic 3D images to communicate the solution proposed by the project (Fig. 2).

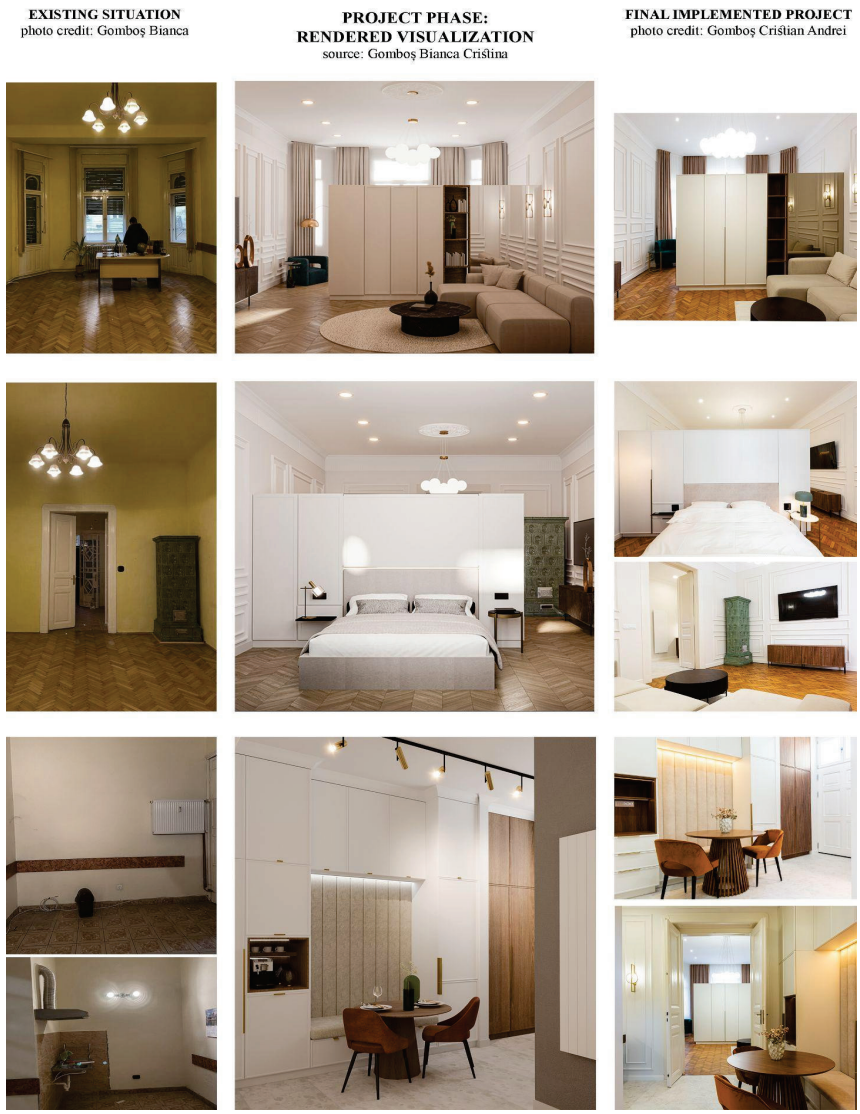

Fig. 2. Case study of a studio apartment in Oradea, Romania. Existing situation/ Rendered visualization/ Final implemented project.

The practical application of the digital workflow supports the evaluation of intervention strategies and defines how HBIM and XR can operate together. Image production is characterized by an increasingly blurred distinction between image and reality (Pinotti, 2017). The integration of digital technologies with HBIM allows the dissemination of information to specialized users as well as to the non-specialized public through interactive visualizations. The correlation of the 3D model with visualization tools becomes a tool for virtual access to the built heritage (Bastem & Cekmis, 2022).

In the analyzed case study, the digital approaches became a support tool for comparison and scenario testing. Integrating VR into the design process optimized the duration and reduced the degree of uncertainty, by creating immersive representations of the studied framework. The virtual tour of the space was also useful for identifying existing vulnerabilities and creating an optimized intervention plan (Bastem & Cekmis, 2022).

4.3 Results: Optimization of Design Solutions and Process Efficiency

The case study illustrates how digital tools are successfully integrated in the rehabilitation process. The building's existing condition was evaluated by correlating the apartment's 3D model obtained through digital methods with the semantic information regarding the conservation condition of the building, historical data, and the identification of successive spatial transformations over time.

The generated complex 3D model allowed the evaluation of heritage values, aimed at identifying authentic elements, including the stove, the window and door joinery and the parquet flooring. HBIM allows studying relevant historical layers and the configuration of the space for optimal function, reducing invasive interventions on the building. Non-structural alternatives were found to solve the design theme, among which we can mention the multifunctional proposed furniture elements.

The XR technologies managed optimization of the design and representation process. The proposed intervention regarding the suggested materials, the restoration of existing heritage elements and the compatibility of the new proposal with the existing situation were illustrated on site through non-invasive methods using Virtual Reality. The immersive 3D model walkthrough enables the experts and non-experts to analyze the proposed intervention in relation to the spatial coherence, volumetric impact and how the proposed scenario engages with the existing geometry of the building.

5 Conclusions

This study opens new directions for research in the field of historic building conservation by introducing digital technologies into the restoration process. The research illustrates the contribution of digitalization and its impact in the design process. Digital tools open up new perspectives for the transmission and conservation of values. In the field of built heritage conservation, digitization becomes both an applied research tool and a way of presentation, contributing to reducing the risk of invasive interventions and supporting an informed decision-making process in the restoration of residential heritage.

The direction presented at the detailed scale of the case study has a broader applicability at the macro level to the scale of historic buildings or cities, with respect for the original material and heritage value. The proposed workflow can be adapted to a wide range of heritage rehabilitation or adaptive reuse projects.

Another potential direction for future research can explore the use of XR tools by integrating the immersive models in the development of interactive digital applications, which can be integrated into museums, exhibitions, art galleries.

Heritage contributes to the sustainable development of society. The use of digital tools facilitates knowledge transfer in architectural education. These innovations support the broader objective of preserving built heritage, facilitating an informed decision-making process, based on a clear analysis of the risks in implementation.

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Received: March 15, 2026
Reviewed: May 05, 2026
Finally Accepted: May 30, 2026