Integrating Laser Scanning, BIM, and Virtual Reality (VR) Technologies for Monitoring and Restoration of Existing Historical Structures

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Keywords: laser scanning; BIM; gaming technologies, structural monitoring

SUMMARY

The preservation of cultural heritage has become a global priority, necessitating innovative and precise methodologies to address challenges related to deterioration and historical authenticity. Beyond conservation efforts, such as protecting historic surfaces, restoring architectural elements, and cataloging artworks, continuous monitoring of the structural integrity of historic buildings is essential. Advanced technologies for spatial data acquisition, processing, and analysis play a crucial role in this domain. These tools facilitate the creation of digital twin-virtual replicas, enabling the modeling of structural components, furnishings, and technical systems. This approach is integral to Building Information Modelling (BIM), which provides comprehensive insights into the condition of heritage structures when combined with specialized applications. This study introduces a multidisciplinary approach to cultural heritage conservation by integrating laser scanning, BIM, and immersive visualization through gaming engines. Using the case of the 13th-century Benedictine Abbey in Sieciechów, Poland, it highlights the transformative potential of modern technologies in safeguarding fragile historical edifices.

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1. INTRODUCTION

Historical structures worldwide face accelerating risks due to environmental degradation, aging, and human impact. Traditional methods of documentation and conservation often fall short of providing the accuracy or efficiency required for these complex challenges. Geodetic monitoring of historical sites employs a range of technologies and inventory methodologies, broadly categorized into invasive (tactile) and non-invasive (contactless) approaches, depending on their impact on the structural integrity of the surveyed objects (Woźniak, 2009). Invasive techniques encompass instruments such as inclinometers (Ornoch et al., 2021) and crack meters (Woźniak & Woźniak, 2020), alongside geometric leveling, which facilitates high-precision analysis of vertical displacements (Łapiński, 2024). Classical tachymetric surveying also remains a widely adapted method (Karsznia et al., 2023). While these techniques yield highly accurate results, their implementation necessitates the installation of sensors or reference points on heritage structures, which requires formal approval from conservation authorities. Consequently, only non-invasive methodologies, including photogrammetry and remote sensing, are deemed universally permissible for repeatable data acquisition (Markiewicz et al., 2019; Di Stefano et al., 2020). A particularly effective alternative is laser scanning technology, which utilizes a spatial polar coordinate system to generate high-resolution point clouds—quasi-continuous digital representations of the surveyed surfaces—thereby enabling precise documentation of an object's geometric characteristics (Woźniak et al., 2015; Buill et al., 2020). Mapping structural elements in historic buildings frequently involves architectural components that are difficult to access. Ćmielewski et al. (2023) propose a solution that enables precise measurement of such inaccessible areas by integrating high-precision electronic total stations with a custom-developed device designed to enhance targeting accuracy in problematic regions. However, this approach adheres to the principles of classical geodetic surveying, which inherently limits the number of points captured within a single measurement epoch. Given the uniqueness of historic structures and their cultural significance, measurement methodologies should ensure both high spatial accuracy and detailed fidelity while remaining non-invasive.

To address these requirements, two primary scanning approaches are considered: active and passive methods. Active techniques encompass various terrestrial and airborne laser scanning forms, including mobile solutions, while passive methods primarily rely on photogrammetry (Luhmann et al., 2020). Both approaches offer the capability to acquire millions of data points per second, a crucial advantage given the geometric complexity and accessibility constraints of heritage structures. This high-density data acquisition significantly enhances the accuracy and comprehensiveness of documentation compared to traditional geodetic techniques.

A careful methodological review of the use – mainly of laser scanning – in the process of documenting historical elements and artifacts is presented in the paper (Gomes et al., 2014). Many interesting examples of documenting sculptures and various architectural elements were presented there. The technological aspects of the process of acquiring point clouds, as well as their development, are presented. Since the publication of the material, there has been a significant development in technology – mainly the dissemination and introduction of many facilitations for users of advanced point cloud processing programs. In addition, BIM itself is becoming popular, currently used in virtually every construction project (Doumbouya, 2016).

The application of modern mapping technologies in assessing the technical condition of monuments is further exemplified in the work of Liritzis et al. (2015). The authors introduce and elucidate the concept of cyber-archaeology, highlighting its integration with contemporary technological solutions, including laser scanning and 3D printing (Karsznia et al., 2023). These advancements form the foundation for conducting modern information audits and documenting heritage collections with minimal physical contact, ensuring more remarkable preservation and accuracy.

The integration of advanced measurement technologies, particularly laser-based methodologies, is comprehensively examined in the handbook by Fotakis et al. (2007). Beyond providing a theoretical foundation for the application of lasers in the documentation of historic structures, the authors explore a wide range of conservation applications, critically assessing both their advantages and inherent limitations. Rapid technological advancements have driven the widespread adoption of these methodologies in museum environments, significantly enhancing the accuracy and reliability of heritage artifact mapping. This progress facilitates the precise modelling of individual objects, larger architectural components, and even entire monuments. Additionally, the continuous evolution of mobile technologies further supports this approach by enabling more flexible and efficient data acquisition (Barbosa et al., 2021). Furthermore, the study highlights other crucial aspects, such as the development of virtual heritage tours and the enhancement of interactive museum experiences, thereby expanding accessibility and engagement for visitors. The significance of spatial data modeling in Cultural Heritage, particularly through mobile technologies, has been extensively examined by Aljadire and Khalaf (2024). Their study focuses on the application of geodetic measurement techniques, primarily short-range photogrammetry and robotic electronic total stations, in heritage documentation. A similar research framework is explored by Świerczyńska et al. (2024), who present the results of initial measurement epochs conducted using diverse surveying technologies and their integration in the context of the historic palace in Będzin, Poland. Furthermore, an increasingly prominent trend in Cultural Heritage research is the adoption of virtual reality (VR)-based methodologies (Ibis & Çakici Alp, 2024). The implementation of VR headsets not only facilitates immersive virtual tours but also enhances the inspection and analysis of museum artifacts, positioning this technology at the forefront of contemporary heritage conservation and digital engagement strategies.

The presented state of knowledge has inspired the authors of this research paper to carry out analytical and conceptual work aimed at:

- elaborating a system concept of using laser scanning and its optimization in a specific historical object rich in numerous architectural elements and historical artifacts,
- building a coherent BIM model for the examined object (13th Century Benedictine Abbey in Sieciechów, Poland),
- applying modern data processing approaches aided by gaming technologies to visualize modeled structural elements in order to elaborate a structural health monitoring system.

2. SYSTEM ASSUMPTIONS

Technical details and differences in the functioning of current structural monitoring systems concern the type of recommended surveying instruments, the methods of capturing, processing, and analyzing spatial data, as well as the diversity in their use. While discussing the appearing challenges, the following criteria inspired our special attention:

- The integration of laser scanning with BIM enables highly precise documentation of historical structures, ensuring accurate geometric and material representation.

- The use of black-and-white targets during scanning enhances the registration accuracy of point clouds, allowing for more reliable spatial alignment.

- Structural deformations, cracks, and material deterioration can be effectively identified and incorporated into BIM models to support long-term monitoring and restoration planning.

- The combination of point cloud data with Cintoo Cloud (https://cintoo.com – accessed on 3.02.2025) enhances collaborative decision-making by enabling stakeholders to interact with structural models remotely.

- The use of immersive visualization through Unreal Engine allows for detailed analysis of restoration plans, providing an interactive environment for experts and the public.

Virtual reality (VR) and other cutting-edge digital technologies (Koeva et al., 2017) are crucial for enhancing the monitoring and restoration of historical buildings. Stakeholders can participate in immersive heritage experiences by integrating virtual reality (VR) into the workflow, which enables them to examine, evaluate, and interact with digital reproductions of historical locations. Unreal Engine's VR-based visualization offers accurate models of structural issues, providing conservationists, engineers, and architects with a hands-on approach to assess restoration plans. Furthermore, VR improves public participation by providing virtual tours, making cultural assets more accessible to a larger audience. The capacity to envision potential interventions prior to physical restoration decreases the risk of error and increases planning efficiency. Furthermore, dynamic monitoring is made possible by combining digital twins with real-time sensor data, guaranteeing that conservation initiatives stay proactive rather than reactive.

Cintoo's mesh-based technology optimizes data processing and improves accessibility by enabling smooth point-cloud-to-mesh and mesh-to-point-cloud conversions. The accuracy of restoration plans is further increased by its BIM/CAD interface, which guarantees that scanned data can be easily compared with as-built models. By automating data classification, the AI-based AI Tagging function improves organization and makes it possible to retrieve important structural features. To help engineers make decisions, Cintoo's real-time measuring technology also offers dimensional analysis in real time. While the BIM Inspection Tool facilitates in-depth comparisons between digital models and real structures, guaranteeing thorough documentation and inspection, the Asset Tool provides organized recording and management of heritage items. By fusing cutting-edge computational methods with conventional restoration concepts, these technical developments eventually aid in the preservation of historic structures.

3. METHODOLOGY

This study employs a structured workflow that integrates laser scanning, Building Information Modeling (BIM), and immersive visualization technologies forrestoring historical structures. The methodological framework ensures high-precision data acquisition, processing, and structural analysis to facilitate restoration planning.

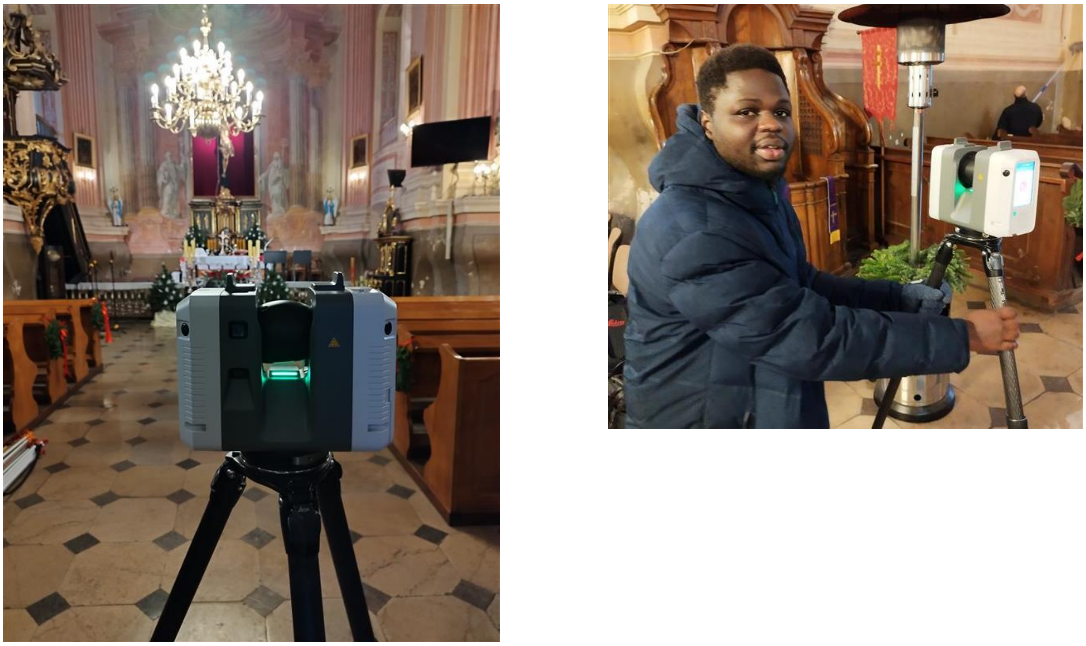


Fig. 1 Lecia RTC 360 Scanner at the abbey to Capture Point Clouds

3.1 Research Design

A mixed-method approach was adapted, combining quantitative geospatial analysis with qualitative visualization techniques. The research follows a systematic workflow, ensuring accurate data acquisition, processing, and integration for immersive visualization. The process is divided into key stages:

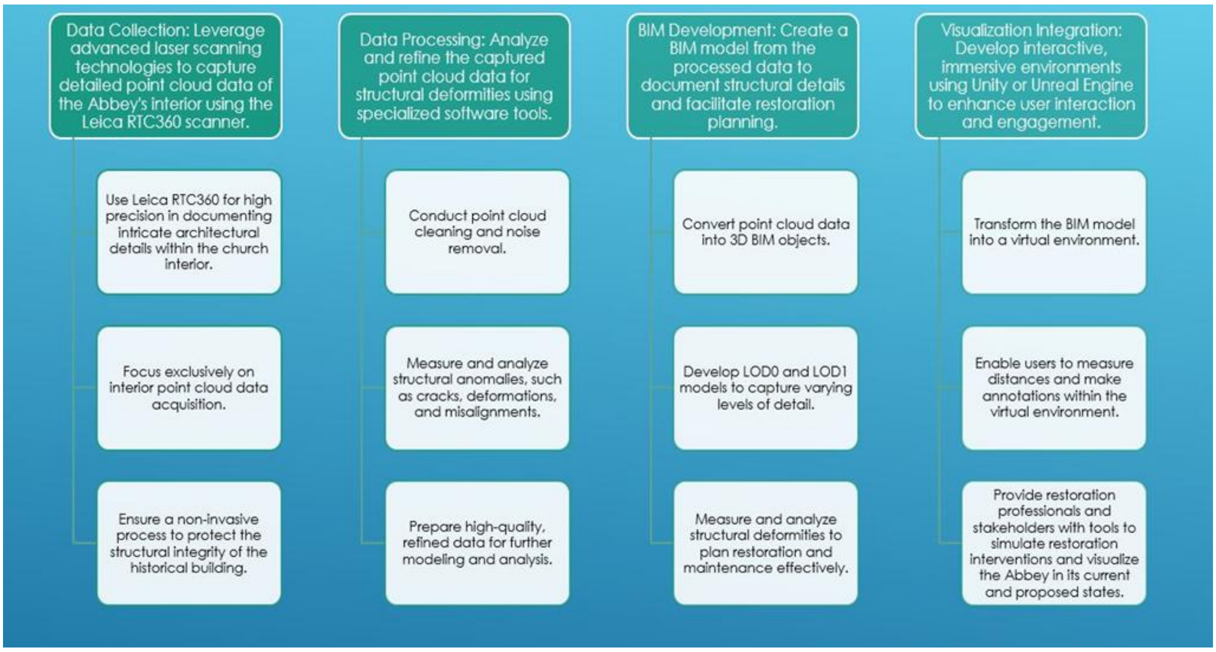
- Data Acquisition: high-resolution 3D scans were obtained using the Leica RTC360 scanner as shown in Fig. 1.

- Data Processing: point cloud data were cleaned, registered, and optimized for structural analysis.

- BIM Model Development: the structured data was used to create a digital representation of the Abbey.

- Immersive Visualization: the finalized BIM model was visualized using gaming technologies.

A block diagram representing the research workflow is illustrated below:



Data Collection: Leverage advanced laser scanning technologies to capture detailed point cloud data of the Abbey's interior using the Leica RTC360 scanner.

Use Leica RTC360 for high precision in documenting intricate architectural details within the church interior.

Focus exclusively on interior point cloud data acquisition.

Ensure a non-invasive process to protect the structural integrity of the historical building.

Data Processing: Analyze and refine the captured point cloud data for structural deformities using specialized software tools.

Conduct point cloud cleaning and noise removal.

Measure and analyze structural anomalies, such as cracks, deformations, and misalignments.

Prepare high-quality, refined data for further modeling and analysis.

BIM Development: Create a BIM model from the processed data to document structural details and facilitate restoration planning.

Convert point cloud data into 3D BIM objects.

Develop LOD0 and LOD1 models to capture varying levels of detail.

Measure and analyze structural deformities to plan restoration and maintenance effectively.

Visualization Integration: Develop interactive, immersive environments using Unity or Unreal Engine to enhance user interaction and engagement.

Transform the BIM model into a virtual environment.

Enable users to measure distances and make annotations within the virtual environment.

Provide restoration professionals and stakeholders with tools to simulate restoration interventions and visualize the Abbey in its current and proposed states.

Fig. 2 Block chart for the modelling workflow phases (own elaboration)

3.2 Data Collection and Processing

The measurement data was processed in Leica Geosystems Cyclone Register 360 2025.0.0 software(https://leica-geosystems.com/pl-pl/products/laser-scanners/software/leica-cyclone/leica-cyclone-model - accessed on 3.02.2025). Examples of images from processing point clouds captured during the church scanning in Sieciechów are shown in Figure 3.

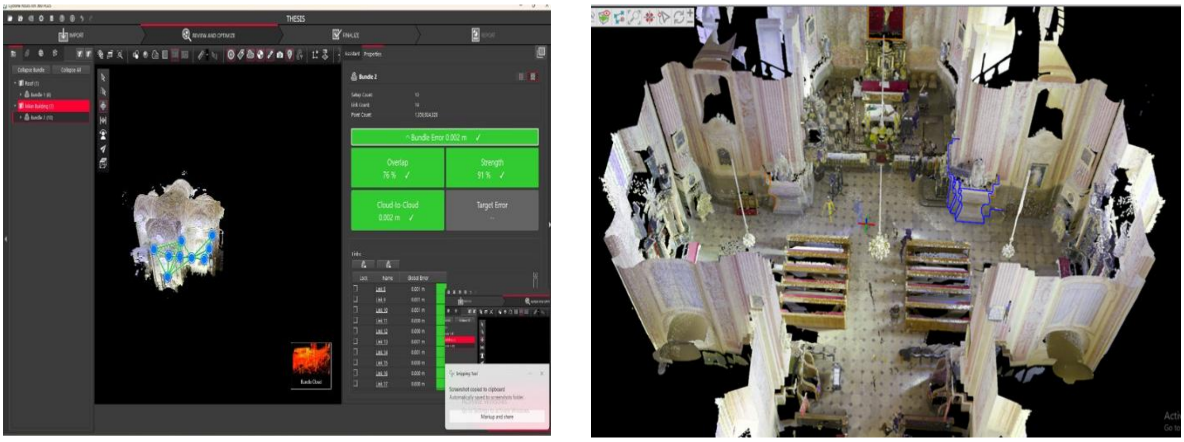


Fig. 3 The results of point cloud processing based on the abbey laser scanning (own elaboration)

Due to the significant number of architectural details, sculptures, and other artifacts, the scanning process had to be properly prepared and carried out according to strictly defined rules (Moussa, 2014).

3.2.1 Laser Scanning Process

The Leica RTC360 terrestrial laser scanner was used for data acquisition, providing high-precision 3D point clouds of the Benedictine Abbey (Fig. 1). The abbey has dimensions of length 27 meters, a width of 9 meters, and a height of 20 meters. The scanner was positioned at multiple locations within the abbey to ensure full coverage of the interior of the structure, including architectural details, floor levels, and observable structural deformations.

A total of nine (9) scan positions were used during the survey campaign. The RTC360 was operated at its highest resolution setting, enabling the capture of fine geometric details, such as stone joints, surface irregularities, and ornamental features, required for reverse engineering and BIM modeling. Each scan setup required approximately 3 minutes to complete, including high-resolution point cloud acquisition (up to ~2 million points per second) and 360° panoramic image capture.

The Leica RTC360 was operated at its highest resolution setting, resulting in a high point density that significantly enhanced the reliability of geometric interpretation, edge definition, and deformation analysis. At typical heritage scanning distances of approximately 20–30 m, while the scanner's range accuracy is within 1–2 mm. Meanwhile, the achieved multi-scan registration accuracy of approximately 0.002 m(2 mm) confirms the high quality of scan alignment. The resulting point spacing of approximately 3–6 mm at 10 m distance from the scanner enabled clear delineation of wall edges, reliable detection of cracks, and accurate measurement of surface irregularities and deformations. This level of accuracy was essential for documenting the Abbey's irregular historic masonry, where subtle geometric deviations and fine cracks needed to be captured and preserved rather than generalized.

Although terrestrial laser scanning is an active sensing technique and does not rely on ambient illumination for distance measurement, several practical challenges were encountered during data acquisition:

- Limited daylight hours constrained the acquisition of high-quality 360° panoramic images using the scanner's onboard cameras, which are essential not only for visual documentation and visual–inertial scan alignment but also for achieving a high level of visual realism in subsequent VR-based visualization.
- The need to capture the complete interior, exterior façades, and lower floor levels of the Abbey increased acquisition time.
- As a result, the scanning campaign was conducted over two days, whereas under longer daylight conditions (e.g. summer), the survey could have been completed within a single day for an abbey of about 243 m^2 .

3.2.2 Point Cloud Registration and Cleaning

Captured scans were imported into the Leica Cyclone 360 Register (https://leica-geosystems.com/pl-pl/products/laser-scanners/software/leica-cyclone/leica-cyclone-register-360 - accessed on 3.02.2025) for registration and alignment results shown in Fig.3. The scans were linked through black-and-white target points to ensure spatial consistency. During the process, the noise mitigation steps were undertaken:

- Noise Reduction: automatic filtering and manual editing removed unwanted reflections and extraneous points.
- Edge Detection: algorithms were applied to enhance structural details, improving clarity for later analysis.
- Decimation: the dataset was optimized by reducing redundant points while preserving structural integrity.

As mentioned, the processed point cloud is presented in Fig. 3, illustrating the high-resolution spatial dataset acquired from the Abbey. This dataset, generated through TLS surveying, provides a geometrically accurate basis for subsequent analyses, including deformation studies, material degradation assessment, and the development of BIM-compatible geometric models.

Figure 4, in turn, shows the results of the damage and material-loss measurements performed on the historic masonry walls using the derived modelling products. The integration of the classified point cloud with mesh-based surface models enabled precise quantification of surface detachments, erosion patterns, and structural discontinuities. These outputs supported the creation of thematic maps and diagnostic layers, which are essential for conservation planning, structural evaluation, and long-term monitoring of the monument's condition.

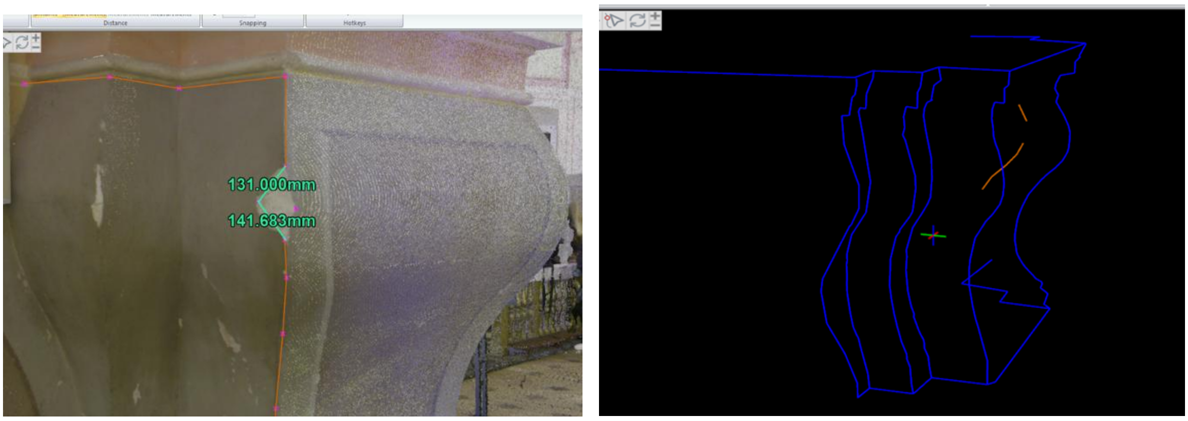


Fig. 4 Crack Measurements and BIM Model of two Separate Walls in the Abbey (own elaboration)

3.3 BIM Model Development

Once the point cloud data was processed and registered, the next step was to transform this dataset into a **Building Information Model (BIM)** of the Abbey. The BIM integrates both the geometric form of the structure and descriptive information about its components, materials, and condition, enabling analysis, documentation, and planning for restoration.

The BIM was created directly from the high-resolution point clouds acquired with the Leica RTC360 scanner. The point cloud provided accurate measurements of walls, floors, openings, and architectural details, allowing the model to represent structural deformations and irregularities typical of the 13th-century masonry. Identified cracks, material deterioration, and geometric deviations were incorporated as annotated features, supporting structural assessment and restoration planning. The point cloud served as the primary reference for modelling architectural and structural elements. BIM components were generated directly from the measured geometry, ensuring that irregularities typical of historic masonry—such as non-uniform wall thickness, surface deformation, and non-orthogonality were preserved rather than idealized. This was particularly important for identifying and analysing structural weaknesses, including cracks, material deterioration, and geometric deviations.

Identified defects and areas of deterioration were incorporated into the BIM as spatially referenced features, allowing the model to function both as a geometric representation and as a tool for structural assessment and restoration planning. In this way, the BIM serves as a digital twin of the Abbey, preserving its current condition and providing a reference framework for conservation works. It enables detailed analysis of weak spots, allowing the model to function not only as a geometric representation but also as a tool for structural assessment and restoration planning:

- LOD0 and LOD1 BIM Models: the LOD0 model provided a simplified floor plan, while LOD1 included detailed representations of walls, structural elements, and deformations.

- Integration of Structural Monitoring Data: identified cracks and material deterioration were incorporated into the BIM model for restoration planning, as shown in Fig. 4.

3.4 Cloud-to-BIM Operations

The transformation from point cloud to BIM involved extracting geometric features from the registered point cloud data and converting them into parametric or semi-parametric BIM elements. In practice, this meant:

- Surface and edge extraction: Walls, floors, ceilings, and openings were identified from the point cloud by analyzing planar and curved surfaces.
- Feature fitting: Irregular geometries typical of historic masonry were represented using best-fit planes, polygons, and simple 3D volumes, preserving deformations and non-orthogonal alignments.
- Annotation of defects: Cracks, material deterioration, and geometric deviations were incorporated as attributes or separate elements within the BIM, enabling structural assessment.
- Integration into a digital twin: The resulting model combines both geometry and descriptive information, providing a unified reference for conservation and restoration planning.

These operations allowed the high-density point cloud captured by the Leica RTC360 scanner to be directly converted into an accurate, analysis-ready BIM, representing both the shape and condition of the Abbey.

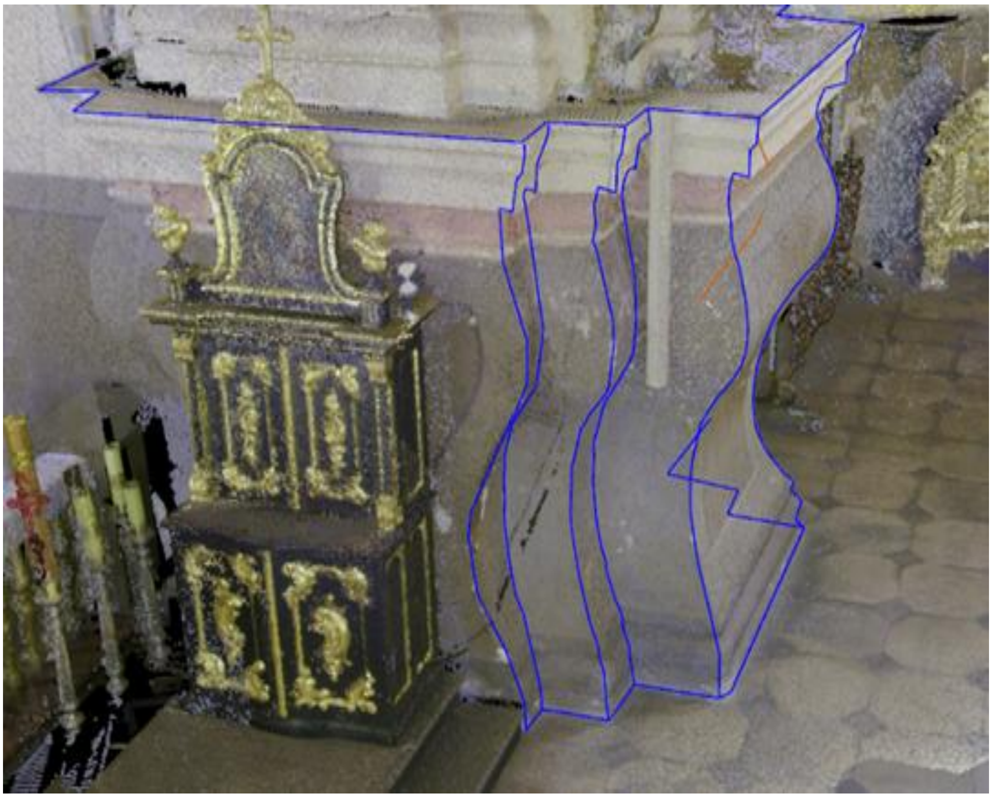


Fig. 5 An example of how a point cloud-based BIM modelling is generated (own elaboration)

The aforementioned activities enable the development of models for the architectural and historical valuation of heritage sites. The design process must be founded upon the identification and comprehension of historical structures, primarily through condition assessment and so-called chronological stratification (Głuszek, 2022). This process is conducted by comparison with reference objects, utilizing spatial data acquisition tools (e.g., laser scanners) and invasive techniques that necessitate the disturbance of the physical fabric (sampling). Consequently, in addition to an in-depth historical archival search, it is essential to capture and model spatial data representing the object—in this study, the post-Benedictine abbey—with the highest possible precision. As stated by the cited author, such a graphical record should also incorporate a series of historical, scientific, and artistic attributes. The resulting H-BIM (Heritage Building Information Modeling) model facilitates informed decision-making regarding facility management, including ongoing maintenance, potential modernizations, and structural repairs.

Fig. 6 An example of the final point cloud-based BIM model (own elaboration)

3.5 Immersive Visualization

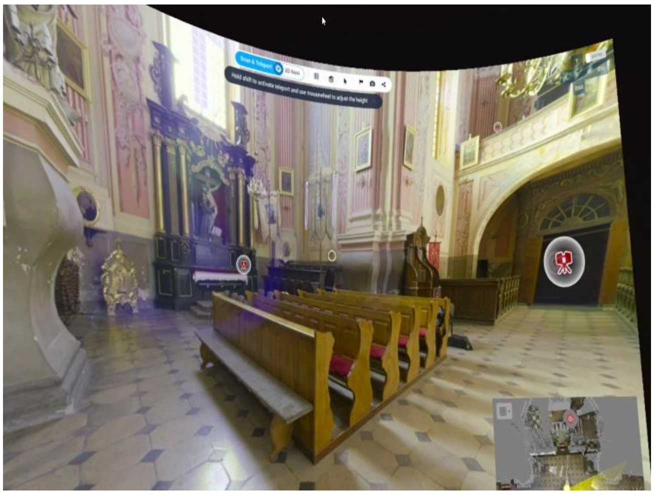
To enable interactive exploration and detailed analysis, the BIM model of the Abbey was imported into Unreal Engine (accessed on 03.07.2025) for immersive visualization (Fig. 7). The digital model was processed to maintain high geometric fidelity while optimizing performance, allowing smooth navigation of both interior and exterior spaces.

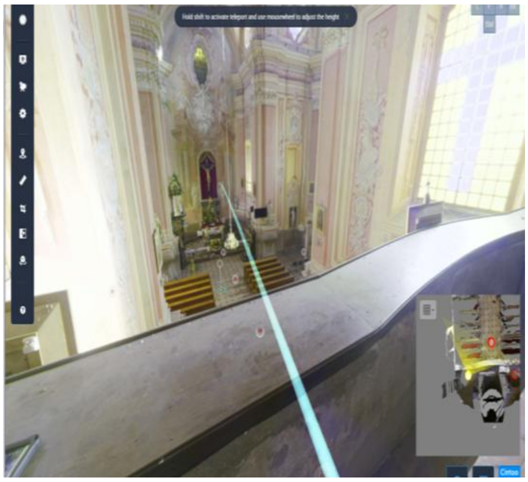
Key operations and features implemented in Unreal Engine included:

- Structural inspection: Experts could navigate the virtual Abbey, measure distances, and examine cracks, deformations, and material deterioration identified in the BIM.

- Simulation of restoration interventions: Proposed repairs, reinforcements, or material replacements were tested virtually to evaluate their impact on the structure before implementation.
- Interactive annotation: Users could add notes, highlight areas of concern, or display additional metadata associated with structural elements, facilitating collaborative assessment.
- Immersive public engagement: The model supported virtual tours for non-expert audiences, allowing exploration of architectural and historical features, and providing an educational experience without accessing the physical site.
- Lighting and texture visualization: High-resolution textures and realistic lighting were applied to enhance visual realism and support evaluation of material conditions.

This workflow allowed the Abbey to be experienced as a digital twin, combining accurate geometric and material representation with interactive and analytical capabilities. The immersive environment supported both expert decision-making and public engagement, providing a versatile platform for heritage conservation, restoration planning, and educational outreach.





Hold shift to activate teleport and use mousewheel to adjust the height

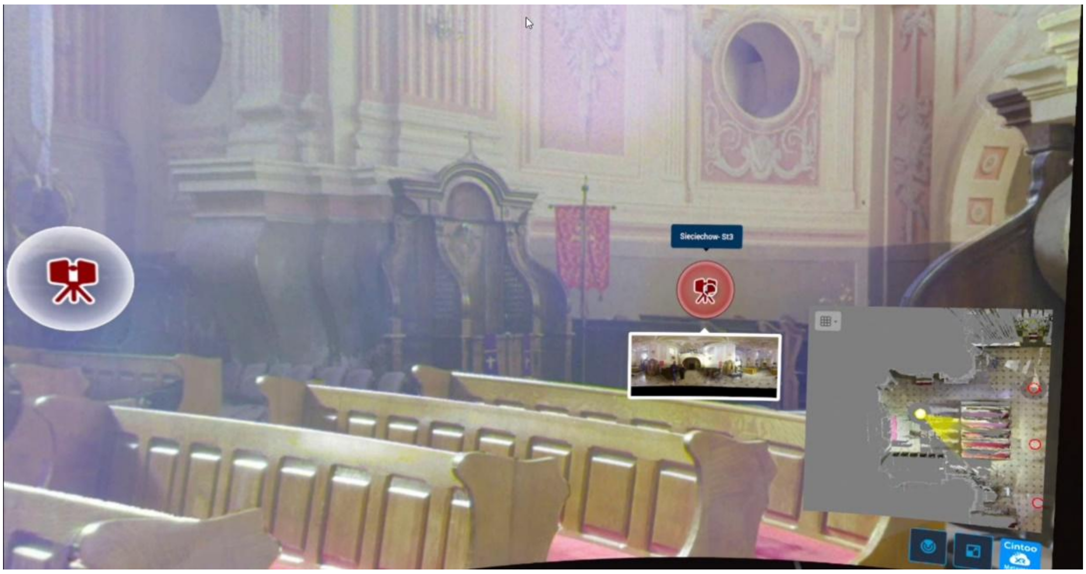


Fig 7. Point Cloud Visualization in Unreal Engine- Cintoo (own elaboration)

4. RESULTS

The Leica RTC360 scanner successfully captured high-resolution point clouds, documenting the Abbey's existing condition. The final dataset was refined through multiple filtering steps, yielding a registration accuracy of 0.002 meters and an overlap rate of 76%, ensuring highly reliable data as shown in Fig 3.

Extraction of 3D lines from N4CE was the subsequent vital step after data importation to establish wall boundary definitions. Toward wall edge extraction in N4CE the "Pick Point" tool was operated as shown in Figure 5. The extraction process enabled the generation of 3D lines which revealed the exact wall geometry in the building structure (Fig. 8).

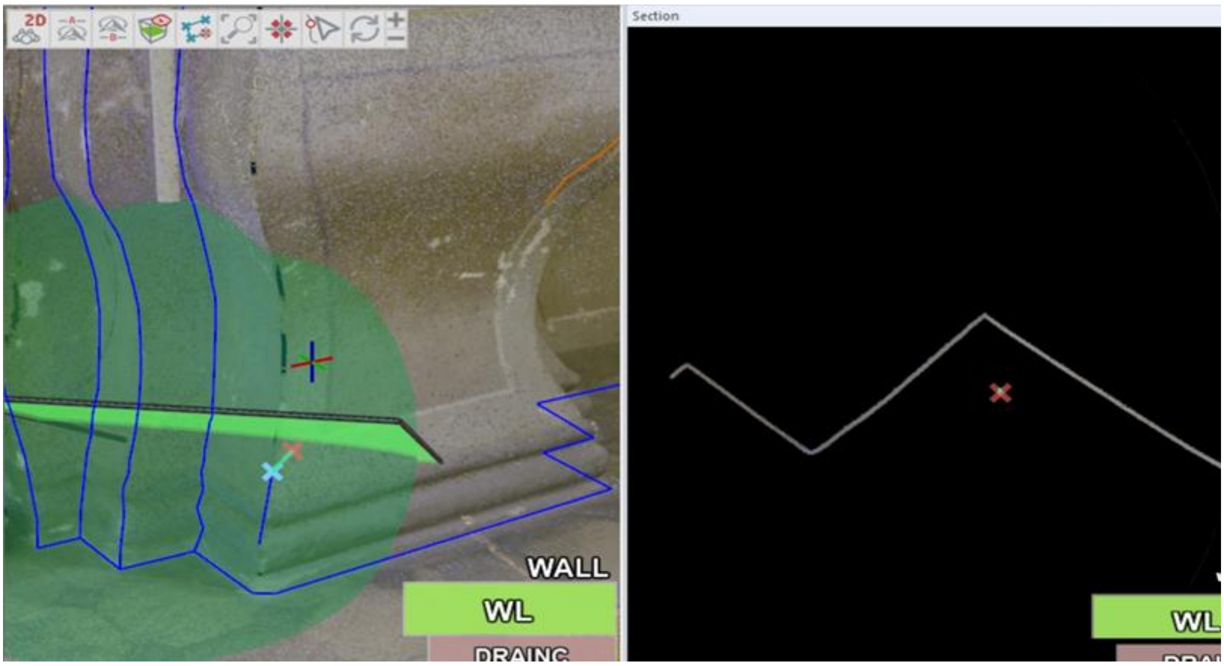


Fig.8 A wall geometry in the building structure (own elaboration)

After the walls were accurately delineated, structural issues such as cracks were identified and measured. For instance, a prominent crack was found on the wall in the church section, and its dimensions were noted for further analysis. The cracks identified during the analysis were critical for assessing potential restoration and reverse engineering, with the data providing insights into areas requiring immediate attention.

A key outcome of the survey was the detailed identification and analysis of wall deformations at the Sieciechów Abbey. High-precision point cloud data acquired with the Leica RTC360 scanner enabled accurate detection and measurement of cracks, surface irregularities, and geometric distortions in the masonry walls. The clarity of wall edges—both straight and curved—provided by the laser scanning technology was particularly valuable in the context of this historic structure, where many structural issues are not readily visible to the naked eye.
As illustrated in Fig. 4, cracks were clearly identified and measured, revealing deformations of up to 141.7 mm in critical wall sections. These values reflect long-term dimensional shifts within the masonry and indicate potential structural weaknesses that may compromise the building's stability. The ability to precisely locate and quantify such deformations provided essential input for subsequent BIM generation and structural assessment.

The extracted crack and deformation data were incorporated into the BIM environment, where they serve as a foundation for reverse engineering and restoration planning. By visualizing and measuring these defects within a unified digital model, conservation specialists can prioritize interventions, assess vulnerable areas, and plan targeted repair strategies. This approach supports informed decision-making and contributes to the long-term preservation and structural stability of the Abbey.

The above-demonstrated features make it possible to perform the following survey tasks:

- Crack Analysis: measurements revealed deformations up to 141.7 mm in critical wall sections as shown in Fig. 4.
- Surface Irregularities: the point cloud clearly depicted material degradation, enabling targeted restoration efforts.

4.1 Structural Monitoring and BIM Integration

The LOD1 BIM model was developed to incorporate key structural defects—such as wall cracking patterns, geometric deformations, and weakened ceiling struts—as already illustrated in Fig. 4. By embedding these deterioration features directly into the BIM environment, the model served not only as a geometric reference but also as a diagnostic layer supporting structural health monitoring workflows.

The integration of point cloud data with the Cintoo Cloud platform enabled continuous condition tracking through periodic scan-to-BIM comparisons. This workflow allowed for the detection of subtle geometric changes, including progressive crack widening, differential wall displacement, and deformation of timber or steel ceiling elements. Real-time visualization and cloud-based analytics facilitated rapid anomaly identification, supporting early-warning strategies and reducing the risk of undetected structural degradation.

Furthermore, the BIM model functioned as a comprehensive restoration and monitoring framework (Fig. 6), consolidating spatial data, historical documentation, and engineering assessments into a unified digital environment. This data-driven approach enhanced decision-making for conservation teams by enabling scenario testing, prioritization of interventions, and long-term planning based on quantifiable structural performance indicators.

4.2 Fire Safety Enhancements

One critical outcome was the identification of fire safety deficiencies, which is particularly significant given the stringent requirements for safeguarding historic buildings. In accordance with widely adopted standards—such as the European fire safety directives, national building regulations, and conservation guidelines issued by heritage authorities—historic structures must be equipped with adequate passive and active fire protection measures. The assessment revealed gaps in compartmentation, insufficient escape route provision, and outdated or non-compliant detection systems, all of which pose elevated risks due to the combustible nature of aged materials and the limited structural redundancy typical of heritage architecture. Identifying these deficiencies is essential for developing a compliant fire-protection strategy that balances regulatory obligations with the need to preserve the building's historical objects, following best-practice frameworks.

To strengthen safety precautions for the historic building, a fire hydrant system was created and incorporated into the BIM model as shown in Fig. 9 (in this particular case, it would be necessary to place the confessional in a slightly different location). As part of the fire safety plan, escape routes are analyzed to make sure they are structurally sound and properly designated. The viability of incorporating contemporary early-warning systems without sacrificing the building's historic integrity was also evaluated by modeling sensor-based fire detection systems in BIM. Using the Abbey's digital counterpart, simulations were run to assess fire evacuation scenarios and identify the safest and most effective ways for residents to evacuate. Modern suppression techniques, including misting systems, which effectively control fires while reducing damage to the structure's fragile materials, are also taken into account by the system. This all-encompassing strategy, which combines fire mitigation techniques with BIM-based risk assessment, greatly improves the safety of both people and the cultural site.

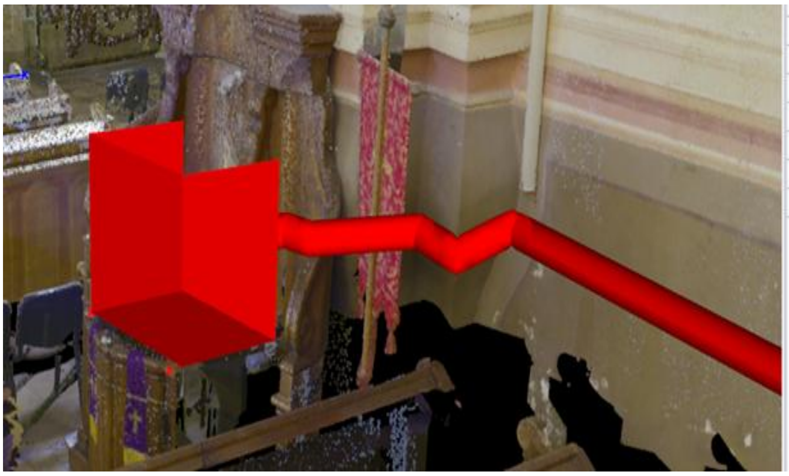


Fig. 9 BIM Model for proposed fire hydrant system (own elaboration)

4.3 Visualization and Stakeholder Engagement

The conducted modelling makes it possible to build an integrated risk-management system for the heritage structure under testing, and—after expanding the proposed methodology—to enable the supervision and monitoring of the condition of any building structure. The Unreal Engine–based visualization enabled stakeholders to:

- Virtually explore the abbey’s structural condition as illustrated in Fig. 7. By integrating the photogrammetric mesh with the semantically enriched BIM structure, users are able to examine wall deformations, material losses, and spatial relationships between load-bearing elements. Within the VR environment, it was possible to switch between multiple Levels of Detail (LOD), supporting both macro-scale assessment of the overall geometry and micro-scale inspection of architectural details.

- Interact with restoration plans and assess the feasibility of different interventions. The combination of BIM models with Unreal Engine simulations allowed real-time testing of conservation scenarios—from reconstructing missing components to analysing the impact of proposed interventions on adjacent structures. Interactive tools enabled visualization of work phasing, comparison of alternative strategies, and preliminary risk assessment, thereby strengthening the decision-making process for design and conservation teams.

- Enhance public engagement through immersive virtual tours. The VR-based presentation made it possible to disseminate the digital reconstruction of the abbey to a broad audience, including individuals without physical access to the site. Owing to the high-fidelity geometry and texture reproduction—derived from photogrammetry and laser scanning—visitors could experience the spatial qualities of the monument in a manner closely resembling on-site presence, supporting heritage education and awareness-raising initiatives.

"The conducted research also makes it possible to formulate conclusions and to comment on the obtained results within a broader context related to cultural heritage.

5. CONCLUSIONS

This work has demonstrated that the integration of terrestrial laser scanning (TLS), Building Information Modelling (BIM), and immersive visualization provides a powerful and effective framework for the documentation, analysis, and conservation of historic structures, as exemplified by the 13th-century Benedictine Abbey in Sieciechów, Poland. By combining geospatial precision with interactive digital environments, the research addressed key challenges associated with the preservation of aging heritage assets, including limited accessibility, structural deterioration, and the need for informed decision-making among diverse stakeholders.

High-resolution point cloud data acquired with the Leica RTC360 scanner enabled the accurate documentation of the Abbey's complex geometry and current structural condition. The non-contact nature of laser scanning proved especially valuable for heritage conservation, allowing fragile architectural elements to be recorded in detail without physical intervention. Subsequent processing and refinement of the point cloud ensured a reliable dataset, which formed the foundation for the creation of a detailed digital representation of the Abbey.

The development of the BIM model transformed raw spatial data into an intelligent digital twin that integrates geometry, material condition, and structural information. By representing cracks, surface irregularities, and deformations directly within the BIM environment, the model became more than a visualization tool—it evolved into an analytical platform supporting structural assessment, restoration planning, and future monitoring. The use of multiple levels of detail allowed both strategic planning and detailed analysis, ensuring that interventions could be evaluated in relation to the Abbey's historical fabric and architectural significance.

The incorporation of immersive visualization further expanded the value of the digital twin by enabling stakeholders to explore, analyze, and discuss the Abbey in an intuitive virtual environment. This approach facilitated collaboration between conservation professionals, historians, and non-expert audiences, while also supporting the simulation of restoration interventions prior to physical implementation. By making complex heritage data accessible and understandable, immersive technologies helped bridge the gap between technical analysis and public engagement.

Beyond the specific case of the Sieciechów Abbey, this research demonstrates the broader potential of integrated digital workflows for heritage management. The methodology aligns with global trends in digitization, digital twin development, and preventive conservation, emphasizing early detection of structural issues and proactive intervention to extend the lifespan of cultural assets. Similar approaches have proven effective in major international heritage projects, and the workflow presented here is scalable and adaptable to other historic sites facing comparable challenges.

In conclusion, this research confirms that the thoughtful integration of laser scanning, BIM, and immersive visualization can significantly enhance heritage preservation practices. By uniting technological innovation with respect for historical authenticity, the study contributes a robust, future-oriented model for sustainable cultural heritage management—one that supports accurate documentation, informed restoration, stakeholder collaboration, and long-term safeguarding of irreplaceable historical structures.

The methodology presented in this study, centered on HBIM and architectural valuation, provides a robust foundation for the responsible digital asset management of heritage sites. Future research should focus on the integration of real-time monitoring through Internet of Things (IoT) sensors, allowing for the continuous assessment of structural health within the BIM environment. Furthermore, the implementation of Artificial Intelligence (AI) algorithms for automated defect detection in point clouds offers a promising avenue to enhance the efficiency of stratigraphic analysis. Integrating Laser Scanning, BIM, and Virtual Reality (VR) technologies will not only facilitate the monitoring and restoration of existing historical structures but also improve stakeholder engagement through immersive digital twins. Such advancements will transition HBIM from a static record into a dynamic, predictive tool for the long-term preservation of the physical fabric.

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BIOGRAPHICAL NOTES

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