# Reliability in HBIM-XR for Built Heritage Preservation and Communication Purposes

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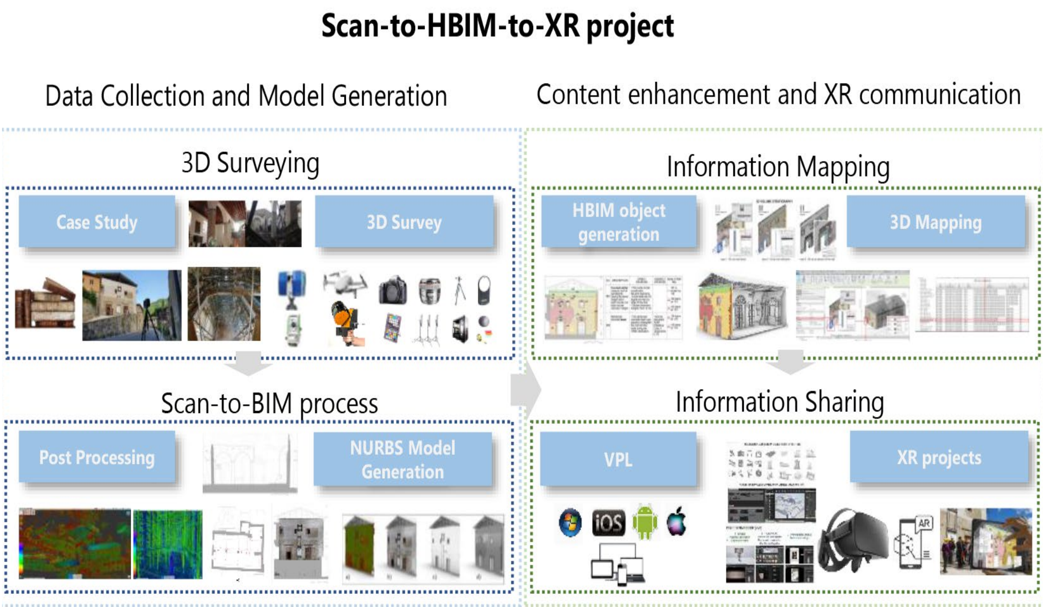
*Abstract*

In recent years, applied research and building information modelling (BIM) have been directed to the scan-to-BIM process by implementing increasingly high-performance methods capable of managing a large amount of data such as laser scans and high-resolution orthophotos and textured mesh models from digital photogrammetry (terrestrial and aerial). On the other hand, the digitisation process of built heritage and the paradigms of the "reliability" and "transparency" of HBIM models have not yet been wholly considered by the main international BIM standards. For that reason, this study proposes a method and the development of HBIM parameters capable of communicating heterogeneous values to support the life cycle of the building, from the survey campaign to the restoration and maintenance of the asset. In this context, 3D modelling, HBIM, building archaeology, visual programming language (VPL) and extended reality (XR) have been directed to a scan-to-HBIM-to-XR method able to improve the information sharing of earthquake-damaged buildings such as the San Francesco church in Arquata del Tronto, moving from for different types of users, digital devices and virtual experiences.

*Keywords*
HBIM, XR, reliability, built heritage, VPL.



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## Introduction

In recent years, the "digital revolution", technological developments and applied research in the Architecture, Engineering and Construction (AEC) industry are increasingly directing professionals update themself in their daily practices, exponentially changing the design and management of the building, from the first design phase to construction and management over time. We have seen how design and architectural representation have evolved in the last decades: from the advent of CAD vector drawings to the more complex forms of 3D digital modelling and BIM projects. In addition, we are already seeing how BIM, BIMcloud and InfraBIM are evolving into increasingly interactive and immersive forms such as digital twins. Thanks to the integration between models and sensors, it is possible to manage and monitor building behaviour. Furthermore, thanks to eXtended Reality (XR), we can give life to objects with visual programming language (VPL) and artificial intelligence (AI) and investigate new forms of "digital proxemics" and digital communication [Gironacci 2020, pp. 105-118; Ioannides et al. 2017]. Moreover, software manufacturers are progressively changing and improving the software interface to define the market in support of existing buildings and not only the new ones. In this context, various projects have demonstrated how the integration between 3D survey and digital modelling can support the scan-to-BIM process and more advanced forms of informative models oriented to preserving built heritage. On the other hand, the creation process of historic building information modelling (HBIM) models requires in-depth knowledge in many disciplines and different digital tools to go beyond the simple creation of geometric representation. Professionals need high digital skills such as computer graphics, computer programming, digital representation, restoration and archaeology. In this context, the paradigms of "reliability" and "transparency" of HBIM models are values to be shared appropriately to all professionals (and non-professionals) involved in the building preservation process and the subsequent forms of communication associated with it. Consequently, this research has tried to improve what is now called the scan-to-BIM-to-XR process aimed at heritage buildings that require a completely different approach to modern buildings, trying to improve the metric, geometric and informative reliability of digital models for preservation and communication purposes. Several tests related to the quality of the modelling process (i), the interoperability of the 3D exchange formats (ii), real-time synchronisation among the various software applications (iii) and human-computer interaction (iv) were conducted to give life to HBIM objects and interactive virtual objects (IVOs) of San Francesco church in Arquata del Tronto (Italy) damaged by the earthquake in 2016 (Figs. 1-2). The case study has allowed the authors to investigate and define a research method capable of increasing the communicative value of the digital model for different types of users, from experts in the construction sector to virtual tourists and students.

Fig. 1. San Francesco Church before and after the 2016 earthquake.

Fig. 2. 3D surveying campaigns and construction scaffolding as a temporary structure for support safety in the construction site.

## The Case Study: San Francesco Church's Historical and Cultural Background

Arquata del Tronto was struck by the earthquake that hit Central Italy in 2016. The seismic sequence began in August 2016 with epicentres located between the upper Tronto valley, the Sibillini Mountains, the Laga Mountains and the Alto Aterno Mountains. Norcia and Arquata del Tronto suffered considerable damages, while Amatrice and Accumuli were almost razed. The loss of human life was relevant, togheter with the destruction of cultural heritage, such as the church of San Francesco in Arquata [Gailè, Vecchioni 2006].

Arquata del Tronto has always been on edge between territories with different cultural, administrative and economic backgrounds, on the western side of Regione Marche, which borders Lazio and Umbria. Arquata is enclosed within two protected natural areas: on the north, the Sibillini National Park, and on the south the Gran Sasso and Monti della Laga National Park. It was founded on a few mountain passes that provided an easy route from the Adriatic Sea to Rome through the ancient via Salaria. The strategic and military importance of Arquata arose around the 13th, with the fight for hegemony between Ascoli and Norcia, traces of which remain in the construction of the Stronghold on the top of the hill, overlooking the town. In this framework, the convent and church of San Francesco were founded. One Franciscan settlement is attested in 1251, although a church of the Minors is mentioned only 40 years later. The scarcity of information, mainly due to the dispersion of the archive, does not help reconstruct the history of the convent of San Francesco [Ciociola, Castelli 2010].

However, thanks to a careful study of the church – whose external walls are not plastered – building archaeology analysis, together with the study of documents, it is possible to make some assumptions about its construction phases. First, a small church was built and transformed with a single hall, without side chapels, a square choir around the 14th century. Then, a second nave was added between the 16th and the first half of the 17th century. The 20th-century restorations introduced concrete beams on the top of the wall and replaced the roof. The church stands on one of the fourth aisles of the convent, on the south, which is arranged around a courtyard.

The August 2016 earthquake caused slight damage to the church, which was still accessible. The most significant damages occurred during the second shock in October 2016 and the heavy snowfall in January 2017, which caused the roof collapse, the wooden carved ceiling, and, partly, the walls [Giallini et al. 2020].The safety measures involved reinforcing the walls with hydraulic lime mortar and strips of galvanised steel or basalt fibre mesh (main façade). Inside, a metal profile structure was built to support the arches and scaffoldings, which made the laser scanning survey challenging (Fig. 2). In 2019 the Municipality of Arquata del Tronto tasked the research group of the Politecnico di Milano to draw the preliminary design project of San Francesco Church. It included the creation of an HBIM oriented to geometrical, material and historical analysis and a VR project. The same project encloses the study of the Stronghold of Arquata. The preservation plan of the Church and the Stronghold is part of a broader vision that includes the rebirth of the communities devastated by the earthquake that has severely affected Central Italy in 2016. Although the community of Arquata was deeply unsettled by the seismic event, which caused the abandonment of the houses in the historic centre and the construction of temporary houses, just outside the town, the church of San Francesco represents a landmark for the citizens, where intangible values are kept.

## The Paradigm of Complexity in Digital Architectural Representation for Heritage Buildings: the Reliability and Transparency of HBIM Objects for Preservation and Communication Purposes

The paradigm shift from 2D CAD drawings to BIM has already overtaken the experimental phase with guidelines to standardise the 3D model generation. The AEC sector had to adapt to the new technological developments and methods. Guidelines are set both on a national level (i.e. the well-known NBS) or an intermediate level, i.e. the one set in 2012 by Bloomberg, Burney and Resnick of the Department of Design and Construction in New York City.
At the same time, BIM uses were affected by the companies' needs and ranged from the design to the construction site phase. In the last decades, the interoperability among different software became of primary importance due to the necessity to integrate point clouds (coming from terrestrial and aerial surveys), photogrammetry and historical documentation within the 3D modelling process, overcoming the logic of preset libraries of objects which do not adapt to the existing buildings. When dealing with historic buildings, the Level of Development and the Level of Detail (LOD) go into crisis, and the complexity of shapes and information turns out.
The uniqueness of the 3D architectural objects often requires modelling each element avoiding "copy and paste" operations. This involves a not easily interoperability among as-found, as-designed and as-built models and requires the knowledge of different types of 3D exchange formats. The difficulty also lies in the information associated with the objects, which sometimes are only based on assumptions, and may change, i.e. wall stratigraphy or the properties of the materials can be unknown, or historical hypotheses or interpretations
The paradigm of complexity in the HBIM domain refers to the shape, geometry, and physical features of objects and the information and values associated with them.
The last few years have been characterised by many HBIM projects and methods capable of managing the paradigm of the complexity of historical buildings and archaeological sites in an appropriate way, extending the concept of BIM to that of heritage (HBIM). HBIM projects have been improved by integrating different technologies such as 3D surveying, laser scanning, digital photogrammetry (terrestrial and aerial), and advanced modelling techniques [Russo, Manferdini 2015]. Furthermore, it was found that the understanding and interpretation of each artefact detected from a typological point of view is fundamental in the first model generation phase.
The need to increase the LOD and LOI (Level of Information) of HBIM models was consequently directly proportional to its decomposition into sub-elements capable of representing semantic structures, not necessarily dictated exclusively by the geometry or constructive logic of the building. The determination of intelligent parametric objects and the bidirectional relationships that they establish are fundamental for the subsequent phases of mapping information and sharing complex scenarios such as archaeological sites, earthquake buildings, and historical infrastructures. Accordingly, in a more general and holistic context, it is essential to update one's knowledge constantly and skills not only at a digital level, trying to reach a level of autonomous management of these technologies, digital tools, and methods.

## The Digitisation Process: from 3D Surveying to HBIM Objects

In Italy, the reliability of a 3D model is mainly associated with the UNI 11337-4: 2017. The UNI describes the terminological distinction between LOD, LOG, and LOI. LOD (Level of Development of digital objects) comprised LOG (Level of development of objects – Geometric attributes) and LOD (Level of Development of objects – information attributes). Thus, we can find two main levels of reliability: on one hand, the geometrical and physical characteristics of each architectural object, on the other, the information associated with them. Transparency may be referred to the communication of the precision and accuracy of the model and related information. However, the LOD works mainly for new buildings, while it does not always easily apply to existing or heritage buildings. Many studies have shown that heritage objects do not fit with the BIM objects libraries due to their uniqueness. This is even more true in the case of archaeological sites, ruins, building damaged by natural disasters, such as the San Francesco church. Moreover, when dealing with complex shapes (i.e. damaged or out-of-plumb walls) the geometrical reliability of the 3D object often depends on the modeller. Sometimes, the LOD is defined without feasible rules – not acceptable for the historical objects – or adopted with no reference to the required representation scale. Thus, the "reliability" of the model should not only be based on the LOD concept and the main international guidelines of LODs should be oriented towards historic buildings, defining new scan-to-BIM parameters which accurately describe the quality of the model and its reliability in both metric-geometric and semantic terms. The 3D survey of the church was carried out in two survey campaigns. In the first one, 65 scans were acquired with Faro Focus 3D laser scanner, based on a geodetic network to allow a strong reference for the alignment. Multiple connections between inside and outside stations were established to guarantee a good redundancy of the network. The network was measured with Leica TPS1200 total station and a final least-squares adjustment provided an average precision of ±2.0 mm. The scans' final registration (Faro SCENE 6.2.30) provided an average precision of the target of ±4.5 mm (Fig. 3). During the second survey campaign, the data were integrated with the dataset acquired with a handheld Mobile Mapping System (MMS) to complete the external pathways of the convent. Then, UAV was used to get the dataset of the whole area.The 2D as-built CAD drawings refer to the main plans, overlapping plans, two sections, and internal and external facades. These first drawings were the basis for the first draft of the preservation plan, which included the material and construction technique analysis and damage assessment [Doglioni 1997]. Then, a Building Archaeology of the façade was carried out to understand the historical traces and transformation of the building. The HBIM was realised following the specific scan-to-BIM requirement based on Non Uniform Rational Basis-Splines (NURBS) algorithms to capture each architectural object's geometrical and semantic complexity [Banfi 2020]. The building archaeology analysis was transferred into the HBIM, trying to cope with the complexity of a historical building damaged by the earthquake. An auto-

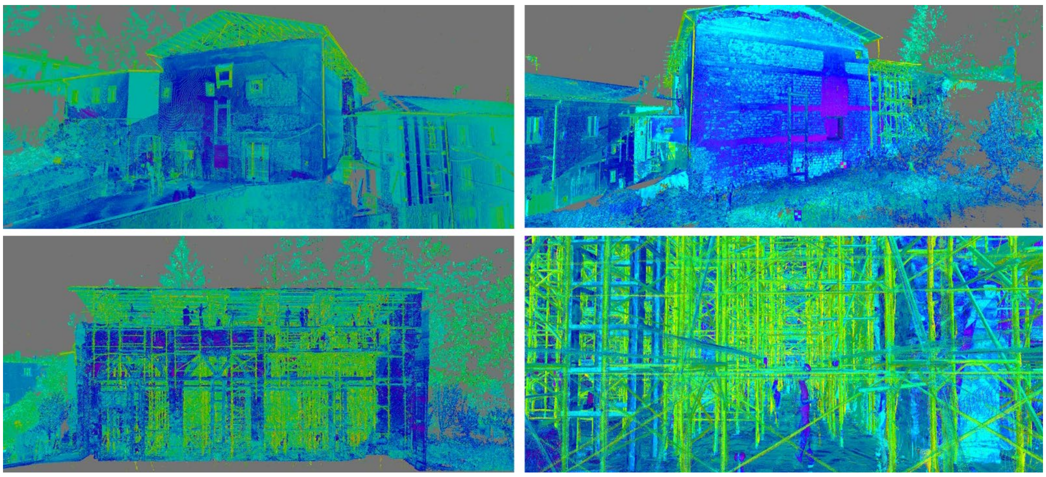

Fig. 3. 3D scans of the Church.

matic verification system (AVS) based on the standard deviation value between the 3D scan and digital model was used to verify the geometric and metric reliability of each architectural and structural element of the church. This approach made it possible to communicate the quality of HBIM objects created in geometrical-metric terms to the client (Municipality of Arquata) and the professionals involved in the building restoration process. Consequently, the HBIM parameters for each single modelled element have been developed to share the grade of accuracy (GOA), the source data used to model the elements, and data type (laser scanning, terrestrial/aerial photogrammetry, historical records). At the same time, the communication of specific information relating to each single modelled element ensured the "transparency" of intrinsic parameters of each data source used. The analysis that results from building archaeology is derived from integrating direct sources with indirect ones. In architectural research, common direct sources are geometrical surveys, on-site inspections, and material/decay analysis. All of these give first-hand information about a building. Indirect sources are reconstructions from primary and/or other indirect sources, such as reports and interpretations. Building archaeology resulted in a stratigraphic units (SU) subdivision of the walls differentiated according to the different construction techniques and stratigraphic relationships [Boato, Pittaluga 2000]. The HBIM of the church was then realised with the different SU so that each wall layer has its consistency and properties. HBIM properties were added regarding materials, observation and documentation for each SU, trying to transmit even the hypothesis (about construction phases or materials) and the source's reliability (if the information derived from observation or archival documents,…). For those reasons, building archaeology is used to represent the geometric and semantic complexity of the San Francesco church. The communication of these values will allow the professionals involved in the church restoration process to view the data used and the level of knowledge reached for each HBIM object (Fig. 4).

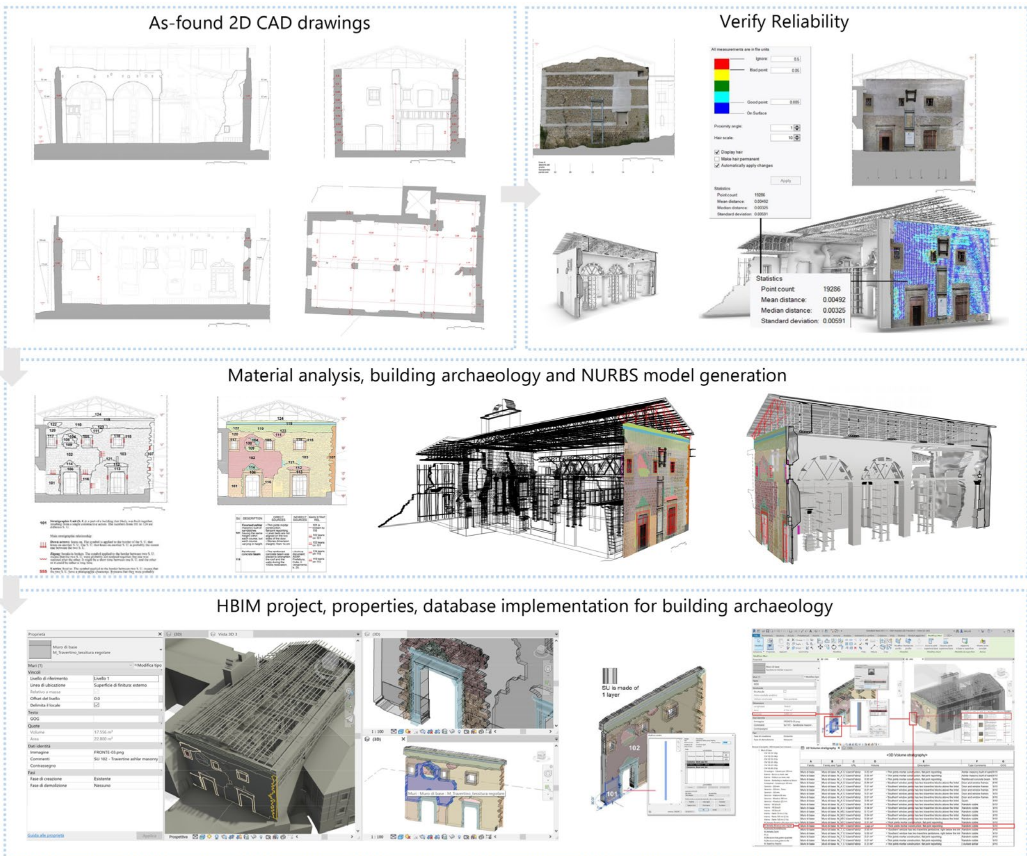


Fig. 4. From 2D CAD drawings and building archaeology to NURBS model, HBIM objects and properties.

## Improving Communication Using XR Development Platforms: from Visual Programming Language (VPL) to Real-Time Immersive Architectural Experiences

Once the model was created and verified in reliability terms, the authors improved the flow of information associated with the HBIM objects created using XR development platforms. The ultimate goal was to reach a broader range, moving from professionals involved to virtual users who did not have specific digital skills. The VPL and XR development platforms have proved useful in increasing the communication of the church's historical and cultural background, the survey process, and preliminary information to virtual users. Given the objectives set, the authors opted to define a process capable of synchronising the building's HBIM model in real-time with the latest generation immersive environments without having to resume the orientation and adaptation phase of the model. Thanks to recent developments in the field of gaming development, it has been possible to use specific add-ins (developed by Epic games) able to synchronise in a single software flow such as Mc Neel Rhinoceros (oriented to geometric modelling), Autodesk Revit (used to create HBIM models) with Twinmotion and Unreal Engine 4 platforms, the latter able to associate the VPL with 3D objects. The transition between modelling environments and XR development platforms also made it possible to avoid a second phase of 3D mapping, using orthophotos and HD images from digital photogrammetry. The final step was to associate key blueprints (visual scripting by unreal Engine) to the various objects created in Rhino and then in Revit, passing from static entities to interactive virtual objects (IVOs). Once the development phase (VPL and HBIM objects) was completed, it was possible to use the platform's packaging functions to create specific apps oriented to VR and AR devices (Fig. 5).The VR project of the church envisaged the definition of virtual visual storytelling (VVS) capable of providing a virtual experience to the end-user. As is well known, a VR project requires three elements: content, geometry and dynamics. Objects and information associated with the environment define the content. Instead, the geometry indicates the physical extension that the user wants to attribute to the digital environment. Finally, the dynamics refer to interaction rules between the contents and the environment. By interpolating these three elements, a virtual environment is created, meeting the definition of a "real illusion" in which one or more users can interact with it through the use of specific devices (PC workstation, laptop, VR headset, tablet or mobile phone). In this context, the most exploited sense of the human body is sight, which is stimulated by factors that lead to an optimal configuration of virtual environments with high

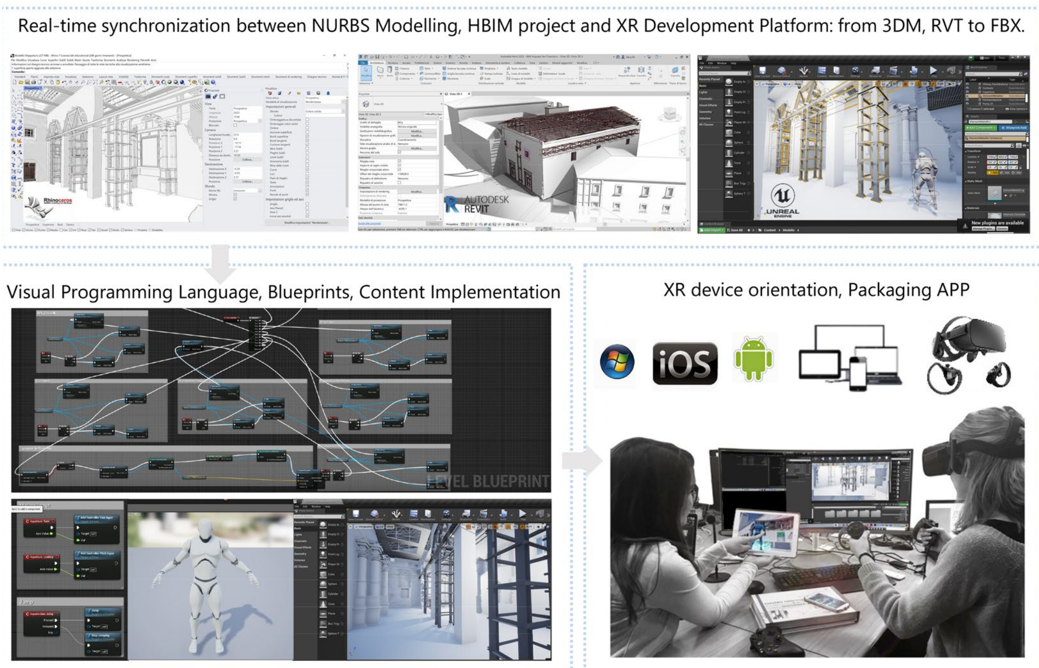


Fig. 5. From real-time synchronisation models to Visual Programming Language and XR devices.

visual quality. The research objective was to create an exclusively digital environment built to induce the user to experience sensations, emotions, and discoveries, consciously decided by the programmer who decides to make specific experiences three-dimensional and dynamic.

## Conclusion

This research aimed at optimising a scan-to-HBIM-to-XR process that defines digital parameters to declare the quality of the informative models created in metric and semantic terms. The paradigms of reliability and transparency of the models are discussed and developed through the case study of San Francesco Church in Arquata del Tronto, where the building archaeology allows the authors to go beyond a pre-established semantic decomposition for architectural and structural elements. Different modelling approaches have been reported that show how the generations of stratigraphic units, identification of materials, construction techniques, historical phases can become real BIM parameters and shared to all users involved in the preservation process. Furthermore, thanks to new programming languages such as blueprints it has been possible to go beyond the static representation of digitised elements. The process, as demonstrated, allowed authors to pass from textured meshes and NURBS and HBIM models and manage interactive virtual objects (IVOs), thus allowing the possibility to increase the level of interactivity and immersion of accurate scan-to-HBIM projects.

### Notes

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