Virtual Archaeology Review, **11**(23): 16-33, 2020
https://doi.org/ 10.4995/var.2020.12416

Received: October 4, 2019
Accepted: February 5, 2020

HBIM, 3D DRAWING AND VIRTUAL REALITY FOR ARCHAEOLOGICAL SITES AND ANCIENT RUINS

HBIM, DIBUJO 3D Y REALIDAD VIRTUAL APLICADOS A SITIOS ARQUEOLÓGICOS Y RUINAS ANTIGUAS

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Highlights:

- The concept of 'granular HBIM objects' is introduced to show the unexpressed potential of the scan-to-BIM process for different types of data analyses and uses.
- Sustainable development of VR projects for archaeological sites is proposed, allowing users to discover the hidden historical values with new levels of interactivity and information.
- HBIM and VR projects have been improved through the integration of laser scanning, digital photogrammetry (terrestrial and UAV) and advanced modelling techniques.

Abstract:

Data collection, documentation and analysis of the traces of ancient ruins and archaeological sites represent an inestimable value to be handed down to future generations. Thanks to the development of new technologies in the field of computer graphics, Building Information Modelling (BIM), Virtual Reality (VR) and three-dimensional (3D) digital survey, this research proposes new levels of interactivity between users and virtual environments capable of communicating the tangible and intangible values of remains of ancient ruins. In this particular field of development, 3D drawing and digital modelling are based on the application of new Scan-to-HBIM-to-VR specifications capable of transforming simple points (point clouds) into mathematical models and digital information. Thanks to the direct application of novel grades of generation (GOG) and accuracy (GOA) it has been possible to go beyond the creation of complex models for heritage BIM (HBIM) and explore the creation of informative 3D representation composed by sub-elements (granular HBIM objects) characterized by a further level of knowledge. The value of measurement, 3D drawing and digital modelling have been investigated from the scientific point of view and oriented to the generation of a holistic model able to relate both with architects, engineers, and surveyors but also with archaeologists, restorers and virtual tourists.

Keywords: Historic Building Information Modelling (HBIM); 3D drawing; Grade of Generation (GOG); Granular HBIM objects; Archaeology; Virtual Reality (VR)

Resumen:

La captura de datos, la documentación y el análisis de los restos de las ruinas antiguas y de los sitios arqueológicos representan una herencia inestimabile que debe ser transferida a las generaciones futúras. Gracias al desarrollo de las nuevas tecnologías en el campo de los gráficos por ordenador, el modelado de información de la construción (BIM), la realidad virtual (RV) y el levantamiento digital tridimensional (3D), esta investigación propone nuevos niveles de interacción entre los usuarios y los entornos digitales que pueden comunicar los valores tangibiles e intangibles de los restos de las ruinas antiguas. En este particular ámbito de desarrollo, el dibujo 3D y la modelización digital se basan en la aplicación de las nuevas especificaciones escaneado-a-HBIM-a-RV, capaces de transformar puntos simples (nubes de puntos) en modelos matemáticos e informacción digital. Gracias a la aplicación directa de los GOG (grados of generación) y GOA (grados de exactitud) ha sido posible ir más allá de la creacción de los complejos BIM patrimoniales (HBIM) y explorar la creacción de representaciones 3D, formada por sub-elementos (objetos HBIM granulares) caracterizados por un mayor nivel de conocimiento. El valor de la medición, el dibujo 3D y el modelado digital ha sido investigado desde un enfoque científico y orientado a la generación de un modelo holístico capaz de relacionar tanto a arquitectos, ingenieros y aparejadores con arqueológos, restauradores y turistas virtuales.

Keywords: modelado de información de la construción; dibujo 3D; grado de generación (GOG); objetos HBIM granulares; arqueología; realidad virtual (RV)

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1. Introduction

In recent years, the development of the most modern 3D survey techniques, digital modelling and mixed reality (XR, virtual and augmented reality VR-AR) has led to the generation of complex models able to represent the heritage buildings with different levels of information (LOI), and detail (LOD) (Brumana et al., 2019; Georgopoulos 2018a; Grussenmeyer et al. 2008, Ioannides et al., 2017, Lerma et al., 2010). As we saw recently, it has been possible to increase the reliability of digital models also for more complex architectural and structural elements such as irregular vaulted systems, walls damaged by earthquake destructive action, double curvature walls with variable section and wall stratigraphy characterized by the use of different materials such as stone and brick (Banfi 2019; Brumana et al.,2018; Khalil & Stravoravdis, 2019, Oreni et al.,2014; Stanga et al., 2017;). In particular, a Scan-to-BIM process is a useful tool able to represent the uniqueness of the elements detected both from the morphological point of view (value of the measurement) and from the semantic and typological point of view (value of the 3D drawings and digital modelling). Furthermore, in recent years we have witnessed how attention to detail has become an added value for the generation of HBIM models of buildings of high historical and cultural value (Antonopoulou & Bryan, 2017; Arayici et al., 2017; Fai & Rafeiro, 2014, Kuo et al., 2018, Previtali et al., 2019; Tucci et al., 2019). The value of the measurement in digital models was respected, on the one hand, thanks to the introduction of a new parameter in the HBIM models: the grade of accuracy (GOA) of Scan-to-BIM models based on the standard deviation between point clouds and final model (Banfi, 2017). On the other hand, the potential of new generative requirements such as the grades of generation (GOG) 9 and 10 have made it possible to generate any type of architectural and structural element, avoiding the pre-set logic of the libraries of the main BIM application which are developed for the management of new buildings. Thanks to the definition of these generative requirements for historic buildings, this research investigates the state of current art in this specific field and proposes a rigorous method for the generation of archaeological sites characterised by the remains of ancient ruins composed by sub-elements (granular HBIM objects). In particular, this research proposes a digital process able to maximize the usefulness of the data collected and linked to informative HBIM objects that are unique, where the paradigms of complexity and utility are articulated at different levels of knowledge and graphic representation.

In summary, it is proposed the generation of complex models from point clouds, able to

(i) increase the quality level of scan-to-BIM models also for ancient ruins and archaeological sites, through the integrated use of accurate 3D surveys and novel GOG and GOA;

(ii) combine new parameters, customize new field descriptions, associate historical phases to each parametric objects and insert state of conservation of the materials and the interventions needed to restore the building in a detailed HBIM project;

(iii) increase the level of use of HBIM models in VR applications, providing new levels of interactivity and knowledge to professionals such as archaeologists, historians and restorers, but also virtual visitors unable to visit archaeological sites in person;

(iv) demonstrate the applicability of the method for a real case study of high scientific, archaeological, architectural and cultural value: the church of san Nicolò in the ancient village of Bajardo (Italy) (Fig. 1).

2. Related works and research objectives

The most modern 3D surveying techniques such as laser scanning and digital photogrammetry (Alby et al., 2019, Barba et al., 2019; Riveiro, & Lindenbergh, 2019; Böhler & Marbs, 2004; Masiero et al., 2019) allow professionals to represent buildings with new LOI and LOD (Brumana et al., 2019). In recent years, the benefits of BIM for heritage buildings (HBIM) have been found in various sectors such as structural analysis (Barazzetti et al., 2015, Dore et al., 2015, Korumaz et al., 2017) construction sites (Kumar & Cheng, 2015), restoration (Biagini et al., 2016, Trizio et al., 2019) and facility management (Kang & Hong, 2015). On the other hand, the use of HBIM models in sectors such as archaeology and VR has not been fully investigated in its full potential. One of the main reasons is the difficulty in accurately representing elements that were once part of a building. The 3D representation of irregular wall elements, ancient traces of structures corrupted by natural events such as earthquakes, floods, and even by non-careful safeguarding of the historical heritage, require a high level of knowledge of the artefact (Della Torre 2012; Cuca & Barazzetti, 2019). For this reason, HBIM models should become more beneficial for archaeology as they offer access to both geometric and archaeological information to a wider audience as well as high levels of interactivity with the users (Fazio & Lo Brutto, 2019; Georgopoulos et al.,2018b; Russo et al., 2011; Valente et al., 2017).

(a) (b)

Figure 1: Liguria region, Italy: (a) The village of Bajardo; (b) The ancient ruins of the archaeological site of S.Nicolò.

Therefore, in-depth knowledge of the artefact requires the application of a generative method capable of faithfully representing each type of object from the largest to the smallest, thus becoming a useful analysis tool for archaeologists and restorers. For this research, in light of the requests of professionals, the need to further increase the LOD and LOI connected to the virtual model has grown, following the path traced by previous studies in this particular field of application (Chiabrando et al., 2017; Garagnani et al., 2016; Diara & Rinaudo, 2019; López et al., 2018; Parrinello et al., 2017; Rossi, 2019; Scianna et al., 2014; Stampouloglou et al., 2019).

Furthermore, in Banfi et al., 2019, they have been defined as the main steps of a digital workflow applied for quality management and quality assessment of HBIM and VR projects for heritage buildings. In this study, the main goal was to transfer an accurate HBIM with high LOI mapping and information sharing for different types of analysis and users. Concerning this proposal, it was necessary to include in the various stages of work: (i) Surveying data collection, (ii) Scan-BIM generation, (iii) Information mapping, and (iv) Information sharing a further step: '*Granular HBIM objects for archaeological sites*' (Fig. 2). This new step required a deepening of the 3D modelling techniques oriented to the generation of semantic elements not always easily represented three-dimensionally.

In this precise context, the generative process had to consider two aspects:

- the morphological aspect: management of the data detected through advanced 3D survey techniques such as digital photogrammetry, laser scanning, UAVs;
- The typological-semantic aspect: the possibility of linking different types of information to unique models of their kind, facilitating the operations of data storage, organization, computing, management of archaeological sites, creation of digital repository (HBIM clouds) and database extracted from parametric models.

In particular, from a semantic point of view, the transition from an HBIM model of heritage buildings to an HBIM model for archaeological sites and ancient ruins required a LOD capable of further subdividing predetermined HBIM objects as walls, vaults and coverings in sub-elements able to represent masonry stratigraphy, mosaics, painting, typological breakdowns of a single wall according to the excavation process, and the evolution of the restoration process or safeguard of the good. These new elements, therefore, required a process of 3D subdivision of the general model into sub-elements to incorporate different types of information. Starting from the assumption that in BIM logic, it is possible to insert information to an object if it is first modelled appropriately, for archaeological sites, it is essential to fully understand its high levels of 'semantic decomposition' given that the parameters to be transmitted are quite different compared to new buildings and heritage buildings composed of real architectural and structural elements. Consequently, the proposed process is based on an in-depth study of the artefact and its subsequent subdivision into sub-elements both in modelling terms and in semantic terms to be able to orient the HBIM model to the connection and sharing of specific information. Fig. 2 summarizes the process applied to the case study of the archaeological site of Bajardo.

3. The foundations for a comprehensive and coherent approach

As briefly anticipated, in recent years, thanks to the request by government bodies, public and private, it has been possible to define new generative requirements for the creation of Scan-to-HBIM models. Thanks to the definition of novel GOG, it was possible to support users in the creation of accurate digital models from 3D survey data (point clouds) (Banfi, 2017) (Fig. 3).

In particular, the GOGs 9 and 10 made it possible to directly use the point clouds through the automatic interpolation of NURBS algorithms (Piegl & Tiller, 2012), the latter not present in BIM applications. They make it possible to manage complex wall elements and achieve a GOA of the HBIM model corresponding to 1 mm (standard deviation value between point cloud and model) compared to the surveyed artefact.

Furthermore, GOA also made it possible to go beyond the simple representation of complex models of heritage buildings, proposing a scale of representation according to the level of geometry (LOG) required. In particular, Brumana et al., 2019, propose a reference scale, able to relate to the various scales of representation for the HBIM mode.

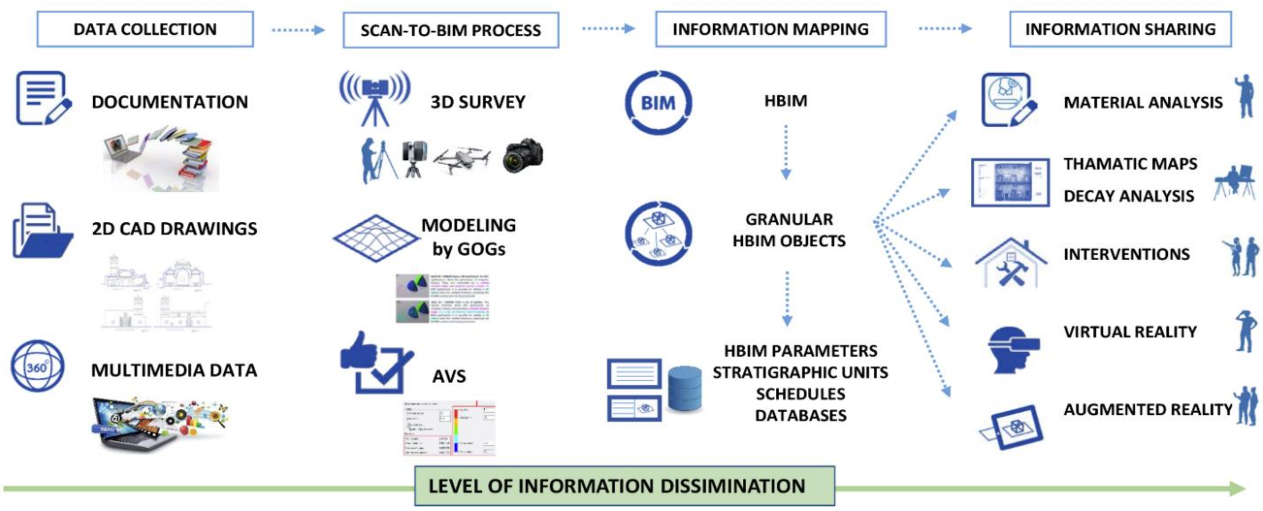

Figure 2: The research method applied to the archaeological site of S.Nicolò, Bajardo, Italy: from points to granular HBIM objects and VR projects.

This previous study shows how the LOD of a double-curved masonry with a variable section can be represented digitally in different ways, adapting as much as possible to the design requirements and different types of analysis such as the finite element analysis (FEA) (Barazzetti et al., 2016, Quattrini et al., 2019) material and surface analysis (Reina Ortiz et al., 2019), storage of stratigraphic units (Chiabrando et al., 2017), sharing of information via cloud and database (Cogima et al., 2019) and finally VR-AR (Bolognesi & Aiello, 2019; Pybus et al., 2019; Rua & Alvito, 2011).

Consequently, the following research proposes a conversion process of the HBIM model, able to communicate the richness of the data connected to the digital model through different VR devices, facilitating the immersion of users in a multi-level interactive environment. In summary, the bases of the proposed method were:

- Integrated use of GOGs 9 and 10 for the generation of unique elements, such as historical walls, vaults, columns, decorations (not present in the libraries of the main BIM platforms);
- Properly represent HBIM objects with a high GOA and LOI based on the required representation scales;
- Properly manage the generative process of HBIM granular objects.
- To orient the model and information for the management of archaeological sites and ancient buildings through one of the most widely used BIM applications;
- To transfer detailed models in open virtual reality application such as Unreal Engine.

Once the bases were defined both from a theoretical and generative point of view, it was possible to establish a digital workflow capable of communicating high LOI to different categories of users (BIM experts, restorators, archaeologists, historians, students and virtual tourists) with different types of devices such as Oculus Rift, mobile phone and personal computer (PC).

4. The context: the research case study and its unexplored riches

Liguria is one of the most visited regions of the north of Italy in the summer period. This region directly borders with France and welcomes millions of tourists from all over the world thanks to its renowned tourist destinations. It offers long miles of beaches, hotels and tourist villages for the hottest months of the year.

The coast is known for its seaside towns such as the Cinque Terre, Portofino, Porto Venere, Genoa and many others. Most tourists, however, are not aware of the existence of the ancient villages of the Ligurian inland.

This unexplored area represents an inestimable value both from a cultural and architectural point of view (Alia & Cuomo, 2017).

Leaving the coast and the crowded beaches, it is possible to discover authentic Liguria. A few kilometres from both the city of Sanremo and the national border, it is possible to penetrate along the valley of the Argentine stream and reach the mountainous area of the Ligurian Alps.

In these valleys, characterized by woods and national parks, reside ancient communities that have handed down over the centuries their culture, customs, art and historical architecture from the prehistoric, Roman and Medieval ages.

Following the Sanremo-Arma di Taggia, Badalucco, Molini di Triora and Monte Ceppo sections, it is possible to reach Bajardo. The village is perched on a ridge at an altitude of 900 s.l.m.

Ascending the cobbled footpaths (called "carrugi" by the inhabitants of the region) and arriving at the main square, it is possible to wander along the old historic village.

These trails, just over a meter wide, were and still are the only access to the top of the village, where the ruins of the ancient church of San Nicolò and the ancient castle, devastated by the earthquake of February 23, 1887, are located (Fig. 4).

4.1. Historical framework

Age of druids: history has not handed down throughout the centuries official documentation that allows us to know the certain origins of Bajardo. The attestation of the first settlement is certified around the year one thousand in the Cartulary of Saint Victor of Marseille.

The areas of the Argentina and Nervia valleys have been inhabited since prehistoric, later becoming a house of worship of Celtic druids Celtic priests built a temple in order to venerate the nature spirits and the sun.

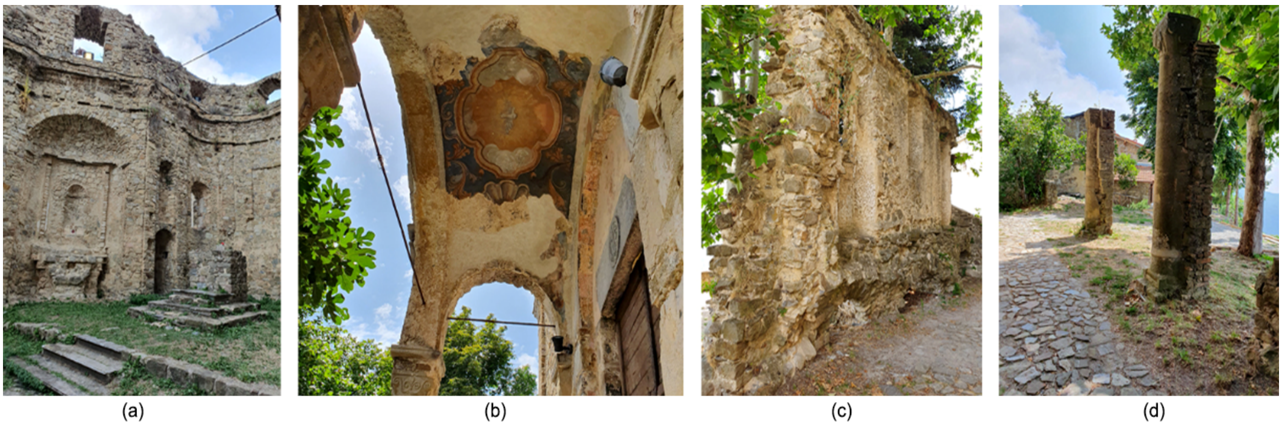

Figure 3: The unique elements of the ancient construction of San Nicolò and its archaeological site: (a) The remains of the church after the earthquake of 1887, (b) The main entrance with its painted sail vault, (c) The few remains of the medieval fortification, (d) Detail of the ruins.

Even nowadays, a pagan feast knows as ‘Ra boat’, attracts tourists and pilgrims from the nearby villages. On the Pentecost Sunday according to the tradition, a pine tree is raised in the town centre accompanied by folk songs and dances.

Roman conquest: A few centuries later, Romans settled in the nearby villages and transformed the cult site and the old druidic shrine in a military fortress still visible today. Several barbaric invasions and two Longobardians and Byzantine dominions followed after the fall of the Roman empire.

Middle age: Bajardo, under the jurisdiction of the Ventimiglia municipality, was heavily besieged by a part of the Genoese army. The siege decreed the domination of the village by the city of Genoa. Shortly after, Bajardo passed into the hands of the Ventimiglia counts, which formed an alliance with the Pisa Republic. The pressure of Genoa did not stop, and the Bajardo was transferred under the control of the Republic. In the following years, the village was taken over by Savoy troops for a short time. When the Genoese Republic fell at the end of the 18th century, Bajardo became part of the Ligurian Republic.

Following centuries: In 1814, the Vienna Congress, passed on the control to the Kingdom of Sardinia. Finally, in 1861 the town of Bajardo took a place in the Sanremo district in the province of Nice after the Italian unification.

4.2. The earthquake of 1887

On February 23, 1887, three strong earthquakes affected Western Liguria (at 06:22, 06:29 and 08:51). (Solarino, 2007). The earthquake struck differently the countries included in the area of maximum intensity. The seismic movement acted in different ways by proving numerous damages to most of the Ligurian built heritage (Anzani et al., 2004; Binda et al., 2004; Penna et al., 2019). The level of intensity of the earthquake oscillated, between the 8th and the 10th degree of the Mercalli scale. The municipalities in the coastal strip between Sanremo and Alassio suffered serious damage. Diano Castello, Diano Marina, Bussana, Albisola Marina, Castellaro, Ceriana, Laigueglia, San Remo and Taggia were closer to the epicentre and suffered the destruction of many buildings and above all of the churches. The earthquake caused serious damage also to Bajardo and the structure of the old church of St. Nicholas, and the collapse of the roof of the death of 216 (Saglietto ND) (Fig. 4). King Umberto was among the first to show solidarity with the populations. On February 26 was sent a telegram of condolence to the prefects of Genoa and Porto Maurizio, accompanied by a significant offer for survivors. The village today, returns its history through the architecture of the place. Among the ruins, today it is possible to see the remains of the ancient medieval castle, the columns of the Roman temple and a Celtic stele. In this oleographic scenario, the façade of the church shows a mixture of different styles and eras passed down from generation to generation. The architecture has a typically rural character. Its linear and annular structure has many architectural aspects typical of Ligurian villages: narrow alleys, houses constructed from stones connected by counter-thrust arches. Considering all these multiple historical, constructive and cultural uniqueness of the archaeological site and the church, it is clear and evident that HBIM and VR projects should support multidisciplinary teams composed by restorers, historians and archaeologists, which can validate and strengthen the vision of the architect and address the construction of the model according to their needs at the same time.

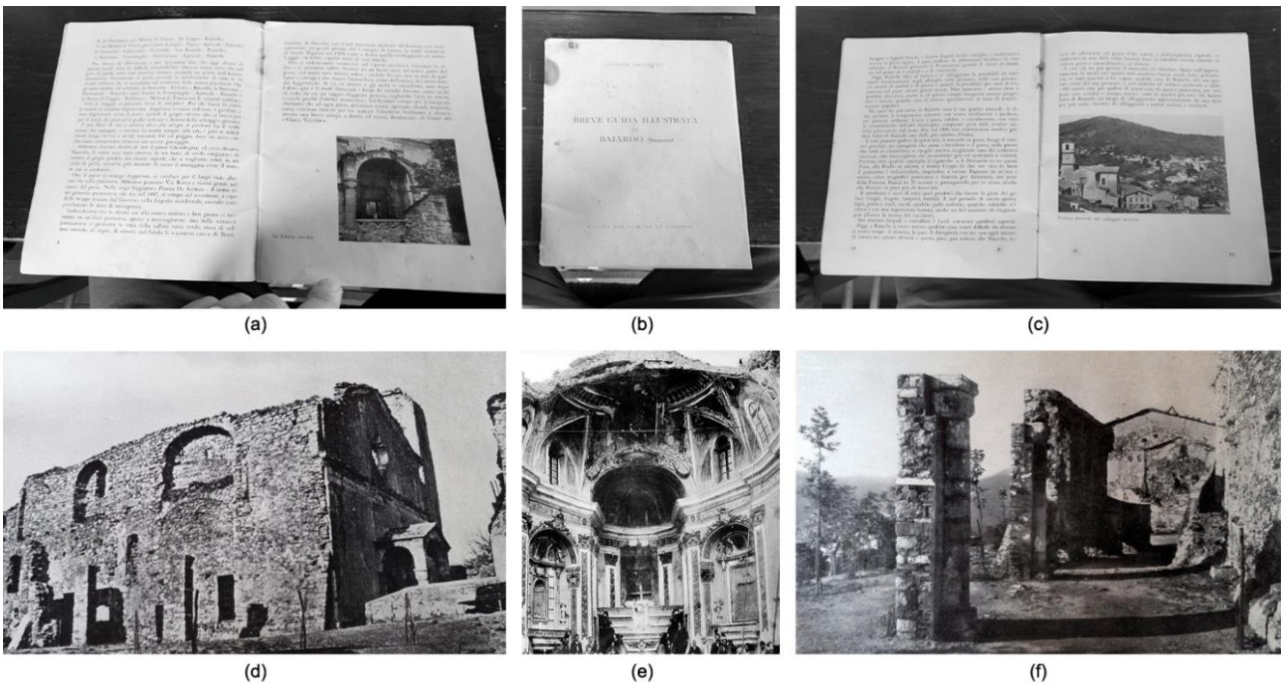

Figure 4: Historical records of Bajardo: a-b-c) Saglietto G., Brief Illustrative Guide to Bajardo by the Municipality of Bajardo, Como, Nani s.d.; (d) General vision of the ruins of the church; (e) The apse area after the earthquake; (f) The ancient Roman wall.

5. 3D MODELLING AND GOG FOR HBIM: FROM POINT CLOUDS TO HBIM OBJECTS

In the last few years, close-range terrestrial digital photogrammetry (CRTDP) and terrestrial laser scanning (TLS) are increasingly used as mapping tools to describe the morphology of architectural and structural elements. In addition to the collection and study of a great deal of historical documentation of Bajardo, a 3D survey of the old church of San Nicolò was conducted. As briefly anticipated in the previous paragraph, advanced survey techniques do not allow professionals to return 3D informative models. Nowadays, in this specific context, the process of converting point clouds to 'informative' models is not immediate: it requires specific knowledge of the main 3D modelling techniques, cleaning and post-processing operations on point clouds in dedicated software, the appropriate use of geometric primitives for the generation of complex elements and the knowledge of a large number of 3D exchange formats for different types of software and analysis. Furthermore, BIM application is oriented to the management of new buildings, presenting different barriers for the generation of scan-to-BIM projects. The main technical barriers found in the last decade are:

- the assent of parametric objects that can be customized for heritage buildings and archaeological sites;
- a limited set of modelling commands oriented to create simple shapes;
- the inability to convert points into complex objects automatically;
- semantic recognition of complex architectural elements in point clouds cannot be automatic; it requires long phases of advanced modelling based on user knowledge;
- the lack of NURBS algorithms and modelling tools able to directly use the points that make up the 3D survey data in BIM application;
- the need to use multiple applications to manage complex architectural and structural elements such as walls with double curvature, walls with variable section, damaged elements, ancient ruins and archaeological excavations;
- the absence of 3D mapping commands able to simplify the decay analysis.

Regarding the last point, also previous studies have shown how the decomposition of HBIM models for complex scenarios can improve the LOI. The creation of sub-elements, therefore, is essential to identify stratigraphic units and link different type of data such as orthophotos, material features and operations (Nieto & Moyano, 2014; Caballero, 2010).

5.1. The main 3D modelling techniques: pros and cons

To better understand this modelling barrier, the following research has tested the main modelling techniques with the final objective of creating unique objects of their kind, both from the morphological point of view (faithfully following the point clouds) and from the typological point of view (information mapping, semantic categorization of sub-elements). The main modelling techniques differ in three families:

Mesh modelling: the mesh models derive mainly from the automatic generation of point clouds. They represent a set of polygonal surfaces, the latter obtained automatically from the main digital photogrammetric software. At the beginning of the transformation process (from scan to model), point cloud processing applications lead an automatic generation of mesh models. Software as MeshLab, Bentley ContextCapture and Agisoft Metashape enable the automatic creation of mesh from dense point cloud thanks to specific algorithms that recognise the scan's point like the data source to generate the mesh's polygons. Mesh interprets the complexity of the shapes through the union of points through polygons based on different algorithms. This type of model equivalents a sparse representation of a point cloud in the space. In fact, to convert a point cloud in a mesh is similar to create a great number of polygon anchoring their vertices to each point of the scan. Modelling tests between free-form software and BIM application found that the mesh model's physical features represent the main problem for the object recognition: the great number of polygons that try to simulate a continuous curved surface lead to increase in the size of the model and obstruct the proper functioning of both software (free-form modelling software and BIM application). For this reason, the studies and tests on the advanced modelling techniques (AMT) have not considered the mesh as a modelling data source. In particular, as will be explained in the following paragraphs, the first reason was the impossibility to transform huge polygonal models in a BIM parametric environment, because of their physical features such as size, weight, accuracy and not smooth shape. However, interesting studies have overcome this issue converting meshed 3D objects with a very small size into parametric objects, resulting very useful for real and accurate parts such sculptural pieces or potential elements that must be catalogued (Nieto et al., 2013; Yang et al., 2018).

Parametric modelling in BIM platforms: the main advantage of BIM modelling is the possibility to expand the information value of each object, thanks to the inclusion of a large number of parameters. BIM applications are directly materialised using an internal database of 3D groups of architectural elements (family) to accommodate a variety of information (Properties). This ability allows users to change the morphological and typological aspects of each element before/after their generation through tools that update their physical quantities (Parameters) such as height, width, scale and their physical and thermal characteristics (i.e. types of materials, stratigraphic information). At the same time, the BIM application can create links and intelligent interactions with other architectural elements that make up the model by increasing the control of the generation and management of the model.

In computer language, this enormous amount of data to be translated into 3D parametric objects, each of which belongs to a specific class or object type. Objects represent a specific 3D model that translates not only geometrically the construction element, but it contains all of its features, also descriptive.

On the other hand, however, the regular objects of BIM libraries are driving the experts to the 'normalisation' of the complex shapes, sacrificing spatial, formal expression and the real value of information of built heritage. In the field of HBIM and Scan-to-BIM, the connection between information and complex geometric entities is not always possible, disfavouring the preservation, conservation, and restoration of buildings.

The primary cause is the lack of advanced modelling tools in BIM applications. BIM libraries do not allow an accurate HBIM generation of churches, basilicas, castles, and medieval bridges. The 3D digital representation and the correct production of architectural and structural elements play a vital role to improve the dissemination of information during the life cycle of the building. Advanced modelling techniques should help to increase the GOA and the LOD, of each single detected element, quantifying and precisely identifying their dimension, material, and physical and thermal characteristics, and especially their shapes and irregularities. At present, only through hard, long and complex modelling practices will be possible to reach a proper LOD.

The lack of elaborate architectural elements like vaults, arches, domes, complex structural elements prevents the proper construction of HBIM. Accordingly, the digital management of the built heritage is affected exponentially, because it cannot guarantee adequate models from a qualitative point of view. The intrinsic value of the 2D and 3D representation of a historical artefact must be able to correspond to the surveyed reality and facilitate the reading of the tangible and intangible values of any type of building. What is important in this respect is that the limitations of the modelling tools incorporated in a BIM software cannot be confused with the efficient management of heritage structures. The specific training and experience of users (who model and manage) are very important key factors. It should also be considered that the creation of a detailed HBIM model would be formed by a multidisciplinary team, where the main value is the workflow or interoperability of historical, archaeological and architectural information.

Free-form modelling based on NURBS algorithms: free-form modelling based on Non-uniform Rational Basis Spline (NURBS) algorithms, allows users to reach high levels of detail. The main peculiarity of the free-form modellers as McNeel Rhinoceros, Autodesk 3DStudio Max and Autodesk® AutoCAD, is the generation of complex surfaces by a large number of advanced modelling tools based on NURBS algorithms. Through a large number of advanced modelling tools, it is possible to create surfaces and solids starting from the primitives such as lines, points and NURBS. On the other hand, 3D models composed by NURBS and mesh cannot be considered real BIMs. As already mentioned, these entities cannot be generated directly in the BIM application and they have to undergo long parameterization steps through the use of different modelling software.

5.2. The basis of the research method

To solve this modelling gap, in recent years, different results have been published to improve complex modelling within BIM applications.

For the generation of the ruins of the church and the castle, a generation based on the application of GOGs 9 and 10 were chosen, able to overcome these operational barriers and generate information objects from 3D survey data.

As described in Banfi 2017, it was possible to generate complex historical elements by directly interpolating the point clouds using GOGs.

Thanks to their ability to manage a large number of points through the extraction of geometric primitives and the automatic generation of 3D elements directly from point clouds, this research has tried to go beyond the traditional representation of wall elements, and to deepen the generation operationally of complex sub-elements within macro wall elements. Figure 5 shows the point clouds generated for the research case study and its archaeological site characterized by the remains of the medieval castle. To facilitate post-production operations, it was decided to generate (i) a project capable of incorporating all geo-referred point clouds and to create (ii) an archive of point clouds portions divided by elements of interest: such as the remains of the castle, monoliths, columns, vaults and altars. This approach allowed one to post-produce point clouds and mesh models via the .OBJ and .PTS and .FBX exchange formats. Furthermore, the export of point clouds (subdivided by elements) from Autodesk Recap Pro 2020 made it possible to maintain the same geo-referenced system in NURBS software (useful for modelling of complex elements) and BIM (useful for translation of complex elements into parametric objects using GOGs).

Once the point clouds were imported on different levels in Rhinoceros V6, the geometric primitives (2D/3D) were extracted using an integrated approach based on three different modes:

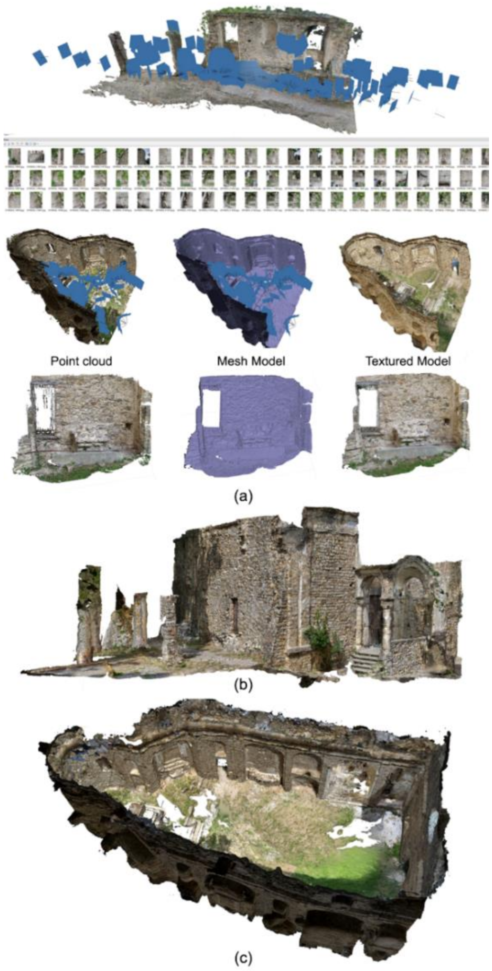

Figure 5: Mesh models and Point clouds portions produced for the various elements of the church and the ancient ruins brought to light after the earthquake: (a) The photogrammetric process of the ancient wall; (b)The textured models of the main entrance; and (c) The internal structure of the church.

i) Automatic extraction of geometric primitives: thanks to the development of algorithms for the extraction of geometric primitives in AutoCad and Rhinoceros, it is possible to generate wireframe models from portions of point clouds (called in technical jargon slices). The adopted solution for a proper 3D drawing was the fourth mode (Fig. 6).The curve passes through each point, without inappropriate deformations or simplifications such as the first three modes (automatic extraction of a straight line, a broken line and a curved line via its control points).

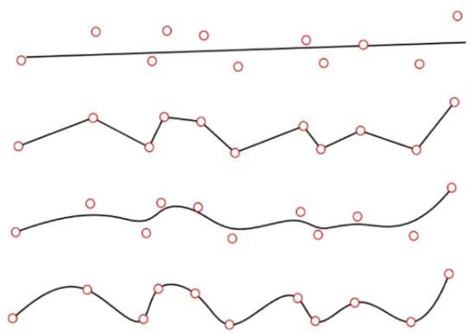

Figure 6: Four mode of automatic extraction of geometric primitives from slices (portions of point cloud).

ii) Generation of geometric primitives in a semi-automatic way: extraction of geometric primitives (as indicated in the previous point) and reduction of the points of interest used for the generation of the primitive itself (Fig. 7).

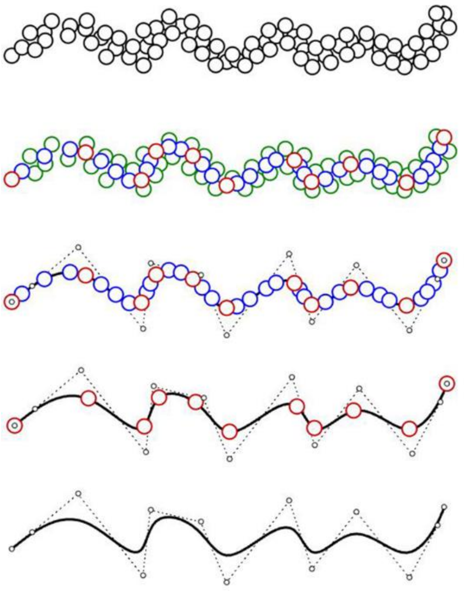

Figure 7: Reduction of the points used for the extraction of the geometric primitives. The number of minimum points (red points) for the 3D drawing curve requires the proper interpretative phase of the data by the modeller.

iii) Manual generation of wireframe models (3D drawings): thanks to the import of cleaned point clouds in advanced modelling software such as Rhinoceros, it is possible to manage every single point that makes up the point clouds. Thanks to the activation of advanced modelling functions for each point of interest, users can be managed and made usable. This step requires a great knowledge of the artefact and an appropriate interpretative phase (Fig. 8).

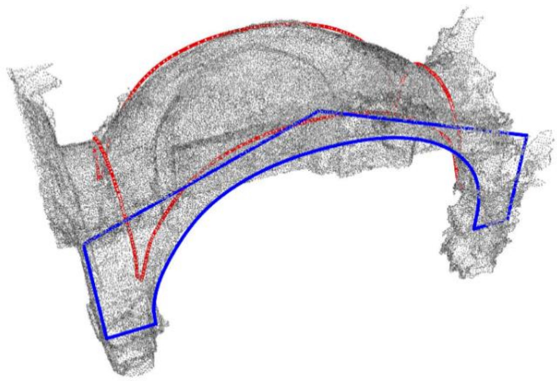

Figure 8: Generation of a wireframe model using the main 3D drawing techniques and a proper interpretation of each element (sail vault in red).

For the generation of such complex elements, this last mode was preferred to the first two. The interpretation of the data and the identification of the main lines of discontinuity of the elements, allowed to minimize the errors produced by the automatic extraction tools. It should be emphasized that the points used for the extraction of primitives do not have a typological differentiation: each point is equal to the other. There are no indications by software that show that a point is part of a wall or another element such as arches, pillars and vaults. The absence of advanced tools in the BIM software and the presence of modelling tools such as the extrusion (GOG 1), edit profile (GOG2), edit profile with empty space (GOG 3), and any subsequent GOG, do not allow the generation of complex elements. The test results laid the foundations for the establishment of modelling procedures able to fill this modelling gap. The tests highlighted the possibility to create HBIM objects without to directly model in Revit, maintaining a high level of interoperability and information. The transition from NURBS model to 'informative' model in Revit took place through an automatic transformation process. Importing the NURBS model into the BIM platform using the 'Mass command' and the subsequent application of the 'wall by face command', allowed the automatic recognition of the element and its transformation into an HBIM object, ready to accommodate different parameters and information. The transition process from the NURBS model to the 'informative' model in Revit is explained in detailed stages in Fig. 10. For a better understanding, the commands and exchange formats used for each step have been indicated in addition to the various steps and modelling phases. The reliability of the model is transmitted to the user through the automatic verification system (AVS) able to show the GOA and GOG values used in the generative phase (Banfi et al., 2019). These type of values have been included as HBIM parameters for every single object realized for the research case study (Fig. 9).

The reliability of the model can be communicated to the various users who will use the model for subsequent BIM-based analysis, stating

- the grade of accuracy obtained for each individual component;
- the grade of generation applied for the realization of each individual component;
- the number of points used for the realization of each individual component.

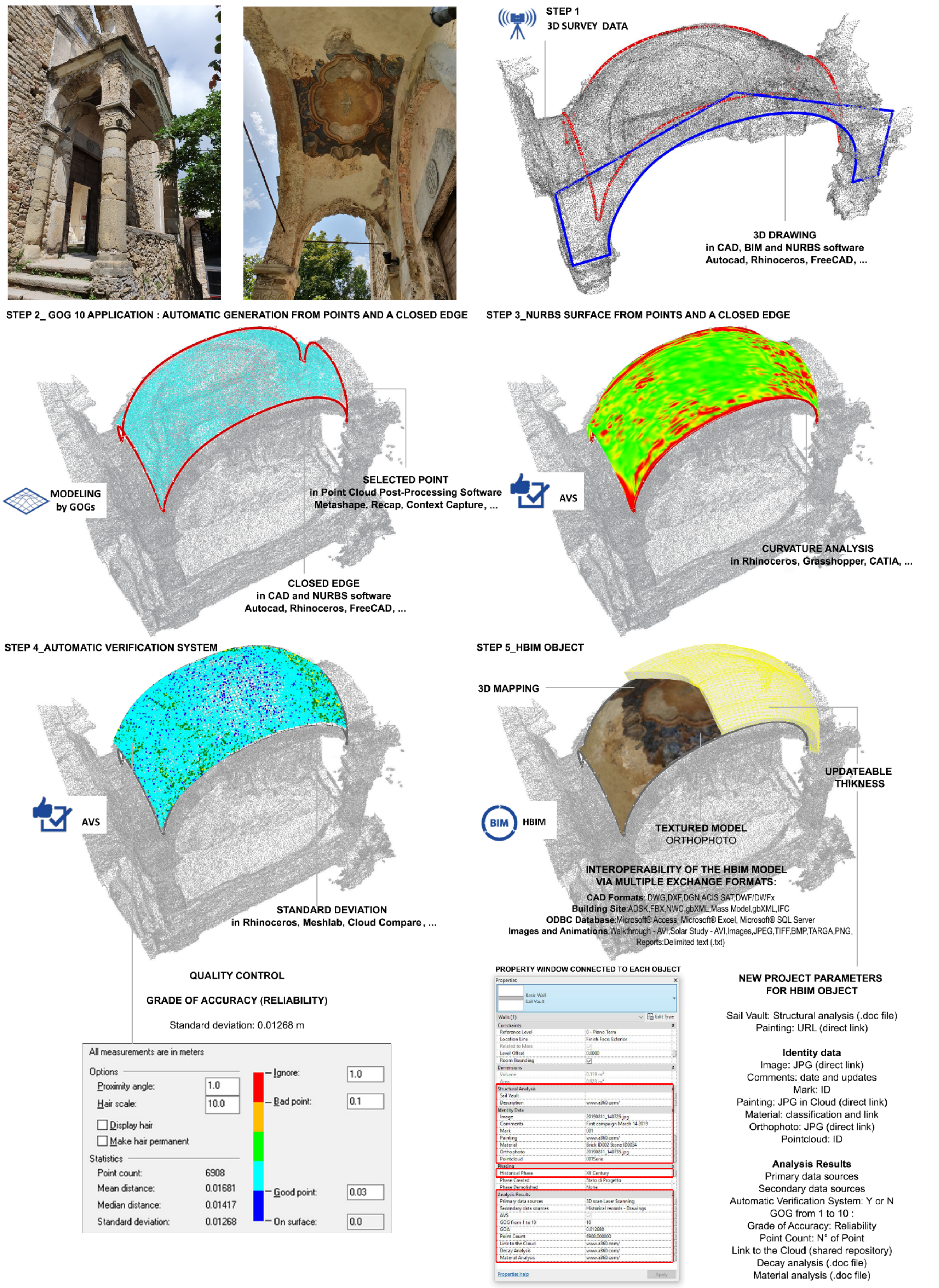

Figure 9: From point clouds to HBIM models**:** the application of GOG 10 for the parametric object of the sail vault. The HBIM object incorporates a different type of information: from customised descriptions to new type of HBIM parameters. HBIM model can be also exported via multiple exchange formats.

6. THE GENERATION OF SUB-ELEMENTS: FROM HBIM MODELS TO 'GRANULAR' OBJECTS

The inclusion of attributes in an HBIM object requires in addition to a high knowledge of the artefact itself and high knowledge of advanced modelling techniques, a holistic and collaborative approach able to incorporating reliable and accurate information. 3D modelling based on the application of GOG 10 would serve as a 'reinforcement' to modelling and subsequent data injection.

In particular, regardless of the type of sub-element, GOG 10 is composed of the following steps:

- Identifying of a closed perimeter (vertical, horizontal and oblique elements);
- Manual selection of points of interest from the point cloud considering that the point selection must exclude points outside the perimeter corresponding to the boundary of the object to be returned;
- Automatic transformation of the NURBS object into an HBIM sub-object;
- Enabling parameter mapping functions (typical of BIM application).

It was applied to determine the following objects:

- stratigraphic units;
- decay areas;
- heterogeneous stratigraphic elements incorporated into larger wall elements;
- heterogeneous architectural and structural elements incorporated into paving and portions of multilevel excavation fields.

Figure 10 shows the applied process: from the point cloud to the generation of sub-elements corresponding to architectural elements that make up larger elements.

The identification and recognition of these sub-elements, for the most part, can also occur with the naked eye, but thanks also to historical sources it has been possible to proceed with a typological connotation and a differentiation by temporal phases and materials. As anticipated the ruins of the church of San Nicolò evoke a tragic event. The action of the earthquake led to the collapse of the entire roof structure: a holy site open to the sky. This tragedy, responsible for numerous casualties, howsoever allowed to bring back to light the old relics of the druidic temple on which the church was built upon, discovering columns and a Celtic stele. The elements characterised by their very specific identity led to the definition of a generative method capable of giving consistency to sub-elements. Figure 11 shows how the remains of the ancient structure can be characterised from the semantic point of view and generated three-dimensionally using directly the points of the clouds.

The advantages encountered through the application of GOG 10 for the various sub-elements are:

- Accurate and fast 2D, 3D and temporal generation (historical phases) of the site
- Creation of a digital archive of the site: through the creation of information models it is possible to store, analyse and share parameters and information in the form of digital data
- Generation of HBIM elements easily shared and accessible through open-source cloud applications such as Autodesk A360.
- Generations of elements able to interoperate with the main open-source software of virtual reality such as Unreal Engine.

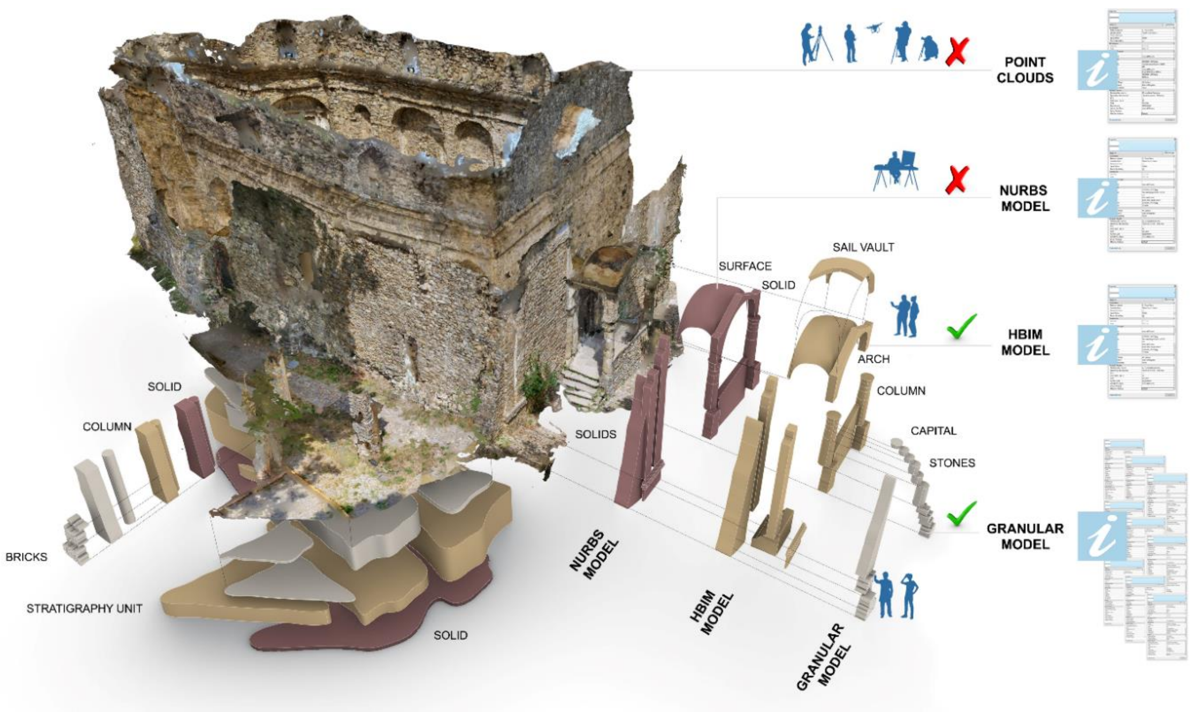

Figure 10: The sub-elements generated by GOG 10: the granular model of the ruin of San Nicolò, Bajardo, Italy allow users to improve information mapping and sharing stages exponentially.

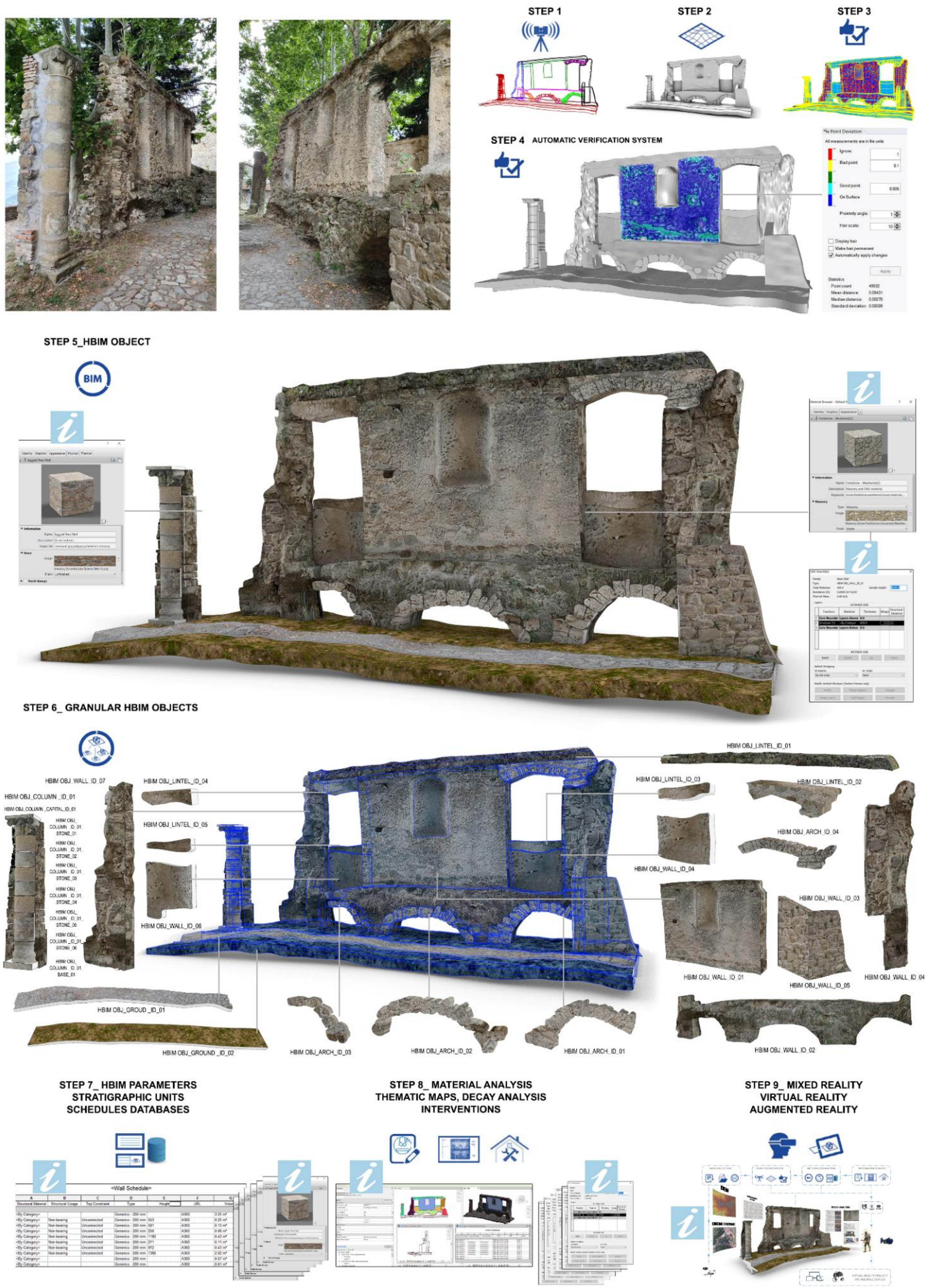

Figure 11: The granular HBIM objects of ancient ruins of the Bajardo's archaeological sites. GOG 10 allow users to improve the generative process of different type of HBIM objects, favouring the information mapping and sharing stages exponentially.

7. THE DEVELOPMENT OF A VIRTUAL REALITY PROJECT

7.1. From HBIM model to the virtual storytelling of a heritage site

Thanks to the research activity and in-depth studies in the field for 3D modelling and the main 3D survey techniques, nowadays it is possible to generate informative models useful for different types of analysis. In recent years, innovative research has shown that structural analysis, energy analysis, cost analysis and management of the entire life cycle of the building can be improved through the use of accurate HBIM models coming from point clouds.

As demonstrated in the previous paragraph, the generation of sub-elements not always corresponding to architectural and structural elements, was possible thanks to the application of the GOG 10, greatly limiting the advanced modelling phases and consequently reducing costs and times of the generative process.

Once the model was obtained, it was almost completely logical, to transfer the wealth of information accumulated over the years, into a VR project where the user can discover the site and the history of this wonderful archaeological site. Thanks to the most modern techniques of immersive environment development and open source software for VR it was possible to "give life" to the church of San Nicolò and its stories accumulated over the centuries. The research approach oriented to develop a VR project was based on the following assumptions:

to develop an open project (upgradeable): the possibility of increasing the information value of the site through a digital structure that can be implemented over time, where the developer can enter new information and update the VR project over time.

to increase the level of interactivity between user and information: the development of new levels of interactivity based on the study of virtual proxemics and on the ability of users to easily recall information and virtual objects.

to enable the usage of multiple devices for different types of users: an open platform able to allow the user to develop a digital world interacting with different devices such as the Oculus Rift, mobile phone and computer (desktop and laptop).

To reach the goal, the first condition for the development of an open VR project was the choice of the application (Fig. 13).

As mentioned, the process was based on the generations of complex models in Rhinoceros and the transformation of them in 'informative' granular HBIM objects into Autodesk Revit. Thanks to the model conversion tests, Unreal Engine was selected as a development platform for the virtual environment.

In particular, thanks to high levels of interoperability between Rhinoceros 6.0, Revit 2020 and Unreal Engine 4 (UE4), it has been possible to keep the three digital environments for model generation aligned.

The same georeferencing of the three environments allowed to avoid the spatial transformation procedures, and to be able to update the models according to the project needs.

This operational expedient was useful above all to be able to transfer the historical phases of the HBIM model to Unreal Engine. The main exchange formats used are listed in the following figure (Fig. 12).

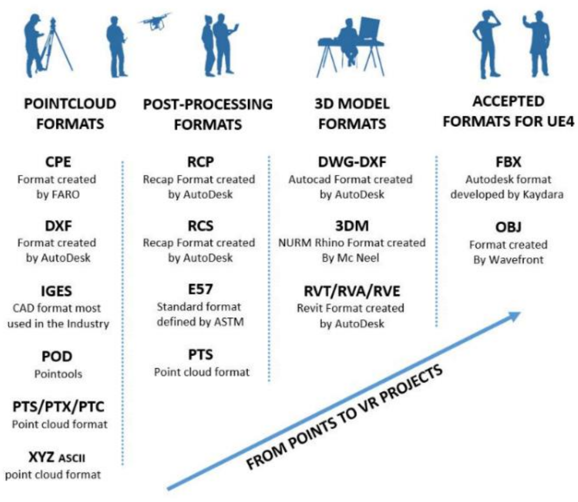

Figure 12: The main exchange formats of each type of model used during the generation of the VR project.

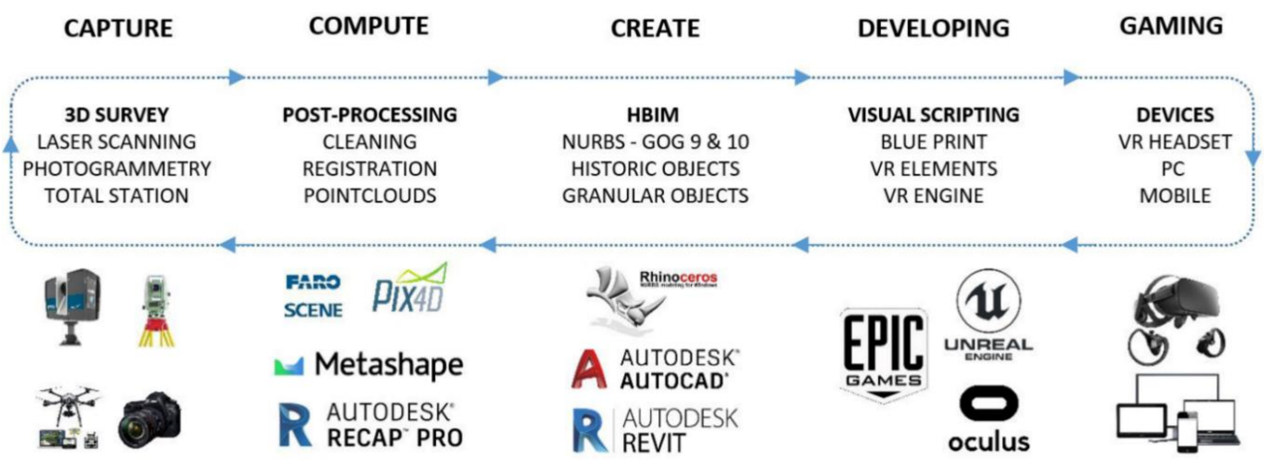

Figure 13: The digital workflow and tools of the implemented VR project.

8. Handing down the memory over generations

The signs of the earthquake of 1887, so evident until a few years ago in the whole region of Liguria, are slowly disappearing, as much as the testimonies coming from the descendants of the survivors. Archives and historical documentation are not always able to hand down the past of a building in its entirety. For the most part, testimonies and documents are lost or destroyed over time. The only way to remember and transmit the knowledge of our built cultural heritage is to work for the future. For this reason, this research has investigated and developed a method capable of transferring the richness of the 3D survey of HBIM (primary data sources) and historical and multimedia data (secondary data sources) into the latest generation virtual environments where user interaction and knowledge turns out to be of vital importance. From an immersive point of view, even the most used devices in the field of VR have been investigated. In recent years many products have been launched on the market to increase the interaction of digital models and the user. The main VR headsets are Oculus Quest, Oculus Rift, Playstation VR, Oculus GO, HTC Vive, Pansonite 3D VR Glasses, Samsung Gear VR, Lenovo Mirage Solo, Google Daydream View and HP VR1000-100 MR Headset. Thanks to touching hand controllers and fitting facial interface, the transfer of the movements and gestures within virtual worlds are realistic. On the other hand, the interaction of these worlds is not always easy to develop. In the last few years, Oculus VR has made great strides, achieving an excellent compromise between the VR headset and its components, software programming, computers and hardware.

For this reason, Oculus Rift was chosen as the main device for the VR project of the archaeological site of Bajardo. Furthermore, thanks to the possibility offered by the Unreal Engine software, the same project was converted for the mobile version.

In particular, for both solutions, the development of the immersive environment was based on the use of the previously realised HBIM. The transfer of the model from Revit to Unreal Engine took place through the importation of every single element generated: from the main walls to the sub-elements that distinguish the ancient ruins. The main objective was to be able to identify and manage the HBIM granular objects and their related information individually. Thanks to the single management of each object it has been possible to enter the software architecture and interact with its development logic based on visual scripting.

The Blueprints Visual Scripting system is a complete scripting system based on a node-based interface to create gameplay objects from within the Unreal Editor. As with many common scripting languages, it is used to define object-oriented (OO) classes in the virtual engine. This system is extremely powerful and flexible as it provides the ability for users to use virtually the full range of concepts and tools only available to programmers.

In order to tell the story of the church of San Nicolò, an interactive path has been developed that can communicate different types of data and information (Fig. 14). The users can interact with animated virtual objects, documentaries, historical phases, videos taken by drones and read stories through informative screens as if they were inside a real museum (Fig. 15).

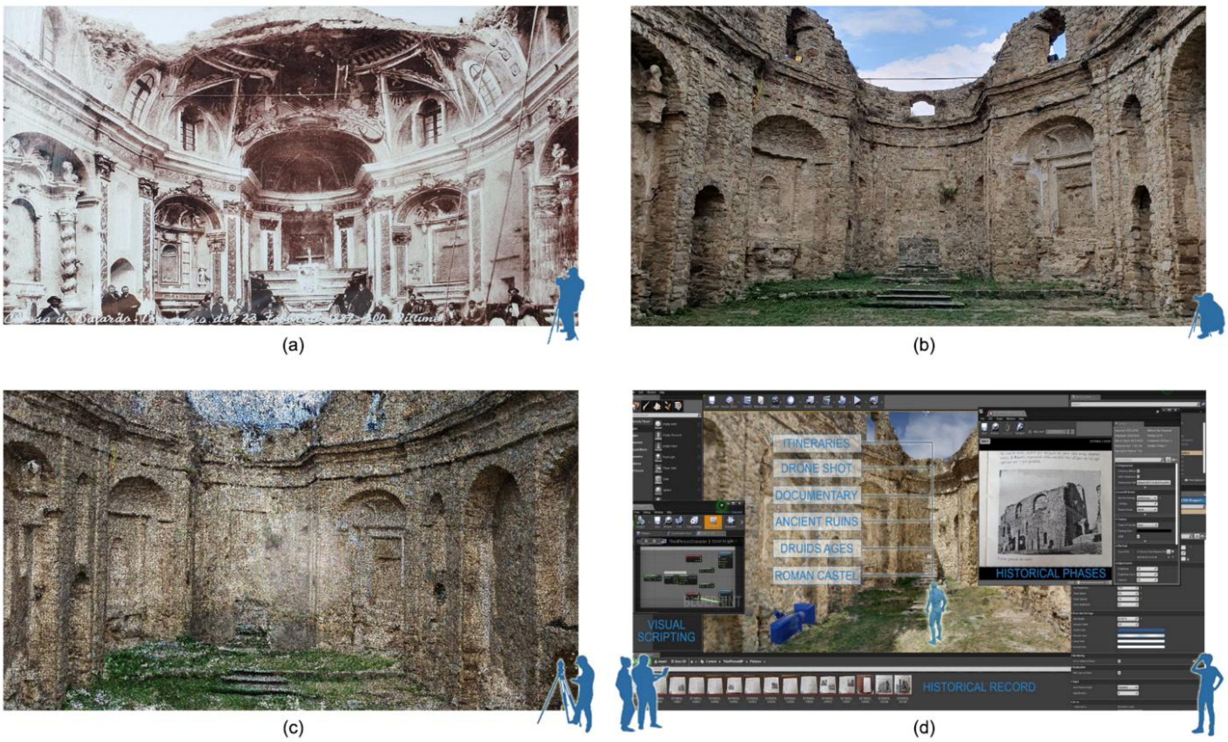

Figure 14: From historical pictures and 3D survey to the VR project of the archaeological site of San Nicolò, Bajardo, Italy: (a) Photos immediately after the earthquake; (b) Picture of the ruins in 2019; (c) 3D survey data, internal point clouds; (d) VR project connected to different type of multimedia data with an informative trajectory.

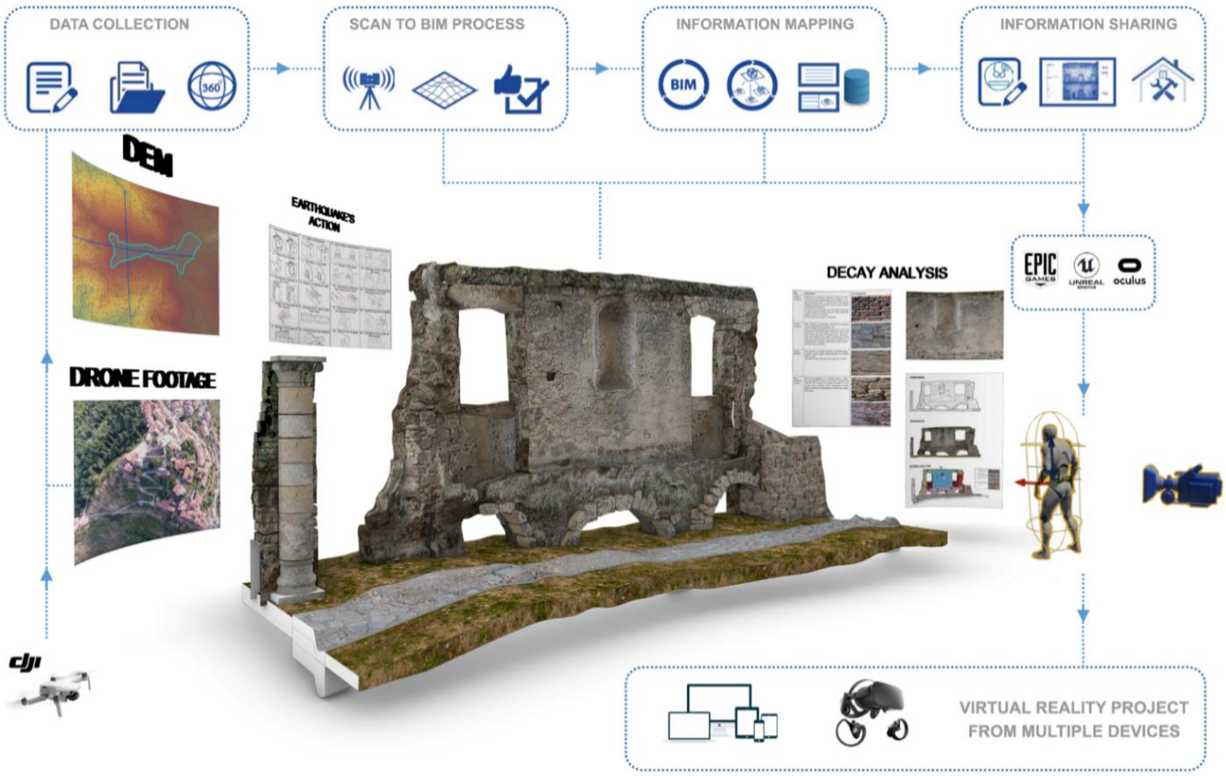

Figure 15: The VR project of the ancient ruin of the archaeological site of Bajardo. The user can interact with animated VR objects and discover the historical and cultural values of one of the most important built heritage of the western Liguria.

9. Results

The most well-known existing technologies in the field of digital cultural heritage (DHC) are 3D survey (laser scanning - digital photogrammetry) and Building Information Modeling for historic buildings (HBIM), which has turned productivity in architecture, engineering and construction (AEC) around.

When used to its fullest extent, HBIM allows professionals to take active roles during the long life cycle of building (LLCB).

Even though BIM software has been around for a while, the programs are constantly improving (AutoCAD was born in 1982, ArchiCAD in 1983, Allplan 1 in 1984, Vectorworks Nemetschek in 2000 and Revit Architecture in 2007).

Specifically benefiting the management and post-processing of 3D survey data, they are increasing the processing power and the levels of interoperability (cross-program integration and open file format such as the IFC). On the other hand, 3D drawing and digital modelling represent a real barrier for beginners.

Furthermore, in a country like Italy (where the use of BIM is not mandatory), sectors such as restoration and archaeology do not benefit of this powerful tool, because they are based on traditional methods and outdated instruments.

For this reason, this research proposes a method able to bridge the gap between users and modelling, leading to the generation of complex HBIM object from 3D survey data.

According to the results of testing for the generation of scan-to-HBIM objects, global processing time can be subdivided as follows:

- generation of geometric primitives with NURBS: 5 min (manually); 3 s (automatically);
- automated generation of the NURBS surfaces, including curves as boundaries and the point cloud as a constraint for interpolation: < 3 s;
- the geometric parametrisation of the thickness with the multilayer object: < 2 s (the user must only select the object and assign a specific family);
- inclusion of attributes: depends on the information available for each object (such as material, physical and mechanical properties).

Furthermore, to take advantage of this research method to benefit construction directly, it is vital to be connected to the BIM cloud. Project data such as 3D survey data, HBIM models, pictures, historical records and general user progress all depend on the information stored and analysed in the common data environment (CDE). Most design software companies like Autodesk have developed open-source BIM cloud where the user can share each type of format. As shown in Figure 11, the research method shows how a further decomposition of a complex wall in granular objects allows users to create a new type of parameter and improve the information mapping and sharing stages. Finally, this study underlines the importance to orient HBIM and VR projects of archaeological sites and ancient ruins to each participatory discipline, creating correct structure composed by granular objects (sub-elements) for each stratigraphic units, construction systems or elements to be catalogued, always considering a holistic collaboration between architects, archaeologists, historians and restorers.

10. Conclusions

Today's technology trends such as HBIM, cloud computing, VR technology, social connection, and collaboration are driving professionals alike to explore profoundly different ways to manage complex heritage sites. This kind of transformation is happening now and the pace of change is now much faster compared to the first digital era. For this reason, this research shows how a heritage site can be managed and shared among all involved users, extending them to the virtual reality thorough a granular HBIM-based decomposition able to improve the knowledge of one of the most important archaeological site of the Ligurian inland. Such new ways of visualisations and representations, as demonstrated in this study, require a proper knowledge capable of improving the management of an archaeological site characterized by a varied number of morphological complexities. HBIM and VR projects can be improved through the integrated use of different technologies such as laser scanning, digital photogrammetry (terrestrial and UAV) and advanced modelling techniques. Furthermore, it was found that the understanding of each individual artefact from a typological point of view is crucial in the model generation phase. The identification of the stratigraphic units, the materials used, the historical vicissitudes that have alternated over the centuries such as earthquakes, restorations, structural consolidations and other types of analysis are crucial for a correct representation, both two-dimensional and three-dimensional. In this specific context, the proposed method outlines a process capable of maintaining high levels of detail and accuracy as faithful as possible to the geometric reality of the artefact.

As noted, the need to increase the level of information of HBIM models is directly proportional to its breakdown into sub-elements capable of representing theoretical and semantic decompositions, not necessarily dictated solely by geometry.

The determination of 'granular objects' is therefore vital for the subsequent stages of information mapping and sharing of complex scenarios such as archaeological sites, ancient ruins and heritage buildings.

It is therefore crucial, in a more general and holistic context, to constantly update one's knowledge and skills also on a digital level. In the future, traditional methods of representation and management will be gradually abounded and replaced by increasingly innovative and cutting-edge tools and methods. Professionals who are experiencing this generational change have the luck and above all the duty to better inherit the knowledge and methods handed down by their predecessors and direct them to the best for future generations.

Finally, it should be considered how the disciplinary fields of restoration, representation and geomatics can promote an increase in the cultural and social awareness of archaeological sites and historic buildings still not fully considered by the various administrative bodies and international BIM standards and guidelines.

The proposed case study turns out to be a valid example of how the tangible and intangible values of an archaeological site and a mediaeval village like that of Bajardo are not yet known nationally and globally. Immersive digital environments such as VR-AR can be a valid option capable of telling intangible aspects inherited over the centuries to future generations, favouring large-scale digital dissemination, even at a distance and after years.

Future developments will seek to optimise the proposed method with the ultimate aim of minimizing the number of applications used and making access to these virtual projects that still require expensive devices and a high level of integrated expertise needing to be updated frequently and having to be communicated on a real-time basis.

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