CULTURAL HERITAGE DISSEMINATION: BIM MODELLING AND AR APPLICATION FOR A DIACHRONIC TALE

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ABSTRACT:

The research purpose is to present a project of cultural dissemination and enhancement of the “Madonna della Pace” Sanctuary at Rocchetta di Airuno (Lecco - Italy), based on an immersive experience of knowledge of the history and places that characterize not only the sanctuary but also the “Cammino di Sant’Agostino” (of which it is one of the stages). The research goal focuses on the direct employment and exploitation of HBIM models for the digital fruition project. An integrated digital survey based on a terrestrial laser scanner and photogrammetry was conducted to provide a complete geometrical representation of the sanctuary and its surroundings. Both output point clouds were employed as metric and geometric references to create the reality-based parametric model. Specifically, the work focuses on creating a three-dimensional chronological model of the sanctuary, which not only represents the current state of the cultural asset but is also enriched through the definition of different evolutionary phases of the architectural artifact based on an in-depth study of the photographic and bibliographic documentations. Four Project Phasing has been identified to represent the most significant transformations of the building and were managed using the time parameter in the same BIM project. The sanctuary geometric and parametric models were displayed and navigable thanks to the aid of Virtual and Augmented Reality applications. A VR environment was defined to display in the first person the textured model. Finally, an AR smartphone app prototype was developed to show tourists the sanctuary’s historical transformation over time.

1. INTRODUCTION

The topics related to the digital survey of cultural heritage and the geometric and semantic modelling of existing architectures for dissemination purposes have interested the scientific community for years and are still very current (Balletti et al., 2019; Conti et al., 2020; Gonizzi Barsanti et al., 2022; Lo Turco et al., 2016; Parisi et al., 2019). Recent technological and instrumental advancements in range-based and image-based 3D survey methods have greatly simplified and optimized the scan-to-BIM (Building Information Modelling) pipeline, particularly in the event of complex measurements and morphologies like those that characterize the built heritage. Instruments have gotten smaller, lighter, faster, and, in some cases, cheaper for both active and passive sensors. At the same time, raw data processing software has also become more powerful. In general, the technological innovations in the AEC sector (Architecture Engineering Construction) have broadened the prospects for using the BIM methodology by optimizing times and interoperability between the various operators of different areas of expertise (Yang et al., 2020). However, modelling historic buildings in BIM environments is still complex and time-consuming if one wants to obtain a faithful representation of the most irregular geometries. Indeed, for some peculiar shapes and elements (e.g., vaults, staircases, etc.), it can be necessary to integrate the BIM software with 3D CAD or mesh modelling, although these objects cannot be parametric.

The purpose of the research presented is to propose a project of cultural dissemination and enhancement of the “Madonna della Pace” Sanctuary at “Rocchetta di Airuno” (Lecco – Italy), based on an immersive experience of knowledge of the history and places that characterize not only the sanctuary but also the “Cammino di Sant’Agostino” (of which it is one of the stages). The research goal focuses on the direct employment and exploitation of HBIM models for the digital fruition project.

2. CASE- STUDY

The “Madonna della Pace” Sanctuary overlooks the village of Airuno from the top of a limestone hill to the north, just under 400 m. The name of the Rocca (or also Rocchetta) hill evokes the origins of a fortified place (Longhi and Tavola, 1984). Historical documentation attribute to it functions of the observation point, guard, and defence of the entire Adda valley since Roman times, continued by the Longobardos, Venetians of the Serenissima Republic, and then the Sforza, who assigned it to the defence of the Duchy of Milan. Indeed, the sanctuary was initially built within the walls of a fortified fortress in the 14th century and was entirely transformed in the Baroque style between the 17th and 18th centuries.

The architecture of the building, which is positioned on an east-west orientation, was presumable Romanesque. Indeed, the current curved Baroque profile of the facade likely conceals its original, typically gabled form (Figure 1).

The church plan has one span with a central chapel covered by a cross vault. On the west side of the church is a 17th-century rectangular loggia from which one can admire the course of the river Adda and the surrounding landscape in a place of outstanding beauty. The Baroque style is also evident here in the arches and tapered columns. Some studies suggest that the landscape background of the painting of the Gioconda by Leonardo Da Vinci was taken from this point of view of the sanctuary (Figure 2).

The Holy Staircase connects the street below with the entrance to the sanctuary and consists of 130 granite steps. On either side of the staircase, between a double row of cypress trees, rise thirteen aedicules of the Via Crucis (Figure 3), culminating in the Chapel-Sepulchre (14th station) and the statue of the dead Christ.

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Figure 1. The 17th-century loggia on the church’s west side.

Figure 2. The current landscape view from the loggia.

Figure 3. The laser scanning survey from the Holy Staircase.

The sanctuary of Airuno represents the 22nd stage of the Cammino di Sant’Agostino, a pilgrimage connecting fifty Marian sanctuaries in Lombardy. The route has the characteristic shape of a rose (Ornaghi, 2015) and is divided into two stages. The first phase has a characteristic flower shape and is represented by a closed circular route (620 km) that starts and ends in Monza. The second section represents the stem (150 km) connecting Monza with Pavia. The route touches on three Lombardy localities involved with the figure of Augustine of Hippo: Rus Cassiciacum (today Cassago Brianza, the place of his conversion), Milan (the place of his baptism), and Pavia, where the Saint’s relics are found. The Saint was born and died in Africa, but for mysterious reasons, he left his most important testimonies and historical memories in these three locations in Lombardy. In addition to its religious value, the route winds through a little-known territory of Italy, but one rich in monumental and landscape testimonies of significant architectural and cultural value.

3. GEOMETRICAL SURVEY AND MODELING

An integrated digital survey based on a terrestrial laser scanner and photogrammetry (terrestrial and aerial) was conducted to provide a complete geometrical representation of the sanctuary and its surroundings. Both output point clouds were employed as metric and geometric references to create the reality-based parametric model. The reference level of detail used is enough for a 1:50 scale of representation. Consistent with the tolerance associated with this scale, the point cloud and the BIM model maintained a maximum deviation of 30 mm.

The overall geometry of the sanctuary and the associated staircase were acquired digitally using a Terrestrial Laser Scanner (Leica RTC360) by stationing it at 68 points.

The spatial sampling was modified according to the instrument-object distance; in general, a low density (12mm@10m approx.) was used for very small rooms and corridors, medium (6mm@10m approx.) for interiors and high for exteriors (3mm@10m approx.). The VIS (Visual Inertial System) made it possible to make an initial rough registration of the different setups in real-time on-site. During the choice of the station positions, an attempt was made to ensure a minimum overlap of 50% so that the targetless alignment among the scans could then be optimised in the postprocessing phase (Leica Cyclone Register 360 software). Global registration among the scans was improved by removing vegetation and other disturbing elements for the ICP (Iterative Closest Point) algorithm, such as inconsistent geometries of open and closed windows and doors in different scans. After completing and locking the registration process, the individual scans were manually cleaned to produce a visually clearer and more manageable point cloud by removing points that were far from the area of direct interest and areas of overlap. The final output is a point cloud model capable of virtually representing the ‘state of the art’ geometry of the complex in three-dimensional space with a high degree of metric detail.

Due to the special characteristics of certain sanctuary spaces, the TLS survey was integrated with the photogrammetric survey of the sepulchre chapel at the top of the holy staircase and the roof of the sanctuary, which can only be reached with a drone. In fact, the interior space of the sepulchre is rich in chromatic details, which cannot be achieved with a laser survey alone. For the terrestrial photogrammetric acquisitions, a Canon EOS100D Reflex camera (CMOS type 22.3 x 14.9 mm) was used and a focal length of 18 mm. The size of the chapel and the particularity of its finish made the markerless acquisition possible, ensuring an overlap among shots of approximately 80%. The roof survey was carried out with a DJI Mavic Pro equipped with a camera with 4k video resolution (3840 2160 pixels). Structure for Motion (SfM) software was used for the photogrammetric processing, applying the standard pipeline: internal (self-calibration) and

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external orientation of the images and absolute orientation in the TLS reference system. In the case of the chapel, a textured polygonal model was also created within the photogrammetric software to be imported into the BIM environment. Instead, from the photogrammetric project of the drone survey, a point cloud was exported in the same coordinate system as the laser scanner and used for BIM modelling. The point cloud models were imported and managed in Autodesk Revit using Autodesk's proprietary RCP format, i.e., creating a project in Recap Pro.

For a good organisation of the modelling process of various building components, the first step is to carry out a semantic cataloguing of the architectural elements, which provides for the decomposition of the building organism by identifying its various elements and the relationships between them. The Revit BIM software allows cataloguing through the definition of families. Generic System Families have been used for walls, slabs, standard steps/staircases (Figure 4), and the roofing system since there is no documentation of the correct stratigraphy data. Such families also comprise levels, grids, sheets, and viewports.

Indeed, plan reference lines and elevation reference planes were created to define the perimeter walls and floors to which the non-structural elements were added. The limitations of system families, as is well known, is that modelling tools do not allow for a high degree of customisation of geometric shapes.

Instead, numerous Loadable Families were used to customise individual elements of the architecture (windows, doors, pillars, columns). Once the model's basic structure was defined, the different components and sub-components were modelled with their details. The geometry of the modelled details is created using the standard modelling tools: extrusion, union, revolution, extrusion on a path, and union on a path. Therefore, within the working project, there is a generic architectural Family and a series of different types related to each element, renamed and customised (nested structure).

For example, the Portico Columns family exists for the sanctuary project and is used for all the columns that follow the perimeter of the entire portico. After setting the parameters of the essential elements, the details that distinguish each column (base, height, thickness of base and capitals, shaft, etc.) are defined. The created family is loaded into the work environment and placed in the correct position, taking the point cloud as a reference. Therefore, within the working project, one has one family for these components and a series of different types relating to each column, renamed and customised. This procedure for the end columns and doors was also applied for the 13 aediculae along the sacred staircase (Figure 5).

Finally, in-place families are used to modelling all unique elements within the project that cannot be varied using the definition of various parameters. Such families have been used to create façade cornices, step profiles, and all other detailed decorative elements.

The chapel of the sepulchre and the four vaults along the church's nave present a geometry too complex to be schematised within the BIM software. A different approach for these architectural components was followed, which involved using external software for BIM-based modelling. In fact, for both elements, the relative point clouds were used to create a mesh model with a detail compatible with the chosen scale of representation, which was then imported and managed within Revit as an In-Place Mass (Figure 6-7). For this type of object, however, a parametric approach remains impossible.

Another tested approach was modelling the geometry of the elements that characterise the vaults based on the relative generatrixes and directrixes and then working with boolean functions on the solids (Computational binary Solid Geometry). This process can only be applied for the vault modelling but not for the irregular shape of the sepulchre chapel.

This modelling approach is undoubtedly longer than mesh modelling (automatic) but certainly more scientific because the reconstruction process helps to understand the architecture and its structure. However, in this case, the geometric schematisation allowed an ideal reconstruction with deviations related to the current state of the vaulted roofs greater than the prefixed tolerance.

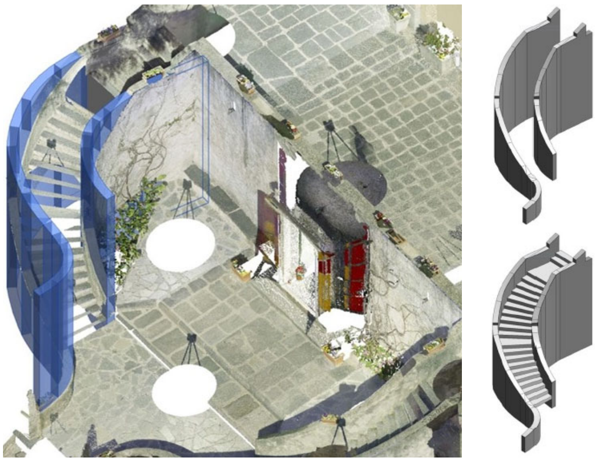

Figure 4. Holy Staircase modelling.

Figure 5. Aediculae modelling.

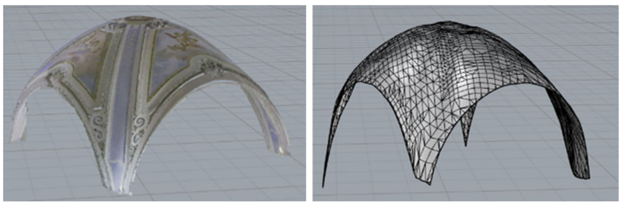

Figure 6. Vault point cloud on the left and mesh on the right.

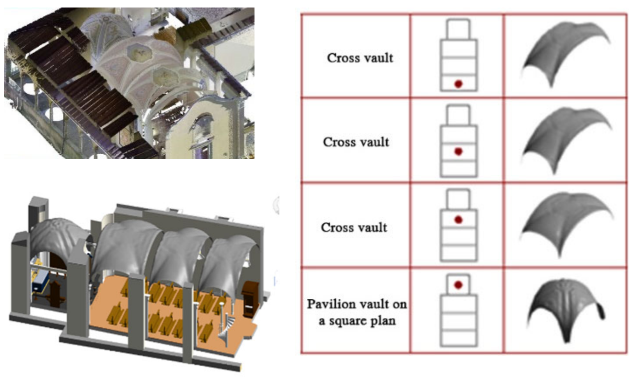

Figure 7.Vault type and modelling: point cloud > mesh > mass.

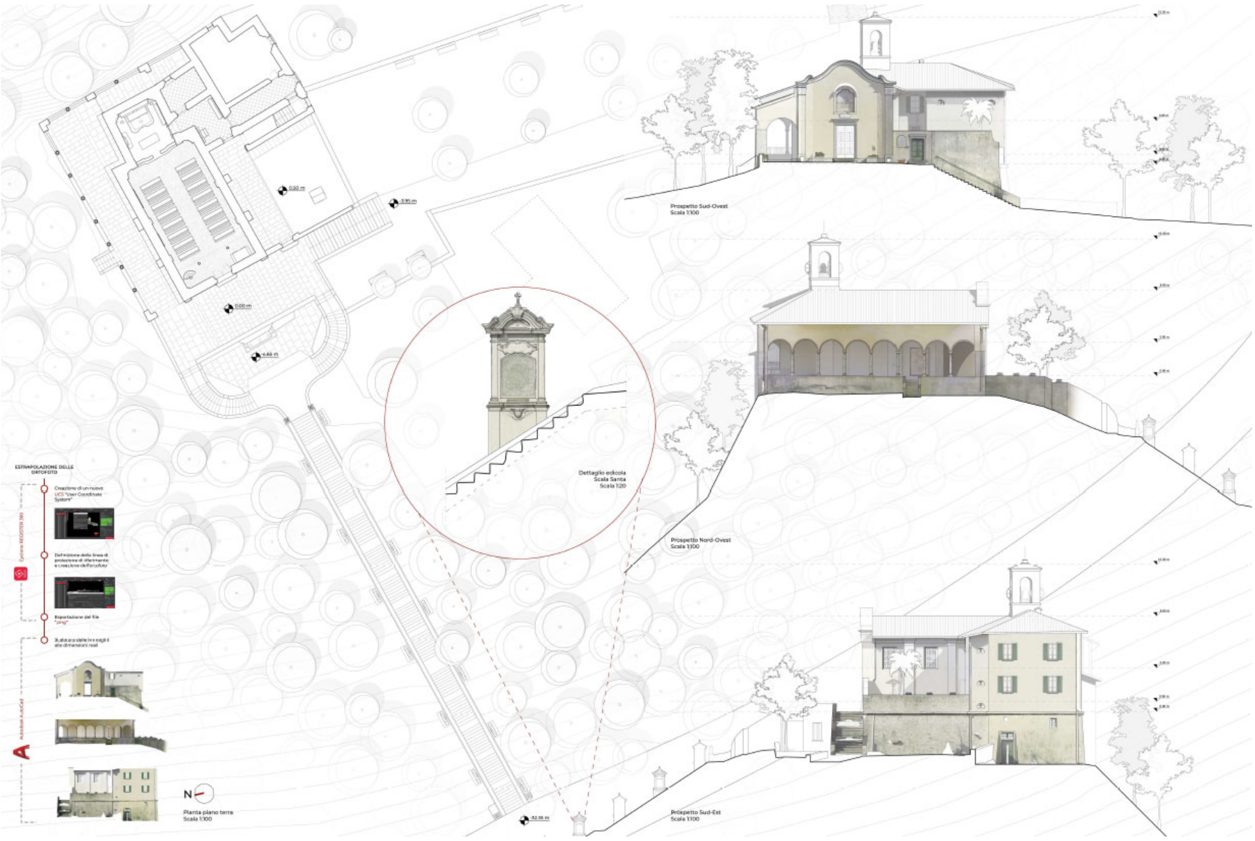

Figure 8. BIM model and technical drawing of the sanctuary based on the surveyed point cloud (graphic elaboration by Brancozzi B., Doria E., and Gamba C.)

4. TIME MODELLING

The sanctuary BIM reconstruction modeled on the surveyed point cloud model and some related technical drawings are shown in Figure 8. Specifically, the work focuses on creating a three-dimensional chronological model of the sanctuary, which not only represents the current state of the cultural asset but is also enriched through

the definition of different evolutionary phases of the architectural artifact based on an in-depth study of the photographic and bibliographic documentation (Borghi and Luzzana 1997). Four Project Phasing has been identified to represent the most significant transformations of the building and were managed using the time parameter in the same BIM project.

In the Revit environment, it is possible to keep track of design changes to the same BIM model (i.e., within the same project file) by defining different construction Phases. Generally, this is done by assigning to each object the phase in which it was created and the one in which it was eventually demolished. Phase Filters are available to control model data flow in views and schedules. These allow the management of the display elements in a specific view or schedule according to the assigned Phase value. Thus, it is possible to set both views (plans, elevations, sections, etc.) and schedule tables to show the state of the building at a specific time defined by a Phase.

There are 4 temporal conditions within the software: “existing” when an object is created in a phase before the reference phase; “new” when an object is created in the reference phase; “demolished” when an object is created in a previous phase and demolished in the reference phase; “temporary” when an object is created and demolished in the same reference phase.

Furthermore, by setting filters for the graphic display of modelled objects according to the temporal condition to which they refer, it is possible to control the graphic parameters (colour, line type, etc.) of lines, fills, and associated materials.

In order to proceed with the timing of the BIM model of the “Madonna della Pace” sanctuary according to its historical-architectural evolution, 4 Phases were defined in chronological order.

Phase 1 – 1571 (Figure 9). In 1571, the church, called “Santa Maria del Castello della Roccha”, corresponds in shape and position to the current one: it has a nave divided into three bays with transverse arches and a large cross-vaulted main chapel elevated above the nave. Two rectangular windows and a door connecting an atrium preceded by a small sacristy are opened on the right side. During this same period, the small church dedicated to St. Michael, dating back to the Longobards, was demolished and replaced by a wooden cross.

Phase 2 – 1610 (Figure 10). A large bastion with a watchtower overlooking the Adda Valley stands out on the southern side. On the wall of this bastion, to the right of the tower, only two windows can be seen instead of the current three, while at the foot of it, the structure of a presumed chapel.

Phase 3 – 1730 (Figure 11). The structure built on the east side is dated no earlier than 1730. It has two floors, and to it belong: the atrium where the votive offerings are kept, the sacristy, and the bell tower. On the upper floor, the date 1731 is engraved on the fireplace in the hall. On the other hand, the watchtower is demolished.

Phase 4 – 1924 (Figure 12). The construction of the Holy Staircase, with its 130 steps and 13 Via Crucis aedicules, dates back to 1924. At the top is the chapel-sepulcher of Christ, wholly decorated with depictions of Mary’s sorrows. From here, on both the right and the left sides, a further 23 steps lead up to the square and the loggia of the sanctuary.

After completing the time modelling, each of the four models has been textured to define the material properties.

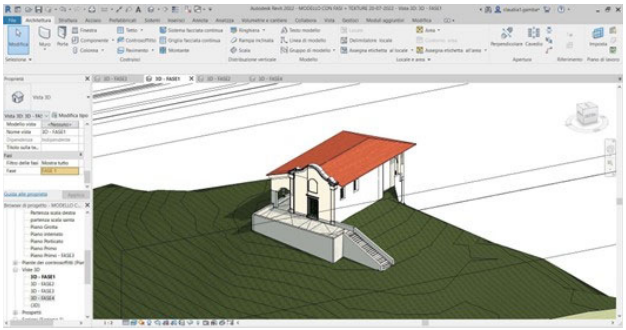

Figure 9. Phase 1 (1571) BIM model of the original church.

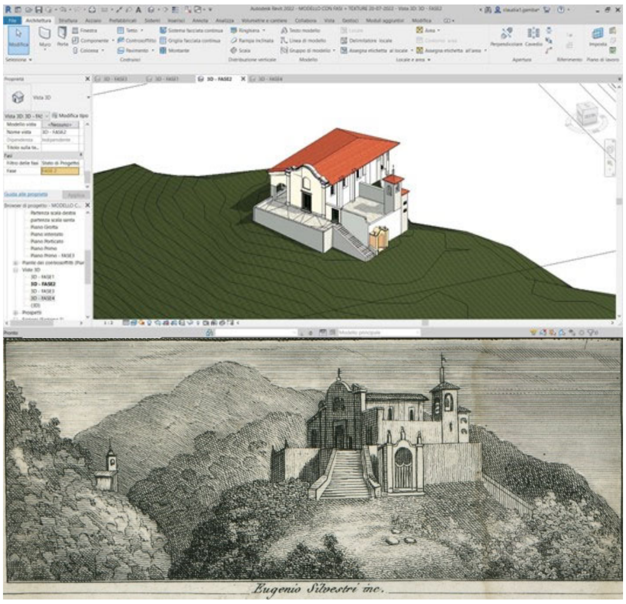

Figure 10. Phase 2 (1610) BIM model and corresponding historical drawing.

Figure 11. Phase 3 (1730) BIM model and corresponding historical image.

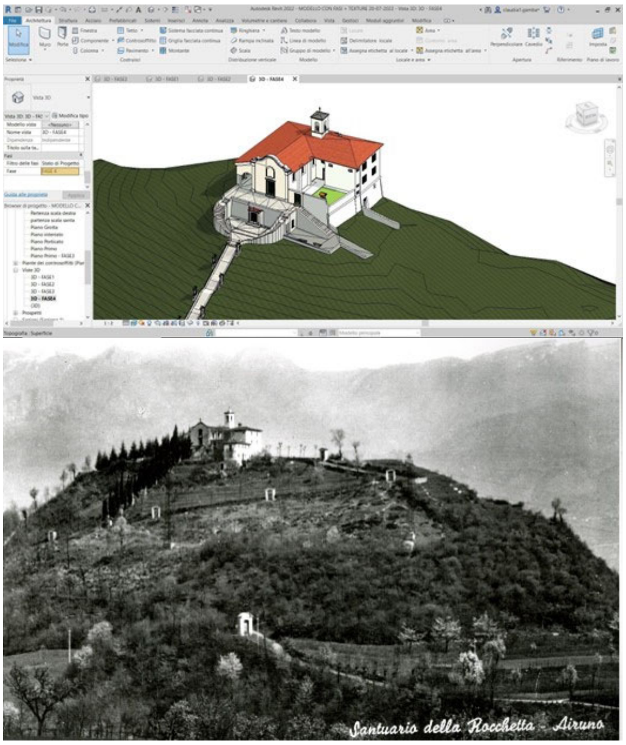

Figure 12. Phase 4 (1730) BIM model and corresponding historical image.

5. VR AND AR APPLICATIONS

The sanctuary geometric and parametric models generated based on the point cloud surveyed were displayed and navigable thanks to the aid of Virtual and Augmented Reality applications. Indeed, the tourism sector identifies immersive technologies as a tool to give rise to new developments and opportunities for innovation. The first benefit of VR/AR applications for tourism is unquestionably related to destination marketing, i.e., the promotion of products and services employing not only text-based tools but also captivating "sensory" information. Currently, many operators in the tourism market offer, for example, the possibility of digitally exploring a tourist destination not only with photographs or brochures but through Virtual Tours navigable from a browser, thus anticipating the travel experience with the possibility of partially enjoying some of the destination's contents before going there. More generally, VR and AR technologies have numerous spin-offs and potentialities in tourism activities, allowing users, for instance, to access various practical and helpful information (accesses, routes, navigation tools, translations, online guides) but also additional historical-cultural-artistic-architectural content with appealing and engaging character.

The purpose of VR is the immersion of the user in a virtual environment isolated from its surroundings that, from the collaboration of Hardware and Software tools, offers the enjoyment of environments that do not necessarily exist (Trizio et al., 2019). In this specific case, the model of the sanctuary and the surrounding environment is perfectly faithful to the surveyed reality and can be used both for disseminating Cultural Heritage and for remote fruition (Argiolas et al., 2022).

Indeed, following the Laser Scanner survey, a parametric model was entirely developed in Revit, provided with all the families and nested objects typical of a Cultural Heritage case like this one; it is known that the libraries of software modelers in the current BIM environment are insufficient for any reconstruction in the cultural-historical field (Rocha et al., 2020), and in this, as in other cases we resorted to plug-ins or external software to be able to model individual objects as surveyed objects. The texturing process was completed first in the BIM environment adding texture from the proprietary libraries as well as from specific photogrammetry sessions. The plug-in that allows direct export of the Revit model is “Enscape,” which allows real-time rendering with a real-time update when changes are made to the parametric model. The plug-in’s own features were explored and used, facilitated by the proper construction of the model: inspection and selection of Data Base information linked to the model, same object cataloguing, inclusion of asset libraries for application of vegetation directly usable from within the application placed after the export of the model. Before the selection of essences within the Escape library, the essences had been recognized by in-place surveying and selection using a mobile device application that allows the identification of plant species by part of them. When the model was imported into Enscape, not all applied textures were recognized, and replacement and scaling work had to be done for the similarity of some parts, giving up some detailed textures to allow faster fruition within the headsets. Within the application Enscape, annotations can be shared via an online portal, “BIM TRACK,” which is directly integrated with the software, within which a project can be created, and the file can be monitored in real-time through the compilation of forms that can be updated. After exporting to the “.exe” format from the Enscape software, a virtual reality environment has been organized to host the model and allow its visualization through a viewer. This aspect can be accomplished by linking the “.exe” file within the Oculus program related to the viewer. The headset “Oculus Rift S” allows the display of images in full HD resolution by exploiting stereoscopic 3D technology by showing, therefore, a different image to each eye. The experience has been to be displayed in the first person to allow a better perception of the environment.

Figure 13. VR exploring

Finally, to make the sanctuary’s historic transformation accessible to tourists over time, a smartphone application prototype was created, taking advantage of AR technology. In this manner, any user can easily explore and view the 3D models of the four architectural building phases. Interactive information and multimedia content are superimposed on reality to have a knowledge frame of the architecture in an attractive way (Teruggi et al. 2021).

AR applications allow the combining of the physical and digital worlds, affecting human perceptions, mainly visual and acoustic ones (Russo, 2021). Therefore, they do not replace the physical context with a completely artificial environment but offer its “augmented” version with new content. The digital world is integrated with the physical one, allowing the user to continue to experience physical reality simultaneously. It is possible to enjoy additional multimedia elements in real-time, contextualized within reality. Therefore, AR systems can also represent a stimulating educational environment with considerable potential for active involvement in the learning experience.

AR systems are characterized by the following elements: the device, the tracking system, and the digital content to be integrated into the scene. Devices for accessing AR content can range from the most complex, such as wearable smart glasses and headsets or holographic displays, to the simplest, such as standard smartphones and tablets. Usually, head-mounted displays are strictly connected to specific museum installations or exhibitions. Instead, specific apps allow AR content to be used on personal smartphones or tablets. Therefore, AR systems are more readily usable by a broad spectrum of users compared to VR applications. One of the most crucial AR issues is ensuring accurate and consistent registration between artificial virtual elements and the physical environment. Various methods like sensor-based (optical, inertial, magnetic, GPS - Global Positioning Systems, or acoustic), vision-based (image marker and markerless), and hybrid systems are developed to track the digital contents in AR (Gupta et al., 2019; Teruggi and Fassi, 2022). Image tracking allows additional digital information (e.g., a 3D model, 3D video, etc.) to be displayed when the camera frames 2D images. Marker tracking is similar but activated by pre-defined markers and symbols. In general, location-based systems allow additional information to be displayed based on the user’s position. The user can move freely in space, and augmented content adapts the information according to what is displayed through the camera. In this specific case, it was decided to design an app for any user with their smartphone based on an image target tracking system for displaying digital content.

The Vuforia Engine platform was adopted to build and manage AR content and applications for mobile devices. Indeed, this software development kit can be imported into the assets of the Unity local project. Importing the unity package allows a script to make the necessary changes to the Unity project to install or upgrade to the latest Vuforia Engine SDK (Software Development Kit). Thus, it is possible to create interactive content for AR experiences through the Unity platform.

The conversion of standard materials into real materials of the textured BIM models of the 4 phases of the sanctuary is necessary for them to be compatible with the AR development software. Therefore, the files (.fbx format) were first imported by rendering the scene in 3D Studio Max and then imported into Unity. As the image target, which constitutes the visual marker for the AR creation, the corresponding floor plan of each of the individual phases was chosen (Figure 14). Thus, by framing each of the floor plans in sequence, it will be possible to visualise four three-dimensional models through augmented reality. Once the scene has been organised and built, it can be exported in .apk format. Currently, the prototype of the smartphone application has been developed, designing the specific user interface (Figure 15).

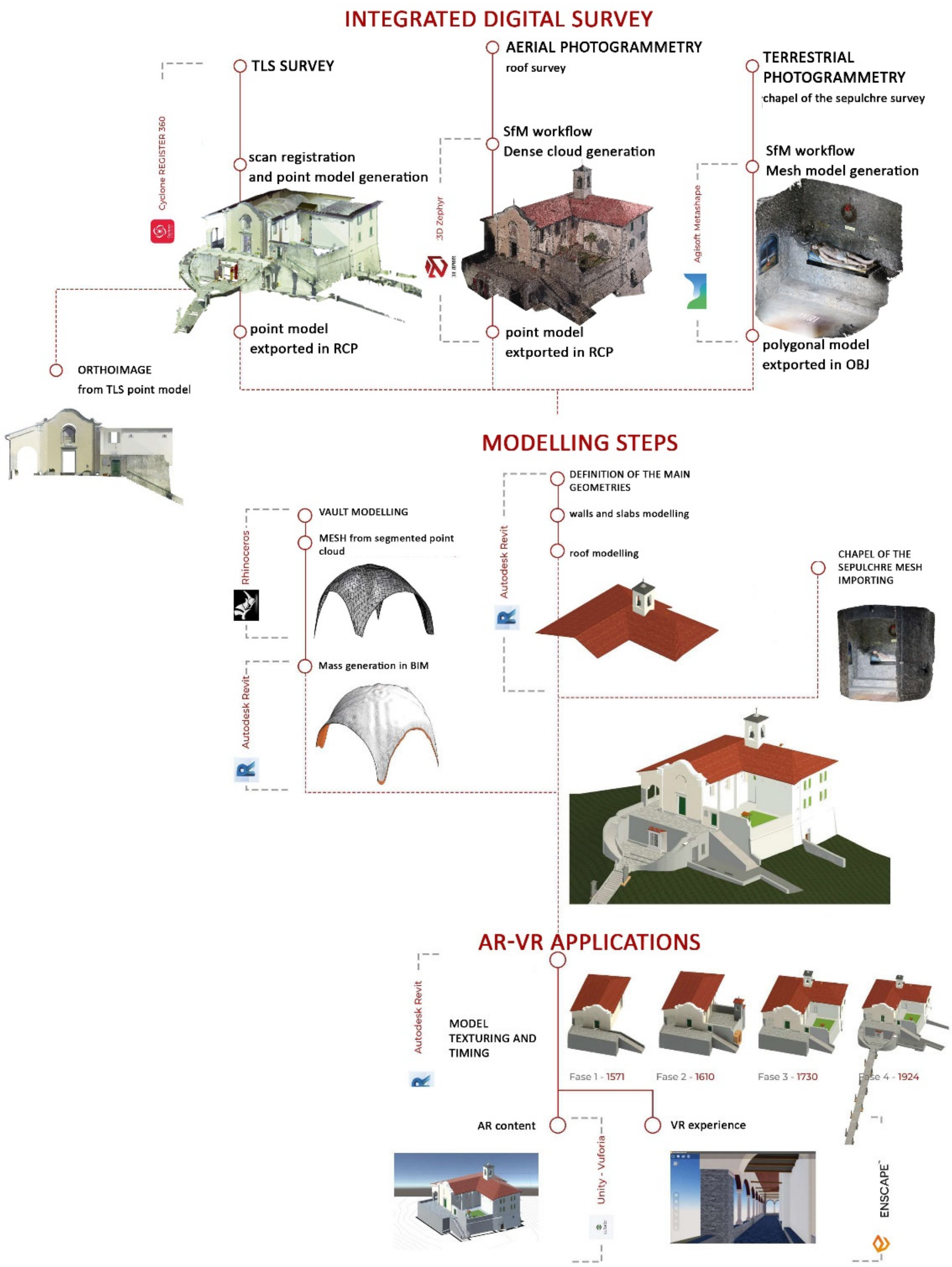

Figure 14: The entire workflow from digital survey to AR/VR application based on BIM models.

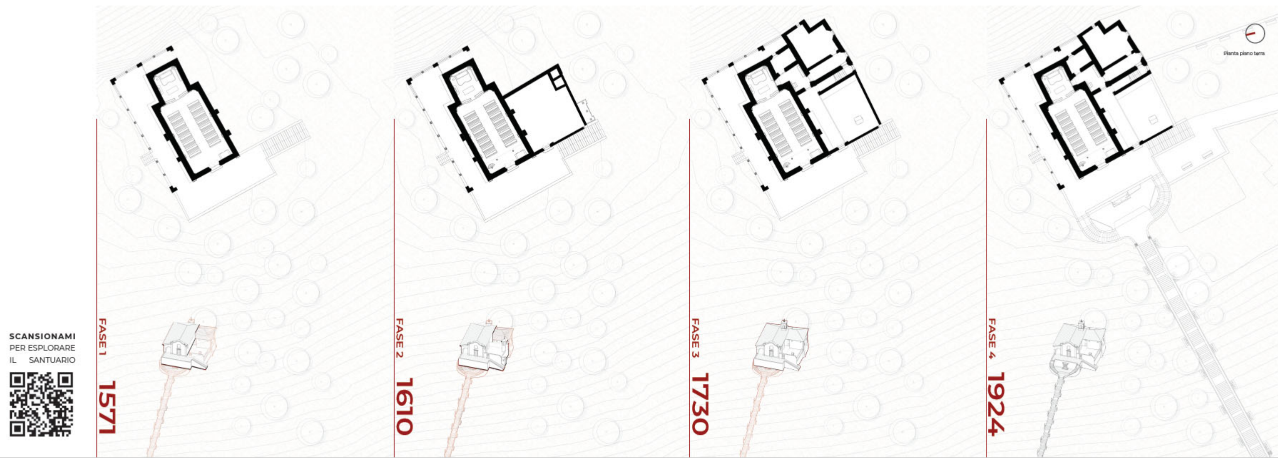

Figure 15: Sanctuary architectural evolution that can also be experienced with AR application; the floor plans are the image marker.

Figure 16. The interface of the smartphone app prototype.

6. CONCLUSIONS

Even if the BIM methodology was born and optimised mainly for the modelling of new buildings characterised by geometric regularity and repetitiveness, the workflow implemented was effective, albeit with some limitations, also for the modelling of existing historical-cultural architecture, characterised instead by irregular shapes and often unique components throughout the building. However, the methodology implies the interface and interoperability of various digital work environments and modelling software and, consequently, the need for profession-specific abilities. There are many positive aspects associated with semantic modelling. One example is that the BIM data and the related reality-based reconstructions can be directly used for VR and AR applications. Figure 14 shows the workflow from digital survey to AR/VR application using the BIM modelling approach. Moreover, an exciting aspect closely related to the dynamism of the HBIM model was to develop a backward historical reconstruction, i.e., starting from a model representing the current state of the sanctuary. Thanks to the analysis of historical documentation, it was possible to distinguish the most important phases that characterised the external appearance of the building, allowing a future generic user to have all the information necessary to understand its history. This approach of representing and narrating an architecture can also be very engaging and helpful if rendered with AR and VR applications.
A future aim is to develop a similar cultural valorisation and dissemination project based on VR and AR applications also for the other sanctuaries that make up the Cammino di Sant'Agostino, to create an innovative and interactive digital path to encourage conscious tourism in these places rich in history and attractive by a naturalistic point of view.

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