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From digital survey to Extended Reality. Possible uses for the Cathedral of Udine

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1 Introduction

Digitization is a well-established practice for the protection and enhancement of Cultural Heritage (CH), but it is effective only when based on scientific and rigorous methodologies. Digital acquisition, in fact, involves the creation of a large amount of heterogeneous data, not always easily handled by the authorities, often public institutions, that oversee the overall management of both objects and monuments and their digital copies or restitutions. In the case study, the uses of such data for the creation of Extended Reality (XR) tools are shown, both for the visualization of digital reconstruction aimed at a wide audience of users and for the use of interactive visualization of reconstructions by scholars to formulate increasingly accurate reconstructive hypotheses that can be modified over time.

The case study is the Cathedral of Santa Maria Maggiore in Udine (Fig. 1), a building located in the center of the city, in which traces of its period of greatest development and growth (14th century) are still visible, while others have been lost with the transformations of subsequent centuries. Data about the building were acquired by integrating different tools and methodologies such as Terrestrial Laser Scanner and digital photogrammetry, depending on the purpose of the survey and accessibility conditions. The requests made by the team of scholars and the Instituto Pio Paschini (co-financier of the digitization project) concerned the digital reconstruction of two different historical phases (with reference not only to the architectural volumes, but also to the sacred furniture themselves, the frescoes, and the overall appearance of the liturgical space) and the subsequent proposal and application of strategies for dissemination of the collected and processed data. The accurate description of the process of digitization and creation of 3D models related to the reconstructive hypotheses is included in another contribution by the authors [1]. For the overall architectural, religious and cultural history of the cathedral, see the volume edited by Scalon [2].

The use of extended reality technologies has now become increasingly recurrent in CH enhancement projects as a useful tool for engaging the public in multiple cultural contexts [3]. However, the spread of such technologies requires a careful assessment of the characteristics of the project to be enhanced as well as the context of application. In this sense, before proceeding to the design of the possible forms of fruition related to the reconstructions of the cathedral, it appeared necessary to conduct a preliminary analysis that took into account: the principles widely shared in the field of digital CH; the peculiarities of the place and the people who use it; the fruitive solutions and technologies adopted in similar case studies.

The article analyzes the methodology that led from data acquisition and processing to the possible uses of XR applications for knowledge, dissemination and fruition of CH.

Fig. 1. The cathedral is located in the historic center of the city of Udine, in north-eastern Italy (Source: Google Maps); (Editing: authors); (Photo: authors).

2 State of the art

The use of immersive technologies makes possible an approach geared toward education but at the same time also toward entertaining the public [4]. The use of XR systems for the enhancement of Cultural Heritage is documented in a growing body of literature, which provides exhaustive reviews of the available technologies and detailed descriptions of the many projects that adopt them for fruition projects [5, 6, 7, 8, 9, 10]. Cathedrals are very special contexts, being places of worship or otherwise imbued with an aura of sacredness that may be ill-suited to technological artifice. However, there are numerous positive examples of how such systems can be employed in a sacred space. For example, an open world has been created for St. Andrews Cathedral in Scotland, that reproduces the environment as it might have looked in medieval times and allows users to participate in the religious life of the time by being accompanied by historical figures, attending functions and even consulting some digitized volumes. In addition, they can communicate with each other while visiting the virtual space, fostering collaborative exploration among experts in the field [11]. As part of the European Vista-AR project, several augmented reality outputs were developed to encourage visits to Exeter Cathedral, including animation of the singing angels in the Minstrels' Gallery and the original visualization of the colors that characterized the west facade of the building [12, 13]. On the other hand, the 3D point model of the Milan Cathedral was used to develop a prototype in Mixed Reality to support maintenance work; the application, developed with Unity 3D, allows through the HoloLens 2 system to inspect 3D models and point clouds of entire sectors and the macro-elements that compose them, facilitating interaction with these objects through hand gestures. Such a model should eventually permit survey data to be consulted, updated, and communicated to other operators in real time [14, 15]. Finally, some proposals for dynamic visualization of architectural models that allow real-time interaction with digital representations and related data are particularly interesting. For the medieval monastery of Mont-Saint-Michel, a mixed-reality system allows a holographic tour of the abbey from a map made in the 17th century by Benedictine monks; again, the tour employs a HoloLens 2 device thanks to which users can explore points of interest, observe details invisible to the naked eye and access explanations presented in the form of text, video and audio [16, 17].

The use of extended reality technologies certainly represents a very promising field of investigation because it meets the needs of users with different backgrounds and predispositions and facilitates the transmission of complex knowledge through an experiential and accessible approach [17]. In addition, the case studies mentioned are excellent models of effective use of the opportunities offered by such methodologies even in monumental settings where liturgical practice is still present and where they might be, without proper planning, inappropriate.

3 Objectives

The case study of the cathedral was chosen for testing XR tools as part of a larger project for the study and knowledge of the Cultural Heritage (CH) of the Friuli-Venezia Giulia Region, promoted and co-financed by the Instituto Pio Paschini of Udine. The main needs behind the data acquisition were the in-depth study of the present building and its earlier phases, especially those related to the transformations undergone in the 14th and 15th centuries, respectively, and the dissemination of the results. The parameters to be taken into account are related to (i) the characteristics of the case study; (ii) the fulfillment of the study, management and dissemination requirements; and (iii) the different types of end users of the outputs (scholars, CH managers, general public).

The main building characteristics taken into account in organizing the data acquisition and processing phase (i) were:

- the presence of architectural elements added over the centuries that change the internal volumes, making it difficult to read the medieval phases (e.g., 15th-century vaults, 17th-century chapels);
- the easy legibility of the external volumes starting from the facade, accompanied, however, by a difficult view of the building as a whole, due to its considerable size and the presence of building parts subsequent to the medieval age;
- the sacred furniture and frescoes: the current position is different from the original one and the restoration of the past conditions is not possible because of the different boundary conditions (especially in the apsidal area);
- inaccessibility of some spaces (like the attics).

The requests of the coordinator of the project (ii) concerned the need to formulate reconstructive hypotheses related to the 14th and 15th centuries, phases affected by important transformations both internally and externally, not only related to the architecture, but also to some sacred furniture and frescoed wall decorations. Both some of the furnishings and some of the frescoes are preserved today in the Baptistery and in the rooms and storerooms of the cathedral museum (Museo del Duomo), but because of the changes undergone by the apsidal area and the adjacent chapels, it is not possible to proceed with the repositioning. Given the complexity of the building and its transformations in the periods analyzed, it was necessary to think of a digital tool that would allow the clear visualization of the spaces and furnishings in a given historical period, in order to facilitate the understanding and verification of the hypotheses formulated. In this case, the 3D model based on the metric acquisition of actual geometries, which could be explored virtually and easily modified in its elements, was the best solution for interactive collaboration among various users. On the level of dissemination, the same digital material forms the basis of different outputs designed for understanding by a general public. In addition, administrations in charge of management can use the collected data to carry out specific analyses, conservation activities, restoration work and maintenance programs.

In addition to the need to consider different types of output to meet these requirements, the different types of users (iii) and the different levels of knowledge they have of digital XR tools were taken into account. To promote accessibility, mixed solutions have been proposed that integrate 2D information with 3D models and virtual reality.

Considering (i), (ii) and (iii), the main objectives of the project are:

- to make the large amount of material related to the cultural and architectural history of the cathedral accessible to different types of users, using different levels of communication;
- to evaluate how the application of XR tools in this specific religious context conveys information, helps to evaluate and define reconstructive hypotheses, and facilitates the fruition and understanding of the monument.

4 Methodology

The workflow applied to the case study was divided into three main stages: (1) digital documentation; (2) creation of the Information System; (3) design of XR applications and initial experimentation.

4.1 The creation of the 3D model and Information System

Digital documentation (1) was set up to meet the proposed objectives. Given the huge size of the cathedral and the multiple issues to be addressed, it was decided to carry out a partial survey of the structure, concentrating the documentation actions on those particular elements capable of providing essential information for reconstruction, such as the facade, with the possibility then of reconstructing the phases by proceeding by subtraction of volumes and elements included in the more recent phases. The survey campaign using Terrestrial Laser Scanner (TLS) covered the exterior and interior at floor level, as well as the northern rooms of the attic (Fig. 2). The main objective was to collect metric data on the form-generating elements and particularly useful for reconstruction (such as the stratifications of the facade, the internal and external heights of the volumes, some architectural elements dating back to the 14th-century phase, and the position of the pillars). This survey was supplemented with data obtained through digital photogrammetry, where it was necessary to document specific elements such as the facade, portals, frescoes and sacred furniture. Repeatable elements, such as openings, decorative arches and cornices, were modeled from scratch, using point clouds as reference.

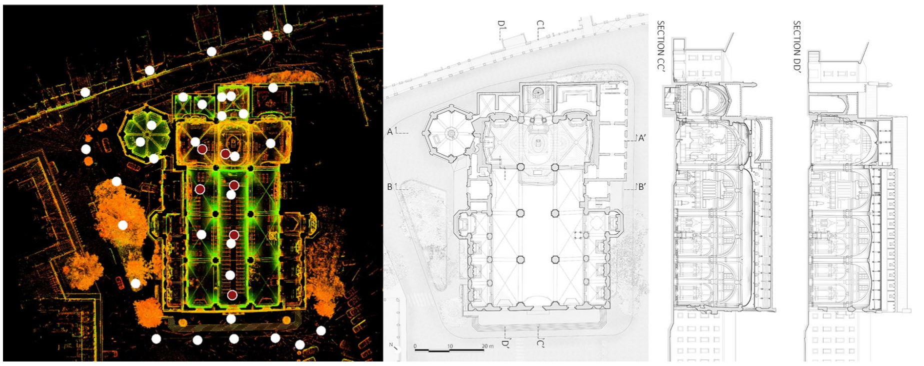

Fig. 2. The survey campaign with TLS was carried out on the ground floor (white points) and in the attics (red points). 2D drawings of plans, elevations and sections were extracted from the point cloud. (Survey: L. Cipriani, G. Bertacchi); (CAD drawing: G. Bertacchi); (Editing: G. Bertacchi).

Metric data acquisition was carried out with a Leica C5 time-of-flight TLS. The interior naves, apsidal space and chapels on either side of the apse were documented with 18 scans, the exterior (facade, north side and east side) with 16 scans, and the attic with 5 scans (nave attic and north one), for a total of 39 different medium-quality (1 centimeter at 10 meters) scans (Fig. 2).

Digital photogrammetry has been applied to both large and medium-sized architectural elements and to elements that make up the sacred furniture. The procedure proved particularly useful for locations that were impossible to access by laser scanner, such as the southern attic related to the apsidal chapels. Two reflex cameras were used for the photographs, a Nikon D5500 (APS-C, 24 MP, 23.5x15.7 mm) and a Sony a6000 (24.3 MP, 23.5x15.6 mm APS CMOS Exmor® HD sensor), and an extendable pole supporting a camera (Sony QX100, 20.2 MP, 13.2x8.8 mm Exmor R® CMOS sensor) with remote control from the ground.

The collected data were processed, first creating a simplified 3D model, which was used as the basis for the creation of a 3D information system (IS) (2), capable of serving as a database for the collection of materials pertaining to the building and all its component elements and for the production of different outputs, both two- and three-dimensional (Fig. 3). The declination as an IS (Fig. 4) lends itself well to such a case, since the continuous evolution of ongoing research, new documents, and new formulations of reconstructive hypotheses can be integrated and/or modified in a continuous updating of the system. In addition, the digital archive function facilitates management and future conservation and dissemination actions by the administrations in charge [18, 19].

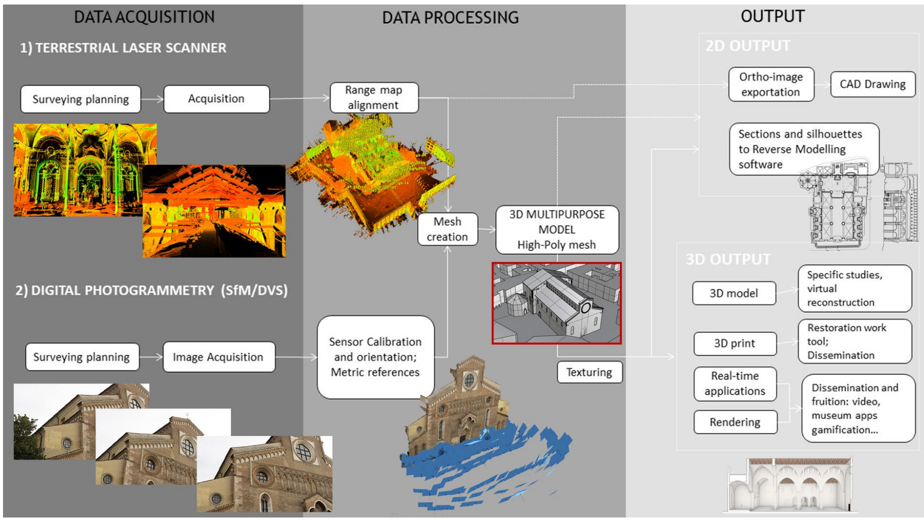

Fig. 3. Workflow followed for data acquisition and processing. Possible outputs that can be obtained from the 3D model (Editing: G. Bertacchi).

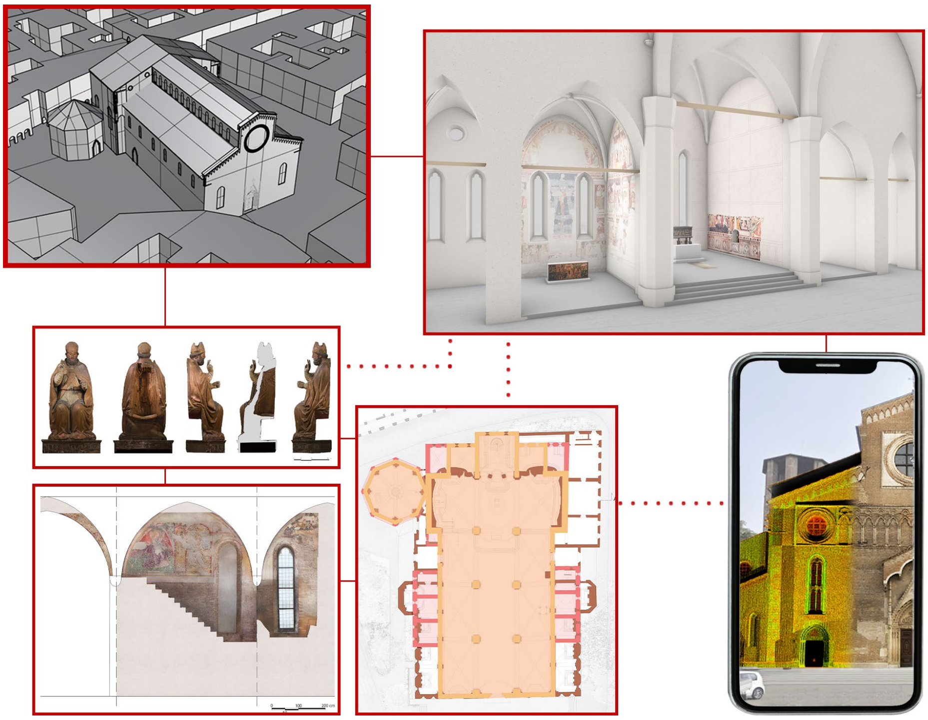

Fig. 4. The 3D model is the basis of the digital archive which collects heterogeneous data, allowing continuous updating and data interconnection (cathedral 3D modeling: G. Bertacchi); (Statue, frescoes: F. Giacomini).

On the basis of the metric information obtainable from the processing of the acquired data, combined with historical and archival information, the two reconstructive hypotheses were set. The first relates to the second half of the 14th century, a period when the 13th-century building had already been replaced and reformed as a result of the major works carried out during Bertrando's patriarchate (1334-50). The second phase, on the other hand, concerns the transformations undergone until about 1470. Compared to the previous phase, vaults were added internally to cover the nave and transept; several chapels were added, both in the apse area and leaning against the aisles; the central rose window was modified in the façade; the bell tower was built above the baptistery.

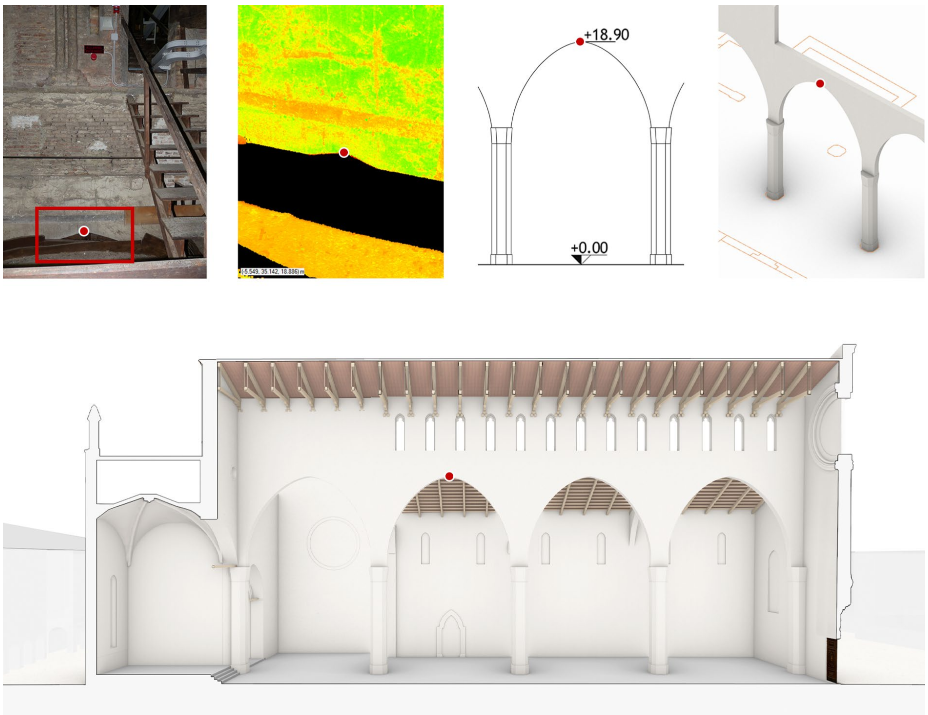

Fig. 5. The keystone, which is visible in the attics, was documented with TLS and this allowed its repositioning and the creation of the entire arch in the 3D model (Photo: G. Trevisan); (Modelling: G. Bertacchi).

The two reconstruction models are based on precise references set in the point cloud, which serve as generating elements of the ancient volumetries (Fig. 5). The exterior walls of the 14th-century church were created from the plan trace of the present walls and pillars. Instead, for the height of the walls, the trace in the facade and the current height of the attics were considered. Specific parts corresponding to openings were then subtracted from the walls, or specific elements added. This basic geometric model was supplemented by 3D models of detailed elements, processed with digital photogrammetry, such as the two portals and sacred furniture. Other elements, for which the exact definition of the geometry did not add essential information to the design, were modeled from the available information.

The development of the entire model follows a semantic subdivision, according to their structural function (wall, pillar, arch, opening, roof), facilitating the creation of the information system as a database, in which heterogeneous data (documents, images, specific analyses, relationships, 3D models) are linked to each element. This structuring of the model as an information system thus allows for timely verification of elements and possible change to fit new reconstructive theories if new studies are conducted or unpublished archival material is found [19, 20].

For each element various parameters were considered before their placement and appearance: traces in the surface, archival material, and similarities found in buildings belonging to the same historical period and geographical and administrative area. It follows that the hypotheses proposed for each element have a different degree of reliability with respect to the real past situation, depending on what could be applied of each parameter taken as reference. From this also comes a different choice of representation, depending on the degree of certainty and evidence found: some openings, for example, are only light traces in the masonry, while certain ones go through it.

Thus, the two reconstructive models (Fig. 6) follow a careful procedure for scientific reconstruction and contain an innumerable amount of information that must be made understandable to the users being considered in order to meet the objectives of the project.

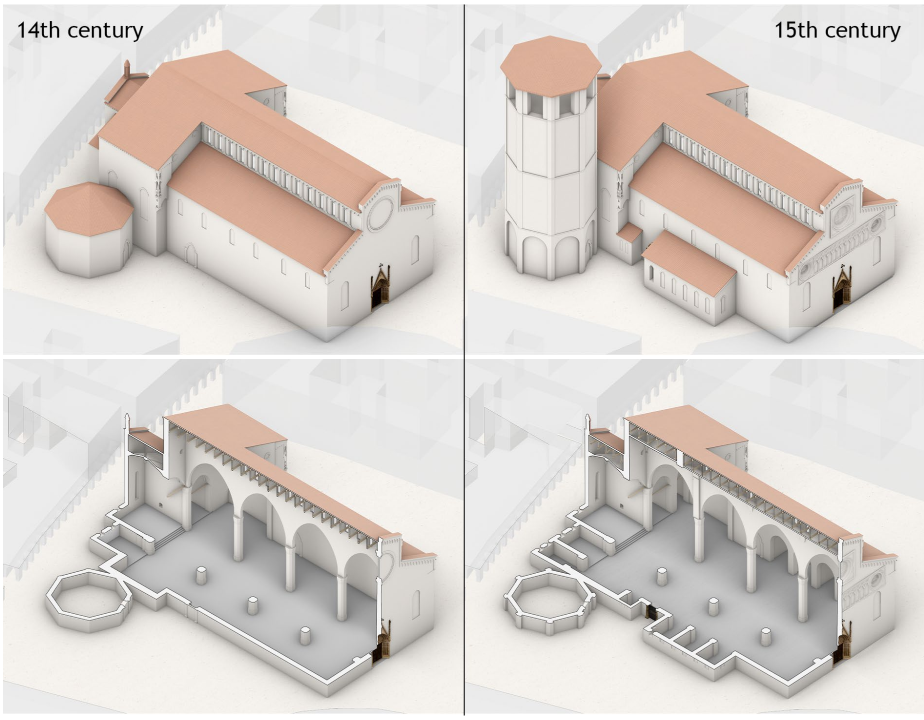

Fig. 6. The two reconstructed phases compared. Thanks to the 3D model, the multiple changes in the structure are easily understandable (Modelling and editing: G. Bertacchi).

4.2 The design of XR applications

Principles. The first step toward the conception of the dissemination methodology was based on a careful reading of the guidelines contained in the London Charter, reviewed in light of the most recent directives expressed in the field of open science and digital transition [21]. In order to obtain a complete and up-to-date framework the instances that emerged were integrated with more recent references, such as the FAIR principles and the Italian National Plan for Digitization (NPD) of Cultural Heritage, which respectively emphasize the nature of the data to be shared and the ways in which such sharing should take place so that the fruition of digital resources is well integrated into the modern digital ecosystem [22, 23]. What emerges most from these documents is the need to make the vast amount of information collected not only widely accessible through the online publication of the information system, but also intelligible by different segments of the public. The FAIR principles and the NPD in particular insist on the burden of adopting dissemination strategies capable of fostering data discovery and reuse by encouraging the design of experiential and interactive forms of use.

Target. Since the object of the work is a place of worship, some studies on religious tourism and the characteristics of users visiting or frequenting cathedrals were considered in the first instance [24, 25]. While the user base includes, as is easily imaginable, both lay visitors interested in historical-artistic aspects and faithful on pilgrimage or interested in liturgical or otherwise worship-related activities, what emerges from such research is that a large part of the public seems to go in search of a spiritual experience [12]. At the same time, the psychographic characteristics of the users, such as age and socioeconomic status, delineate a very heterogeneous target audience and broaden the number of needs to be met [4]. Possible users were also assessed taking into account their knowledge and familiarity with digital technologies and devices for accessing information (smartphones, tablets, viewers).

Workflow. The first step was to import the model into an application for creating interactive environments, in this case Unreal Engine™ v5.0.3. Like Unity, this software allows not only for graphically sophisticated game environments but also for the creation of augmented reality products. Compared to Unity it offers the possibility of using a visual programming language, called Blueprint, which can be integrated with coding in C++ [26]. The reasons for this choice are also dictated by the less availability of documentation and online resources related to the use of this program with respect to augmented reality installations and thus the desire to expand the associated case studies and tests [27]. In case significant limitations with respect to more frequently adopted solutions are evidenced, the use of methodologies based on other applications is not ruled out; however, in this way such issues can be highlighted stimulating the search for solutions by the reference community. Initially, therefore, model layers related to the 14th- and 15th-century phases previously made with McNeel Rhinoceros™ v7 software were imported. In order not to lose any information, we chose to use the Datasmith™ plugin that allows synchronizing the reconstruction project, in the case of the cathedral created in Rhinoceros, with the project dedicated to the development of interactions for augmented reality. After importing the assets, atmospheric elements were inserted to make the visualization more realistic [Fig. 7].

Fig. 7. Two preliminary renderings of the model inserted into Unreal Engine. (Rendering: F. Giacomini).

All the elements created in the reconstruction project were transferred as individual instances for a total of 4119 actors computed within the Outliner; to make the work more fluid, the individual meshes that composed the main architectural elements, such as walls, roofs, pillars or that belonged to the same furniture were merged so as to respect the classification used for the construction of the model, while decreasing the number of components to be managed. In this way it was possible to maintain the categorization made according to the bins in the original project. The models were then exported in .gltf format and uploaded to the 3D resource sharing platform SketchFab™ and then placed within the website. Next, a new layer was created intended for the generation of an initial tracker image for which the floor plan related to the 15th-century phase was used, enabling 3D visualization of the building's exterior structure [Fig. 8].

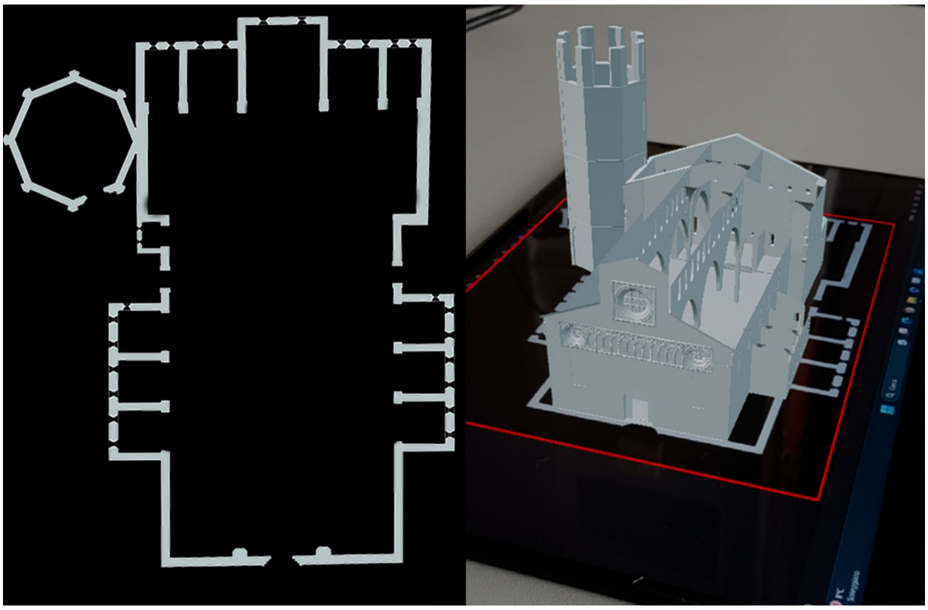

Fig. 8. A test of the visualization of the 3D model on the 15th-century floor plan (Author: F. Giacomini).

The AR visualization, which is still under development, can currently be activated only through a test application that can be downloaded through .apk files.

5 Results

The commitment of ensuring broad inclusivity and accessibility of information combined with the desire not to alter the contemplative dimension that distinguishes the cathedral led to the search for solutions to meet the different requests. Among immersive visualization technologies, those based on augmented representations seemed to be particularly appropriate to the case study; by not completely replacing reality, as is the case with virtual reality technologies, they can integrate into the religious context in a more fluid way. Moreover, the ability to take advantage of familiar, unobtrusive and widely used devices such as smartphones and tablets encourages autonomous, hands-on enjoyment of content [28]. However, these devices may have some limitations; for example, they presuppose the possession of a sufficiently performing Internet-connected device [12]; as such, they should be accompanied by other modes of fruition.

In order to ensure greater inclusiveness, the reconstructions have been made accessible through a dedicated website that can be reached via QR code [29]. In this way, the virtual resources can be accessed both remotely and during an on-site visit through a simple scanning system that ensures access to the models and documentation. In addition, two types of fruition are set up based on extended reality. The first is based on a more classical form of augmented reality that can be activated from panels through mobile devices to allow more autonomous access. The second, on the other hand, concerns the design of an XR Station, which includes an interactive monitor and a form of mixed reality; the latter is designed to encourage data discovery and stimulate a critical and participatory approach toward virtual reconstruction. To avoid trespassing on the sacred space and to limit the digital interaction during liturgical functions, a number of strategic points were identified where the panels and the work-station could be placed [Fig. 9].

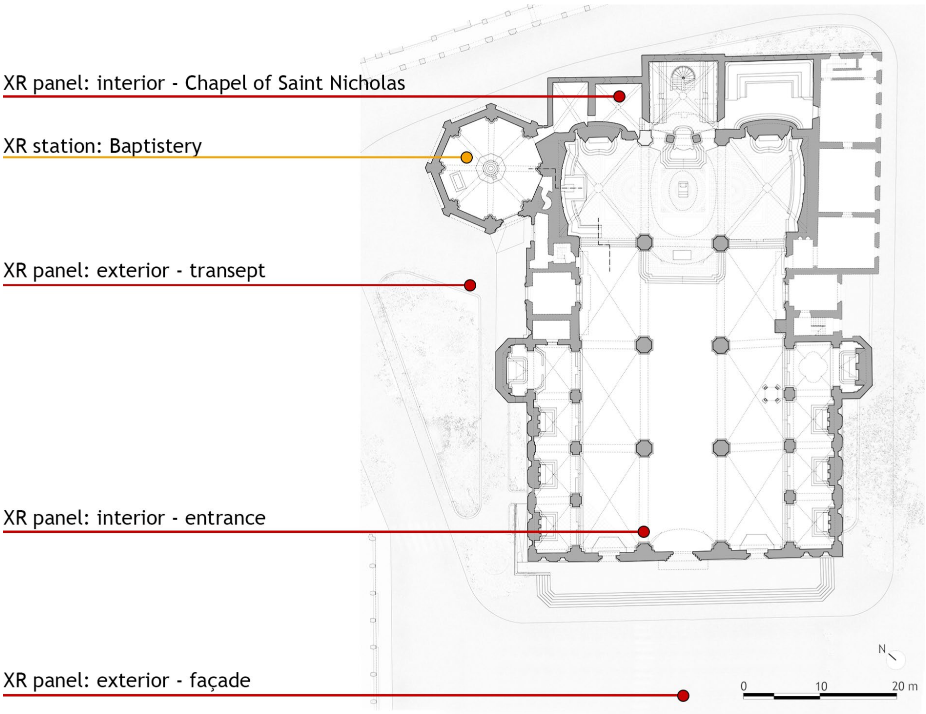

Fig. 9. The design of the internal and external positions of the panels and the workstation (Editing: F. Giacomini).

XR panel. For users less familiar with technological tools, panels containing textual and graphical information have been designed, which contain an additional layer of augmented information, through a QR code that allows access during the visit to various insights, 3D models in online repositories, or allow visualization of the augmented reality model of past eras and the structure of the cathedral in the form of a point cloud. Regarding the position of the panels, two areas have been identified in the exterior: the first from the bottom of the square in front of the Duomo, with a view towards the facade and the second in correspondence with the transept and the bell tower, another point from which it is possible to read many of the transformations that have affected the building over the centuries. The chapel of St. Nicholas, adjacent to the apse on its northern side, was chosen for the internal panel. Currently the chapel is part of the rooms of the cathedral museum, with access from the baptistery, but in ancient times it opened towards the main hall of the cathedral, until an altar was built in the 17th century, effectively blocking the view. The positioning of the panel in this space therefore does not prejudice the performance of liturgical functions and also allows the internal appearance of the church before the 17th-century intervention to be visualized in augmented reality. Finally, the insertion of a panel on the opposite side was planned [Fig.10]. In these cases, hybrid tracking methods and tangible, hand-less interfaces are used, such as those of the most popular mobile devices. Furthermore, to permit the evaluation of the reconstructive hypotheses, representation scales are inserted, to graphically classify, with colors and textual information, the origin of the sources and the logic followed in the work of restoring the architectural elements and sacred furniture [30].

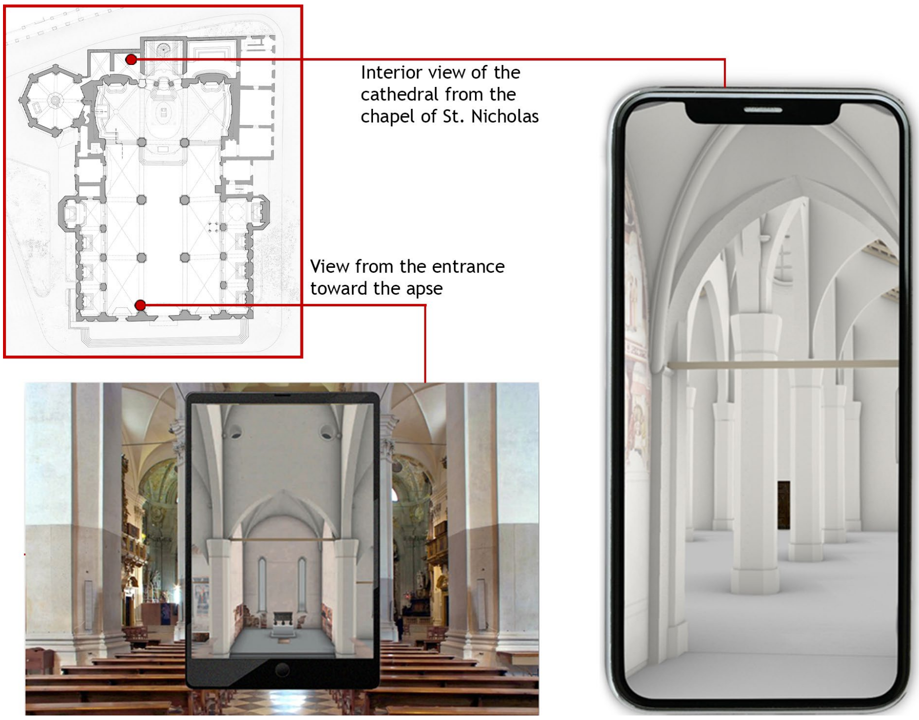

Fig. 10. Simulation of the view of the reconstructed model starting from the position of the internal panels (Rendering and Editing: F. Giacomini).

XR station. For users who need or desire a deeper interaction, a workstation has been designed inside the baptistery (belonging to the exhibition spaces of the cathedral museum) [Fig. 11]. This includes an interactive display for the navigation of the virtual models with access to the related documentation and also includes the addition of a scale plan of the building to be explored through a form of mixed reality inspired by augmented design [31, 32]. In this station the user can use optical see-through Head Mounted Displays and interact with a scaled plan of the model to carry out, through a guided procedure, the main phases of the reconstruction. Through a mixed reality system, he can then access the documentation and data collected, such as measurements, point clouds and images, to understand the work carried out. The purpose of this application is to convey, through practice, the concept of virtual reconstruction and the various hypotheses that the research team has formulated based on all the material available. In this case, tracking devices based on NFC sensors are also used. These, connected to a 3D printed replica as an input device, when touched by the user can return the contents with which to interact [33]. At present it is hypothesized to include a part relating to the furnishings and in particular to those that were once in the apse area, such as Bertrando's sarcophagus and the frescoes that are now partly exposed in the baptistery. Even in these cases, the idea is to lead the user to evaluate different layout hypotheses, as the research team itself had to do.

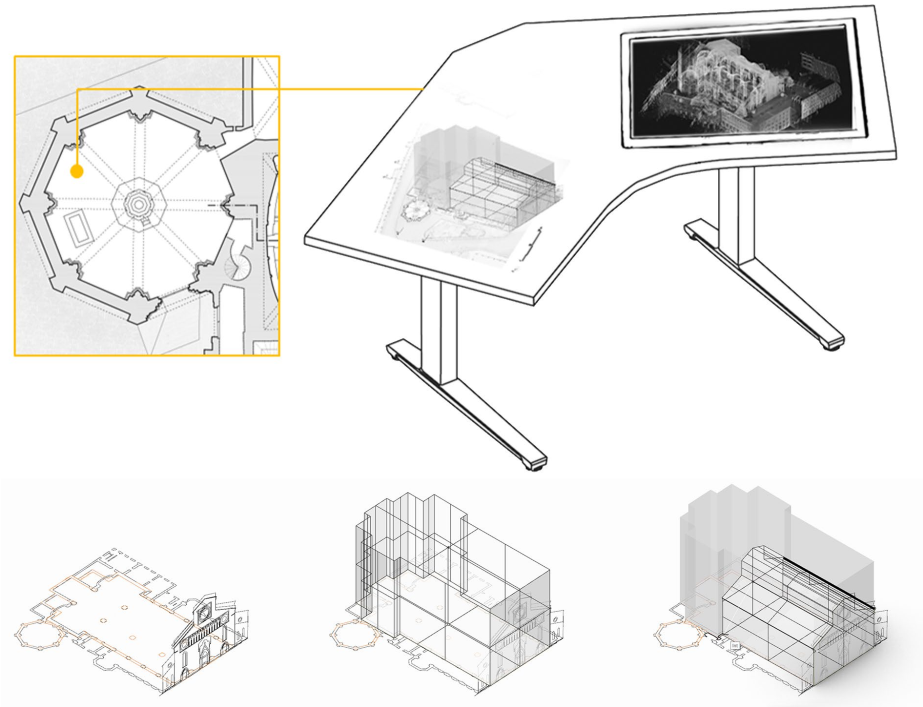

Fig. 11. The XR Station is designed to be an interactive tool for understanding the research project and the data contained in the digital archive. The user himself deals with the virtual reconstruction, aided by XR tools (Editing: F. Giacomini).

6 Conclusions and expected results

The approach followed made it possible to clearly outline the purposes and characteristics that the valorization project should have had to respond effectively to the standards required by today's society, without however ignoring the specific conditions dictated by the case study. In particular, it has allowed a more conscious evaluation of the possibilities offered by current technologies, stimulating the development of solutions suitable for sacred space.

One of the aims of the work was to take a first step towards sharing knowledge and the need for involvement that characterizes many contemporary users and younger groups. In the future this installation, part of the culture of edutainment, could be transferred to research environments to support investigations in a collaborative and more immediate way. The research will continue with the creation of a prototype based on 3D printing of the plan and the configuration of an interactive application based on a see-through Head Mounted Display and somatosensory controllers capable of acquiring movement data and manipulating the architectural elements through gestures of the user [34]. At the same time, markerless tracking methods based on the recognition of the geometric characteristics of the real environment will be selected and tested in order to superimpose virtual reconstructions relating to past eras and interactive textual information onto the on-site visit. The final objective will be the development of an intuitive and non-invasive interaction system, suitable for innovating the methods of use that can be implemented in particular contexts, such as religious ones. In this sense, one of the purposes is to increase public awareness of the virtual reconstruction processes that lead to the formulation of visual representations.

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