Virtual Archaeology Review, **10**(21): 14-30, 2019
https://doi.org/10.4995/var.2019.11923

Received: May 30, 2019
Accepted: July 5, 2019

EXTENDED REALITY AND INFORMATIVE MODELS FOR THE ARCHITECTURAL HERITAGE: FROM SCAN-TO-BIM PROCESS TO VIRTUAL AND AUGMENTED REALITY

REALIDAD EXTENDIDA Y MODELOS INFORMATIVOS EN PATRIMONIO ARQUITECTÓNICO: DEL PROCESO SCAN-TO-BIM A LA REALIDAD VIRTUAL Y AUMENTADA

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Highlights:

- Generative modelling requirements and novel grades of generations (GOG) and accuracy (GOA) are presented in order to improve the digitisation of built heritage from the 3D survey, reducing time and costs of the scan-to-BIM process.
- The holistic value of generative modelling allows experts to create digital worlds able to faithfully and accurately represent the detected reality and improve new immersive environments for Virtual Reality (VR) and Augmented Reality (AR) projects.
- Immersive environments are created with a mixture of the latest generation software and hardware, allowing users to discover the hidden historical values of built heritage with new levels of interactivity and information.

Abstract:

The dissemination of the tangible and intangible values of heritage building represents one of the most important objectives in the field of Digital Cultural Heritage (DCH). In recent years, different studies and research applied to heritage monuments have shown how it is possible to improve the awareness of the architectural heritage through the integration of latest developments in the field of 3D survey, 3D modelling, Building Information Modeling (BIM) and eXtended Reality (XR). On the other hand, this digital workflow requires a huge amount of data sources and a holistic approach to reach a high level of information sharing coming from different disciplines and sectors such as restoration, geomatics, 3D virtual museums and serious gaming. In conjunction with entertainment software and gaming, this research shows the main results obtained during the generative process of digital environments oriented to improve the level of information and to enrich the contents coming from the informative models. The case study is represented by one of the most important Lombard monuments: the Basilica of Sant'Ambrogio in Milan. This study, starting from the 3D survey and the data collection of the historical records of the church, improves the creation of an XR experience that reaches a new level of interactivity for different types of devices (desktop, mobile, VR headset) and users (experts, non-experts).

Keywords: virtual reality (VR); augmented reality (AR); scan-to-BIM; grades of generation (GOG); 3D modelling; virtual museum

Resumen:

La divulgación de los valores tangibles e intangibles en el patrimonio construido representan uno de los objetivos más importantes en el campo del Patrimonio Cultural Digital (DCH). En los últimos años, diferentes estudios han demostrado la posibilidad de mejorar el conocimiento de nuestro patrimonio construido a través de la integración de los últimos desarrollos en el campo del levantamiento topográfico 3D, modelado 3D, Modelado de Información de la Construcción (BIM) y Realidad eXtendida (RX). Del mismo modo, se ha comprobado que este flujo de trabajo requiere de una gran cantidad de datos y un enfoque holístico con el fin de alcanzar un nivel alto de información compartida entre las diferentes disciplinas y sectores involucrados, como por ejemplo, la restauración, la geomática, los museos virtuales 3D y la industria del videojuego. Junto con el software de entretenimiento y los videojuegos, esta investigación muestra los principales resultados obtenidos durante el proceso de generación de entornos digitales orientados a mejorar el nivel de información y el contenido de uno de los monumentos más importantes en Lombardía: la Basílica de Sant'Ambrogio en Milán. Este estudio, que se inicia con el levantamiento 3D y la toma de datos provenientes de los registros históricos de la iglesia, está orientado a mejorar la creación de una experiencia de realidad extendida, con el objetivo de alcanzar varios niveles de interactividad a través de diferentes dispositivos (escritorio, móvil, auriculares de realidad virtual) y usuarios (expertos, no-expertos).

Palabras clave: realidad virtual (RV); realidad aumentada (RA); escaneado-a-BIM; grados de generación (GOG); modelado 3D; museo virtual

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1. Introduction

Recent years have been characterised by a comforting increase of use of digital technologies able to improve the information sharing between the different users during the long life cycle of building (LLFB) (Tucci & Lerma, 2018). The integration of the most innovative 3D surveying techniques, the creation of accurate Building Information Modelling (BIM) based on novel grades of generation (GOG) and accuracy (GOA) allowed the authors to go beyond the simplest geometric representation of the surveyed building (Banfi, 2019). This process, also known as the scan-to-BIM process, has allowed the improvement of different aspects and analyses during the life cycle of the building (Brumana et al., 2018a). The results, broadly published during the last few years, have demonstrated how the passage between the simple two-dimensional (2D) representation to the creation of 'informative' models, has allowed the management of a large quantity of information and contents, from the first phase of data collection until the automatic generation of digital databases able to communicate different contents (Blanco-Pons, Carrión-Ruiz, Lerma, & Villaverde, 2019; Cabrelles, Blanco-Pons, Carrión-Ruiz, & Lerma, 2018; Georgopoulos, 2018; Santana Quintero, Blake, Eppich, & Ouimet, 2008). On the other hand, over the years, the wealth of the collected data allowed the authors to lay the foundations for the generation of immersive environments able to reach not only experts such as architects, engineers, restorers, historians but also non-users experts like tourists and students (Stanga et al., 2017). Thanks to the generation of models that collect a large number of information and multimedia data, it has been possible to develop, through open sources platforms based on coding and visual scripting, an interactive storytelling of the Basilica of Sant'Ambrogio in Milan, sharing the studies and the hidden values acquired during the last five years through an extensive historical research and an accurate Heritage Building Information Modelling (HBIM). The Basilica of Sant'Ambrogio in Milan is one of the greatest monument in the city, visited by thousands of tourist every year (Fig. 1). It was part of a huge project by archbishop Ambrogio (Aurelius Ambrosius Treviri, 339-340-Milan, 397) to make Christianity spread thought out the urban spaces when Milan was the Capital of the Roman Empire (286-402 d.c) (Lusuardi Siena, 1997). The Basilica was built at the end of the 4th century together with S. Nazaro church, S. Simpliciano and S. Dionigi (demolished in the 18th century).

The church underwent several transformations over the centuries, due to the Romanesque reconstruction, the work of many important architects (like Donato Bramante, Pellegrino Tibaldi and Francesco Maria Ricchino) and the 19th- and 20th-century restorations (architects Gaetano Landriani, Fernand de Dartein and Ferdinando Reggiori). Although it has been considered as one of the greatest examples of the Romanesque architecture in Lombardy (Peroni, 1987), it is the results of many construction phases that occurred over the centuries. Sometimes those phases are well known and documented, sometimes remain hidden or not completely investigated. That is why the research adopted two key concepts: the *virtual subtraction process* and the notebook (*taccuino)* that will be described in Section 3.1. The study started by analysing the current arrangement of the church (materials, construction techniques, damages of the World War II,…) and it went back in time so that it is the church and its physical structures the first reliable source.

The paper is structured as follows: Section 2 introduces related works and research objectives. Section 3 reports the research methodology, while Sections 4 and 5 are focused on the main techniques, and technologies applied to improve information sharing. Section 6 and 7 report future works and draw some conclusions.

2. Related works and research objectives

The digital era is transmitting our ways of working. Sectors such as design and restoration are facing a major transformation of the operational processes applied to the built heritage (Oreni, Della Torre, Brumana, & Banfi, 2017). The transition from traditional survey procedures to the most modern 3D surveying techniques such as laser scanning and digital photogrammetry allow experts to represent buildings with new levels of detail and precision (Lerma, Navarro, Cabrelles, & Villaverde, 2010) (Castellazzi, D'Altri, Bitelli, Selvaggi, & Lambertini, 2015). Thanks to the scan-to-BIM process, in recent years, it has also been possible to achieve a proper balance in the generation of HBIM (Brumana et al., 2018b). The benefits of BIM and the employment of survey data for structural assessment have been found in various sectors such as design, structural analysis, construction site, restoration and facility management (Degli Abbati et al., 2019; Korumaz et al., 2017; Volk, Stengel, & Schultmann, 2014). The added value was to move from the concept of 2D static representation to the process concept that can be managed in 3D and over time.

(a) (b) (c)

Figure 1: The Basilica of Sant 'Ambrogio in Milan: a) Internal views; b) The main facade; c) External views.

On the other hand, today, the BIM platforms such as Autodesk Revit and Graphisoft Archicad, are not yet oriented to the management and generation of complex architectural and structural elements that characterise historic buildings such as basilicas (Oreni, Brumana, Della Torre, Banfi, & Previtali, 2014), castles (Gusmeroli & Schiantarelli, 2014) and medieval bridges (Previtali, Barazzetti, Banfi, & Roncoroni, 2019). For this reason, the following research has developed a method based on the use of novel GOGs for the creation of models capable of representing with a high grade of accuracy (GOA) complex elements such as vaults, arches, walls with variable section and double curvatures, different types of materials, pillars and historical decorations starting from 3D survey data (Fig. 2). The main research objectives of this research are based on the followings steps:

- Surveying data collection: the collection and the organisation of a huge quantity of data sources for the generation of digital environments able to transmit the richness of the detected artefact such as historical records, 2D Computer Aided Design (CAD) drawings, multimedia data (videos, audios, 360° pictures), point clouds, photo plans and orthophotos from laser scanning and digital photogrammetry.
- Scan-to-BIM generation: the development of a sustainable generative process of 'informative' digital model able to incorporate the richness of the basilica of Sant'Ambrogio both from the morphological and typological point of view. By doing this, the quality of the generated model was conveyed through the application of new scan-to-BIM modelling requirements (GOG 9-10), and through an automatic verification system (AVS) that shows the standard deviation value between model and point cloud.
- Information mapping: the generation of an HBIM model able to link different type of information to complex and standard 3D BIM objects such as materials, constructive techniques, physical and mechanical parameters, construction phases and building archaeology data (stratigraphic units), archive documents and historical photos.
- Information sharing: the development of a cloud platform (Brumana et al., 2019; Mazzetti et al., 2015), to share data and informative models, as historical databases, schedules based on the automatic extraction of information previously included in the HBIM modelling and to create an immersive interactive environment (VR and AR) for different types of users (experts, non-experts and tourists) and devices (desktop, mobile, VR headset). Even if the process is not yet automatized, the possibility to have different models and data available within a virtual hub platform will open to the VR/AR/MR developers the possibility to enrich the narratives with validated research and related information.

3. Research methodology

The research methodology has been a defining moment for the creation of the workflow of the holistic approach. The starting point has been the definition of the concept of the work: the goals to pursue and the tools that were suitable to reach them. The main concept has been the idea to tell not the history of the basilica, but its many histories.

3.1. A *taccuino* for the virtual subtraction process

Each historic building is characterised by a turbulent past (restorations, demolitions, war damages…) that usually remains almost unknown: their coherent aspect gives the impression that the building has always looked like this and only in some cases 'strange' elements, not coherent with the overall architecture of the building, make the visitors wandering about its past. Those histories are made of many episodes, sometimes very well-known, sometimes not. The history of Sant'Ambrogio church presented in this research collects and puts together the Basilica fragmented past events. The key-word *taccuino* (notebook) exemplifies this concept: *taccuino* means both the plain paper to write on and the collection of different sketches and drawings (Stanga et al., 2017). This is the tool that helped to organise, represent, and show the data collected during each step of the study.

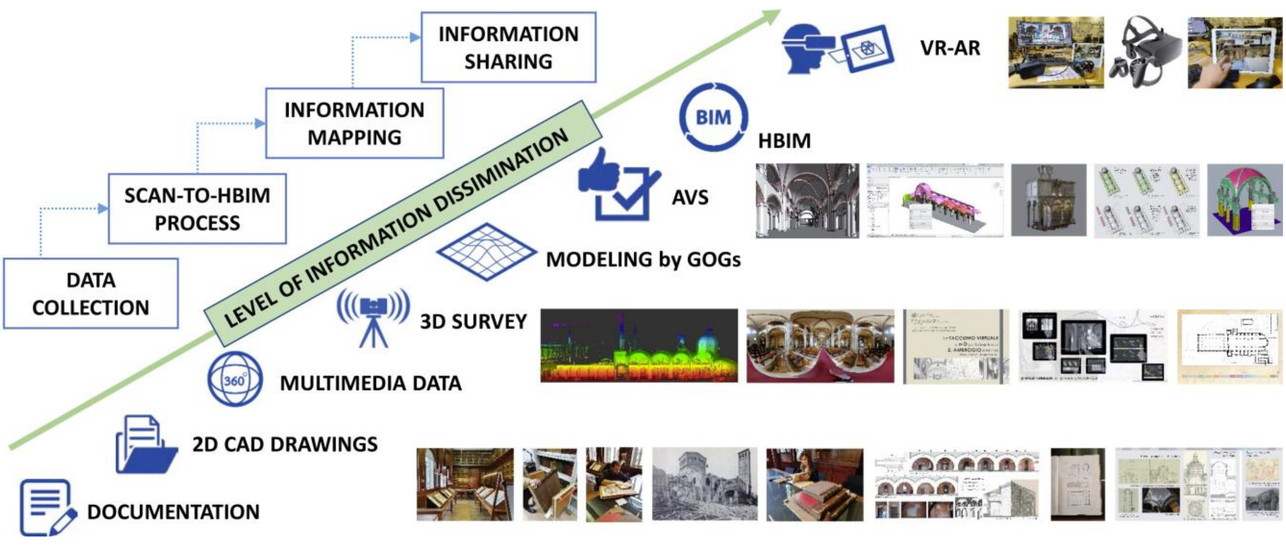

Figure 2: The research method applied to the XR project of Basilica of Sant'Ambrogio in Milan.

The other key-word of the research is the *virtual subtraction process* that helped to explore the different historical phases, starting from the recent elements and going back to the older ones. This was made possible by borrowing from archaeology the excavation methodology: it starts from the recent layers, and it goes back in time while removing the previous phase. Before removing each layer, accurate analysis of the structures is done so that the information will not be lost forever. Nevertheless, it is an inevitably destructive methodology when applied to the physical material traces. In the case of Sant'Ambrogio, it has been possible to do it virtually thanks to 2D and 3D virtual reconstructions of the historical phases of the church.

The *taccuino* mirrors this organisation: it started from the 20th century when the restoration after the damages of the World War II began, and it goes back to the foundation of the Basilica by archbishop Ambrogio, around the late 4th century. Thanks to this methodology the study focused on the physical material of the monument: what is remained after the damages of the World War II, after the 19th- and 20th-century restorations and the events that occurred over the centuries.

The *virtual subtraction process* is based on the correlation of geometrical (3D survey) and historical data (documents, previous studies), and it is the results of the interpretation of each data source. It is based on the correlation of 'direct' and 'indirect' sources: the first one is the building itself (its geometry, materials, techniques…), while the second is its documentation (drawings, chronicles, photos…). The latter is an 'indirect' source because it is influenced by external factors: their authors and the period the document/photo was written/taken. The materials and constructive techniques directly show the information regarding the building: they still need interpretation, but are tangible and visible elements that can be studied through different kinds of surveys - from the geometrical survey to the material and stratigraphic analysis.

Another important aspect of the research is that those two sources (direct and indirect, 3D survey and historical research) were not part of a different plan: they were both performed with the same purpose and by the same interdisciplinary co-working team, where historians, preservation professors and PhD candidates, BIM specialists and surveyors cooperated together for the study. The interpretation of both data coming from the 3D survey and historical research was thus done through an interdisciplinary approach. Moreover, it happened many times that the data acquired from the 3D survey suggested a more in-deep historical analysis. The historical analysis guided the 3D survey in the same way. In the holistic approach, a recurrent feature has been the used of the 3D model. It was realised for a different purpose: to interpret, verify or reconstruct historical building phases; to give a tool for the management of the church; to carry out the VR and AR project. The VR project includes all the previous step of the research, becoming the last phase of the holistic approach. This way, the effort in terms of time and cost invested for the construction of a reliable, informative model becomes effective thanks to its multiple uses. Indeed, models can be used for different purposes: from the maintenance and management of the building to the creation of storytelling, as in the case described.

3.2. Data acquisition: historical records, multimedia data and 3D survey for heritage buildings

The collection of the data of the Basilica has mainly required the study of archives, such as historical documentation, publications by the most important restores, art historians, scholars and art critics who have followed one upon another over the centuries. Thanks to the historical treatises and other studies on the Basilica it has been possible to understand better the historical phases, the ancient configuration of the church structures which were damaged during the bombings of World War II and the architectural renewals brought by master architects such as D. Bramante (Patetta, 2001), P. Tibaldi (Bonavita, 2004), F. M. Richini (Summa, 1995). At the same time, these books are the foundations of the Milanese and Lombard polytechnic culture, kept at the Historical Library of the *Politecnico di Milano*, which has a rich section of illustrated manuals for the civil and industrial construction sector. The Historical Library was founded in 2018 to collect, conserve and enhance the most ancient and precious library heritage of the Politecnico, particularly the books published from ca. 1500 to ca. 1899 (Fig. 3).

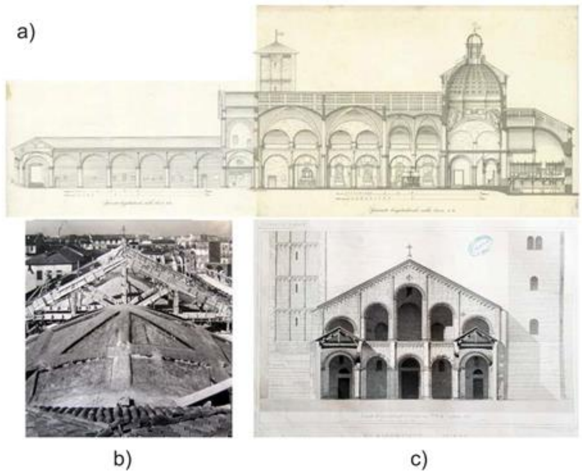

Figure 3: Historical records archived in the Historical Library of the *Politecnico di Milano*: a)The Basilica longitudinal section with the Barlonghe vaults (Cassina, 1844), b) The vaulted system during the 20th century restoration (Reggiori, 1949), c) The Basilica Façade, Plate 30 (De Dartein, 1862-65).

The primary data sources for the generation of an accurate scan-to-BIM model are the data output of the Terrestrial Laser Scanning (TLS) survey and the digital photogrammetry. These two specific non-invasive survey techniques provide data called, in technical terms, point clouds. Through the production of an enormous quantity of point clouds, it has been possible to accurately detect and measure every single internal and external element of the Basilica.

The digital photogrammetry made it possible to fill in the absences of data (dark areas) that are created when it was not possible to reach specific areas of the building due to scaffolding, architectural barriers or vegetation of large dimensions. Unfortunately, there were still some parts of the church that were not possible to reach during the 3D survey, such as the extrados of the vaulted systems. It is only through the open and circular research process that further data and analysis will be later integrated.

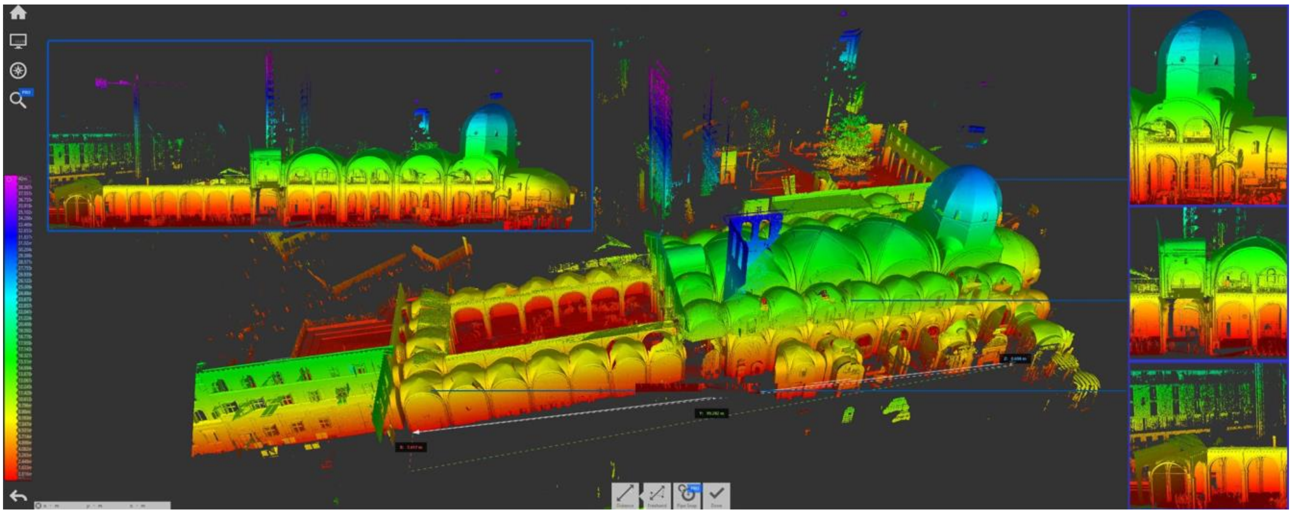

Figure 4: Point cloud data from TLS.

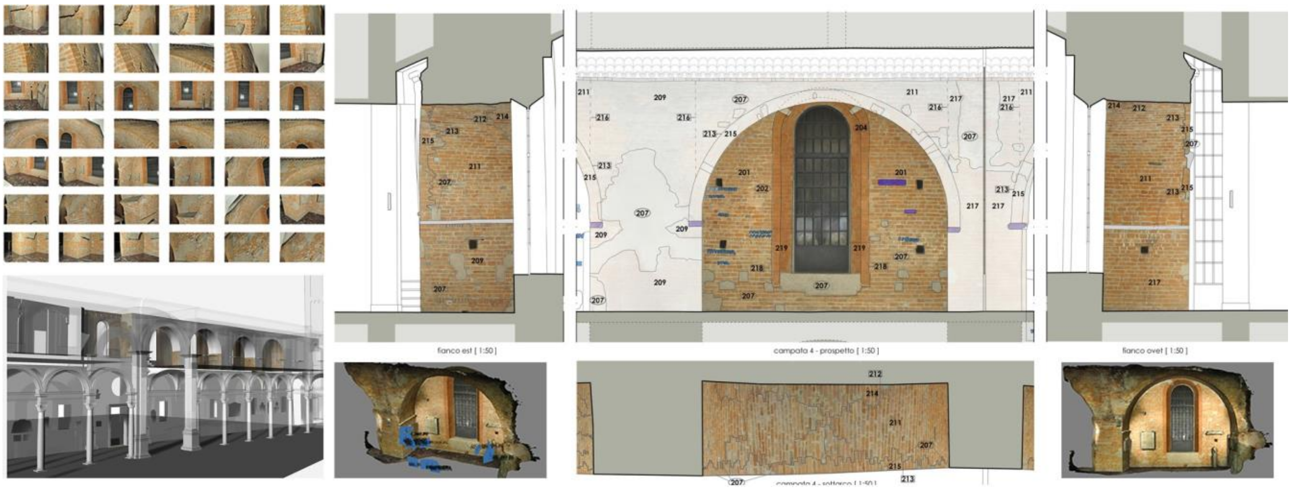

Figure 5: Orthophotos and photo planes obtained from digital photogrammetry that allow accurate material analysis and 3D mapping.

Agisoft PhotoScan v.1.4.5 was used in order to process the data and a set of Ground Control Points (GCPs) and Check Points were derived from the laser scanning survey to constrain the reconstruction and verify the metric accuracy of the final results. A geodetic network was measured and materialized through the Total Station Leica TS30. The network was made of eight stations, and after least squares adjustment the average precision on benchmarks was of about ±1.0 mm. The scan acquisition of internal 3300 m^2 and external 4800 m^2 was carried out with the Faro Focus 3D (Fig. 4). The average precision of 56 scans was ±3.0 mm, using chessboard targets measured with the total station and additional scan-to-scan spherical targets. It was possible to extract the horizontal and vertical profiles and sections: produce the main 2D representations of the detected artefact. Through the production of 2D CAD drawings, it was immediately possible to notice how unique structural and architectural elements characterised the structure of the Basilica (Fig. 5). As described in the next paragraph, double-curved walls, the irregularity of the arcades of the main courtyard and the main façade, the complex shapes of the vaulted systems, have represented one of the main challenges of this research from a representative point of view. Finally, the data collection phase has included a large quantity of multimedia data such as 360° pictures, audios and videos, allowing the geometric/material analysis and the enrichment of the contents of the VR and AR projects realised to tell in a new way the cultural richness of the Basilica of Sant'Ambrogio.

3.3. Scan-to-HBIM process

Most of the built heritage as basilicas, churches, castles and ancient bridges collide with the new paradigm of shaping complexity (Brumana et al., 2018c). From a strictly geometric point of view, complex shapes such as vaults, arches, columns, walls damaged by bombings or seismic events, walls with variable sections or double curvature, and historical decorations represent one of the main challenges in the field of generation of HBIM models. In recent years, various studies and research applied to the field of DCH, have highlighted how the great benefits brought by BIM, lead to improving the entire life cycle of the building (Ioannides, Magnenat-Thalmann, & Papagiannakis, 2017).

For this reason, the presented study, which begun five years ago, proposes a generative process capable of bridging the gap present in the main BIM applications, which is developed for the management of new buildings. In particular, the limited number of modelling tools does not allow the generation of 3D objects from dense point clouds. Most of the time, this gap means the non-use of 'informative' models for built heritage. Different research cases have shown that the HBIM introduces, unlike traditional 2D representation techniques, the concept of 'process' (Azhar, 2011).

Thanks to the generation of 3D parametric elements from point clouds (Scan-to-BIM objects) it is possible to connect a large amount of information such as physical and mechanical parameters, historical phases and automatically extract the dimensional quantities such as volume, area, length, the width of every single element generated.

These specific functions allow BIM experts to support the building life cycle through the use of models able to improve structural analysis (Barazzetti et al., 2015), energy analysis (Attar et al., 2010), construction site (Kumar & Cheng, 2015), facility management (Wetzel & Thabet, 2015), restoration and rehabilitation projects of different type of heritage buildings (Banfi, 2016) and infrastructures (Bradley, Li, Lark, & Dunn, 2015). In particular, the generative process of the Basilica HBIM provided the integrated use of novel Scan-to-BIM modelling requirements based on the GOGs and GOA (Banfi, 2017).

In Banfi (2017) two new modelling requirements (GOG 9 and 10) have been developed in order to simplify the Scan-to-BIM process for BIM applications. The absence of advanced modelling tools based on Non-Uniform algorithms Rational Basis-Splines (NURBS) in BIM application, has been filled with the integrated application of these two generative procedures, allowing the automatic generation of complex elements from point points, and going beyond the first eight GOGs of the BIM software based on simple 3D transformation such as the extrusion (GOG 1), edit profile (GOG2), edit profile with empty spaces (GOG 3), the sweep (GOG 4), the reveal (GOG 5), the extrusion of irregular profile (GOG 6), the revolve (GOG 7) and loft, sweep and swept blend (GOG 8). The benefits of NURBS modelling have been found in many areas such as rapid prototyping, reverse engineering, design, 3D animation, and finite element analysis (FEA) over the years (Piegl & Tiller, 2012). In particular, through a holistic approach, GOG 9 and 10 allow modellers to automatically interpolate geometric primitives such as points, splines and polylines. The key idea for defining these two Scan-to-BIM requirements was to place generative modelling at the centre of the BIM process. In recent years, thanks to the flexibility in the representation of complex shapes, NURBS algorithms have been studied and tested to improve the level of automation in the generation of complex surfaces from a set of points. Furthermore, the patterns and interchange formats have been implemented to improve the levels of interoperability between the NURBS/free form modelling software and the BIM Platforms. GOG 9 and GOG 10, through a simple guided procedure, supported the user in the generation of complex elements, exponentially lowering the times and costs of the generative process. The case study of the Basilica was found to be a perfect field of application. Figure 6 shows how using GOG 9 and GOG 10, it was possible to create the most complex architectural elements characterised by a variable section and double curvature. The first field of application of this process was the Parliament Building in the Canadian capital (Banfi, Chow, Ortiz, Ouimet, & Fai, 2018).

Thanks to its simplicity of use, it was possible to communicate to the experts involved in the rehabilitation and conservation process of the building the reliability and quality of every single element generated. The automatic verification system (AVS) of the standard deviation between the point cloud and the generated element was about 1/2 mm. This particular value has allowed the creators of the model to communicate the GOA achieved for each Scan-to-BIM object.

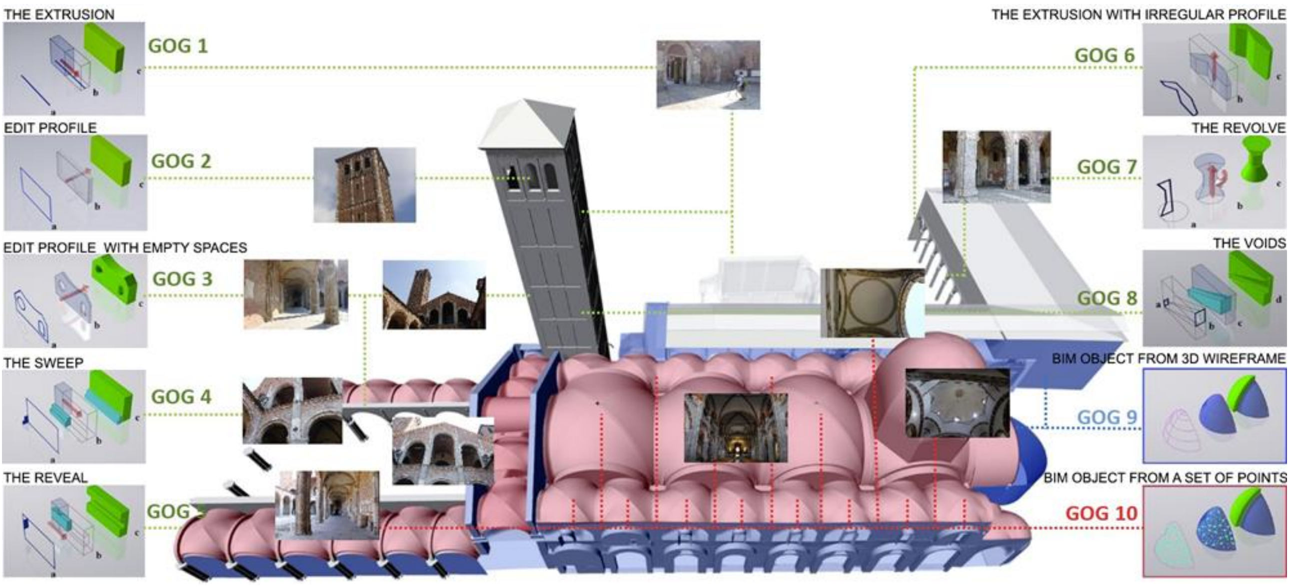

Figure 6: The ten GOG used for the HBIM model.

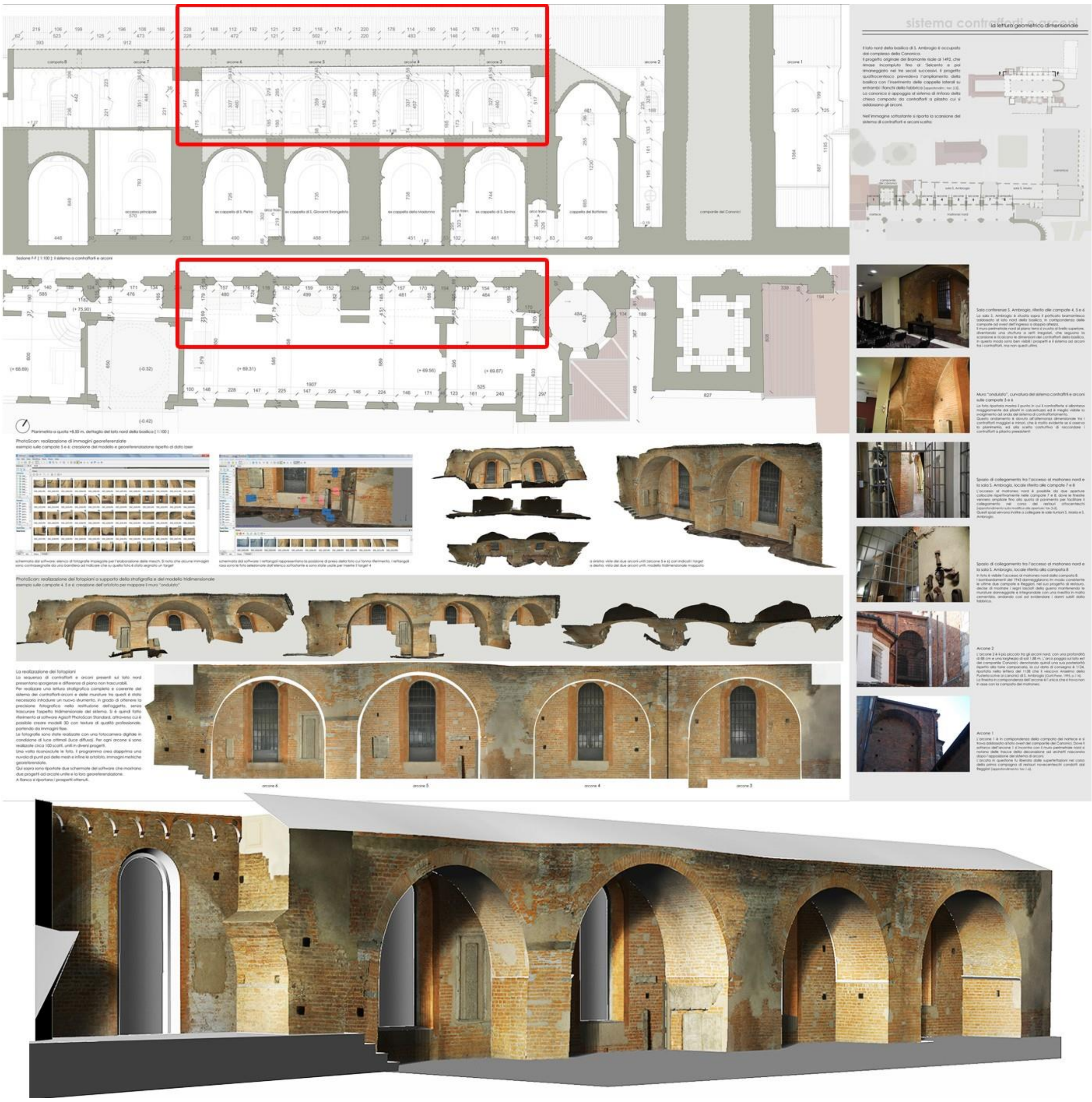

Figure 7: GOG 9 and GOG 10 allowed the generation of complex elements from 3D scans and accurate 3D mapping with high-resolution orthophotos supporting further material and decay analysis.

3.4. Information mapping: embodying the richness of built heritage in 'informative' model

GOG 9 and GOG 10 demonstrated how it is possible to transform a large number of points into a BIM model that is holistically adapted to different analyses, sectors and disciplines. Recent studies in the field of HBIM has shown how the use of the model can change according to the requests of the users of the model. This particular aspect entails the inclusion and connection of specific information in the created model.

For the case study of the Basilica of Sant'Ambrogio, the '*information mapping'* phase provided for the connection of all the data collected over the years, paying particular attention to distinguishing each element from the other both from the material and the historical phase points of view. This semantic differentiation was allowed thanks to the implementation of new descriptive fields for every single type of wall.

The introduction of new BIM parameters in the properties window of each object has allowed model users to discover the historical and constructive process that the basilica has had over the centuries.

Once the main physical and historical information had been entered, it was possible to improve the map-based procedure of the model through the use of digital photogrammetry data outputs. In addition to the production of point clouds, the most advanced digital photogrammetry techniques allow the production of the photo planes and accurate orthophotos.

Consequently, in addition to the physical and mechanical values of the various materials, it was possible to improve the information level by inserting high-resolution textures, facilitating the decay analysis of each complex wall surface (Banfi et al., 2019) (Fig. 7).

On the other hand, for the most part, advanced modelling software and BIM platforms are not easy to use for inexperienced users. Visitors, tourists and scholars of the Basilica do not have the skills to discover the richness of the contents included in the large BIM projects. For this reason, it was essential to investigate the most modern techniques for sharing information collected over the years for a more extensive and non-experienced audience in digital models.

4. Informative model to XR projects (VR/AR/MR)

4.1. Information sharing: the dissemination of tangible and intangible values through new XR virtual environments

Autodesk Research's latest Information Technology (IT) developments have made it easier to share BIM models in 3D clouds. The main clouds used for the research project were Autodesk A360 and Autodesk View. As it is well known, thanks to the connection of information in an HBIM model, it is possible to communicate the different type of contents through different exchange formats (Fig. 8). The main exchange formats, on the other hand, do not allow to exhaustively communicate all the information entered in each BIM object. The main interchange formats such as .DWG, .SAT, .ACIS make it possible to transform the BIM model into a geo-information model without information, while formats such as the .DWF, IFC and many others have been developed to increase information sharing during the building life cycle. Furthermore, another essential format for sharing information is the .TXT format.

Thanks to specific tools, within the BIM platforms, it is possible to extract and create schedules and sheets automatically. Thanks to the transformation of a geometric model into a text file, the information contained in the various objects can be communicated and shared through the main databases.

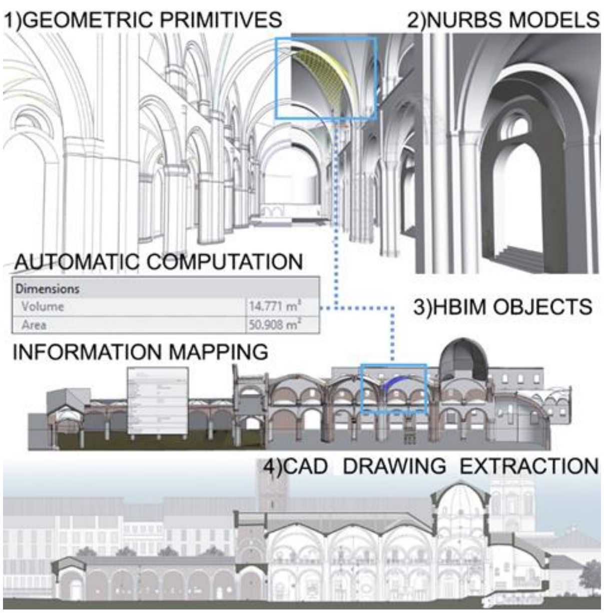

Figure 8: The extraction of geometric primitives (1) and the automatic generation of complex BIM objects (3) from NURBS surfaces (2). GOG 9 and GOG 10 allow the information mapping and the extraction of CAD drawings (4) with a GOA of 1 mm.

BIM cloud users were able to view, commend and modify any format through different devices, desktop and mobile in real time. On the other hand, although these solutions are easy to use and allow information to be displayed at the same time, for the case study of the Basilica it was decided to develop and investigate the most modern techniques of VR and AR. The main was to develop a digital repository able to share any type of formats, data and information to different users (BIM experts and non-experts). Previous research and studies have introduced the concept of Common Data Environment (CDE) to simplify the read of all the data produced during the life cycle of a building. For this research, the final goal was to create a new type of digital repository where any type of user was able to discover and implement a new level of interactivity. As described in the following paragraph, it has been possible to develop an XR project able to expand its level of content over time.

4.2. Virtual interactive CDE: from scan-to-BIM to IT developments for VR-AR

Information sharing is one of the most important research objectives of this research. Dissemination of information for non-expert users as well as construction industry experts was a key objective for all developed functionality and special features. For this reason, the most modern techniques for developing virtual environments have been investigated. It was found that thanks to the development of the basilica XR project, it was possible to increase the dissemination of information through any device.

Technological development in the field of virtual museums and serious gaming in the last few years has allowed users to immerse themselfs in interactive virtual environments from any part of the world. The interactivity has been implemented and deepened through the study and development of open-source applications based on visual scripting and coding such as Unreal Engine 4 and Unity (Statham, 2019) .

For the research case study, the authors opted for the development of a virtual interactive environment with Unreal Engine. The creation of a virtual project involved the testing of different applications. The main applications considered for the VR project were Unity and Unreal Engine 4 (UE4). UE4 is based on the creation of immersive environments where the developer can interact directly with the main programming languages such as Blue Prints and Visual scripting. They allow developers to create digital environments based on an interface structured around functions, events and nodes without resorting to code (Obidah & Bein, 2019).

For the Basilica of Sant'Ambrogio, it was possible to create interactive objects directly within the Unreal Editor, which turned out to be an innovative solution for the development of videogames and serious games. For this added benefit, it was possible to improve the level of interoperability between the HBIM model and the new levels of built heritage virtualisation. Blueprints and Blueprint Classes were the main types of Blueprint developed for the XR project. One of the aspects taken into account in the interactive project has been started from the observation that generally the visitors do not image the narrative hot spots and the richness of the stories virtually reconstructed.

Thus a connection among VR and AR is needed. The main idea is to start a process that would allow in the future to prepare the visit of a monument through VR access (at home…), to plan the tour with the main important key story attracting the visitors, and once on site to identify in an easily way the information related to the monument (Fig. 9).

Thanks to the visual scripting, it has been possible to develop the main interactive VR objects, modifying the behaviour of each 3D actors. In order to improve the dissemination of contents were developed *'information screens*' able to link different type of data such as videos, audios, pictures, drawings and historical sequences.

Furthermore, the integrated development of different Box trigger, BeginOverlal Event and Matinee were allowed to improve the level of interactivity between users, contents and virtual environment. Finally, thanks to the packaging function, it was possible to transform the project into a real app for different types of device such as mobile phone, desktop and oculus rift.

Oculus Rift, compared to the other devices, required the first person template. It offers a viewer with a sensor that tracks the user in the digital world, aligning it with the virtual model. The Organic Light Emitting Diode (OLED) display with a resolution of 2160 × 1200 pixels and a refresh rate of 90 Hz also made it possible to use the device even with PCs not oriented to professional development, increasing the level of immersion.

On the other hand, for non-VR experts, the development of a VR project for mobile phones and tablets was based on the third person. It was found that it was more user-friendly than the first person template which required the use of specific controllers such as Tow Oculus Touch or box one controller. Figure 8 shows the developed VR project and various devices considered to increase the intact values of the Basilica discovered by years of in-depth studies.

The main benefit found through this technology was the possibility to reach every corner of the world without having to force users to visit the real basilica, thus spreading the information content of the project on a large scale. Innovative solutions based on AR technologies have also been considered.

The main objective was to increase the informative impact of the project through the optimisation of the HBIM, the real environment and the accumulated historical knowledge in recent years (Stanga et al., 2017).

From an operative point of view, it has been created a VR object Libray. Every VR object can be modified and shared via a web cloud. Furthermore, thanks to the Collada format based on the XLM code, it was possible to share complex models with high-resolution textures at the same time, without having to update or modify the HBIM. The upload procedure also included the creation of a QR code, with which it was possible to share and send the models via smartphones, posts and emails. Finally, the link between the VR project and the AR library was created through the development of interactive screens capable of showing VR objects associated with their QR code (Fig. 10). The simpleness of scanning the QR code directly in the VR project allowed the authors to increase, in addition to the virtual level of immersion of the user, also the level of disclosure of the contents inserted for each single AR object stored in the AR CDE.

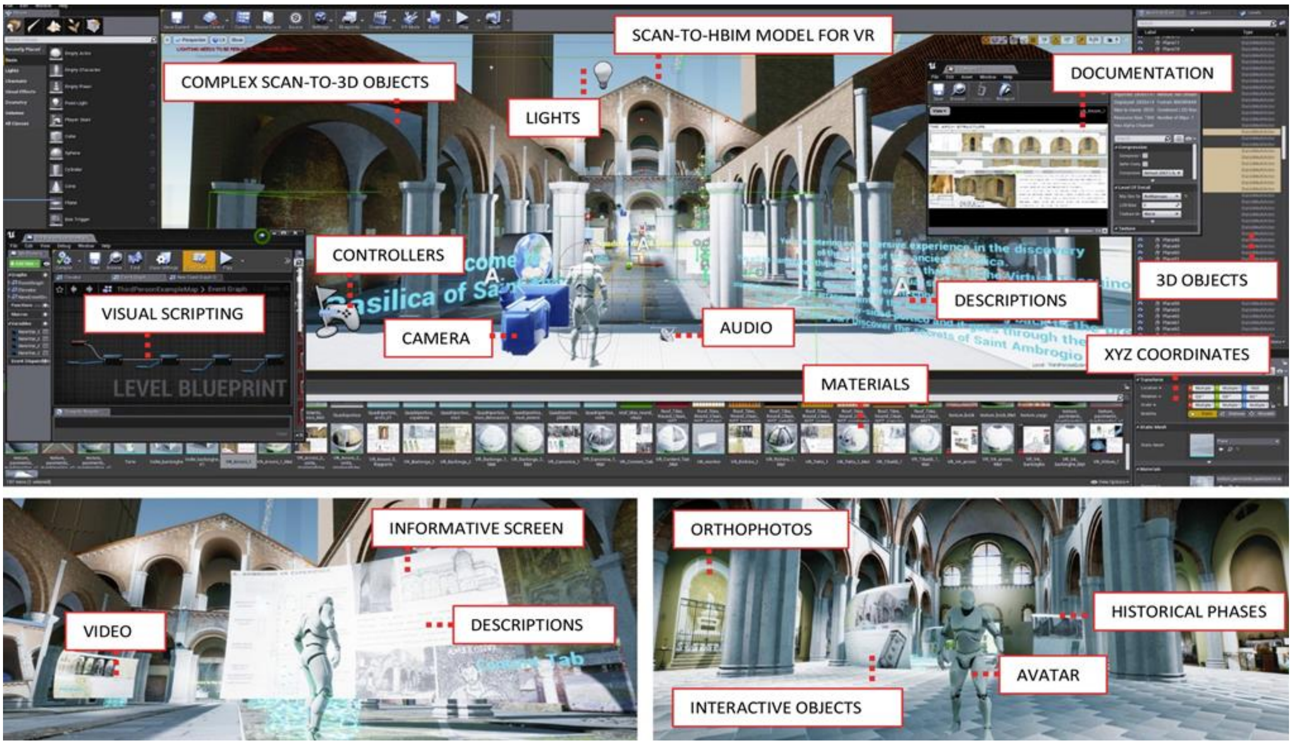

Figure 9: The Unreal Engine 4 Editor allows the development of a VR project using different types of contents.

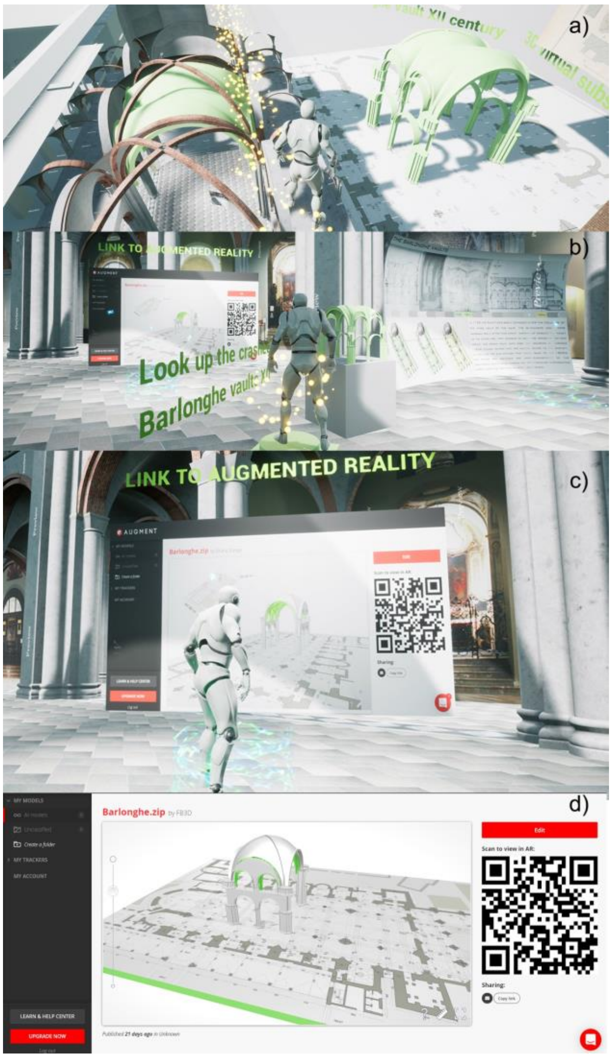

Figure 10: The links between VR and AR by QR codes: a,b,c) allow the creation of an AR CDE;
d) able to show a huge quantity of information connected to the model and the reality, supporting further analysis directly in the field.

5. The virtual storytelling of Basilica of Sant'Ambrogio in Milan

The following paragraphs are not an exhaustive history of the church (for a recent comprehensive publication on the subject see: Gatti Perrer, 1995), but mirrors the *virtual subtraction process* of the different historical phases, and aims to highlight some of the main unknown episodes of Sant'Ambrogio church histories, that are included in the XR experience of the Basilica.

The importance of improving the relationship among the informative models that can be implemented depending on the progress in research and the XR tools, will allow a circular approach to growing awareness among citizens and tourists while growing their knowledge.

This way, the emphasis is not on the simplification of the narratives that often overcomes the authenticity and central focus on the cultural heritage witness, generating gamings without contents. Thus, the core of the research is the monument with lights and shadows and its dense, complex history.

Rising the awareness also means to contribute to enhancing the social perception of the importance of the conservation of each different historical layers, without doing the selection of some periods in favour of others.

5.1. The restorations after World War II and the damages of the Bramante's Canonica

The Basilica suffered a significant material loss due to the aerial bombing of World War II (August 1943). At least eight bombs partially destroyed the north-east side of the church: the vault of the apsis, the crypt, and the wooden roof, but the main damages occurred at the Bramante's Canonica: only four bays out of 13, were not demolished. The Canonica is the porch that leans against the northern wall of the church, commissioned to architect Donato Bramante by Ludovico il Moro, Duke of Milan. It was realised between 1492 and 1499 (Fig. 11).

The Canonica has never been finished: when the bombs damaged it, the porch had a brick façade, and the upper level was built during the 17th century. In the 19th century, a huge restoration of the church was carried out.

For what concerns the northern side, many transformations occurred at the windows overlooking the porch. Moreover, it changed again after the works by architect Reggiori who was in charge of the restoration after the damages of World War II. He tried to retrieve as many debrief as possible in order to use it for the reconstruction of the porch.

Even if Reggiori published many books about his works, there is still a lack of information about the Canonica, and we do not know if he restored the four bays that were still standing or, due to different reasons (for instance the safety of the structures), he had to rebuild them all.

Thanks to the thermal infrared (TIR) image acquisition the authors tried to understand if there were some differences in the construction techniques of the vaults that Reggiori rebuilt and the ones that probably were not demolished by the bombing. However, the data are still difficult to be interpreted, and further analysis needs to be undertaken.

5.2. The Barlonghe vaults and the stylistic restoration in the 19th century

In another case, it was not the damages of the war, but the church restoration. In 1857 the restoration of Sant'Ambrogio Basilica started, funded by the Habsburg Emperor. The works were highly promoted by the abbot of the church, Francesco Maria Rossi, and many architects were involved, like Gaetano Landriani and the Alsatian architect Fernand De Dartein.

The main goal of Rossi was to bring the Basilica back to its Christian origins, both through archaeological discovery, like the findings of the remains of martyrs Gervasio and Protasio (buried by Ambrogio) under the altar, and architectonic transformation.

At that time it was possible to see the Barlonghe vaults covering the bay close to the Presbytery of the church. Engraver Fernand Cassina, architect De Dartein, an old picture and some hand measurements depicted them. The Baronghe vaults were two rib vaults with pointed arches (the ribs of the west one was square, while the ribs of the east one had a toric section).

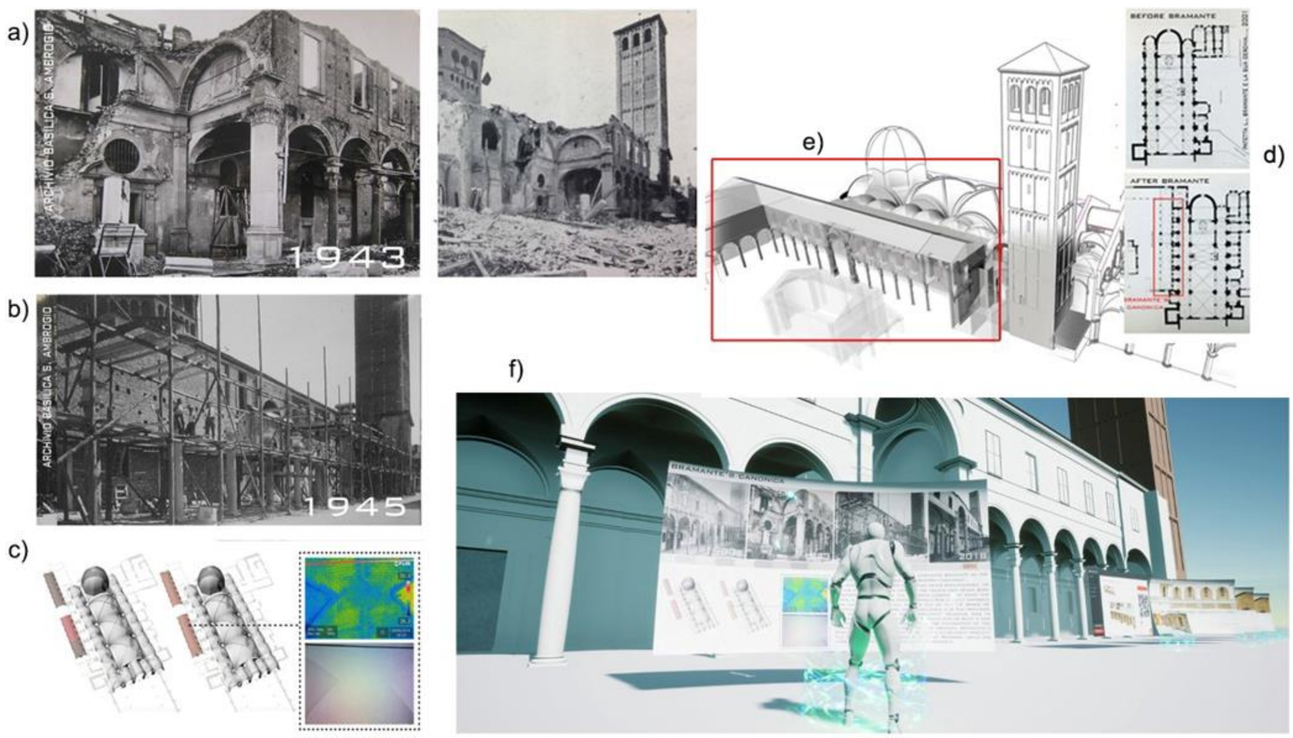

Figure 11: Bramante's Canonica VR experience. Contents: a) the Basilica after the World War II aerial bombing (S. Ambrogio archive); b) The Basilica during the 20th century restoration by architect Reggiori (S. Ambrogio archive); c) Vaults damaged by the bombing and TIR image (Lab. Gicarus) of the porch vaults; d) The Basilica before and after Bramante's Canonica project (Patetta, 2001); e) Current arrangement of the Canonica (HBIM); and f) Information screen.

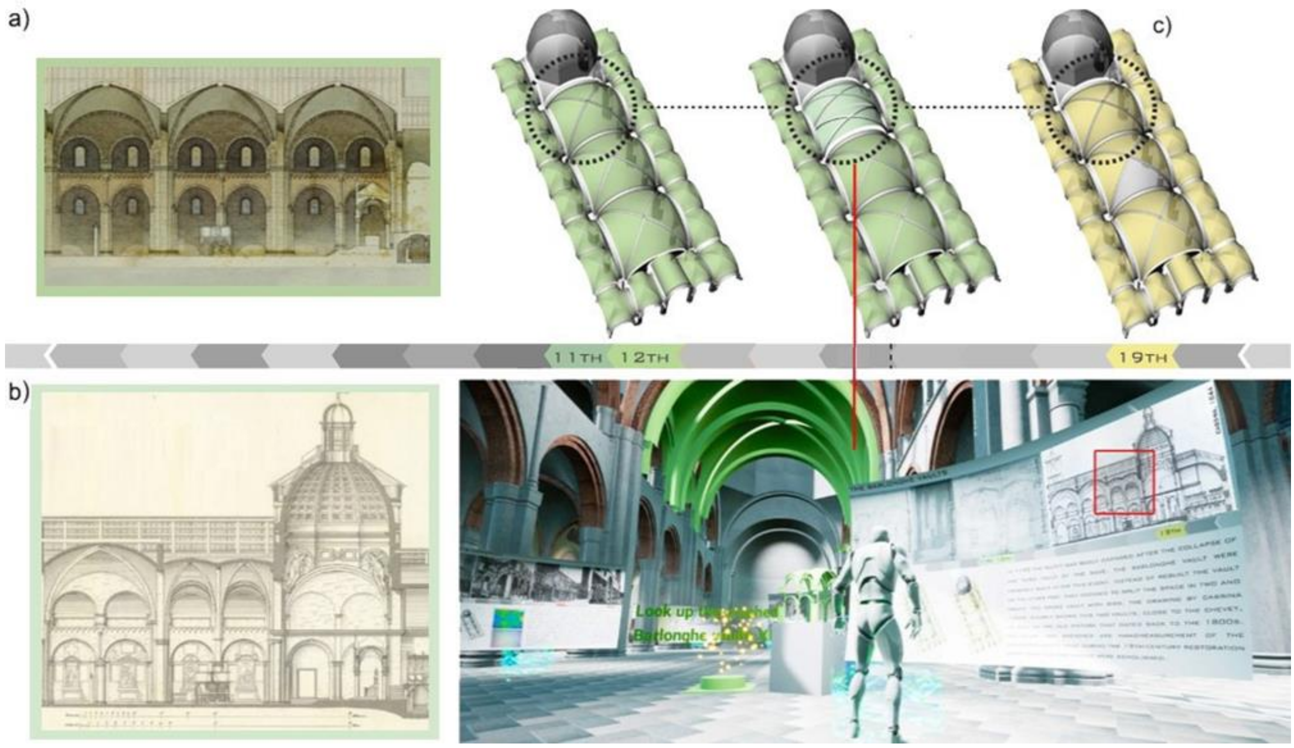

Figure 12: Barlonghe vaults: a) The 12th century Basilica (Romanesque reconstruction), drawings by De Dartein (1862-65); b) The Basilica after 1193 (Barlonghe vaults build in the bay close to the cupola), drawing by Cassina (1844); c) The virtual subtraction process of the vaulted system from the 19th century to the 12th century.

They were built by subdividing the square bay that previously was covered by a cross vault. In 1193 the cross vault collapsed damaging the pulpit as some documents recorded (Ambrosioni, 2003) and this was probably the reason for the Barlonghe vaults to be built. In its chronicle, Abbot Rossi (Rossi, 1884) wrote that the discovery of a round arch on the wall of the nave made him decided to tear down the two Barlonghe vaults and rebuild the cross vault.

In the VR experience, the Barlonghe vaults were dynamically simulated through the virtual subtraction process: once the visitor walks close to the information screen and jump on the green button, the Barlonghe appear from the ground and reach their place up to the top of the bay, overlapping the current cross vault (Fig. 12).

A small maquette of the Barlonghe is located next to the display so that visitors can have a closer look at the vaults. Another VR device was used to highlight the vaulted system: the vault elevator. It is located in the main Courtyard and it brings the visitor at the top of the church, where it is possible to see the Basilica structure: the formeret (the ones in between the bays) and the transversal arches (the ones in between the nave and the aisles), and the ribs of the vault.

An information screen shows the old documentation of the vaulted system and compares the longitudinal section of the church made by Cassina (the Barlonghe vaults) (Cassina, 1844) with the ones made by De Dartein (12th century reconstruction, cross vaults) (De Dartein 1862- 65).

Furthermore, the study of the vaulted system was performed to feed the GeoDB vault database, making the data (3D models, CAD drawings…) accessible by anyone at any given time (Brumana et al., 2019; Brumana et al., 2018c).

5.3. The double-waved curved wall and the Romanesque reconstruction of the church

It is broadly shared that the Basilica founded by archbishop Ambrogio had probably a wooden roof and that was transformed into the vaulted system during the Romanesque reconstruction when the church was rebuilt with the shapes that still characterised it. In the 12th century, the church was probably characterised by polygonal buttresses that leant on the northern and southern walls of the church.

Then these pillars were included in the constructions that were built over the time: the Bramante's Canonica on the northern side and the chapels on the southern ones. This pillars probably helped with the overall stability of the vaulted system.

Thanks to the *virtual subtraction process,* the authors show the transformation occurred at the Bramante's Canonica (northern side). By doing this, the hidden double-waved curved wall was suddenly revealed. It is a structure easily accessible on the first floor of the Bramante's Canonica or at the level of the women gallery of the church. It is made of arches that connect the 12th century pillars. The arches covered the top of the single-lancet windows of the northern wall of the church. The same structure is visible on the southern side, although it has been altered by the construction of the chapels. On the contrary, Bramante did not touch it, probably because he understood its structural role in the overall behaviour of the church (the northern wall he built is 1 m away from the pillars).

Thanks to building archaeology and the correlation of historical records, it has been possible to understand its construction phases.

Going back in time, there were no arches, and the buttresses had a rectangular shape. Going further back into the past, the buttresses had two different shapes: rectangular and polygonal. Then, the arches were built in between the pillars. It is probably due to the different connection between polygonal and rectangular pillars that the wall has a double wave curvature, both on the horizontal and vertical axis.

However, many questions remain open. The construction phases analysis gave back a more complex artefact, especially when related to the building archaeology analysis: it highlighted many construction phases and restorations. As mentioned in the chronicles of Rossi, during the 19th century restoration, the windows were widening in order to let more light entered the church. In fact traces of the widening at the bottom of the windows are visible and it is possible that also the top was restored: that is why at the intrados of the arches there are many cracks.

Currently, the double-waved curved wall is not part of the guided tour of the church and remains a hidden history of Sant'Ambrogio Basilica that our VR and AR applications want to show and share. The double waved-curved wall was not just imported into the VR environment, but it was also developed for the AR experience (Fig. 13). The VR and AR experiences are linked together, thanks to the QR code that can be seen on the Canonica information screen in the VR environment. An online application allows the visualisation of the QR code on mobile devices and tablets. The double waved curved wall appears on the screen, and it can be seen by walking around the room or by tapping the display with the fingers.

6. Future works

The research carried out in the last five years has shown the pro and cons of the latest IT development in the field of DCH. 3D surveys based on laser scanning and digital photogrammetry are particularly effective for the digitization of complex architectural elements. On the other hands, they require long manual post-processing steps such as cleaning and orientation for the generation of HBIM. Also, it was also found that BIM software is not able to support a quick digital reconstruction of 'informative' model for heritage buildings. GOG 9 and GOG 10 have reduced the time required for the generation of complex elements with a high GOA, bridging the gap between generative modelling and BIM software. Future works will be addressed to a further improvement of GOGs and generative modelling tools in Autodesk Revit. In particular, an on-going work partially funded by Regione Lombardia - Bando *"Smart Living: integrazione fra Produzione Servizi e tecnologia nella filiera costruzioni-legno-arredo-casa*" within the project *"HOMeBIM liveAPP: Sviluppo di una Live APP multiutente della realtà virtuale abitativa 4D per il miglioramento di comfort-efficienza-costi, da una*

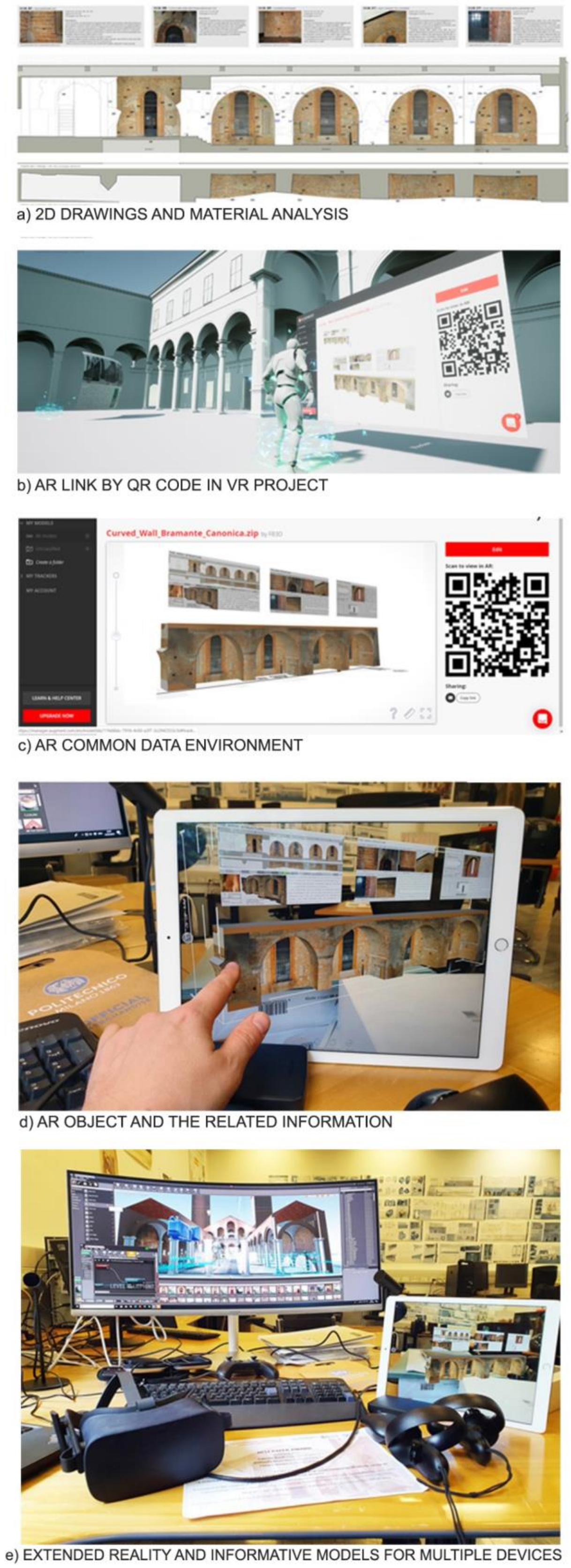

Figure 13: The proposed research method allows the information is sharing from historical records, technical drawings (a), AR (b, c, d) to an extended project for multiple devices (e) such as VR headset, mobile phone, tablet and workstation and multiple operating systems such as Windows, Android and iOS.

piattaforma cloud che controlla nel tempo il flusso BIM - sensori – ID 379270", has developed an add-in (plug-in) to support and improve the scan-to-BIM process in Autodesk Revit. The Basilica of Sant'Ambrogio will be the proper case study to show the research impact of the developed scan-to-BIM add-in, from an economic, operative and qualitative point of view.

Furthermore, the proposed XR project has shown how huge digital virtual environments can be linked to AR libraries and shared by an AR CDE with multiple devices. As well known, all these technologies increasingly require fast HTTPS web connections. In particular, it was found that the main parameters of the VR/AR developed models clashed with the limits of mobile devices such as smartphones and tablets (Lai, Hu, Cui, Sun, & Dai, 2017). Table 1 shows the main model's features in term of 3D exchange formats.

Table 1: The main model features of each type of model from the NURBS model to HBIM and AR objects. The format's sizes are in KB (in green), MB (in orange) and GB (in red). The red values show one of the most barriers for the model sharing for mobile devices.

TYPE	*NURBS MODEL (.3dm)*	*HBIM OBJECT (.rvt)*	*VR OBJECT (.fbx)*	*AR OBJECT (.dae)*
VAULT	448 KB	5 MB	1,1 MB	673 KB
ARCH	116 KB	800 KB	75 KB	53 KB
COLUMN	504 KB	4,9 MB	1,53 MB	679 KB
SIMPLE WALL	82 KB	750 KB	15 KB	10 KB
COMPLEX WALL	3 MB	37 MB	834 KB	680 KB
ENTIRE MODEL	270 MB	1,56 GB	16,5 GB	-

These parameters, most of the time require high performance in terms of connectivity and data loading through the main operating systems such as Windows, Android and iOS.

The Next Generation Mobile Networks Alliance (NGMN) believes that fifth-generation (5G) should be presented by 2020 to meet the demands of businesses and consumers. In addition to simply providing higher speeds, the NGMN predicts that 5G networks will also have to meet the needs of new use cases, such as the Internet of Things (Internet-connected devices), as well as transmission services and communication lines. It is, therefore, appropriate to investigate mobile telephony development and the interoperability of terminals. Therefore, future IT developments will be addressed to improve the integration of the Unreal Engine 4 formats such as the HTLM5 for mobile devices and the new 5G technologies and standards, which should allow higher performance than those that preceded it (4G).

Finally, future developments will face one of the most difficult challenges in generative modelling for VR projects: a character development process. It will be based on the following steps: the creation of a custom skeletal mesh, player controller, pawn or character blueprint developments, a character class setup, animation blueprint and gamemode setup.

7. Conclusions

The presented holistic approach shows a comprehensive process that starts from the data collection (3D survey, historical record…), goes through the realisation of the 3D model and ends with the VR/AR experience, offering an increased level of information of the detected historic architecture. Increasing the level of information also means the increase of the awareness of the intangible value and historical richness of the architectural heritage among citizens.

The research shows many potentials and challenges of the DCH field. One of the potentials is the increasing level of information that is achieved through this holistic approach. The different levels of information are strictly correlated to the generative modelling, that has many outcomes, from the HBIM to the AR/VR experience, from the management of the building (life-cycle analysis, building site management…) to the historical analysis (2D and 3D reconstructions…) until the ludic dissemination of information (serious games...).

On the other hand, each outcome has many challenges: the problems faced for the parametrization of historical building shapes, the difficulty in representing historical hypothesis and in communicating intangible values, the threat to trivialize the informative content of the VR experience. That is why each step of the holistic approach has to be carried out through an interdisciplinary approach, where BIM experts and geomatics engineerings communicate with restorers and art historians.

The study on the Basilica of Sant'Ambrogio in Milan has been the research field over the last five years to experience the combination of digital technologies and historical studies in order to create an immersive environment for both expert users and tourists, where each visitor can visit the church freely, deepen the knowledge of the Basilica depending on their interests and purposes. As mentioned before, the main aim of digital technologies was to show the possibilities of the different outcomes of a reliable 3D model. On the other hand, the main aim of historical research was to give a different point of view and different parameters to see and study the history of one of the main well-known building in Milan. Above all, it opens the mind of the visitors, giving them a different perspective of the built heritage, that is not coherent but the results of different construction phases. The taccuino and the virtual subtraction process are the link between modelling and historical study and the criteria that guided the research. The efforts made in the realization of the VR and AR experience are aimed to make the huge complexity of the Basilica (its past events and histories) easier to be understood by both expert and non-expert visitors, without simplifying or trivialise its intangible meanings. Furthermore, VR and AR increase the sharing of information both because they offer user-friendly applications and devices, and bring the church and its richness everywhere, reaching a wider number of final users.

Acknowledgements

Data from surveying, modelling, HBIM generation, interpretation and communication of the Basilica di Sant'Ambrogio in Milan have been provided and supported by the on-course GAMHer project: Geomatics Data Acquisition and Management for Landscape and Built Heritage in a European Perspective, PRIN, Progetti di Ricerca di Rilevante Interesse Nazionale–Bando 2015, Prot. 2015HJLS7E (Sc. Res. POLIMI Unit R. Brumana), with the contribution of Fabrizio Banfi (HBIM, VR/AR/MR implementation) and Chiara Stanga (content implementation).

Special thanks to Monsignor Carlo Faccendini, new Abbot of the Basilica of Sant 'Ambrogio in Milan and Professor Jacopo De Vecchi, Deacon of the Basilica of Sant'Ambrogio, for hosting surveys and new cues of reflection for VR experimentation.

Special thanks to Alberto Grimoldi who was the supervisor, together with Raffaella Brumana, of the Master Thesis by Chiara Spinelli and Chiara Stanga *A n-D virtual notebook for the basilica of S. Ambrogio in Milan* (2015), Politecnico di Milano.

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