Virtual Reality for Cultural Heritage: New Levels of Computer-Generated Simulation of a Unesco World Heritage Site

F. Banfi and C. M. Bolognesi

Abstract This research proposes a generative method capable of improving the interoperability levels of HBIM models for the generation of immersive environments based on the main game engines such as Unreal Engine. Thanks to advanced modelling techniques based on Non-Uniform Rational Basis-Splines (NURBS) algorithms, able to faithfully represent the surveyed artefact and an open-source visual scripting language for gameplay (blueprint for game engine), it was possible to implement an VR project of one of the most representative Unesco World Heritage Site of Lombard architecture: Santa Maria Delle Grazie in Milan (Italy), according to the Cloister of Dead part. In particular, thanks to HBIM and VR integration, the proposed method brings to light the intangible values of the historical monument, handing down the historical phases and the memory to future generations that have followed over the centuries from the first construction of the convent complex, to the reconstruction that took place after the bombing of the Second World War. Users, through an immersive path, can discover the transformations that took place over the centuries, which are gradually going slowly lost in our common memory. The virtual interactive reconstruction concerns specifically the project carried out and then demolished of the access to the convent from via Sassi and the transformations linked to the Cloister of the Dead before and after the bombing of 1943. Thanks to new levels of interactivity and state-of-the-art technologies, the VR project in Santa Maria Delle Grazie, which is being developed for different devices and platforms (mobile, desktop and Oculus Rift), aims to increase historical and cultural awareness of different types of users such as professionals in the construction sector and virtual tourists, thus becoming a useful dissemination tool for in-depth research carried out in recent years.

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1 The Origins of the Complex; Its Transformation, Until the Surveys of Agnolodomenico Pica and Piero Portaluppi

Probably count Gaspare Vimercati, captain of the Sforza troops, gift the land to a group of Dominican friars in 1460 to set the first stone of the convent in 1463 by a pre-existing military camp of his property. Later on Francesco Sforza, Galeazzo Maria and Ludovico il Moro from the Sforza family made the first donations and intervened in the new construction.

Duke Ludovico, (after a conspicuous donation in 1492) declared that his family had enlarged the main chapel and even built the whole church. During the first years, the new buildings of the old wooden military camp and the new buildings (already given to the friars and lasted till 1497) coexisted. After the lodging of the friars in 1463, the built continued with the construction of the church, next to a previous existing chapel, dedicated to the Virgin Mary. The first convent was completed in 1469, the church in 1490. The design of the first plan was the result of Gaspare Vimercati and Guiniforte Solari's work; its morphology was surely influenced by the presence of the military camp and by the position of the chapel of the Virgin Mary, already in place (Fig. 1).

The rules were typical of a Dominican convent, reflecting the necessity of a self-sufficient organization: spaces for praying, producing, living and resting. Different cloisters with different functions were built by the church, with different functions, such as a vegetable garden by the pharmacy and a cloister to bury the dead friars.

Some constraints were given by the lying of Porta Vercellina and the previous Chapel of the Holy Virgin; the influence was strong and durable; owing to the position of the Holy Virgin chapel the growth of the convent was strictly prolonged to the north and the lying of the Cloister of the Dead also (Bertelli et al. 1983).

In this paper the historical events that linked the development of the convent to the presence of Donato Bramante and Leonardo da Vinci are overlooked, included the decision of Ludovico il Moro to rebuild part of the complex.

In these years Leonardo da Vinci received the task of painting the Last Supper on a wall of the Refectory and the presence of this iconic painting influenced the whole history of the convent. The so-called Old Sacristy and the Cloister of the Frogs were finished before the beginning of the sixteenth century (but after the fall of the Sforza Family), while other spaces were later included, filling the gap between the cloister and the sacristy (Zanzottera 2015).

Fig. 1 The plan of the complex (*Source* A. Pica, P. Portaluppi) (**a**), Basilica of santa maria delle grazie (**b**), internal views of the church (**c**, **d**) the refectory and the last supper (**e**), the main cloisters (**f**, **g**, **h**)

1.1 The Cloister of Dead

The focus of this paper regards one of the bigger cloisters, the Cloister of Dead. After its construction well described by Armando Bruschi (Bertelli et al. 1983) it suffered from different minor interventions, some of them described in a set of photographs collected before the bomb of 1943. Its importance is linked to the history of the morphology of the convent.

The construction of the ehole convent complex must have probably started from the wing of the Cloister of Dead, close to the old Chapel of the Holy Virgin, first of all with the Chapter room, covered with vaults; the position of its opening into the cloister forming the typical design of the door flanked by two mullioned windows was transmitted to the mendicant orders with Cistercian monastic architecture, also Lombard. The Cloister of the Dead is formed by three built-arms: the one with the Chapel of the Virgin Mary, the chapter room, the one with the cells and the one with the refectory. With the side of the church, they form a squared space with columned porches whose principal walls will be able to further extend becoming the line structuring of most parts of the convent.

It may, therefore, be that the position of the main walls in the Cloister of the Dead, which delimit the building with the cells and the one with the refectory towards the outside, was suggested or made obligatory by the pre-existing buildings; this gives the importance to this cloister as an inner heart of the whole construction and could explain the specific lying of the refectory if considering the anomalous east and north side of the cloister; this great room has a perfect proportion of 4 modules with a width of this building bigger than the wing with the chapel and the Chapter. The entrance is considered in the middle of its long side (Fig. 2).

Fig. 2 The cloister of the dead and its architectural details in its actual shape

With this approach, the cloister of the Dead is almost a squared Cloister of almost 30 m each side, while elevation character among its sides is quite different. The first side built was the chapter one; to the north cells on the same length (destroyed in 1943) there were six spans instead of eight trying to correspond internal walls; in this way, the proportions established in the design of the eastern front were deformed here, without any visual concern, widening the centre distances of the columns and lowering the arches. Six arches were also attached to the western side of the Refectory. The fourth side of the portico, attached to the church (perhaps built last and also now destroyed), abandoned the articulation of six spans, changing them to five precisely to match the axes of the columns with the walls of separation of the chapels, without worrying of any irregularity.

In this way, the appearance of this fourth portico differed strongly in a particular way from that of the eastern side towards the chapel and the Chapter. While the eastern and northern arm even if with different heights comprised the cells and the library respectively on the upper floor, the western arm towards the Refectory and the southern arm towards the church, were originally as high as the porch alone. For those who entered the convent, the eastern side of the cloister, the most "proportionate" and regular with its eight-round arches, was the one that, despite an oblique view, appeared first and almost frontally.

1.2 After Renaissance

As many other religious institutions, the more recent history of this complex concerns the suppression of the convent in May 1799, when the building was transformed into a military barrack and the friars were shifted to other convents. Beside this in the middle of the eighteenth century, some urban transformations allowed a better view of the church and convent itself: during the years many buildings had been placed next to the church and their demolition, due to the opening of two new roads, offered better visibility to the apse.

Between the end of eighteenth century and the beginning of 19th, some restoration works were conducted in many areas of it, with the support of Luca Beltrami, who was specifically involved in the restoration of the Refectory. Due to a mixed-use, still divided between laic and religious, the convent underwent several transformations. The Regional Monuments Conservation Office had its seat there (Bascapè and Mezzanotte 1968) while in 1924 the Dominican friars regained possession of the courtyard called Cloister of the Prior and of the entire first floor. In 1929, the whole convent went back to the Dominican order with the exception of the Refectory containing the Last Supper, that remained a State property.

The main document that provides a first summary of the history of Santa Maria delle Grazie, as well as of its development over the centuries, is the book written in 1937 (in occasion of the renovation of the monument started in the 1930s) by Pica and Portaluppi (1938).

The volume contains previous historical researches that had been carried out by reliable scholars in the architectural field, such as Luca Beltrami, but also by friars belonging to the Dominican order, such as Fra Gattico (2004). It describes the origin of the complex, validated by the later writing of Bertelli et al. (1983) at the beginning of the 80s. Considering the complicated history of the monument, this is the most reliable document before the bombing of 1943 and gives the most complete overview of its morphology, giving the opportunity to understand its history (Fig. 3).

2 The Research Method

One of the main key elements for the development of the VR project of the Basilica of Santa Maria delle Grazie was the integration of different advanced modelling techniques able to interact with one of the most widespread applications for video game development: Unreal Engine 4 as already developed in a previous research Bolognesi and Aiello (2019).

The proposed workflow, besides allowing to inherit complex models developed in any 3D modelling software with high levels of interoperability, has allowed the authors to 'give life' to three distinct historical phases before the bombing of 1943 of a single part of the monument and associate useful contents, thus increasing the informative value of the virtual experience. Starting from the assumption that one of the main advantages of VR is the creation of an interactive environment capable of digitally representing the examined artefact, following the example of previous VR projects in this specific field of application (Ioannides et al. 2017) the main steps shown in Fig. 4 have been addressed.

2.1 The First Phase: 'Data Collection'

Data collection phase allowed to deepen the historical heritage of the basilica, analysing the various historical phases prior to the bombing suffered by the basilica during the Second World War in 1943. As is well know, VR allows us to digitally reconstruct and discover some areas of historic buildings forbidden to the public for a number of reasons such as maintenance works, limited use of certain areas to best preserve relevant parts of the building and particular parts of the building reserved for everyday life of the ecclesiastical body. Thanks to the in-depth study of a huge quantity of historical records during the last years, the main objective of this first phase was to reconstruct the historical background of the whole complex, thus facilitating its diffusion and observations among the various users (virtual tourist, students, professionals).

The determination of the various historical phases, as anticipated in the previous paragraph, is based on an in-depth study of historical documentation, scientific studies, restoration treatises and technical drawings made in the previous century,

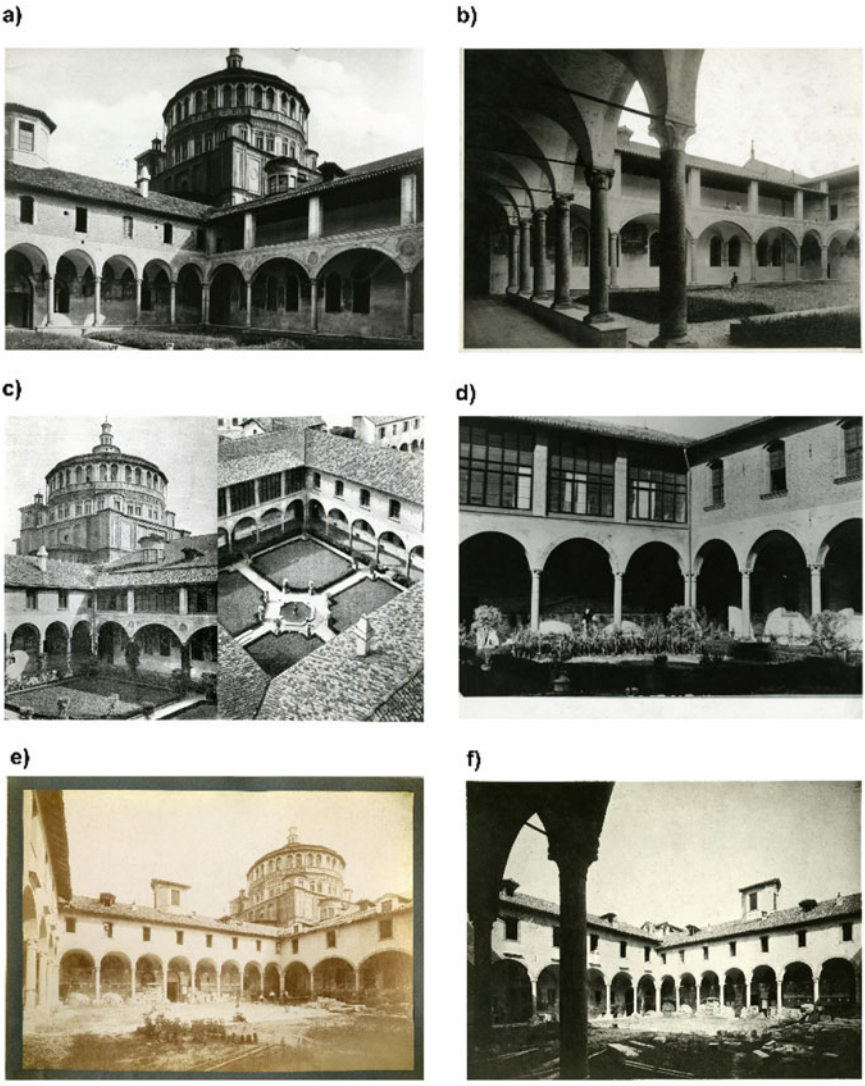

Fig. 3 Historical records of the cloister of the Dead in different temporary periods before the bombing by the Allies on August 16, 1943. *Source* **a-c** da A. Bruschi, in Santa Maria delle Grazie in Milano, 1983 Banca Popolare di Milano **b-d-e-f** Soprintendenza Archeologia, Belle Arti e Paesaggio, Milano

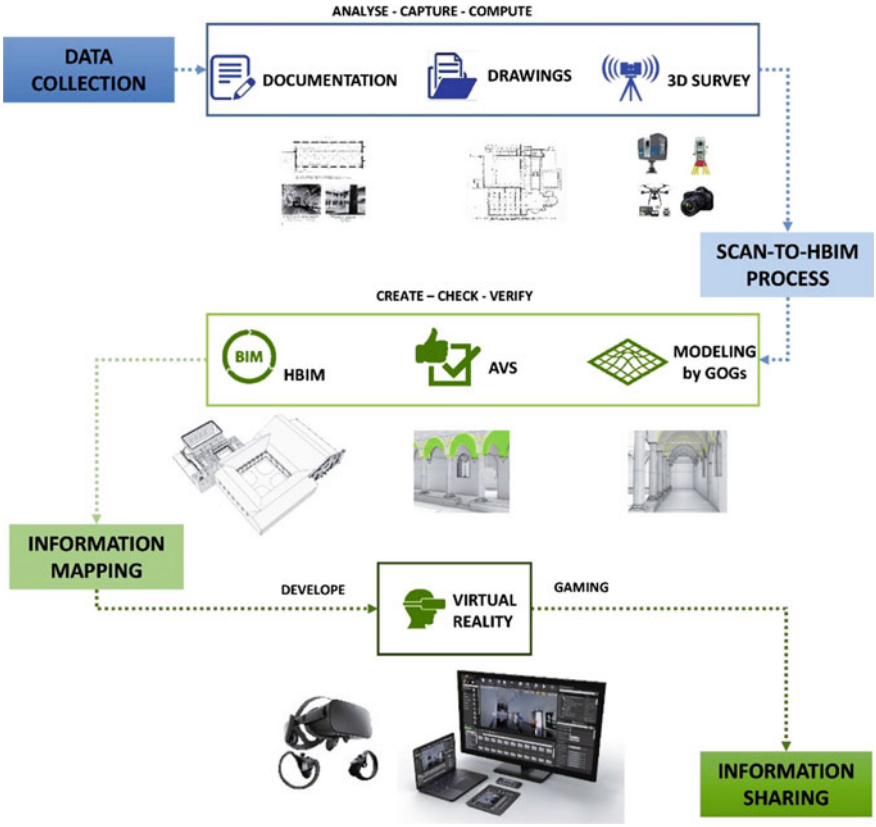

Fig. 4 The digital workflow applied to the VR project of Santa Maria delle Grazie

which have allowed authors to discover the morphology of the building during the centuries, its main historical configurations that took place in the years before the bombing.

In particular, this study makes explicit and compares three historical phases starting from the year 1937, with the main purpose of digitally telling the typological and morphological differences of the main cloister of the church (also known as the Cloister of the Dead) in an interactive virtual environment. In addition to increasing the constructive and geometric awareness of the basilica was to gather a series of information with the aim of validating with certainty the VR model corresponding to each historical phase and improving the level of content of the immersive experience itself.

2.2 The Second Phase: The Scan-to-BIM Process

In recent years a large number of studies and projects in the field of HBIM and VR have allowed the creation of faithful reproductions of a large number of heritage buildings, maximizing the '*value of the measure*' and the levels of information of the surveyed building (Banfi 2019; Graham et al. 2019; Arayici 2008; Antonopoulou and Bryan 2019).

The main objective of the Scan-to-BIM process is to generate detailed models corresponding to reality from different types of digital data. As is well known, today, instruments such as laser scanners, total stations and digital photogrammetry allow us to collect, store and analyze a large amount of data such as point clouds, accurate measurement, geodetic networks, and orthophotos.

These data collected during the first phase, allowed to provide the appropriate basis for the virtual reconstruction process.

2.3 The Third and Fourth Phases (Information Mapping and Information Sharing) for VR Projects

Information mapping and sharing phases have considered a specific selection of historical information relating to the three historical phases identified by the studies carried out with the aim of developing a virtual storytelling for multiple devices such as the VR headsets, portable devices (tablet, mobile phone and laptop) and pc. Starting from the assumption that every device and software requires a high level of knowledge in the field of HBIM modelling, thanks to this open-source application, the main research objective was to maximize the level of content in a virtual environment and to create the most sustainable HBIM-to-VR digital process possible even for future users.

For this reason, the UE4 VR project of the basilica had to provide an open approach able to give the possibility to enrich the VR experience and the virtual storytelling to users and studies successes to the one proposed (Fig. 5).

As shown in the following paragraphs the VR project of the Basilica of Santa Maria delle Grazie will take different forms based on the software and devices used with a single final purpose: to increase the historical and cultural awareness of one of the main Unesco sites in the city of Milan.

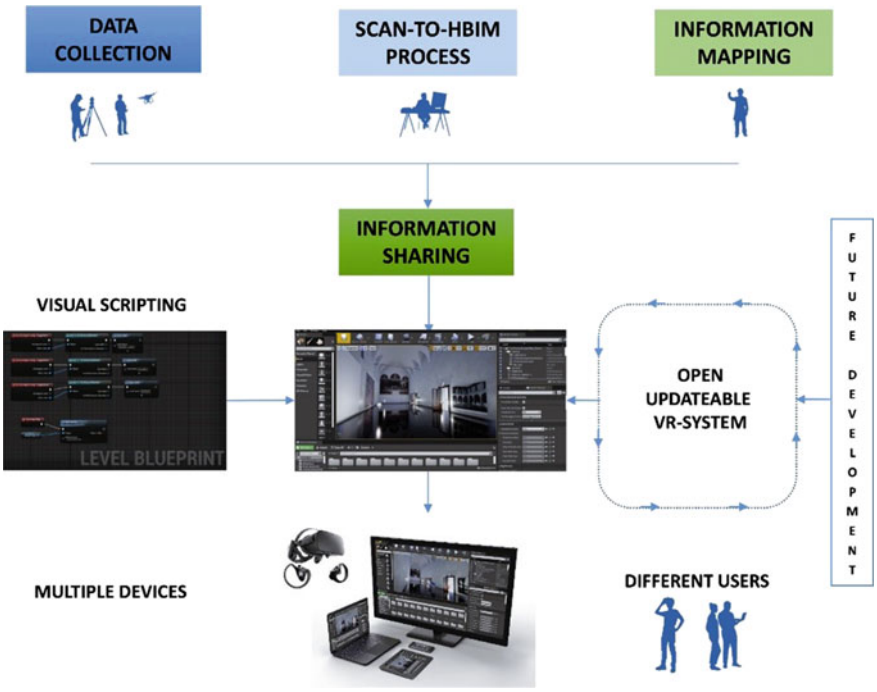

Fig. 5 The holistic approach based on a open visual scripting (blueprint of UE4) allow future users to improve the VR system with new type of contents and orient it for multiple devices

3 From 3D Drawing and Digital Modelling to Virtual Reality (VR)

Considering the previous studies Bolognesi and Aiello (2019), this research proposes a sustainable digital process for the creation of a VR project able to improve the information sharing of one of the most important monuments of Milan. As anticipated in the previous paragraph, HBIM makes it possible to improve different types of analysis thanks to the targeted use of complex models capable of faithfully representing reality with novel frades of generation. The main VR applications such as Unreal Engine and Unity provide a type of mesh-based modelling. Mesh modelling, as is well known, involves a series of pros and cons. Considering the world of digital photogrammetry (Lerma et al. 2010; Barba et al. 2019), thanks to simple sets of photographs it is possible to move from a two-dimensional representation to a three-dimensional geometric representation composed of a large number of polygons, precisely the meshes.

Thanks to the generation of models from point clouds, it is possible to create texturized geometric entities with high-resolution orthophotos. On the other hand, one of the main cons of this type of modelling is the realization of a geometric

model and not of a parametric HBIM model able to communicate different levels of information such as the physical and mechanical characteristics of the materials, historical phases, wall stratigraphy etc.

In this specific field, the integrated application of GOGs and NURBS algorithms (Banfi 2017; Piegl and Tiller 2012) has made it possible to generate the model of the Basilica of Santa Maria delle Grazie by maximizing the benefits deriving from 3D survey for the Cloister of Frogs and of the Priore, and the extraction of geometric primitives from historical drawings such as elevations, plans, detailed sections for the Cloister of Dead here rapresented. A mathematical model able to interact with three different historical phases has been prepared. Thanks to the sharing of a unique 3D project it has been possible to insert 2D and 3D construction details in a georeferenced environment with the aim of fully understanding the construction technique and fixing possible interferences between one historical phase and another. Figure 6 shows the various steps in detail, from the generation of the model to the VR development environment. The main steps were:

- use of different types of data such as point clouds and 2D technical details (plans, elevations and sections)
- generation of geometric models using NURBS and GOGs interpolation algorithms
- verify the main interferences between a historical phase and the other, outlining a sure road to take for the generation of the models;
- texturing of NURBS models using the main mapping and software techniques such as McNeel Rhinoceros with UV mapping tool and Spotlight with its add-in Zbrush; paying particular attention to the direction of the normal of complex NURBS surfaces
- import of the NURBS model in Unreal engine with a workflow based on the main exchange formats (obj and fbx) able to accurately transmit the geometric and material characteristics of each single element created; for this step, satisfactory results have been found also through the use of Datasmith (new add-in for UE4), which allowed to bypass the definition of the export schemes of the two previous formats and directly use the proprietary files such as the 3 dm format (Mc Neel Rhinoceros) and the various CAD and BIM formats in a completely open logic.

3.1 The Development of the VR Project of Santa Maria Delle Grazie

Before the IT development of the Santa Maria delle Grazie VR project, it was necessary to define the "how" to transmit the wealth of studies and research done in recent years. For a correct setting of a VR environment, it is necessary to identify and decide the various LOD that the virtual user must discover when he explores the model. In recent years, some studies on proxemics, perception of virtual space and above all cognitive learning have highlighted key features that can greatly influence the

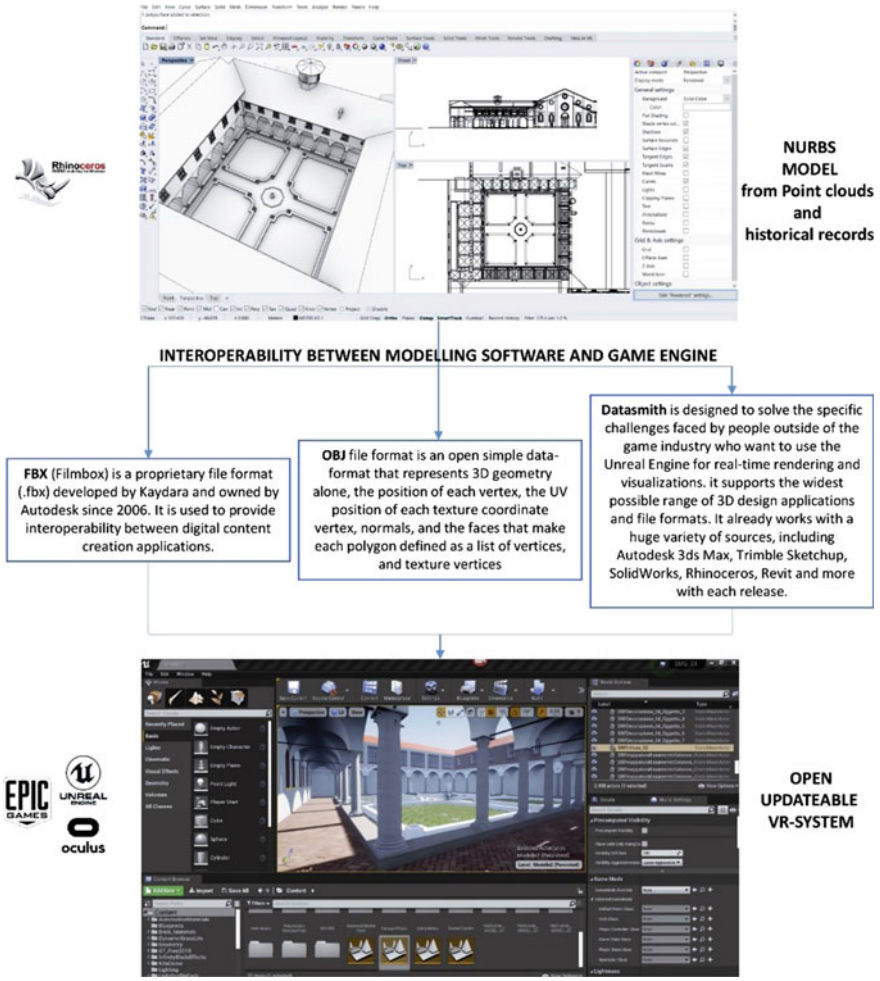

Fig. 6 The three import options of the HBIM model for VR environment and game engine

virtual experience itself (Michael and Chen 2005; Guidi et al. 2007; Westhoven and Alexander 2015; Hayden 2018a, b). Independently from the LOI and LOD achieved in the previous stage, these studies underline the importance of serious games for their ability to fulfil cognitive learning outcomes and motivate users. It has been tried and proven through these studies, serious games are designed for a general audience and often require a user-friendly interface tailored to learning objectives. Notable among studies of selecting game engines for serious games is the work of Petridis et al. (2010) and Pybus (2019), which identifies several key criteria for comparison that are still useful despite changes in technology: audiovisual fidelity, functional fidelity, composability, accessibility, networking, and heterogeneity. Considering all these criteria, for a correct setting of the basilica storytelling and its three historical

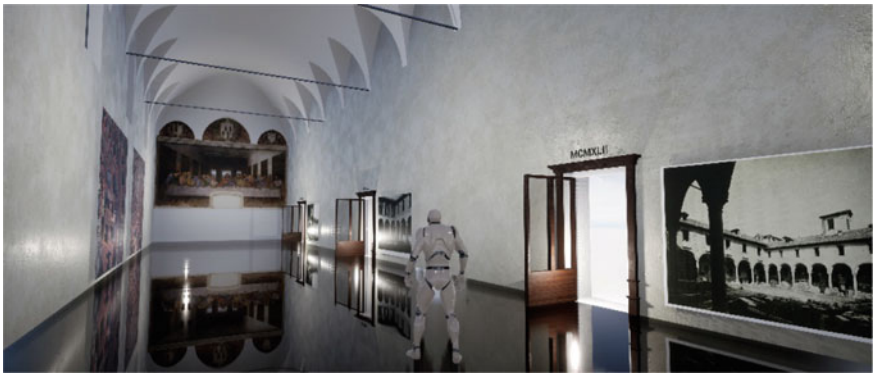

Fig. 7 The 'lobby' of the VR project: the starting point of the virtual immersive experience allow users (through the VR avatar) to select different type of data (on the left) and choice the three time gates corresponding to each historical phases analysed (on the right)

phases, it was necessary to create a starting point where the user can begin to explore and learn key information of the basilica and decide how to interact with the various VR objects and the three historical phases identified. This k-concept was also useful for all those users who are not able to visit the monument directly and to better understand general information such as the context, location and history of the basilica. For this reason, a 'lobby' has been created which takes up the studies done by the restoration of the refectory where Leonardo's last supper is located (Fig. 7).

3.2 The Five Rules Applied to the VR Project

The choice to undertake the modelling of such a famous environment was given by the authors' desire to create three temporal links (one for each historical phase) to the cloister of the Dead (Fig. 8). Starting from the assumption that the storytelling of a building of such a historical and cultural importance of the city of Milan cannot be left to chance, it was useful to identify five basic rules to be able to tell successfully the articulation of the virtual experience, its storytelling and the three identified historical phases.

Linear and engaging story: identification of the protagonist of the narration, periods of the story told, identification of the elements of interest for a target that can go from the historical to occasional virtual users;

Reliability of the model and of the sources used: use of qualified sources that are as objective as possible and that can confirm the assertions made in the narrative and of the models created;

Identification of the best VR devices and software: the creation of a serious game must include a high level of authenticity, realism and persuasive effectiveness. To obtain these results, the main development applications such as Unreal Engine

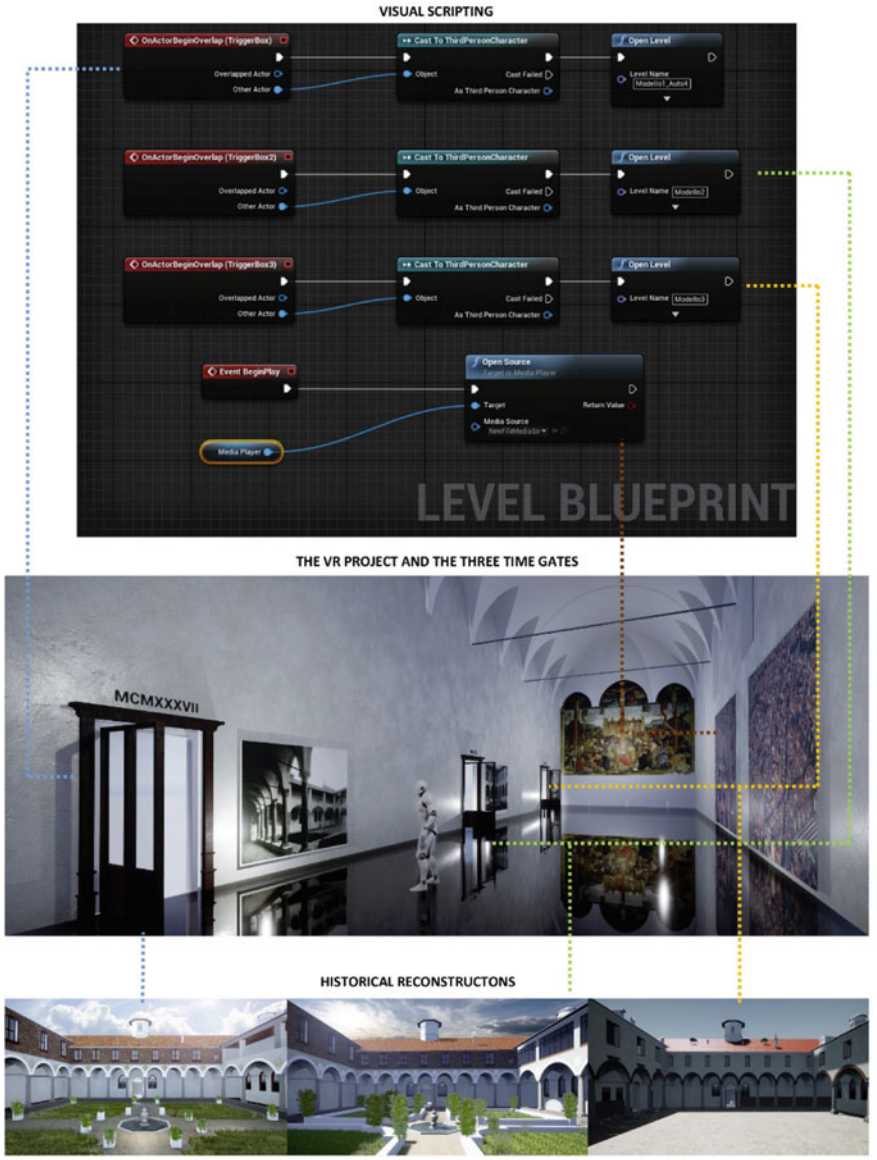

Fig. 8 The main blueprints developed for the VR project of Santa Maria delle Grazie and the main three levels developed

and Unity and the main VR headsets and devices such as PlayStation VR, Oculus Rift S, Samsung Gear VR and Oculus Quest were considered. Unreal Engine was preferred thanks to its visual fidelity, simplicity of scripting, learning curve, and the availability of online resources including documentation and community support; while Oculus Rift S was chosen (Oculus/Developers 2019; Addison and Gaiani 2000; Remondino and Stylianidis 2016; Zancheti 2002) thanks to the latest technological developments that have improved the optics, improved the touch controllers' accuracy and reduced the hardware needed to immerse themselves directly in the virtual experience, eliminating the turrets included in the standard Oculus rift version.

Control of the size of the VR project in terms of bytes and polygons: the size of the VR project depends on the number of mesh polygons obtained from the transformation process of the NURBS models into static meshes of unreal Engine. Thanks to the definition of the exchange format and the use of the Mc Neel Rhinoceros software it was possible to decide the number of polygons of every single element before importing it into the VR engine. This step allowed the modellers to keep the overall size under control, favouring the app package function for different devices such as mobile phone and tablets which require a limited number of polygons.

Guarantee future developments and integrations through a VR project based on open development logic: the advantage of having developed the VR project with Unreal Engine as well as orienting the app for multiple devices, was to develop algorithms and information codes through visual scripting. Thanks to the flexibility of this programming language it has been possible to update the virtual experience and the storytelling with past studies, thus ensuring a flexible and updatable implementation at any time.

4 Discussion and Results. HBIM to an Open VR Project: Data Enrichment and a New Level of Interoperability

In recent years, the generation of complex HBIM models capable of representing the detected reality has been oriented towards disciplines such as restoration, geomatics, structural simulations, maintenance site and facility management. Many studies have dealt with and resolved differently the limits imposed by BIM platforms, implementing methods capable of managing both the latest generation of relevant tools and advanced modelling techniques, the latter not always able to facilitate the generation of complex historic buildings.

A known limitation of the users is the ability to effectively manage, in order to interact satisfactorily, complex three-dimensional models characterized by huge amounts of data, such as those generated by the most advanced technologies today, due to the limitations resulting. It happens, therefore, that information models of considerable dimensions, such as those generated by the 3D survey, are subject to discretization and therefore a choice to reduce the information content, in particular when the purpose becomes the visualization through common devices.

For those reasons, the technological development, operational and modelling aspects have been investigated with the main objective of demonstrating how the proposed method can be useful and sustainable for all those fields of application related to the built heritage, not only to the fields of restoration and safeguarding the good. This study has shown how the new paradigm of the utility of HBIM models can be addressed to new tools and devices capable of increasing the level of information and transmissibility between different types of users, from professionals to tourists and virtual students, through an open and sustainable approach.

In particular, the choice of modelling techniques, the software and the devices used were dictated by the fact of making immersion in digital worlds (made up of VR objects) as user-friendly as possible, moving from static information models to interactive objects and scenarios characterized from its own life, capable of communicating data and information that cannot be associated with traditional HBIM projects. The description of the technologies used, as well as the procedures adopted, should always be related to the characteristics of the target audience considered.

The use of applications such as Rhinoceros V6 and Unreal Engine allow to model with extreme precision deformation states detected through the three-dimensional survey of the actual state of the building; these software solutions have considered from the authors as the best choice to generate models able to interact with different platforms, devices and users. As is well known, Rhinoceros V6 is considered the best digital model converter, including all possible exchange formats within it. Thanks to the choice of formats such as .fbx and .obj, it was possible to use a VR platform based on open development logics, importing complex NURBS model in an open logic.

Furthermore, it is also considered that the presence of developing protocols and procedures shared online by Epic Games for the Unreal Engine software can support both expert and non-expert in creating new and innovative digital storytelling, following their development and storytelling creativity. As a result, semantic enrichment becomes the added value of the proposed VR project, which can tell the story of the building and pass on the historical and cultural awareness accumulated in recent centuries. Informative panels, interactive VR objects, historical phases, descriptions, videos, audios, pictures and other types of multimedia data are therefore the 'key elements' for improving the transmission of information within a virtual model. As briefly mentioned, the intention of using software based on open development logics also opens the door to possible future implementations.

The semantic enrichment of the VR project consequently has no limits, thus depending solely on the will of the creators and future developers to increase the content and the level of information. This open approach has also favoured the development of 'temporal doors' capable of increasing the educational value of the VR project, through which the virtual tourist can immerse himself and discover different historical periods, discovering restorations and architectural differences that have alternated in a specific time period.

This study must, therefore, be seen as the first attempt at digital development and semantic enrichment of the VR project of the basilica of Santa Maria Delle Grazie.

Many other enrichments can be made, following the example outlined by this first phase of development.

5 Future Research, Development Perspective and Conclusion

Today's people are more tech-savvy than any other generation. Thanks to their multiple advantages, gaming technology and VR have been considered very good ways to improve the knowledge of heritage sites.

VR and digital modelling allow users to recreate places normally not accessible to people, to allow realistic immersion in digital environments that normally could not be explored, to share a huge quantity of contents through a digital 3D reconstruction and to improve the level of interactivity and knowledge of different types of users, from professionals to virtual tourists and students.

For all these benefits, one of the main research goals was the integration of the latest modelling techniques, 3D survey and in-depth studies of the Basilica of S. Maria Delle Grazie to create an educational VR project variable and extendable both in terms of contents, interactivity and creativity, increasing the historical and cultural awareness of one of the most famous UNESCO monuments of North Italy.

Furthermore, thanks to its open logic, the proposed method will enable users to extend the storytelling of the church, introducing new historical records and multimedia data, discovering new types of devices and software.

Finally, new development perspectives will able to be based on the proposed digital workflow for other types of heritage sites, considering it a possible base for their case studies.

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