



RELIVING HISTORY: THE DIGITAL RECONSTRUCTION OF THE CONVENT OF SANTA MARIA DELLE GRAZIE IN MILAN

REVIVIENDO LA HISTORIA: LA RECONSTRUCCIÓN DIGITAL DEL CONVENTO DE SANTA MARÍA DE LAS GRACIAS EN MILÁN

Damiano Aiello^{a,*} , Cecilia Bolognesi^b 

^a Department of Civil Engineering and Architecture, University of Catania, Via Santa Sofia 64, 95123 Catania, Italy.
damianoaiello@gmail.com

^b Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Via Ponzio 31, 20133 Milan, Italy.
cecilia.bolognesi@polimi.it

Highlights:

- The study focused on the virtual reconstruction of the convent of Santa Maria delle Grazie, one of the most emblematic Gothic-Renaissance buildings in the city of Milan.
- By combining data from documentary sources, architectural treatises, period photos and digital survey, the main building phases of the convent, from the 15th century to date, were digitally reconstructed.
- The 3D models are enriched with information about the accuracy of the digital reconstruction, creating 3D databases that can be easily consulted and updated.

Abstract:

Can we preserve cultural heritage and, consequently, the memory of the past? To answer this question, one should look at the digital revolution that the world has gone through in recent decades and analyse the complex and the dialectical relationship between cultural heritage and new technologies. Thanks to these, increasingly accurate reconstructions of archaeological sites and historical monuments are possible. The resulting digital replicas are fundamental to experience and understand cultural heritage in innovative ways: they have complex and dynamic relationships with the original objects. This research paper highlights the importance and the scientific validity of digital replicas aimed at understanding, enhancing and protecting cultural heritage. The study focuses on the virtual reconstruction of the constructive phases, from the mid-15th century to date, of one of the most emblematic Gothic-Renaissance buildings in the city of Milan (Italy): the convent of Santa Maria delle Grazie, famous worldwide for hosting Leonardo da Vinci's Last Supper painting. This site proved to be an ideal case study because of its troubled and little-known history that led to numerous changes over the centuries. Thanks to a methodological approach based on the analysis of the documentary sources and three-dimensional (3D) modelling, it was possible to outline the chronological succession of the convent transformations; the way in which these overlapped the pre-existing structures was described starting from the Renaissance harmonious and organic interventions, to finally reach 18th-19th centuries inhomogeneous and incompatible additions. Finally, the research was completed by mapping the 3D models based on the sources used and their different levels of accuracy. The 3D models have thus become a valid tool for checking and verifying the reconstruction hypotheses.

Keywords: digital replica; 3D modelling; digital survey; cultural heritage; documentation; 3D reconstruction

Resumen:

¿Podemos preservar el patrimonio cultural y, por consiguiente, la memoria del pasado? Para responder a esta pregunta, es necesario examinar la revolución digital que ha experimentado el mundo en las últimas décadas y analizar la compleja relación dialéctica entre el patrimonio cultural y las nuevas tecnologías. Gracias a estas, son posibles reconstrucciones precisas de los sitios arqueológicos y de los monumentos históricos. Las réplicas digitales son fundamentales para experimentar el patrimonio cultural de forma innovadora; de ellas destaca también que juegan un papel importante en la comprensión del patrimonio cultural, y que poseen complejas y dinámicas relaciones con los objetos originales. Este artículo de investigación destaca la importancia y la validez científica de las réplicas digitales destinadas a comprender, mejorar y proteger el patrimonio cultural. El estudio se centró en la reconstrucción virtual de las fases constructivas, desde mediados del siglo XV hasta la actualidad, de uno de los edificios gótico-renacentistas más emblemáticos de la ciudad de Milán (Italia): el convento de Santa María de las Gracias, famoso en todo el mundo por ser la sede de la pintura mural de la Última Cena de Leonardo da Vinci. Este sitio demostró ser un caso de estudio ideal debido a su problemática y poco conocida historia que llevó a numerosos cambios a lo largo de los siglos. Gracias a un enfoque metodológico basado en el análisis de las fuentes documentales y en la modelización tridimensional (3D), fue posible esbozar la sucesión

* Corresponding author: Damiano Aiello, damianoaiello@gmail.com



cronológica de las transformaciones; se trabajó desde las intervenciones armoniosas y orgánicas del renacimiento, hasta alcanzar las adiciones desiguales e incompatibles de los siglos XVIII y XIX. Por último, la investigación se completó con el mapeado de los modelos 3D sobre la base de las fuentes utilizadas y sus diferentes niveles de precisión. Los modelos 3D se han convertido así en un instrumento válido para comprobar y verificar las hipótesis reconstructivas.

Palabras clave: réplica digital; modelado 3D; levantamiento digital; patrimonio cultural; documentación; reconstrucción 3D

1. Introduction

In the contemporary meaning of the term, Cultural Heritage represents a complex matrix of meaning and values: in other words, it consists of the legacy of material and immaterial attributes of a group or society that are inherited from past generations, maintained in the present and bestowed for the benefit of future generations (UNESCO, ICOMOS). Cultural heritage, therefore, embodies significant artistic, historical and cultural memory and meaning and merges tangible and intangible elements, such as representations and aspirations, values and interpretations, symbols and narratives. A crucial component of this assemblage is memory: without the notion of memory and everything that it suggests about time and narrative, continuity and change, individual and collective identifications, heritage would be reduced to “old things” (Viejo-Rose, 2015).

Exploring the relationship between memory and cultural heritage (which is the tangible manifestation of memory), you can open a window onto the past, understanding how these two elements are not simply an arid archive of information or unique notions: cultural heritage and memory constitute a much more complex and elusive dimension, constantly subject to the risk of extinction as a result of neglect, decay, inappropriate development, anthropic pressure or war and terrorism (see, for example, the Bamiyan Buddhas in Afghanistan or the Roman archaeological site of Palmyra, destroyed in 2013 by the Isis militia). How, then, can we preserve cultural heritage and, consequently, the memory of the past? To answer this question, we need to look at the digital revolution that has been affecting the world in recent decades and analyse the complex and dialectical relationship between the cultural heritage domain and new technologies (Piccialli & Chianese, 2017). Since the 1990s, tools aimed at documenting and communicating cultural heritage have been introduced (Addison, 2001). In the following two decades, technology in this field has continued to progress, developing sophisticated tools in terms of manageability and reliability, accuracy and speed (Wong & Santana Quintero, 2019), offering great opportunities for 3D reconstruction to revive cultural heritage (Garstki, 2018; Kargas et al., 2019). These digital replicas play an important role in the understanding of cultural heritage, considering the complex and dynamic relationships they have with the original objects (Jeffrey et al. 2015; Jones 2010; Joy 2002).

Since digital replicas tend to resemble the original object more and more accurately, ethical questions arise about if and how to replicate cultural heritage. A heated debate arises on the concept of authenticity, central for the definition of digital heritage, which has the power to indefinitely replicate cultural heritage (Benjamin, 1968; Trilling, 1973; Witcomb, 2010; Latour & Lowe 2011; Manžuch, 2017).

The dichotomy between original and replica is much more complex than it may appear at first sight. As stated in the NARA Document (1994), the authenticity of cultural

heritage implies specific meanings and values that are applied by different groups of people at different times (UNESCO, 1994). Consequently, in the age of digital reproductions there is a redefinition of the concept of the replica authenticity, whose level can be defined according to the mode of production and consumption of the replica itself and the social values linked to it by different cultures and at different times (Jeffrey and Beale, 2018; Jeffrey et al. 2015; Jones 2010; Joy 2002).

The work presented in this article is part of this debate and tries to demonstrate the usefulness of digital replicas for the interpretation of cultural heritage. Specifically, the research has focused on the potential offered by new digital survey and modelling technologies for historical and geometric analysis and the communication of one of the most emblematic Gothic-Renaissance buildings in the city of Milan: the convent of Santa Maria delle Grazie, famous worldwide since it hosts Leonardo da Vinci's Last Supper.

An analysis of the state of affairs, historical sources and the testimony of the friars, combined with the most modern three-dimensional (3D) modelling techniques, has made it possible to shed light on forgotten pages of the convent history and to identify the construction phases from the 1460s to date.

The paper is structured as follows: Section 2 analyses an overview of significant related works; Section 3 introduces the case study; Sections 4, 5, 6, 7 and 8 describe the adopted methodology to reconstruct the phases of the convent and the accuracy of the models obtained; Section 9 is dedicated to the conclusion and future research development.

2. Related works

Before the digital revolution, 3D reconstructions of cultural heritage were used merely as digital replacements for physical models. In recent years, instead, a new trend has occurred: digital imaging solutions, such as 3D laser scanning and photogrammetry, and 3D modelling technologies are increasingly being developed and employed to produce detailed virtual reconstructions of cultural heritage, useful for the analysis, interpretation, restoration and dissemination of the existing, destroyed or partially destroyed sites (Arnold & Geser, 2008; Wong & Santana Quintero, 2019; De Vos & De Rijk, 2019, Forte et al., 2006; Forte, 2008; Forte, 2014).

In addition, with the rapid advancement of technology, these tools are becoming very accurate in capturing not only the artefacts but also the many modifications and adaptations they have undergone through the ages (Affleck et al., 2008). In particular, when the aim is to investigate and promote no longer existing heritage, the biggest challenge to face is not related to the technological advancement of the tools used, but to the interpretation of the historical sources (Arnold & Geser, 2008). In this context, 3D modelling technologies offer a chance not only to digitize existing sites but also to

virtually reconstruct no longer existing objects, on the basis of available documentation (Münster & Köhler, 2016, Verdiani, 2016; Verdiani 2017, Denker, 2017). These 3D models can be used to share information: tools such as 3D printing, Virtual and Augmented Reality (VR and AR) allow virtual reconstructions of ancient sites both to reignite the public's interest and to allow the new generation to develop personal connections with the artefacts, contribute to their study and understanding, and henceforth to their preservation (Boezia, 2018).

It is precise because of these infinite possibilities that researchers, museums, universities conservation centres and cultural institutions worldwide have embraced the possibility of creating 3D reconstructions and databases of threatened or altogether lost cultural heritage (Affleck et al., 2008). Specifically, VR and AR have a lot to offer in terms of understanding and promoting cultural heritage: Innovative technologies can shorten the distance between cultural spaces and users, becoming a sustainable tool through which people can enjoy and learn more effectively about culture. Thanks to these technologies the user can experience the artefacts in their original contexts without the need to come into contact with the real objects and can consult in a much more effective way than has previously been possible cultural contents useful for their learning process (Bolognesi & Aiello, 2019; Aiello, Fai & Santagati, 2019, Banfi, Brumana & Stanga 2019, Dhanda et al., 2019).

3. Case study: the convent of Santa Maria delle Grazie in Milan

The Dominican complex of Santa Maria delle Grazie (Fig. 1 and 2), located in the heart of Milan, represents one of the highest examples of Gothic-Renaissance architecture in Italy and, for this reason, in 1980 it was



(a)



(b)

Figure 1: Convent of Santa Maria delle Grazie: (a) Aerial view; (b) Main facade.

included in the UNESCO World Heritage List, together with the Leonardo da Vinci's Last Supper.

According to historical sources, the birth of this complex dates back to 1460 when Count Gaspare Vimercati,

Legend

- 1 Chapel of Our Lady of the Rosary
- 2 Church built by Guiniforte Solari
- 3 Tribune
- 4 Small Sacristy
- 5 Coister of the Frogs
- 6 Old Sacristy
- 7 Cloister of the Prior
- 8 New Sacristy
- 9 Chapter House
- 10 Locutory
- 11 Cloister of the Dead
- 12 Cloister of the Dead's Northern wing, above which is the Library.
- 13 Refectory

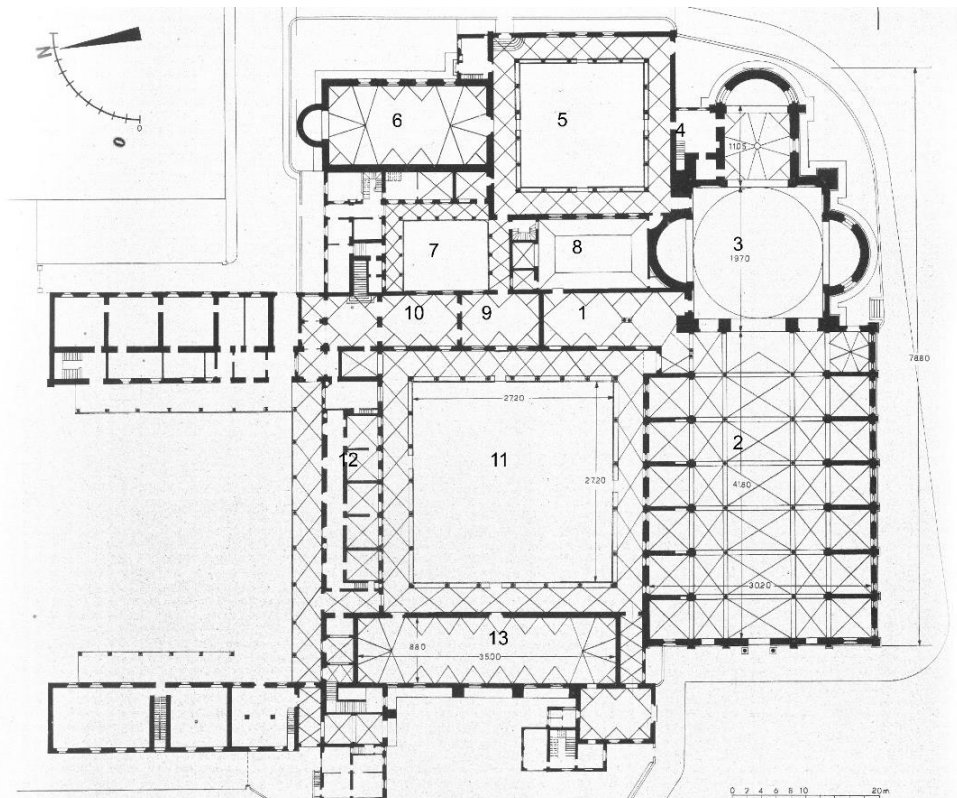


Figure 2: Plan of the convent of Santa Maria delle Grazie, 1937 (by A. Pica).

commander of Francesco Sforza's militia, donated the land on which a small chapel dedicated to Our Lady of the Rosary was located to the Dominican friars of Milan, to allow the construction of a church and a convent. The project, entrusted to Guiniforte Solari, was influenced by the presence of the military camps and the chapel. Construction works officially began on 10 September 1463. After the death of Francesco Sforza and Gaspare Vimercati, in 1466 the Dominican order received funding to continue the works of both the convent (completed in 1469) and the church (completed in 1490) (AAVV, 1983). In 1492, the new Duke Ludovico il Moro called "experienced architects" (Gattico, 2004) to transform the complex according to the Renaissance style. Probably Bramante was commissioned to replace the original apse of the church with a new Tribune, and to project the Cloister of the Frogs and the Sacristy (completed at the beginning of the 16th century, after the fall of the Sforza family), Leonardo da Vinci was instead commissioned the Last Supper inside the Refectory.

After the fall of the Duke in 1499, the Duchy of Milan was conquered by the French and, in 1535, passed to the Crown of Spain. The decoration of the convent continued throughout the 16th and 17th centuries.

In 1539 the convent became the seat of the Tribunal of the Inquisition and it was enlarged with the addition of a new wing (leaning against the Refectory), which was demolished in 1785, when the Inquisition was suppressed. As was customary in the Napoleonic era, in May 1799 the building was transformed into a military barrack and the friars were shifted to other convents.

In 1899 the military withdrew from the convent, which became a State property and was entrusted to the Superintendence. Only from 1924 the entire complex returned to the Dominican order (except for the Refectory, which remains a State property) (Martelli, 1980; Gattico, 2004).

Throughout the period between 1899 and the 1930s, various restorations took place involving, among others, the architect Luca Beltrami. In 1935, the decorations of 1840 that covered the interior of the church were completely removed, bringing to light the original frescoes in the nave and the aisles and the graffiti decorations of the Tribune (Fig. 3). Outside, the apse was freed from the buildings that were leaning against it and the bell tower was rebuilt lower, according to the style of the Tribune.



Figure 3: Church of Santa Maria delle Grazie, interior before the 1935 restoration.

Between 13 and 16 August 1943, during the Second World War, a heavy bombardment hit the church and the convent, causing serious damage to the tholobate, the collapse of one of the vaults of the nave and the almost total destruction of the Cloister of the Dead and the Refectory (some walls of the latter survived, including the one that houses the Last Supper, which had been sandbagged to protect it) (Fig. 4).

Extensive restoration work began in the summer of 1945 and lasted until 1974, when the convent was officially reopened to the public.



Figure 4: Period photo of the Cloister of the Dead after the 1943 World War Two bombing attack.

4. Adopted methodology

The complex of Santa Maria delle Grazie represents an architectural palimpsest (word deriving from the Ancient Greek palímpsēstos, "again scraped") since it is characterized by overlapping of interventions and additions ranging from the original 15th century core to the most recent 20th century restoration work. This means that remains of different buildings from different periods coexist in a single artefact. For this reason, the research has focused on reconstructing the main development phases of the most important environments of the convent (Cloister of the Dead, Refectory, Bramante's buildings, New Sacristy and Cloister of the Prior) from its origins (the 60s of the 15th century) to date, creating 3D databases that can be easily consulted and, if necessary, updated by researchers and experts in the field. The methodology adopted to achieve this goal is characterized by four stages that are summarized below:

- Cognitive phase: it consists in the study of the state of affairs and the consequent analysis of historical sources (archival documents, correspondence between clients and experts, restoration projects, period photos, sketches provided by the friars).
- Surveying phase: it consists in the acquisition of the metric, geometric and material information of the actual state of the complex through the use of photogrammetric and laser scanning techniques. Through the data acquired during the digital survey, it was possible to obtain extremely accurate models of the current configuration of the surveyed environments.
- Comparison phase: the cross-checks between written documents, digital survey data,

two-dimensional elaborations, period photos, 20th century sketches, Renaissance architectural treatises, etc. made it possible to verify the reliability of many reconstructive choices, especially in cases where elements that no longer exist had to be correctly modelled and sized.

- Digital reconstruction phase: all the collected data were channelled into various 3D models in order to describe the diachronic succession of the transformations of the convent from around 1463 to date. It is not a mere visualization but is part of the interpretative and cognitive process since it helps to verify the reconstructive hypotheses and to identify possible new solutions.

The 3D model obtained from this workflow is therefore configured as a digital palimpsest that must be segmented through a stratigraphic approach in order to make visible the virtual reconstruction of each historical period (Demetrescu, 2018).

Finally, to ensure adequate scientific rigour and high transparency in the decision-making process, the components of the 3D models have been associated with the information about their level of accuracy, which depends on the types of data used for the digital reconstruction.

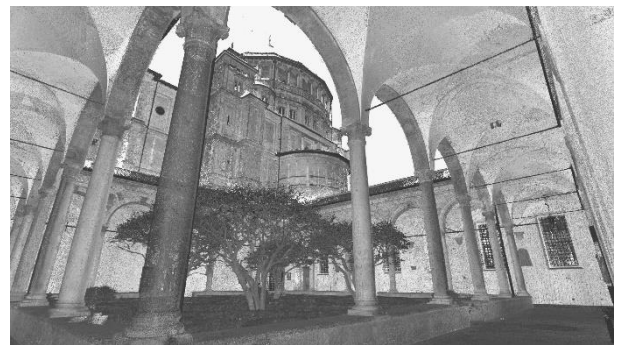
5. Digital surveying campaign

Considering the complexity of the case study (in terms of morphologies and textures), Terrestrial Laser Scanning (TLS) has been chosen as the best solution to survey the building geometric features; photogrammetry was used to reconstruct the most complex and interesting chromatic information. The instruments used were a Leica HDS 7000, a Leica ScanStation P30 (Fig. 5) and a Canon EOS 70D camera equipped with a traditional lens. The first is a phase-based laser scanner, characterized by a speed acquisition of more than 1 million points/s and a linear error less than 1 mm. The laser acquisition range is from 0.3 m to 187 m, with an average accuracy of 0.5 mm when the scan is less than 10 m from the surveyed object. The second TLS is characterized by a scanning speed of 1 million points/s, and a range that goes from a minimum of 0.4 m to a maximum of 120 m. It is equipped with an integrated HDR camera with a resolution of 4 megapixels for each image 17° x 17°, 700 megapixels for panoramas. Finally, the Canon used for the photogrammetric survey is a reflex camera, with a 20.2 megapixel APS-C CMOS sensor (22.5 x 15 mm) and equipped with a 18 mm lens.

The research group acquired 53 scans with the laser scanners and collected a photographic dataset of the most characteristic elements such as the decorations of the Small Sacristy, the elegant frescoes of the vault of the Old Sacristy, the wall of the Tribune that delimits the southern side of the New Sacristy, some decorative elements of the Cloister of Frogs. The laser scans were processed within the Cyclone software v. 9, obtaining a highly detailed point cloud of approximately 800 million points. The collected photographic dataset instead was processed within the photogrammetric software Metashape v. 1, obtaining point clouds of the decorative elements, subsequently geo-referenced with the reference system of the laser scanner point cloud.



(a)



(b)

Figure 5: (a) Leica ScanStation P30 at work; (b) Detail of the laser scanner point cloud.

6. 3D modelling

To reconstruct a reliable model from a scientific point of view, two modelling approaches were followed:

- Reality-based modelling, i.e. the virtual reconstruction of existing contexts, based on the metric data acquired during the in-situ survey campaigns. Specifically, the point cloud obtained through the combined survey was imported within the CloudCompare v. 2 software where it was converted into a mesh. The latter was used to reverse model, i.e. to obtain a mathematical model from the real data, through the extraction of directories and generators that identify the geometric genesis.
- Source-based modelling, i.e. the virtual reconstruction of the lost contexts, based only on documentary sources (period photos, technical drawings, sketches, treatises, etc). This modelling approach involves a phase of interpretation and elaboration of reconstructive hypotheses that inevitably lead to inaccuracies.

In the first case, the model accuracy is based on quantitative data and can, therefore, be expressed in units of measurement, while in the second case it is based on qualitative data since it derives from merging different sources with different levels of reliability. The result of the first approach is a closed output that is not intended to be modified in the future, instead, the result of the second approach is iterative and generates an open output that can be modified and improved (Demetrescu, 2018).

The tool used for digitally reconstructing the complex is Rhinoceros v. 6, a software for 3D modelling of free form

surfaces, based on Non-Uniform Rational Basis Spline (NURBS) algorithms. The choice of the software was dictated by the need to accurately model complex elements, deformations and irregularities typical of historical heritage (an operation difficult to achieve with other modelling software).

The environments analysed, their evolution over time and how they have been digitally reconstructed are described in detail below.

6.1. Cloister of the Dead

6.1.1. 1464 – 1480

The cloister was built in 1460s. Together with the church, it constitutes the oldest core of the convent (prior to Bramante's interventions, which would have led a few years later to the creation of the Tribune, the Old Sacristy, the Cloister of Frogs, etc.). This environment was built taking into account the pre-existences, represented by the Chapel of Our Lady of the Rosary and perhaps the Chapter house and the Fire Room, which are an extension of the chapel. These ancient environments delimited the eastern side of the cloister and probably determined the entire development of the convent, as well as the size of the church (whose width was limited between the Chapel of Our Lady of Grace and the street).

Between 1464 and 1469, at Gaspare Vimercati's behest, the upper floor of the eastern wing was built above the Chapel and the Chapter house in order to host the friars' dormitories. This building originally had small windows overlooking the cloister (probably two for each bay of the portico below). Gattico mentions some disagreements between the count and the friars, who would have liked modest rooms with a flat roof, while Vimercati provided a higher and vaulted environment.

In 1469, therefore, the east side of the cloister was on two levels, while the remaining three sides were made up only by the cross-vaulted portico, without elevations. The four sides of the portico had a variable number of arches: eight on the east side with regular centre-to-centre distances, not corresponding to the windows of the Chapter house and the chapel, six on the west and north sides, five on the south side, bordering the church, where the arches number and width were determined by the centre-to-centre distance between the side chapels windows.

The 3D reconstruction of this historical phase was particularly difficult due to the few sources available: the site was modelled essentially based on the descriptions by Gattico. When these descriptions were not sufficiently exhaustive, assumptions were made. This criterion was used, for example, to model the pitched roofs: specifically, concerning the environment on the northern front, it was decided to model a simple double-pitched roof, considering that the interior of this building still probably housed a single environment without internal partitions (which leads to excluding more complex roofing solutions).

A similar criterion was followed to reconstruct the openings of the Refectory: in the absence of reliable information on the matter, we modelled the 1495 small squared openings.

As regards other elements such as the arches and the portico, which remained unchanged until 1943, it was carried out a more accurate reconstruction, based not

only on the plan of 1897 (drawn starting from descriptions by Gattico), which made it possible to obtain the intercolumns and the dimensions of the cross-vaulted bays, but also on the 1937 sections by A. Pica and the photographs taken between the end of the 19th and the beginning of the 20th century. The latter documents ensured a faithful reconstruction of the columns, the capitals (which appear as a variant of the Corinthian capital, with two orders of simple leaves, four smaller and four larger in angular position) and the curvature of the arches, which are stilted on the east side (under the dormitories), slightly segmental on the north and west sides, and markedly segmental with strong asymmetries on the south side. In the case of the segmental arches, the study of the curvature revealed a geometrical scheme based on a single centre: each of these arches was built following the profile of a single circumference arc with a centre lower than the springing line (Fig. 6).

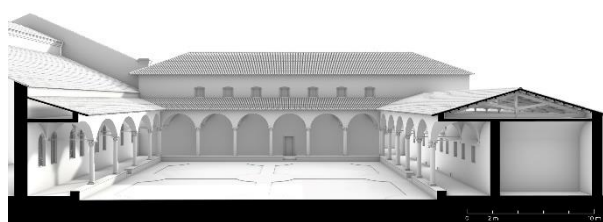


Figure 6: Digital reconstruction of the Cloister of the Dead before 1480: west-facing perspective section.

6.1.2. 1480 – XVI century

In 1480 a second level housing the library was built above the north portico, about 1 m higher than the pre-existing dormitory level. The other two sides of the cloister remained on one level. This arrangement probably lasted until the 16th century: the cloister must have this appearance when Donato Montorfano and Leonardo da Vinci decorated the Refectory.

The reconstruction of the northern wing in this historical phase was more accurate than in the previous one: the library and the roofs are documented by the Pica's works, which made it possible to obtain a discrete metric accuracy (Fig. 7).

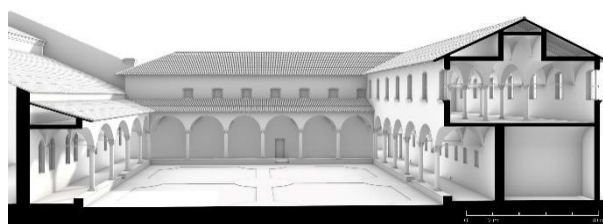


Figure 7: Digital reconstruction of the Cloister of the Dead shortly after 1480: west-facing perspective section.

6.1.3. XVI century – Beginning of the 1900s

In an unspecified period between 1495 and 1595, two loggias were built above the arches of the south and the west side. Their existence is attested by Gattico in 1595, when the Inquisition was granted the use of the loggia adjacent to the Refectory. Their construction led to a radical change in the roofs of the church and the Refectory: in particular, a mono-pitched roof covering half the church and the south side loggia was built.

In 1602 the small windows of the dormitory were replaced by 7 larger windows. One of the original small openings survived in the south-east corner.

Probably in the second half of the 17th century, after Gattico's death, the windows of the Refectory were also modified¹: the small square openings placed in the lunettes were replaced by larger rectangular windows placed at the level of the loggia floor (as shown by an 1879 section). The cloister was preserved in this configuration for over two centuries, until the beginning of the 20th century (Fig. 8).



Figure 8: Period photo of the Cloister of the Dead between the end of the 19th century and the beginning of the 20th century.

The 3D modelling of the main elements dating back to this historical period has been made particularly reliable thanks to the drawings by Pica and a discrete 19th century photographic documentation, in particular an 1893 picture of the south-west corner, showing the loggia, the openings and the garden (Fig. 9).

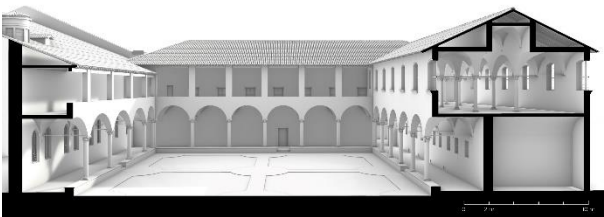


Figure 9: Digital reconstruction of the Cloister of the Dead after 1647: west-facing perspective section.

6.1.4. Beginning of the 1900s – 1943

Between the end of the 19th and the beginning of the 20th century, the two loggias on the first level were closed by large windows. More or less in the same period, starting from 1891, Beltrami restored the Refectory, bringing back the openings in their presumed late 15th century configuration: the large rectangular windows were therefore eliminated and were replaced with small square windows. At the same time, the garden characterized by a simpler geometric design of the flowerbeds was modified.

¹ It is likely that this intervention was made after Gattico's death in 1647: this explains why he does not mention it, even though

Until this period, the presence of frescoes on the internal walls of the portico and the arches (decorated with geometric motifs) is documented (Fig. 10).

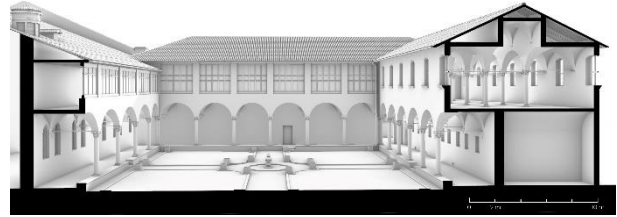


Figure 10: Digital reconstruction of the Cloister of the Dead shortly before 1943: west-facing perspective section.

6.1.5. 1943 – to date

The 1943 bombings caused the almost destruction of the cloister. In the post-war period, the cloister underwent partial and inhomogeneous restoration work: only the east and the west side of the portico were rebuilt as the originals (but without paintings): the dormitories, the library and the two loggias disappeared. The north side building was rebuilt according to a rationalist style, dissonant with the rest of the complex, and its walls were detached from those of the Refectory, whose east side was rebuilt without windows. The roofs of the church and the Refectory were restored to a configuration similar to the 16th century one (before the loggias were built). Finally, the cloister garden was redesigned following a geometry similar to the oldest configuration.

In modelling the current state of the cloister, it was possible to refer to satellite images, which allowed an accurate reconstruction of the roofs and buildings in their present configuration (Fig. 11).

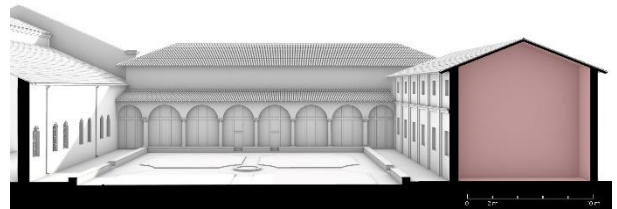


Figure 11: Digital reconstruction of the Cloister of the Dead in its current configuration: west-facing perspective section. In red, the not surveyed environments.

6.2. Library

Summarily mentioned by Gattico and documented by some period photos published in the essay by Arnaldo Bruschi, the Library consisted of a single room with a nave and two aisles divided by columns and surmounted by vaults. The nave, higher and narrower than the aisles, had no windows and was covered by nine cross vaults; the aisles, instead, were lit by seven large rectangular windows (one per bay) and covered by seven cross vaults. The environment was therefore characterized by low and bright lateral spaces, suitable for consulting books, and by a high and shaded central space used as a corridor. The proportions of the environment and the position of the columns were probably determined by the walls of the five cells below.

he was always extremely scrupulous in describing the changes that occurred to the complex until the years in which he had lived.

The library was entirely destroyed during the 1943 bombings and was no longer rebuilt. In order to model this environment, reference was first made to the plans and sections by Pica, which made it possible to accurately reconstruct the correct proportions and the curvatures of the vaults and the segmental arches. To recompose the original spatiality, we compared it with other similar rooms, in particular the Biblioteca Malatestiana in Cesena (1452) and the Michelozzo's Library in Florence (1454), which represent the prototype of the Renaissance libraries and have a layout extremely similar to that of the analysed one (probably influenced by the presence of Tuscan masters in Milan in the 15th century). We used a period photo of the interior to reconstruct in detail the decorative elements, such as the Corinthian capitals, the columns shafts and the corbels on which the vaults rest (Fig. 12).



(a)



(b)

Figure 12: Library: (a) Period photo showing the environment before the 1943 bombing; (b) Digital reconstruction.

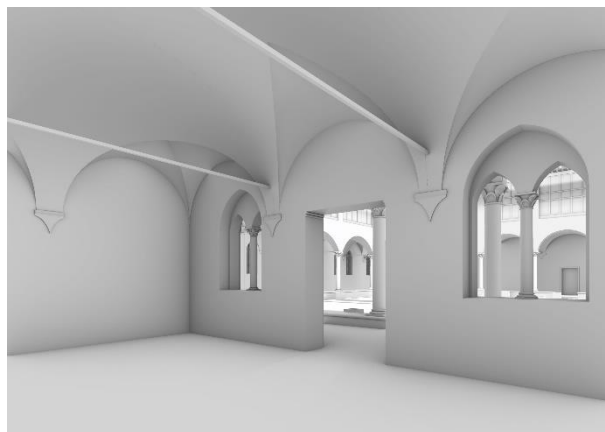
6.3. Chapter House and ancient Locutory

The Chapter House is probably one of the oldest rooms of the entire complex: together with the adjacent Locutory, called Fire Room (identical to the first in terms of size and vaults geometry), it is an extension of the Chapel of Our Lady of the Rosary. The original appearance of this environment, heavily damaged during the 1943 bombings, was reconstructed thanks to technical drawings and period photos (in particular, a section and

a plan by Pica, one photo by Zuecca (1930) taken from the Cloister of the Dead, one 1929 drawing by G. Ramorino and one photo taken just after the bombing). These sources were fundamental to reconstruct the openings and the complex lunette barrel vault, generated from a three-centred arch, and ending with two semi-domes on the short sides (Fig. 13).



(a)



(b)

Figure 13: Chapter House: (a) Period photo of the room just after the 1943 bombing; (b) Digital reconstruction.

6.4. Refectory

6.4.1. 1467 – 1495

The Refectory was built around 1467 and was completed around 1488. The vault was probably built by Bramante in the final phase of the works. This hypothesis seems to be supported by the similarities between the vault of the Refectory and that of the Old Sacristy.

In its first configuration, the big room had perhaps nine low rectangular windows on the west wall, close to the floor². These original windows were probably closed not long after the Vimercati's death in 1467 (Gattico, 2004): in this period, in fact, the buttresses in the west wall were built without taking into account these ancient openings, which had been consequently walled up before.

Given the lack of information in this regard and the many doubts regarding the actual position of the windows on the east side, it was decided not to reconstruct this very early

² Traces of these windows were found during Beltrami's late 19th century restoration work.

historical phase, which, however, seems to have been short-lived.

Immediately afterwards, eight small square windows (about 1.3 x 1.3 m) were opened in the lunettes on the west wall, seven in the lunettes on the east wall (the window of the lunette next to the Last Supper was painted, since here the wall bordered the library).

In 1495, Donato Montorfano painted the fresco of the Crucifixion on the south wall and, probably, the bands on the long sides depicting a false entablature (Martelli, 1981).

It was chosen to digitally reconstruct this configuration, considering that this historical phase, between about 1488 and 1495, is documented in a sufficiently precise manner to give an accurate idea of the interior layout during this period.

Based on the drawings by Pica and Martelli, it was possible to model the room, with its 35 x 8.80 m plan based on the repetition of four square modules, and the elaborate barrel vault, generated from a three-centred arch, ending with two half umbrella vaults and intersected with ten lunettes on each long side. In the absence of detailed drawings showing it before its destruction in 1943, the vault was modelled on the basis of the geometric rule extrapolated from the vault of the Old Sacristy. The analogies between the two vaults support the hypothesis that both were realized in the second half of the 15th century by Bramante (Fig. 14).



Figure 14: Digital reconstruction of the Refectory shortly after 1488: north-facing perspective section.

6.4.2. 1495 - 1650s

Around 1498, Leonardo da Vinci completed the Last Supper, painted on the northern wall, exactly in front of the Crucifixion of Montorfano. In the same years, probably on the impulse of Leonardo, the windows on the west side were modified to allow better lighting conditions for his painting: specifically, the eight small square windows were all walled up and replaced by six larger windows (about 1.7 x 2.9 m) in correspondence of the lunettes II, III, IV, VI, VIII, IX counting from the south wall (interrupting the old pictorial decoration), while lunettes V and VII were left without openings. The windows of the east wall were not modified.

After the construction of the inquisitor's offices (next to the west side of the Refectory) in the 16th century, the window in lunette II on the west side was walled up, although its internal profile was not modified (Fig. 15).



Figure 15: Digital reconstruction of the Refectory shortly after 1495: north-facing perspective section.

6.4.3. 1650s - 1891

Around 1650 the Refectory was heavily modified: to standardise the windows on the two long sides and increase the amount of light coming from the eastern front (changed because of the addition of the loggia of the Cloister of the Dead), it was decided to replace the seven ancient 15th century windows on the eastern wall with seven large windows measuring about 1.7 x 2.3 m. The Leonardesque openings were then shortened and two new windows were added in the lunettes V and VII, which had been left unopened since Leonardo's era. As a result of this intervention, the Refectory had equal and symmetrical openings on both sides. In the same period, the paintings on the longitudinal walls (increasingly damaged by the continuous changes of the openings) were probably covered with white plaster.

In 1652, the little door (dating back to 1625) underneath the Last Supper was enlarged and raised: this operation led to the loss of the lower part of the painting, including the feet of Christ and some Apostles.

In the Napoleonic era, the convent was requisitioned and transformed into a barracks and the Refectory, probably plastered in white (with the only exception of the north and south walls), was converted into a stable and disfigured by the addition of a wooden loft next to the Crucifixion by Montorfano. To make the loft accessible, a door was opened in the lunette I of the east wall (right at the corner with the Crucifixion), in order to connect the Refectory to the loggia of the Cloister of the Dead.

The 17th century configuration, still existing until 1891, is, unfortunately, the least documented: this intervention is known only by the few traces surviving on the west wall, by the reports drawn up by Beltrami at the end of the 19th century and by the historical reconstruction conducted by Martelli. Other documents, such as drawings or photographs from the mid-19th century providing a clear image of the Refectory as it appeared before 1891, no longer exist (probably because they were destroyed during the Second World War) (Fig. 16).



Figure 16: Digital reconstruction of the Refectory between 1650 and 1891: north-facing perspective section.

6.4.4. 1891 – 1943

The Refectory was restored by Luca Beltrami in 1891, in order to re-establish the late 15th century state, contemporary to Leonardo. During the restoration, the whitewashings were removed, bringing to light the surviving traces of the painted frieze. After finding the traces of the 15th century openings, all the windows were brought back to their Leonardesque age configuration: specifically, on the east wall all the 17th century windows were walled up and the square windows in the lunettes were reconstructed; on the west wall, instead, the large windows of lunettes V and VII were occluded, while the remaining six windows, shortened during the intervention of the 17th century, were brought back to their original dimensions. The missing parts of the painted frieze on the long walls were finally reintegrated (Fig. 17).



Figure 17: Period photo of the Refectory shortly after the restoration by Beltrami.

The results of Beltrami's intervention are amply documented by the later drawings by Pica, as well as by many photographic shots, showing the painted frieze, the vault above the Last Supper and the 15th century windows rebuilt at the end of the 19th century (Fig. 18).



Figure 18: Digital reconstruction of the Refectory between 1891 and 1943: north-facing perspective section.

6.4.5. 1943 – to date

As mentioned, during the 1943 bombings, the Refectory was heavily damaged: the vault and the east wall were completely destroyed, while the Last Supper and the Crucifixion, fortunately, survived, together with the west wall. After the war, the vault was rebuilt according to the original geometry, while the east wall was rebuilt without the original decoration and the door connecting with the Cloister of the Dead, recently reopened. The small square windows by Beltrami, initially rebuilt, were occluded shortly after (Fig. 19).



Figure 19: Digital reconstruction of the Refectory in its current configuration: north-facing perspective section.

6.5. Cloister of the Frogs

6.5.1. End of the 15th century – Napoleonic era

The Small Cloister, also called the Cloister of the Frogs because of the sculptures that adorn the fountain, is one of the environments dating back to the second construction phase of the convent, promoted at the end of the 15th century by Ludovico il Moro, and was conceived as a connecting space between the new Tribune and the

Old Sacristy; they are therefore probably part of the renovation project attributed to Bramante. In 1497, the cloister was already built (Zanzottera, 2015b), although the last interventions are documented around 1504, a few years after the fall of Ludovico and the beginning of the French domination. The small cloister, with its harmonious proportions and the decorative details similar to Bramante's contemporary interventions in the basilica of St. Ambrogio, has a perfectly square single storey layout and a four-sided cross-vaulted portico, bordered on each side by five round arches resting on Corinthian columns. Critics believe that the terracotta profiles of the arches and the entablature should have originally had a white surface decoration simulating marble, probably similar to the one in the interior of the Tribune.

Considering the similarities between the 15th century cloister and its current configuration, both the 1897 plan and the 2019 survey data were used for digital reconstructing this phase (Fig. 20).

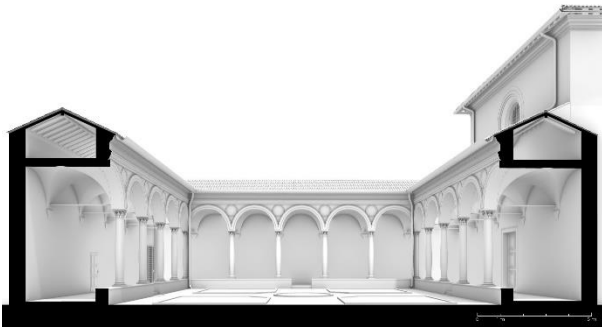


Figure 20: Digital reconstruction of the Cloister of the Frogs before the Napoleonic era: west-facing perspective section.

6.5.2. Napoleonic era – 1901

After the suppression of monastic orders in the Napoleonic era and the consequent conversion of the convent into military barracks in 1799, a period of misuse of the complex began. In these years, the eastern front of the apse, the Cloister of Frogs and the Bramante Sacristy were probably occluded by dilapidated popular houses, and the portico of the cloister was burdened with the addition of a second windowed level, while some arches were walled up. The rooms on the second level were used as accommodations for the military authorities until 1896, before the demolitions decided by Superintendent G. Moretti.

Considering the lack of adequate documentation, this historical phase was digitally reconstructed using photographs depicting the state of affairs between the end of the 19th and the beginning of the 20th century; in particular, the external volumes were modelled using an 1893 photo, which frames the Tribune, the Cloister of the Frogs, the Old Sacristy and the partially demolished buildings. The interior of the cloister was instead modelled using 20th century images showing the second level during the demolition (Fig. 21).

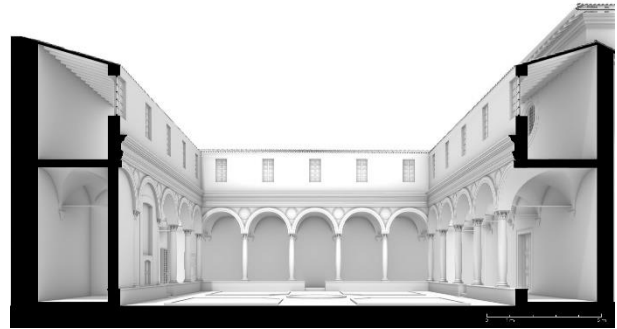


Figure 21: Digital reconstruction of the Cloister of the Frogs between 1799 and 1901: west-facing perspective section.

6.5.3. 1901 – to date

The demolition work continued until about 1901, when the interior of the cloister was restored to its original configuration by demolishing the second storey and freeing the obstructed arches. Four large rectangular windows were opened on the wall common to the New Sacristy. The 1943 bombings did not seriously damage this environment³, so this arrangement remained almost unchanged to date, except for two large windows added on the western side (Fig. 22).

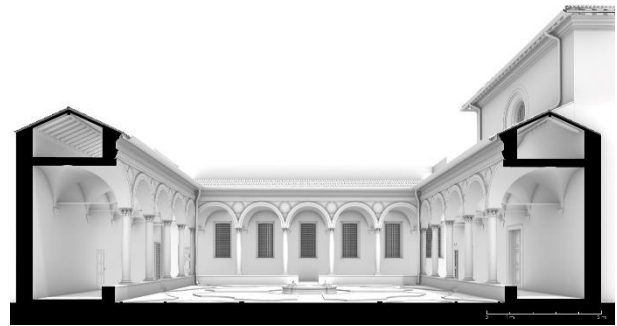


Figure 22: Digital reconstruction of the Cloister of the Frogs in its current configuration: west-facing perspective section.

6.6. Old Sacristy

6.6.1. Late 15th century - Napoleonic era

The Bramante Sacristy, also called the Old Sacristy to distinguish it from the New Sacristy, was built by Bramante in the 1490s, next to the northern side of the coeval Cloister of the Frogs. It was unusually isolated from the church to emphasize the grandeur of the Tribune.

The sacristy was completed by the 15th century, although most of the decorative apparatus was probably realized shortly after 1499, the year of the fall of Ludovico and the beginning of French domination. This is the case of the entrance door, whose lunette (by Bramantino) depicts St. Louis of France, and the wooden furnishings of the interior. In this regard, only the pilasters and the first two doors of the furniture on the left side are decorated with inlays, while the remaining parts are painted in false inlay, probably meaning that the work was completed in

³ During the bombardments, the Cloister of the Frogs was hit by some firebombs, but the fire that spread was courageously

extinguished by the Dominican friars, who had regained possession of the convent in 1924.

economic constraints (after the expulsion of Ludovico from Milan).

The sacristy, in its 14th-16th centuries configuration (which has remained largely unchanged), was a rectangular room (about 11 x 22 m) covered by a barrel vault with umbrella-shaped heads, ending with a small semi-circular apse in the northern wall. Between the 15th and 16th centuries, a starry sky was painted on the vault, probably similar to the one painted in the Refectory. The particular geometric motifs depicted in the ribs of the vault have led some scholars to attribute these paintings to Leonardo da Vinci. Below the vault, the high frieze of the entablature was painted with decorative motifs depicting dragons and shells. The sacristy was probably illuminated by ten rose windows placed in the lunettes (four on each long side, one on each short side) and by eight lower rectangular windows (four on the eastern wall and four on the western wall) documented in the 1897 plan.

Considering the few changes the sacristy underwent compared to its initial layout, the 2019 survey data were used as a basis for accurately modelling the building in this historical phase, with particular attention to the elaborate vault. In this regard, the laser scanner numerical model was used to carry out an in-depth analysis, from which the geometric rule underlying the construction of the vault was obtained, whose curvature is based on a segmental three-centred arch. This geometrical study was essential for reconstructing the geometry of the Refectory vault (similar to the sacristy vault), difficult to interpret because of the lack of documentation and the destruction caused by the war (Fig. 23).

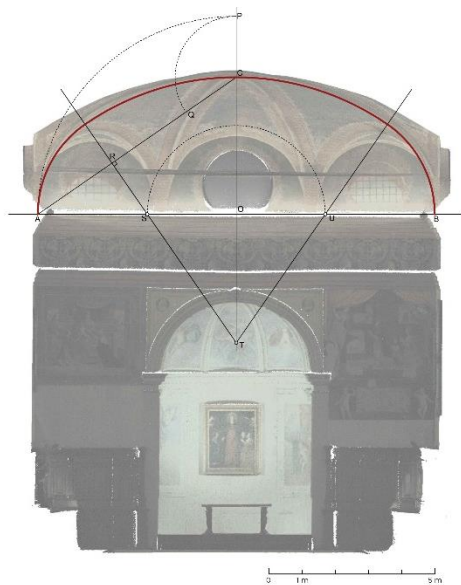


Figure 23: Geometric rule underlying the construction of the vault.

The original 15th-16th centuries openings have been modelled taking as a reference the 1897 plan, which shows the four rectangular windows, no longer existing, located in the west wall (Fig. 24).

6.6.2. Napoleonic era – 1901

After the occupation of the convent by Napoleon's troops, the south and west walls of the sacristy were probably completely concealed by the addition of new buildings.

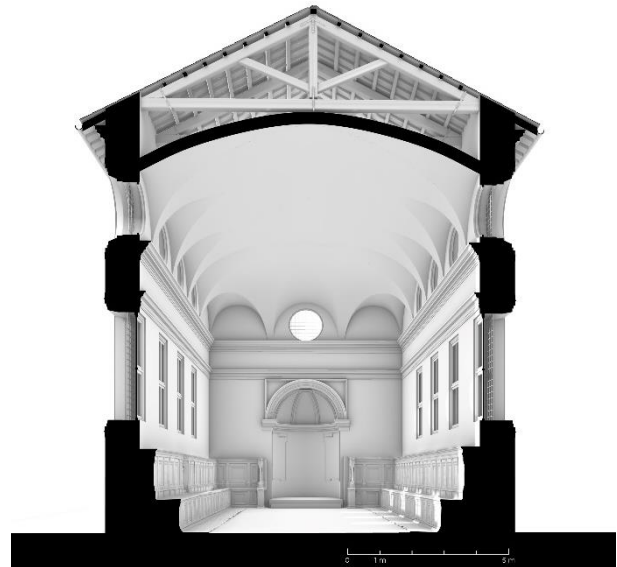


Figure 24: Digital reconstruction of the Old Sacristy before the Napoleonic era: north-facing perspective section.

In this phase, the rectangular windows and the rose windows of the west wall were probably walled up. This was the only significant modification that directly affected the Bramante's building in this historical period.

The digital reconstruction of this configuration was particularly difficult because of the lack of documentary sources: the modelling was based only on some photos from 1900, depicting the additions in the Cloister of the Frogs (Fig. 25).

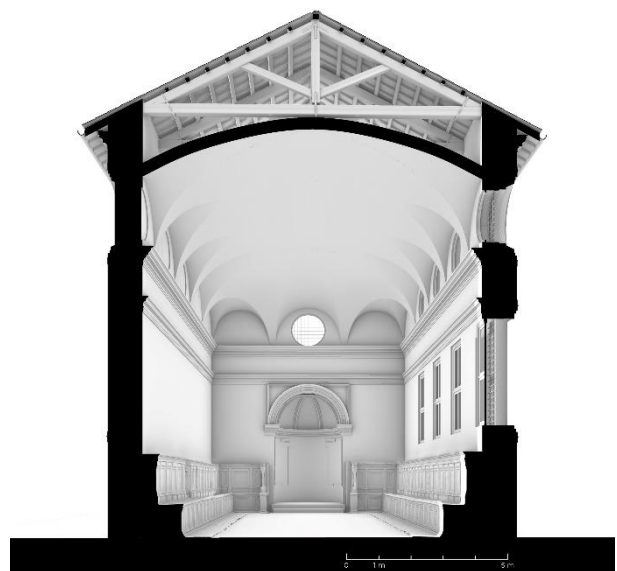


Figure 25: Digital reconstruction of the Old Sacristy before 1901: north-facing perspective section.

6.6.3. 1901 – to date

Around 1901, the additions leaning against the western and the southern walls of the sacristy were demolished. In the immediate post-war period, three of the four rose windows of the west wall were reopened, while the four rectangular windows remained obstructed (Fig. 26).

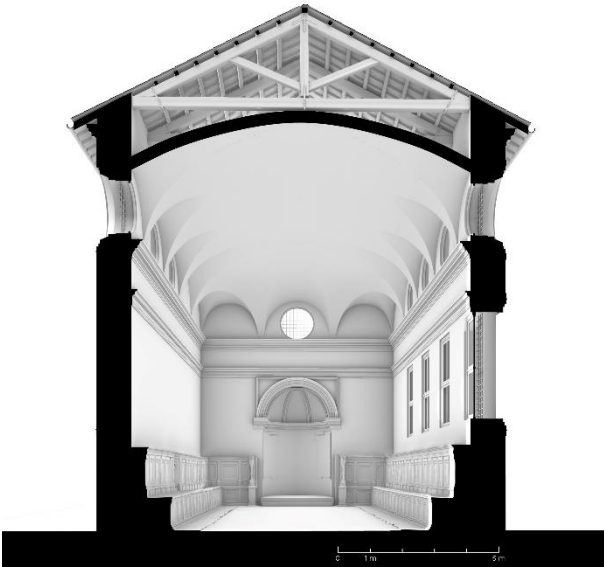


Figure 26: Digital reconstruction of the Old Sacristy in its current configuration: north-facing perspective section.

6.7. Small Sacristy

6.7.1. Late 15th century - Napoleonic era

During the construction of the Tribune, the Cloister of the Frogs and the Sacristy, the problem of communication between the new church choir and the cloister was probably solved through the creation of a new room, called Small Sacristy, obtained in the space between the north wall of the choir, the bell tower and the south side of the cloister. This environment, probably a one-storey building with a mono-pitched roof, was connected to the presbytery through the base of the bell tower or through a second opening, obtained between the wooden stalls of the choir. This passage was opened after the construction of the Tribune, as documented by the stratigraphic analysis carried out during the last restoration. A third door on the north side led into the Cloister of the Frogs. One of the first historical sources that mention the origins of the Small Sacristy is the *Libellus Sepulchrorum* by S. Aldeni, which identifies the small room with the chapel of S. Martino, located "[...] prope murum chori [...]". Although it is not possible to understand when the chapel was built, the information contained in Aldeni's manuscript allows us to establish that the origins of the chapel certainly date back to before 1520. The 16th century decorative apparatus of the walls is characterized by four circular frames, surrounded by panels with refined floral decorations and depicting half-length saints: on the south wall, St. Peter the Apostle and St. Dominic; on the north wall, St. Peter from Verona and St. Paul the Apostle. In the central sector of the east wall, immediately below a fresco depicting St. Martin (detached from the original support and applied on canvas), a fragment of a wall painting depicting a Virgin and Child, probably painted by Leonardo, was found during the 2006 restoration.

6.7.2. Napoleonic era – 1901

The roof was perhaps raised when the various additions were built above the Cloister of the Frogs. There is no precise documentation of this phase except for a photo of the end of the 19th-beginning of the 20th century that shows a sign that the old covering probably left on the wall of the Tribune (Fig. 27).



Figure 27: Period picture showing the roof of the Small Sacristy.

6.7.3. 1901 – to date

After demolishing the additions of the Cloister of the Frogs, maybe the Small Sacristy was lowered again, as proved by the photo of the end of the 19th-beginning of the 20th century showing a low mono-pitched roof. This layout probably remained unchanged until the immediate post-war period, when the New Sacristy with its panoramic terrace was rebuilt and the roof of the Small Sacristy was incorporated into the new terrace.

6.8. Cloister of the Prior and New Sacristy

6.8.1. 1901 - 1946

The history of the Cloister of the Prior (often named by the sources Cloister of the Rector) and that of the New Sacristy are closely connected: in fact, they seem to have been conceived in a relatively recent historical period, in the context of the same restoration works, and have undergone some troubling events, despite their short history.

The area currently occupied by the Cloister of the Prior and the New Sacristy was originally an open space, bordered to the north by Via Sassi, to the east by the Sacristy of Bramante and the Cloister of the Frogs, to the south by the Tribune of the church and to the west by the wing of the convent where the Chapel of Our Lady of the Rosary and the Chapter House were located. This original configuration is documented by the 1897 plan, according to which this area was used as a cemetery of the plague victims in the 17th century. Between the 17th and 19th centuries, this old cemetery was perhaps partially obstructed by various additions built near the Old Sacristy

and the Tribune. These constructions are not documented by any drawing, but they are partially visible in some photos, which show the buildings during the demolition of the second level of the Cloister of Frogs. According to the documents of the Sistema Informativo dei Beni Culturali di Regione Lombardia (Zanzottera, 2015a), the New Sacristy was built in 1901 in the space between the Cloister of Frogs, the northern apse of the Tribune and the Chapel of Our Lady of the Rosary. Another source supporting this dating is the 1869 map of Milan by G. Prada which shows the convent of Santa Maria delle Grazie still without the Cloister of the Prior and the New Sacristy. The construction of the sacristy was dictated by the need for the friars to have newly available spaces next to the church, since, at the beginning of the 20th century, the entire complex (except the church) was still a State property, and therefore the Dominicans could not use it. It is likely that the Cloister of the Prior was built in the same years, bordering the northern side of the New Sacristy. One of the oldest sources proving with certainty the existence of this small environment is a 1906 photo, which frames the east and north sides of the cloister court.

In its original configuration, the New Sacristy appeared as a simple rectangular room measuring approximately 10 x 15 m, covered by a keel vault and lit by four rectangular windows surmounted by lunettes opening onto the Cloister of Frogs. The southern front of the sacristy, bounded by the convex surface of the Tribune apse, was rectified with a wall that entirely concealed it.

The sacristy was digitally reconstructed starting from the section by Pica (which shows, in a schematic way, the height of the room and the curvature of the vault) and some Second World War photographs which show the sacristy during the demolition works: from these images, it has been possible to deduce the curvature of the four lunettes on the eastern side (Fig. 28).

The Cloister of the Prior, on the other hand, was a two-storey neo-Renaissance style environment, with a configuration similar to that of the Cloister of the Dead: the first level consisted of a cross-vaulted portico on three sides, with slightly stilted arches, resting on Corinthian columns similar to those of the Cloister of the Dead; the second level was instead characterized by an open loggia with a wooden roof, supported by similar but lower columns than those on the first level.

The plans by Pica, the 20th century photos and a sketch supplied by the friars were used to digitally reconstruct the correct proportions of the portico, the loggia, the courtyard, the doors and the windows. To trace the correct sizing of the shafts and capitals of the columns, straightened and scaled photographic images were compared with the modular schemes typical of the Corinthian columns according to the Renaissance treatises. In particular, the height of the column follows the Vignola rule for the Corinthian order (height equal to about 9 and a half diameters of the shaft), the taper follows the Vignola rule for the Doric order (consistent with the simplicity of the column), while the base follows the attic style, typical of classic Corinthian columns (Fig. 29).

The roofs were reconstructed using some photos taken after World War Two, which show the sign left by the roof of the old Cloister of the Prior on the western wall of the Bramante Sacristy (Fig. 30).



(a)



(b)

Figure 28: New Sacristy: a) Period photo during demolition; b) Digital reconstruction.

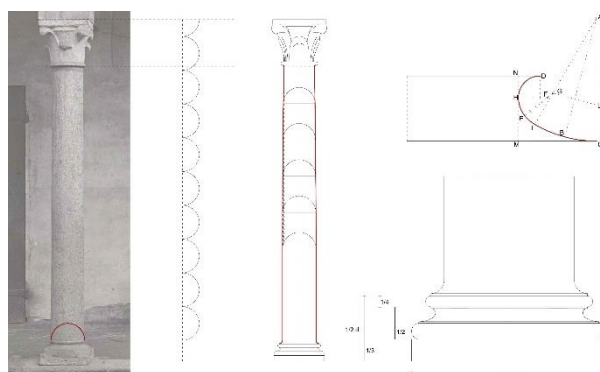


Figure 29: Geometric rules for modelling the Corinthian column according to the Renaissance treatises.



Figure 30: Digital reconstruction of the Cloister of the Prior before 1946: east-facing perspective section.

6.8.2. 1946-1950s

Although the cloister and the sacristy did not suffer significant damage during the 1943 bombing, they were renovated after the war in order to enlarge the New Sacristy, aligning it with the Cloister of the Frogs, and to lower the roofs to give greater visibility to the Tribune and the Bramante Sacristy.

To reconstruct the troubled history of the two environments, numerous documents dating back to the second post-war and kept in the archives of the *Soprintendenza Archeologica dei Monumenti e del Paesaggio di Milano* have been consulted: letters from the Prior about the project by the architect Elio Frisia for the arrangement of the Cloister of the Dead and the Cloister of the Prior; letters from the superintendent about the realization of a project by G. Pica; letters from the superintendent for the demolition of the buildings in via Sassi; letters from the ministry about the rejection of the Frisia-Pica proposals and the request for a new project; tender specifications for the construction of new access in via Sassi; a 1946 letter from the engineer Gallo, who established the beginning of the demolition of the buildings in via Sassi, quickly extended to the Cloister of the Prior and the New Sacristy.

The Cloister of the Prior was replaced by a large open space overlooking Via Sassi, with a monumental staircase that led to a panoramic terrace above the New Sacristy (Fig. 31-32). The latter was enlarged, its keel

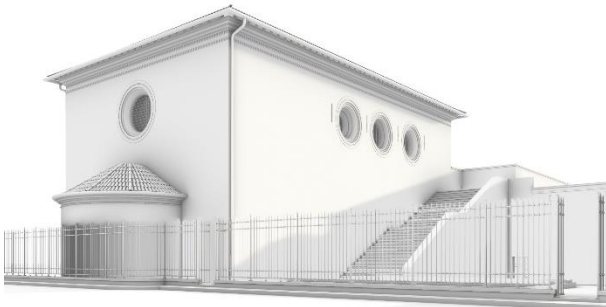
vault was replaced by a lower flat ceiling and the south wall of the Tribune was freed and restored (Fig. 33).



Figure 33: Digital reconstruction of the New Sacristy in its current configuration: south-facing view.



(a)



(b)

Figure 31: Staircase replacing the old Cloister of the Prior after 1946: (a) Period photo of the staircase from Via Sassi; (b) View of the digital model from Via Sassi.

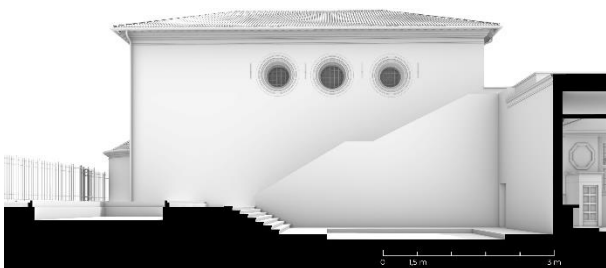


Figure 32: Digital reconstruction of the staircase: east-facing perspective section.

6.8.3. 1950s – to date

The monumental staircase on Via Sassi had a short life: after a few years, it was demolished and replaced with a new cloister (still existing). It is a one-level cloister, smaller than the original one and characterized by a portico with a wooden mono-pitched roof supported by ionic columns.

In digitally reconstructing this configuration, the 2019 digital survey were used to obtain accurate metric and material information (Fig. 34).



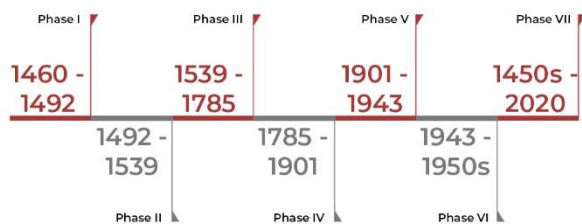
Figure 34: Digital reconstruction of the Cloister of the Prior in its current configuration: east-facing perspective section.

7. Diachronic development of the complex

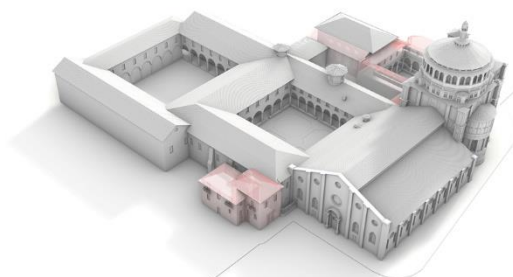
The in-depth analysis of the complex of Santa Maria delle Grazie has led to the identification and modelling of seven macroscopic building phases of the convent, which do not report, except in an indicative way, the changes occurred in the not surveyed environments (the Great Cloister, the Cloister of the Infirmary and the Cloister of the Inquisition). The seven models help to immediately perceive the troubled vicissitudes (Napoleonic occupation, Second World War bombings, etc.) that led to the current configuration, and can be enumerated as follows (Fig. 35):

1. 1460s - 1490s. In the land of Vimercati, Guiniforte Solari built the first complex, consisting of the church

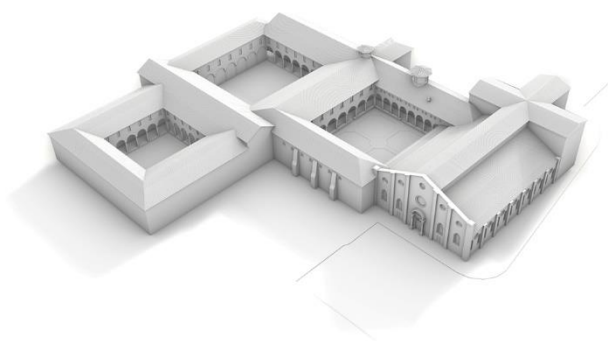
Timeline



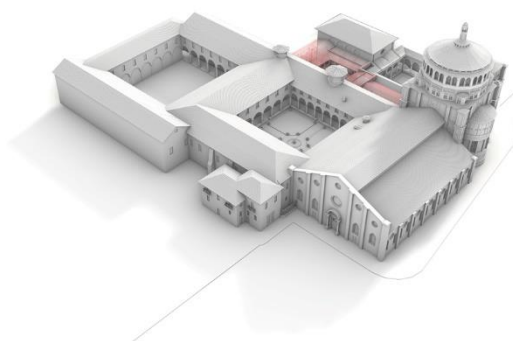
Phase IV. 1785 - 1901



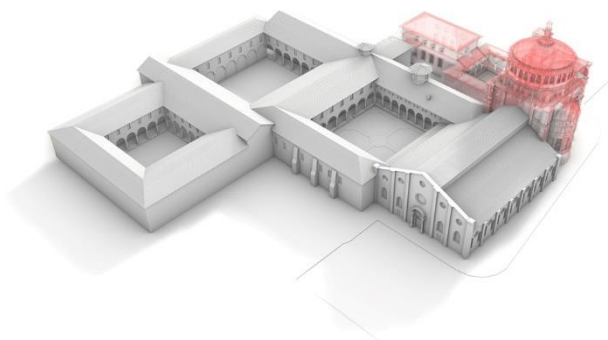
Phase I. 1460 - 1490s



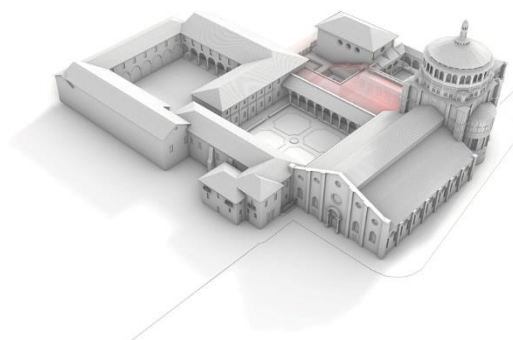
Phase V. 1901 - 1943



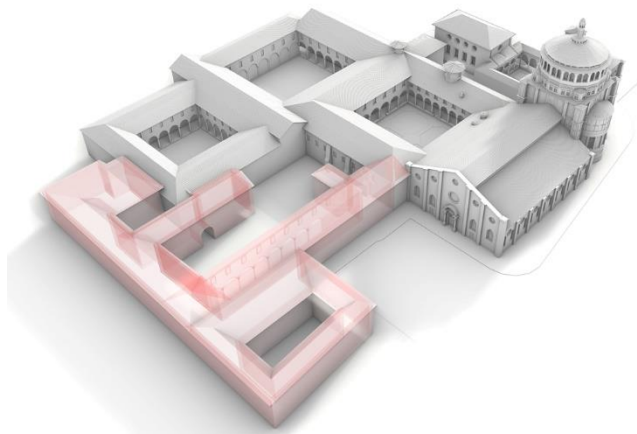
Phase II. 1490s - 1539



Phase VI. 1943 - 1950s



Phase III. 1539 - 1785



Phase VII. 1950s - 2020

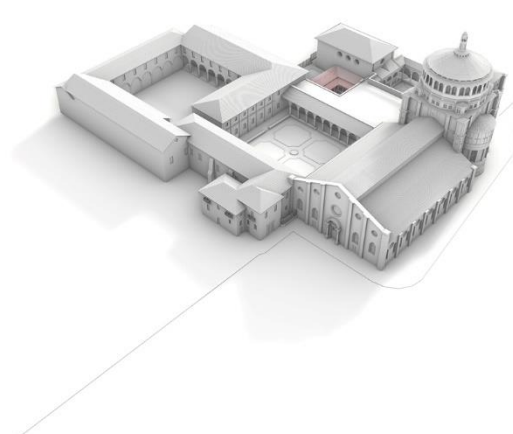


Figure 35: The seven phases of the diachronic development of the convent.

(with the ancient presbytery), the Cloister of the Dead, the Great Cloister and the Cloister of the Infirmary.

2. 1490s - 1539. At the end of the 15th century, the complex underwent an imposing transformation commissioned by Ludovico il Moro and designed by Bramante. The Tribune, the Cloister of the Frogs and the Sacristy were built and the Refectory was completed.
3. 1539 - 1785. Around 1539 the Inquisition wing was added to the west of the Refectory and the loggias of the Cloister of the Dead were built. The complex reached its maximum expansion.
4. 1785 - 1901 approximately. In the 1780s, following the suppression of the Inquisition Court by Maria Theresa of Austria, the Inquisition wing and the Infirmary were demolished. Starting in the 1890s, during Napoleon's occupation, additions were built next to the Tribune, the Sacristy of Bramante and the Cloister of Frogs.
5. 1901s - 2nd post-war period. At the beginning of the 20th century, the Napoleonic additions were demolished and the New Sacristy and the Cloister of the Prior were built in the area previously occupied by the cemetery of the plague victims. The loggia of the Cloister of the Dead was closed by stained glass windows.
6. 2nd post-war period - 1950s. The convent was restored after the bombings. The Cloister of the Dead was rebuilt in its current configuration, the New Sacristy was demolished and then rebuilt in its current configuration, the Cloister of the Prior was demolished and replaced by the monumental staircase in Via Sassi.
7. 1950s - to date. The staircase of Via Sassi was demolished and replaced with the new Cloister of the Prior. The complex reached its current configuration.

8. Model reliability

Finally, the researchers developed a 3D informational model of the entire complex: it contains all the data coming from the different types of sources (graphic works, drawings, period photos, written documents, digital survey data, etc.) used in the digital reconstruction phase.

Specifically, seven categories of reliability were identified by mapping the 3D model with different colours, ranging from the highest to the lowest level of accuracy (Fig. 36):

- Existing elements, whose characteristics were obtained from the survey campaigns;
- Elements modelled based on photographic sources, particularly useful to reconstruct structures and decorative elements existing between the end of the 19th and the beginning of the 20th century;
- Elements modelled based on drawings, useful to reconstruct in a sufficiently accurate way the proportions of the building;
- Elements modelled based on written sources, especially the chronicles by Gattico, useful to reconstruct the most ancient and poorly documented phases of the complex;
- Elements modelled based on architectural treatises, especially "the Canon of the five orders of Architecture" (Barozzi da Vignola, 1732), useful to reconstruct the decorative apparatus (columns, capitals, mouldings, etc.) with plausible proportions;
- Reconstructive hypotheses, based on analogies with similar buildings or personal interpretations, useful to reconstruct undocumented elements which are necessary to give visual completeness to the model.

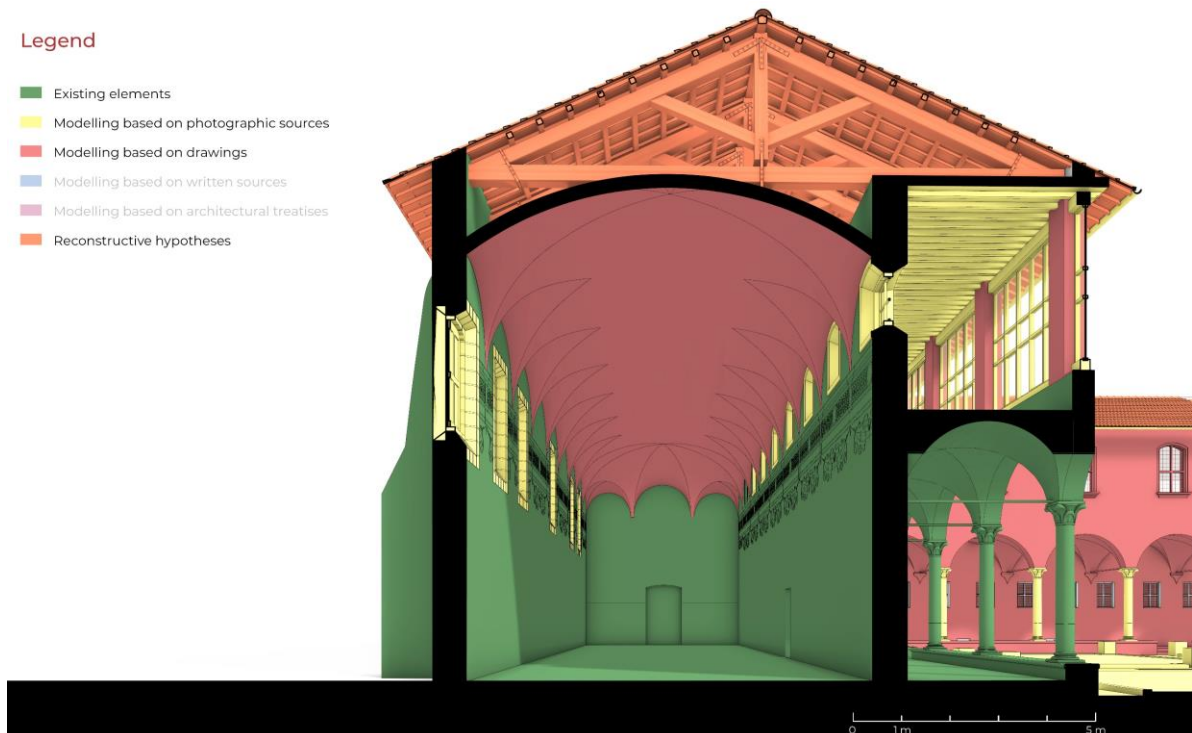


Figure 36: Informational model of the Refectory between 1891 and 1943: north-facing perspective section.

9. Conclusion and future works

This research highlights the importance and scientific validity of digital replicas aimed at understanding, enhancing and protecting cultural heritage. The study focused on the virtual reconstruction of the building phases of the convent of Santa Maria delle Grazie in Milan (from the mid-15th century to date). From this point of view, this site proved to be an ideal case study because of its troubled and little-known history that led to numerous changes over the centuries.

Thanks to a methodological approach based on the analysis of the documentary sources and on 3D modelling, it was possible to understand the chronological succession of the transformations and the way in which they overlapped the pre-existences (starting from the Renaissance harmonious and organic interventions, to the 18th-19th-centuries inhomogeneous and incompatible additions). In this way it was possible to shed light on some events in the convent history, often not analysed with a holistic approach, considering that many of the previous researches focused on single environments without evaluating the relationship between the parts. Finally, the study was completed by mapping the 3D models on the basis of the sources used and the different levels of accuracy. The 3D models have thus become a valid tool for checking and verifying reconstructive hypotheses.

The results of this research will be extended to the digital reconstruction of the historical phases of the not yet investigated environments (the church, the Great Cloister, the Cloister of the Infirmary and the Cloister of the Inquisition).

The complete models can then be used in different applications in the field of restoration, art history, gaming, etc. A possible development may consist of uploading the semantic models into online platforms useful for viewing, disseminating and sharing the research results with scholars and users. Currently, in order to make the large amount of collected data accessible and implementable, the researchers are testing the allocation of the 3D models of St. Maria delle Grazie in a BIM-based platform, developed since 2010 by the 3D Survey Group of Politecnico di Milano and already tested in the pilot case of Fabbrica del Duomo di Milano (Rechichi et al. 2016).

References

- Addison, A. C., 2001. Virtual heritage: technology in the service of culture. In VAST '01 *Proceedings of the 2001 conference on virtual reality, archaeology, and cultural heritage* (pp. 343-354). New York (USA): Association for Computing Machinery. <https://doi.org/10.1145/584993.585055>
- Affleck, J., Kalay, Y., & Kvan, T. (2008). *New Heritage: New Media and Cultural Heritage*. New York, New York: Routledge. <https://doi.org/10.4324/9780203937884>
- Aiello, D., Fai, S., & Santagati, C. (2019). Virtual museums as a means for promotion and enhancement of cultural heritage. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W15*, 33–40. <https://doi.org/10.5194/isprs-archives-XLII-2-W15-33-2019>
- Arnold, D., & Geser, G. (2008). *Research Agenda for the Applications of ICT to Cultural Heritage*. Full Report. EPOCH. Budapest: Archaeolingua 2008. http://public-repository.epoch-net.org/publications/RES_AGENDA/research_agenda.pdf
- AAVV. (1983). *Santa Maria delle Grazie*. Cinisello Balsamo: Amilcare Pizzi Arti Grafiche. Banca Popolare Di Milano.
- Banfi, F.; Brumana, R., & Stanga, C. (2019). Extended reality and informative models for the architectural heritage: from

It uses point cloud formats and modelling software such as Rhinoceros, making the .3DM files freely usable via the web. This platform uses the 3D model as an information database container and is therefore particularly suitable for projects related to restoration activities, as well as for the management of geometrically complex models typical of cultural heritage (in this regard, after the experimentation on the Duomo di Milano, it has been used in several large UNESCO historical sites, such as the Sacri Monti of Piedmont and Lombardy). The platform includes both a section in which researchers can implement data, modify point clouds, NURBS and meshes, and a section dedicated to the visualization on the web, also possible from mobile devices without special hardware requirements. In summary, this tool can represent an effective means for the dissemination of cultural heritage, as well as a virtual laboratory in which any interested researcher can freely consult the database contained in the 3D model or can help to add new data and update existing data.

Another possible application could be the development of an immersive and interactive VR simulation, which would allow reconstructing, in a realistic way, the convent and to relive its history, in a journey through time to discover the ages, the patrons and the great artists who shaped the site. This virtual simulation could be not only a valid and innovative scientific tool able to help researchers to study environments that no longer exist or have been profoundly altered over the centuries, but can also address a wider audience thanks to the language of the serious game which, with emotionally engaging storytelling, can teach visitors the history of this extraordinary example of Renaissance architecture.

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scan-to-BIM process to virtual and augmented reality. *Virtual Archaeology Review*, 10(21), 14-30. <https://doi.org/10.4995/var.2019.11923>

Barozzi da Vignola, J. (1732). *Regola delli cinque ordini d'Architettura*. Roma: G. Zempel.

Beale, G. (2018). Volatile images: authenticity and representation and multi-vocality in digital archaeology. In P. Di Giuseppantonio Di Franco, F. Galeazzi, & V. Vassallo (Eds.), *Authenticity and cultural heritage in the age of 3D digital reproductions* (pp. 83-94). Cambridge (UK): McDonald Institute for Archaeological Research. <https://doi.org/10.17863/CAM.27029>

Benjamin, W. (1968). *Illuminations*. New York: Schocken Books.

Boezia, E. (2018). Ektypa and 3D models of Ektypa: the reality(ies) of a digital object. In P. Di Giuseppantonio Di Franco, F. Galeazzi, & V. Vassallo (Eds.), *Authenticity and cultural heritage in the age of 3D digital reproductions* (pp. 97-110). Cambridge (UK): McDonald Institute for Archaeological Research. <https://doi.org/10.17863/CAM.27029>

Bolognesi, C., & Aiello, D. (2019). From Digital Survey to a Virtual Tale: Virtual Reconstruction of the Convent of Santa Maria delle Grazie in Milan. In C. Bolognesi, C. Santagati (Eds.), *Impact of Industry 4.0 on Architecture and Cultural Heritage* (pp. 49-75). Hershey, Pennsylvania (USA): IGI GLOBAL. <https://doi.org/10.4018/978-1-7998-1234-0.ch001>

Broggi, S. (n.d.). *Milano – Santa Maria delle Grazie, interno, Cenacolo*. Retrieved from <http://www.lombardiabeniculturali.it/fotografie/schede/IMM-3a280-0000048/> Last accessed 10/05/2020.

Bruschi, A. (1983). L' Architettura. In AAVV, *Santa Maria delle Grazie in Milano* (pp. 35-89). Milano: Banca Popolare di Milano.

Demetrescu, E. (2018). Virtual reconstruction as a scientific tool: The Extended Matrix and source-based modelling approach. In S. Münster, K. Friedrichs, F. Niebling, A. Seidel-Grzesińska (Eds.), *Digital Research and Education in Architectural Heritage: 5th Conference, DECH 2017, and First Workshop, UHDL 2017, Dresden, Germany, March 30-31, 2017, Revised Selected Papers* (pp. 102-116). Cham (CH): Springer. <http://osiris.itabc.cnr.it/extendedmatrix/wp-content/uploads/2015/08/Demetrescu-2018-Virtual-Reconstruction.pdf>

Denker, A. (2017). Rebuilding Palmyra virtually: Recreation of its former glory in digital space. *Virtual Archaeology Review*, 8(17), 20-30. <https://doi.org/10.4995/var.2017.5963>

Dhanda, A., Reina Ortiz, M., Weigert, A., Paladini, A., Min, A., Gyi, M., Su, S., Fai, S., & Santana Quintero, M., 2019. Recreating cultural heritage environments for VR using photogrammetry. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W9*, 305-310. <https://doi.org/10.5194/isprs-archives-XLII-2-W9-305-2019>

Forte, M., Pescarin, S., & Pujol, L. (2006). VR applications, new devices and museums: visitors' feedback and learning. A preliminary report. in *The e-volution of information technology in Cultural Heritage. Where hi-tech touches the past: risks and challenges for the 21st century*. Proceedings of the 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage, Vast 2006 (pp. 64–69). Nicosia, Cyprus: Eurographics.

Forte, M. (2008). *La villa di Livia, un percorso di ricerca di archeologia virtuale*. Roma: Erma di Bretschneider. [10.13140/2.1.2107.4887](https://doi.org/10.13140/2.1.2107.4887)

Forte, M., (2014). 3D Archaeology. New perspectives and challenges. The example of Çatalhöyük. *Near Eastern Archaeology* 2, 1–29. <https://doi.org/10.13140/2.1.3285.0568>

Garstki, K. (2018). Virtual authority and the expanding role of 3D digital artefacts. In P. Di Giuseppantonio Di Franco, F. Galeazzi, & V. Vassallo (Eds.), *Authenticity and cultural heritage in the age of 3D digital reproductions* (pp. 75-81). Cambridge (UK): McDonald Institute for Archaeological Research. <https://doi.org/10.17863/CAM.27029>

Gattico, G. (2004). *Descrizione succinta e vera delle cose spettanti alla chiesa e convento di Santa Maria delle Grazie e di Santa Maria della Rosa e suo luogo, et altre loro aderenze in Milano dell'Ordine de'predicatori con due tavole infine*. Milano: Castello Sforzesco Ente Raccolta Vinciana.

Jeffrey, S. (2018). Digital heritage objects, authorship, ownership and engagement. In P. Di Giuseppantonio Di Franco, F. Galeazzi, & V. Vassallo (Eds.), *Authenticity and cultural heritage in the age of 3D digital reproductions* (pp. 49-56). Cambridge (UK): McDonald Institute for Archaeological Research. <https://doi.org/10.17863/CAM.27029>

Jeffrey, S., Hale, A., Jones, C., Jones, S., & Maxwell, M. (2015). The ACCORD project: Archaeological Community Co-Production of Research Resources. In F. Gillign, F. Djindjian, L. Costa, P. Moscati, & S. Robert (Eds.), *Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology* (pp. 289–295). Oxford: Archaeopress Archaeology. <https://doi.org/10.5284/1042733>

- Jones, S. (2010). Negotiating authentic objects and authentic selves: beyond the deconstruction of authenticity. *Journal of Material Culture*, 15(2), 181–203. <https://doi.org/10.4324/9780203165744>
- Joy, J. (2002). Biography of a Medal: People and Things They Value. In J. Schofield, W. Gray Johnson, & C.M. Beck (Eds.), *Material Culture: The Archaeology of Twentieth Century Conflict* (pp. 132–142). London: Routledge. <https://doi.org/10.4324/9780203165744>
- Kargas, A., Loumos, G., & Varoutas, D. (2019). Using different ways of 3D reconstruction of historical cities for gaming purposes: the case study of Nafplio. *Heritage*, 2(3), 1799–1811. <https://doi.org/10.3390/heritage2030110>
- Latour, B., & Lowe, A. (2011). The Migration of the Aura or How to Explore the Original through Its Facsimiles. In T. Bartscherer & R. Coover (Eds.), *Switching Codes*. Chicago: The University of Chicago Press.
- Manžuch, Z. (2017). Ethical issues in digitization of cultural heritage. *Journal of Contemporary Archival Studies*, 4, 4.
- Martelli, G. (1981). *Il refettorio di Santa Maria delle Grazie in Milano e il restauro di Luca Beltrami nell'ultimo decennio dell'Ottocento*. Roma: Istituto Poligrafico e Zecca dello Stato.
- Münster, S., & Koehler, T. (2016). 3D reconstruction of Cultural Heritage artifacts A literature based survey of recent projects and workflows. In S. Hoppe, & S. Breitling (Eds.), *Virtual palaces, Part II. Lost palaces and their afterlife. Virtual reconstruction between Science and Media* (pp. 87–102). Munich: PALATIUM e-Publication 3. <https://doi.org/10.11588/arthistoricum.83.79>
- NARA Document (1994). UNESCO NARA Document on Authenticity. Last accessed 5 April 2020. <http://whc.unesco.org/document/9379>.
- Paoli, S. (2017). *Incisione - Pianta di Milano - Parrocchia di Santa Maria delle Grazie - Vigna di Leonardo*. Retrieved May 5, 2020, from <http://www.lombardiabeniculturali.it/fotografie/schede-complete/IMM-3a010-0001413/>.
- Paoli, S. (2017). *Milano - Corso Magenta - Via Caradosso - Chiesa di Santa Maria delle Grazie – Sacrestia*. Retrieved May 5, 2020, from <http://www.lombardiabeniculturali.it/fotografie/schede/IMM-3a130-0006892/>.
- Piccialli, F., & Chianese, A. (2017). Cultural heritage and new technologies: trends and challenges. *Personal and Ubiquitous Computing*, 21, 187–189. [10.1007/s00779-016-0984-y](https://doi.org/10.1007/s00779-016-0984-y)
- Ramorino, G.N., (1930). Milano, Chiostrò della Chiesa di Santa Maria delle Grazie. Retrived May 10, 2020, from <http://www.lombardiabeniculturali.it/stampe/schede/H0110-09293/>.
- Rechichi, F., Mandelli, A., Achille, C., & Fassi, F. (2016). Sharing high-resolution models and information on web: the web module of bim3dsg system. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLI-B5*, 703–710. [http://dx.doi.org/10.5194/isprsarchives-XLI-B5-703-2016](https://doi.org/10.5194/isprsarchives-XLI-B5-703-2016)
- Trilling, L. (1973). *Sincerity and Authenticity*. Boston: Harvard University Press. <https://doi.org/10.2307/j.ctvjhzrdp>
- UNESCO (1994). *Nara Conference on Authenticity*. K. E. Larsen (Ed.). Paris: UNESCO World Heritage Centre.
- Verdiani, G. (2017). From the archaeological reality to the digital reconstruction: An architectural drawing challenge. *DISEGNARECON*, 10, 4.1-4.13.
- Verdiani, G., Pucci, M., & Gira, C. (2016). A special eyesight to a lost past: Oculus Rift, Google Cardboard and SketchFab to support the digital reconstruction of the St. Donato cathedral in Arezzo, Italy. In C. Busch & J. Sieck (Eds.), *Kultur und Informatik: Augmented Reality*. Berlin: Verlag Wemer Hülsbusch. <https://www.academia.edu/25695591>
- Viejo-Rose, D. (2015). Cultural heritage and memory: untangling the ties that bind. *Culture & History Digital Journal*, 4(2), 1-13. <https://doi.org/10.3989/chdj.2015.018>
- Vos, P., & Rijk, M. (2019). Virtual reconstruction of the birthplace of Rembrandt Van Rijn: from historical research over 3D modeling towards virtual presentation. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W15*, 397-404. <https://doi.org/10.5194/isprs-archives-XLII-2-W15-397-2019>
- Witcomb, A. (2010). The Materiality of Virtual Technologies: A New Approach to Thinking about the Impact of Multimedia in Museums. In S. Kenderdine & F. Cameron (Eds.), *Theorizing Digital Cultural Heritage: A Critical Discourse* (pp. 35–48). Cambridge (MA): MIT Press. <https://doi.org/10.7551/mitpress/9780262033534.003.0003>
- Wong, L. & Santana Quintero, M., (2019). Tutankhamen's two tombs: replica creation and the preservation of our Cultural Heritage in the digital age. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W11*, 1145–1150. <https://doi.org/10.5194/isprs-archives-XLII-2-W11-1145-2019>
- Zanzottera, F. (2015a). *Chiesa di Santa Maria delle Grazie*. Retrieved May 10, 2020, from <http://www.lombardiabeniculturali.it/architetture/schede/LMD80-00014/>

Zanzottera, F. (2015b). *Chiostrino del convento di Santa Maria delle Grazie*. Retrieved May 10, 2020, from <http://www.lombardiabeniculturali.it/architetture/schede/LMD80-00362/>

Zuecca, U. (1930). *Milano - Chiesa di Santa Maria delle Grazie - sacrestia, particolare della decorazione del soffitto*. Retrieved May 10, 2020, from <http://www.lombardiabeniculturali.it/fotografie/schede/IMM-3a010-0002879/>