POLITECNICO

ABC PHD DOCTORAL PROGRAMME
in ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING

Ph.D. Thesis

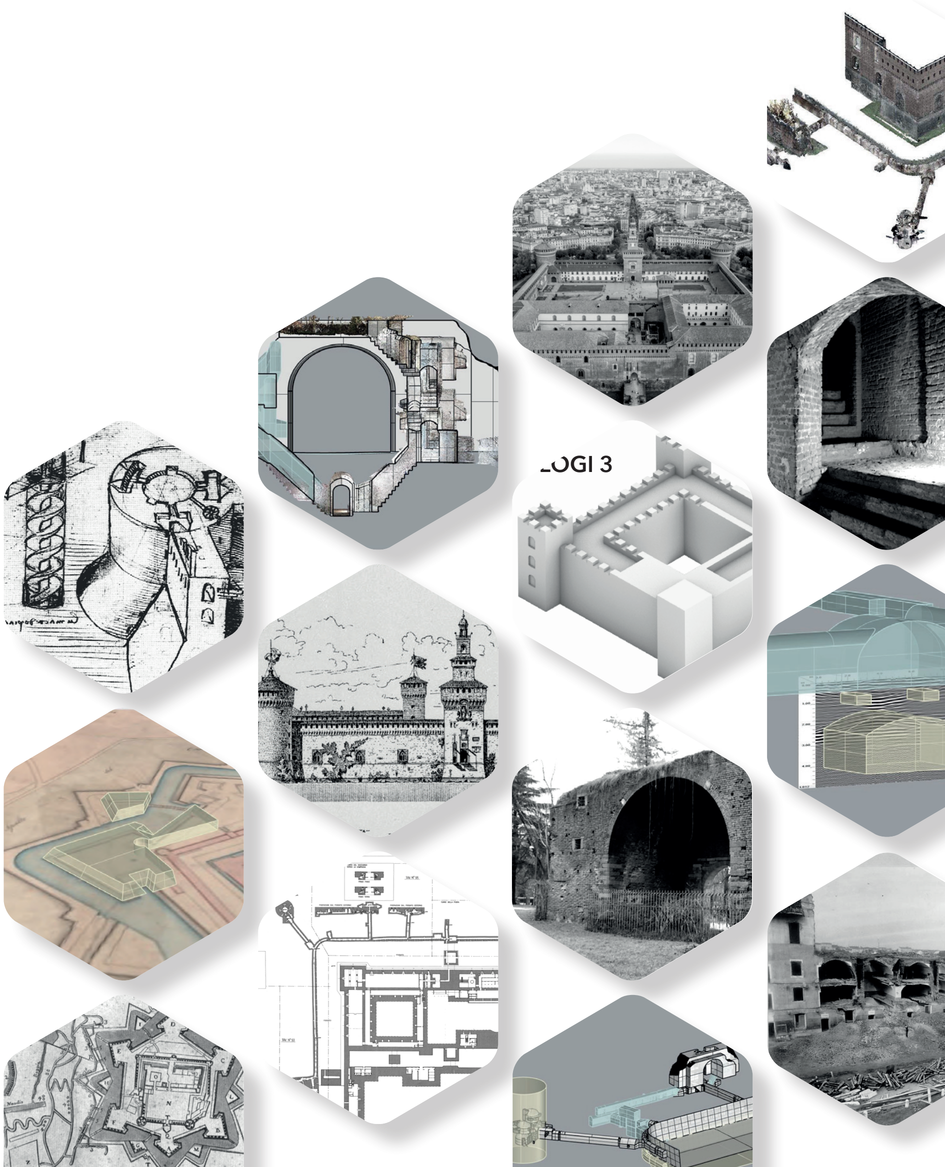
Architectural heritage digitisation through a Levels of Geometric Information-based approach

The case study of the Ghirlanda of the Castello Sforzesco in Milan

Ph.D. Candidate
Francesca Biolo - 35° cycle

Supervisor
Prof. Franco Guzzetti

Tutor
Prof.ssa Corinna Rossi



October 2023

On the cover:

Bird's eye view of the Castello Sforzesco from Parco Sempione side. Https://upload.wikimedia.org/wikipedia/commons/8/8a/Castello_Sforzesco_da_alto.jpg.

Drawings bearing 'snail' scales. Leonardo Da Vinci, *Manoscritto B, f. 69 r.*).

The entrances to the three casemates inside Torre della Colubrina. Photo from the website http://www.milanoneicantieridellarte.it.

Print with general view of the south-east front of Castello Sforzesco. C. 1900s. Document in the "Achille Bertarelli" Civic Collection of Print (Milan).

The current volume of Porta del Soccorso. Photo from the website https://www.milanocastello.it.

The plan of the castle and the Ghirlanda. The elements investigated are highlighted in red. Survey by Gruppo Archeologico Milanese, 1994.

Etching of the Castello Sforzesco indicating the names of the bastions and minor structures. Giovanni Battista Sesti and Francesco Agnelli, 1707. Document in the "Achille Bertarelli" Civic Collection of Print (Milan).

Photo of the demolition phase of the Ghirlanda, during the restoration of the castle. 1893. Document in the Civic Photographic Archive (Milan).

POLITECNICO
MILANO 1863

ABC PHD DOCTORAL PROGRAMME
in ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING

PhD Thesis

Major academic discipline
ICAR/06 – Topography and cartography

PhD Candidate
Francesca Biolo - 35° cycle

Supervisor
Prof. Franco Guzzetti

Tutor
Prof.ssa Corinna Rossi

Architectural heritage digitisation through a Levels of Geometric Information-based approach

The case study of the Ghirlanda of the Castello Sforzesco in Milan

CONTENTS

AA

Appendices 173

ABSTRACT

The research presented addresses the domain of architectural cultural heritage digitisation, with an emphasis on developing an approach for the digital transformation of the geometric information of such objects. Specifically, the primary concern is a matter of collecting in a single 3D model the profusion of information typical of an architectural asset. The purpose is to develop a 3D model that comprehensively describes the structure, including elements that are no longer in place or no longer visible, by managing information of a heterogeneous nature. This work, therefore, aspires to provide a solution, capitalizing on state-of-the-art methodologies and technologies of survey and digitisation, which are precious in comprehending complex structures. The work carried out has indeed started from the architectural heritage itself and from the idea that a comprehensive knowledge of it is essential for conscientious manipulation thereof.

The knowledge of cultural heritage is the result of a multifarious and composite data collection, derived through variegated processes and products. The proposed approach aims at creating a three-dimensional model able to gather the heterogeneous geometric data available while concurrently facilitating the management of the progressive expansion and change of the available information package. The resultant 3D model encompasses information of various natures, and due to its heterogeneous sources, will inevitably have to handle data characterised by different levels of accuracy. This is typical when working with built heritage, whose sources have accumulated over time in very discordant forms.
The blueprint of the 3D model requires the harmonious coexistence of objects at different Levels of Geometric Information (LOGI) so that all data is correctly arranged in defining the overall geometric information, including both the reference documentation and the tridimensional elements (of the developed model) in its subdivision, according to their respective levels of accuracy. In such a way, it is possible to incorporate what is obtained from a modern geomatic survey and information emerged from historical sources in a consistent collection that encompasses all elements of the building, from those surveyed to those hypothesised because no longer visible or exist.
Furthermore, thanks to the rigorous use of georeferencing, the object can be updated with emerging information or additional research and survey activities. The modelling phase has been designed to be reiterated whenever new information and surveys are available, so that the 3D object will result constantly updated. Due to this approach, knowledge never stops at the first supply of information, while it accumulates and evolves progressively into an increasingly complete vision of the object. The digital twin of the architectural asset, once modelled, is completed by inserting the information useful for the identification and description

of the sources that provided the geometric reference information. This is accomplished within the modelling environment itself, exploiting the functionality of the chosen software (Rhinoceros) and setting up a structure for metadata. This metadata framework then links to an external database, containing the material used, that maintains its accessibility and consultability.

To develop this work, the case study chosen has been the Castello Sforzesco in Milan. Specifically, the area analysed consists of the northwest corner of the Ghirlanda, between Torre della Colubrina and Porta del Soccorso. The history of this building, the articulated architectural evolution and its multiple roles (war apparatus, the centre of the city's political power and artistic receptacle) give to this architectural cultural asset a remarkable degree of complexity. This abundance of information about this building has set valuable conditions for the experimentation conducted. Such attributes collectively render the Castello Sforzesco an ideal case study to evaluate the effectiveness of the paradigm proposed in the research work. It is worth noting that while the sperimental phase is anchored in the specifics of this historical building, the overarching ambition pertains to the formulation of a methodological framework of broader applicability within the realm of architectural cultural heritage.

This doctoral research describes a possible approach to the description and digitisation of the geometric information apparatus of an architectural asset. The *modus operandi* is intended to be an instrument tailored to those involved in the management of the building as a whole, thereby helping to understand its spaces and its interconnections with external systems. In light of this, the present research seeks to address this exigency by encouraging the organic collection and sharing of knowledge directed towards the conservation and valorisation of our heritage. Moreover, by aggregating information of a different nature, this instrument unveils pivotal points and issues requiring further investigation and research, thereby fostering additional refinements of the model and progressively enriching the information dataset.

01

THE RESEARCH QUESTION AND ITS RELEVANCE

01.1 _ Digital transformation, oriented processes and social changes

In recent decades the global landscape has dealt with an increasingly preponderant Digital Revolution and with the socio-economic changes that it has ensued. This exponential phenomenon, which has taken on unparalleled relevance, has led objects, services and processes to change their form, thus assuming a digital character.

This transformation, supported and fueled by communication and information technologies, has also heavily affected people's habits and skills, as shown by the results of some surveys (Figure 1.1.a) (ISTAT, 2018; ISTAT, 2019).
The very essence of numerous human activities, encompassing but not confined to communication, household management, working, and many others, have somehow lost their analogical character, crossing the line of the Digital Era. It has also changed the way people retrieve and access information. The Italian National Institute of Statistics, ISTAT, interestingly reports in the 2022 analysis on the duality of citizens and ICT (ISTAT, 2022.a) that nearly 45% of respondents use digital channels to get information. Other corroborative insights come from a different Italian Government survey (AGCOM; 2018) on communication and information among citizens, as can be seen from Figure 1.1.b, quantifying the various communication modes. The graph shows how the information process, especially the short-term one, is shifting to non-traditional channels. The paper reports that the information power of the Internet is still on the rise and that more and more people are relying on this means to search for knowledge (more than a quarter of the population considers it the most important way to get informed). These concise spots help to understand the current trend: people are increasingly inclined to base their communication, information and knowledge processes on digital channels rather than analogic tools and systems. Observing these trajectories is very significant when work deals with the use of new technologies for information management.

This migration towards a digital version of systems has been and is still encouraged by the possibilities that this evolution is offering in terms of facilitation, improvement and efficiency, also widely affecting the production sector and multiple professional domains (ISTAT, 2020; ISTAT, 2022.b). In this context, the field of architecture has seen a growing interest in digitisation, both for new buildings and for architectural cultural heritage. By taking advantage of ICT and the specific technological advances in the sector, this discipline has recorded a huge phenomenon of experimentation, which has resulted in a proliferation of research streams and new technical solutions.
This trend is reinforced and supported by the governmental and legislative initiatives, with important incentives and guidelines affecting this area (European Commission, 2011; Council of Europe, 2015; Direzione

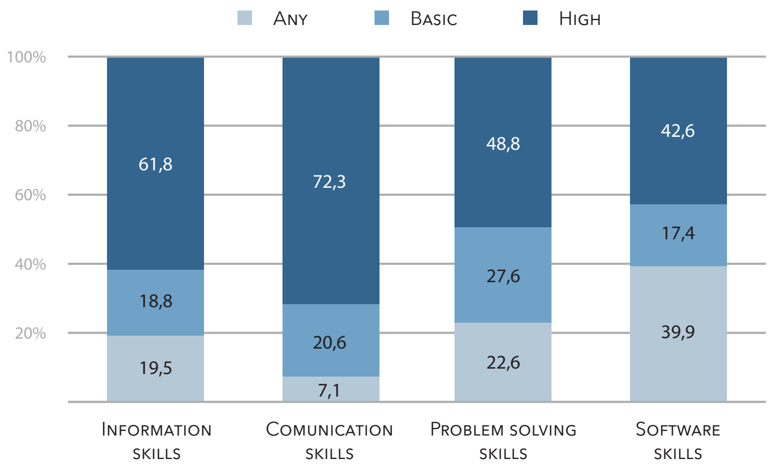


Figure 1.1.a Domains of digital competence. Data taken from the ISTAT report "Cittadini e ICT" (2019).

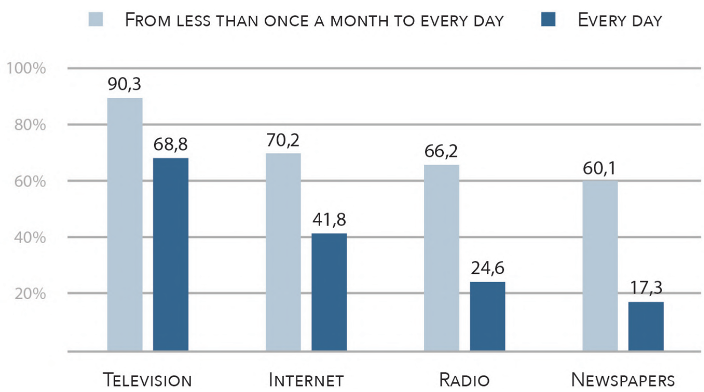


Figure 1.1.b The use of media in the information process. Data taken from the "Rapporto sul consumo di informazione" by AGCOM (Autorità per le garanzie nella comunicazione, Italian Government) (2018).

Generale Musei, 2016; MiBACT, 2017; IPER, 2018). An outstanding international example is the 2030 Agenda (United Nations, 2015). The program, signed in 2015 by the 193 UN countries, contains seventeen goals for sustainable development. Among the objectives, the document promotes the strengthening of efforts to safeguard the built heritage, emphasising at the same time the centrality of the advancement of information and communication technologies for overall development. Analogous indications have come at the National level in Italy with the recent adoption of the PNRR (M.E.F., 2021), the National Recovery and Resilience Plan approved in 2021 to revamp its economy after the COVID-19 pandemic, to enable the country's green and foster digital development. Focusing on digitisation, innovation, competitiveness, culture and tourism, Mission 1 pushes hard on the theme of safeguarding and enhancing cultural and architectural heritage in the wake of the possibilities offered by the ongoing digital transformation.

The descending frenetic activity of innovation and experimentation involves specific aspects in the field of architecture and in particular the ones that relate to the built heritage, through different spheres of interest: surveying, 3D modelling, facility management, information fruition, etc. The general aim that is promoted is to find new solutions and approaches to better knowing, managing and dealing with the architectural heritage.

One strand of work deals with data collection for knowledge and management of existing buildings where numerous endeavours are in place, for example, with current survey technologies. The aim is two-folded: understanding how far these tools can be pushed in the analysis of architectures and exploring the potential in terms of information gathering and possible uses of the output products. First and foremost are the point clouds and the related laser scanner and photogrammetric technologies required to produce these digital models. Another example in the area of data collection is the use of the Internet of Things (IoT) for construction monitoring. Some examples have shown its usefulness for safeguarding cultural heritage (Pierleoni et al., 2018) and for structural monitoring in areas of particular attention (Lee & Lee, 2019; Lerario & Varesano, 2020; Tarani et al., 2020). The impact of IoT is by no means confined to architecture management, rather, it extends beyond, with many experiments using these solutions to encourage and improve the tourist use of the built heritage (Chianese & Piccialli, 2015).
Returning to the management of the built environment, a further very prosperous issue revolves around the conception of digital twins, an overarching thematic which will be widely addressed in the description of the thesis work. In this context, many developments are emerging, and they are being addressed with different tools and approaches. There is much talk of HBIM (Heritage Building Information Modeling), born in the wake of BIM, but targeted at pre-existing buildings. Net of HBIM, many other studies aim to formulate approaches on the subject of digital twins, providing solutions that combine three-dimensional visualisation and the ability to manage information. This receptivity to embrace new solutions, coupled with the physiological response to the difficulties in adapting the BIM approach to a built heritage building, requires heterogeneous and more flexible frameworks than those offered by these conventional tools.
A different point of view is validated by works using technologies such as augmented reality (AR) and virtual reality (VR) (Flavián et al., 2019). They have demonstrated the validity of these solutions when applied to architecture and declined for various purposes: facility management (Baek et al, 2019), emergency management, planning (Cirulis & Brigis Brigmanis, 2013) but also site knowledge (Dhanda et al., 2019).

This last case, centred on the use of AR and VR, allows establishing a connection with a second thematic basin that gathers many works and research, that of large-scale communication. The great push of digital transformation has led to work not only on solutions dedicated to professionals and processes within the AEC world but also on

Figure 1.1.c Augmented reality con site (Canciani et al., 2016).

new solutions for the world of education (Petrucco & Agostini, 2016; Luna et al., 2019) and tourism (Chang et al., 2015; Carrion-Ruiz et al., 2019). The proposals are countless and include a variety of solutions such as the use of the aforementioned AR and VR (Figure 1.1.c), mobile applications, etc.; they exploit 3D models, point clouds and other solutions with strong communication potential. Although tourist information is not the field of work for this doctoral research, it is important to mention it because from these works emerges the constant spread of new digital habits and inclinations that society is showing. The point is that they all aim to promote through new technologies, the transmission of knowledge, large-scale awareness of cultural heritage and thus architecture enhancement.

The digital transformation phenomenon which, as already said affects also the field of architectural cultural heritage, is generating a lot of in-depth discussions and issues. However, two crucial cross-cutting themes for the present research are emerging. On the one hand, technological research seeks to improve digital methods for managing information, in particular with a major trend to associate the data with the reference object or its digital copy. The information is a single body with the building and its components, creating informative copies of the architectural asset for efficient management. On the other hand, there is a desire to facilitate the flow of knowledge with solutions that embrace and follow people's new digital habits, to catalyse the transmission of information.

Today's technological impetus seems to have infused new energy to revive the management and enhancement of architectural heritage, which is becoming increasingly important within the identity of territories and their communities. Indeed, the new opportunities should not be used only for "re-platforming" analogic systems and structures within the digital language, but they should be the impulse for a significant overall improvement.

01.2 _ Architectural heritage and digital twins: new places for new knowledges and innovative researches

The previous brief introduction outlined a very broad context on the digital transition topic and related experimentations between both the architectural domain and the broader context of cultural heritage. As it turned out, the declinations on the subject are manifold and, starting from them, so many branches of work and research arise. The text also attempts to emphasise how digital twins are becoming a place of knowledge and insight, where architectural objects can also be comprehended and investigated.
The doctoral work presented here takes its place at this fundamental juncture, carving out a delimited space in which to operate, that of the digital twin for the knowledge and management of the built heritage.

This research arose from the intersection of two conditions. At the same time, there is the observation of technological and digital advancements that now offer a boundless range of opportunities. As seen in the previous chapter, the study and experimentation of such tools is a *sine qua non* within the world of research (and not only) for architecture and built heritage.

The second determining factor stems from the analysis of the needs of the architectural heritage itself. Although awareness of the preservation and enhancement of this heritage is constantly growing within our society, it is equally evident that there is a lack of tools to manage it correctly and to support decision-making and planning processes that occurs in these structures.
In recent decades, a new way of looking at these buildings has been increasingly consolidated, more aware, attentive and respectful. The community, and those in charge of its administration, have developed a deeper understanding of the impact of these assets on the territory and its socio-cultural dynamics and are increasingly aware of the need to manage and maintain this heritage. Such cognizance should also be partially explained by today's growing consciousness of the imperative to reduce land use. This shift, compared to the tide of past dynamics, has turned its gaze back to pre-existing structures. The focus has now changed, the aim is to better manage what is already there rather than limitlessly expanding the boundaries of the urbanised.

The recorded condition, therefore, denotes a conspicuous dearth of tools and systems requisite to manage the built heritage according to today's most careful approach, in alignment with the new awareness and contemporary sensitivities. This observation is even more pronounced and urgent when considering the context of architectural cultural heritage. Indeed, these structures are often characterised by a predominant architectural-spatial and narrative complexity: they are composite buildings, sometimes deeply rooted in history, and therefore extremely stratified. This condition has heavy implications both on architecture, whose

reading is therefore exponentially complicated, and also on their associated information heritage.
The latter issue is at the heart of the research question.

Throughout history, architectural assets have seen their archive of documents and related information records expand. Most of this material has come down to the present day, providing a significant basis for understanding the dynamics that affect the various cases. However, the problem lies in the accessibility of this information, which is often spread in a non-homogeneous way across multiple archives and funds, contained in several documents and sources. This frequent condition greatly complicates the knowledge of the buildings, with repercussions on the management of the structures themselves. Due to these aspects, it is essential to remember that the proper study and accurate knowledge of architectures are the prerequisites for working with built elements and on systems interconnected with them. When it comes to cultural heritage, it is equally necessary to master historical events and changes in architectural layouts. As taught by too many contemporary events, not everything that has survived history is visible, in fact many parts are hidden underground. The awareness of the past is an important factor to keep in mind when working on digital twins for the built environment.

Following this series of considerations on the digital world and architectural heritage, the issue underlying the work was structured. The research aims to investigate how today's technologies and techniques (those for data collection, for their organisation and those for information) can contribute to formulating a methodological framework that allows the development of a precise digital twin. Such an apparatus has to be considered an aid, to facilitate the spatial understanding of architectures and collecting information and related sources necessary for the knowledge generation process. The digitisation structure should leave the possibility to both understand the current layout and also the past ones, differentiating but still enlighting what could still be present albeit hidden from view. It has to link the data (and the reference source) to the digital model in order to control the information assets and their use in the digitisation process. In addition, the approach should respond to any new information that changes knowledge about the building. Finally, and summarising, the proposed approach should support knowledge of the asset, understanding of the phenomena taking place, and proper asset management by handling the reference data internally.

The research and experimentation work started from this issue and with these objectives. The state-of-the-art analysis, as exposed below, was necessary to frame what has been done so far and outline the boundaries of what has already been attempted or achieved. The aim is to understand, on the basis of the assumptions just mentioned, what the next step in this direction might be. Furthermore, it helps to understand within the digital twin context how to pursue the dialogue between new information, derived from modern surveying operations, and geometric and historical data, retrievable from more classical reference sources.

02

THE STATE OF THE ART

02.1 _ Digitisation and digital twin in the architecture domain: current trends

Having established the framing within the first chapter, which contains the introduction to the issue addressed by the research work, the text now revolves around an exploration of the state of the art in the current landscape.

The analysis, divided into two parts, discusses today's trends in the fields of digitisation and digital twins, considered within the world of architectural cultural heritage.

The first section will delve into the methods and tools for developing such digital objects. In particular, the focus will be on works that have addressed the issue of combining the historical phases portrait and the description of buildings, encompassing also the point of view of stratifications and previous spatial layouts. To complete this, the text will also deal with the management of information with different levels of accuracy, a typical condition when facing architectures stratified over time, and the study of the corresponding documentation.
The necessity to address this area arises from the assumptions set out in Chapter 1, in particular sponsoring the approach that built heritage, for its complete knowledge and proper management, must be analysed in the totality of history and transformations that have affected it.

The second part of the chapter, instead, deals with information management within digital twins by critically recapitulating what has been found in the reference bibliography in terms of methods, tools, and general approaches. This data will be of reference for the management, within the doctoral work, of the linkage between the digital model and the underlying information and sources.

This chapter aims to understand and describe the work and experiments already underway on the topic. This process is essential to clarify the starting point for the present work.

02.1.1 _ Digital twin for telling the history

The analysis of the state of the art on digital twins for architectural heritage highlights a prolific process of research and experimentation. The scenario is still multifaceted over a considerable number of sub-themes, consequently generating multiple strands of research. As a result, there is a vast set of digital twins that, from time to time, interpret reality by creating a specific replica of the building mediated based on the processed information.
All this also stems from the strong push towards the digital transformation that is growing also in this sector.

The first analysis deals with the reconstructing process for no longer existing architecture (Pescarin et al., 2011; Campi et al., 2019).

Such works and research on this issue have become increasingly relevant and recursive as the general awareness and sensitivity to built heritage, as part of a community's culture, has consolidated. This first type of digital twin often aims to evoke shapes, features and geometric characteristics. They aim to tell a piece of history that has been lost, totally or in large part. For this reason, they are often geometric models with communicative purposes, detached from the world of information models, in the strict sense (such as the BIM world). The development process ranges widely from case to case, as well as the choice of modelling tools and communication technologies. Considering the aims of these works, often dedicated to information and dissemination on a large scale, the communication process intercepts a broad number of possibilities. These types of goals are explored in recent years also through a great ferment in experimentation with virtual reality (Barone & Nuccio, 2017; Bolognesi & Aiello, 2020) and augmented reality (Canciani et al., 2016).
Since they are developed from pre-existing documentation (which rarely coincides with digital survey outputs) (Portalés et al., 2009), the level of accuracy tends to be negatively affected. However, this condition does not influence the purpose for which they have been developed.

A second and vast area analysed is the digital transposition of existing architectural assets, in their current configuration. Since these buildings are still physically present on the territory, digital twins respond to different needs and functional purposes: fruition, knowledge, management, preservation, etc. This multiplicity of scopes of use implies that the internal system of the various models and their development process can vary depending on the final goal (Lopez et al., 2019).
Nevertheless, in most cases, these procedures have the same starting point, namely a point cloud (laser scanner or photogrammetric) (Aveta et al., 2017) from which the necessary and accurate geometric information for the development of the model is extracted. These products, which are now the basis of any process of investigation and knowledge of the built heritage, have a great power to collect and transmit information and high accuracy. Despite these strengths, it is rare to find digital twins based directly on such systems nowadays.
An exception is the web tool for remote visiting the archaeological area of Ercolano (https://ercolano.beniculturali.it/herculaneum3dscan/): the online portal provides both partial point clouds (Figure 2.1.1.a) and one of the entire site (Figure 2.1.1.b), that make it possible to explore and precisely visit the excavations. This project collects the material produced in years of on-site surveys, then made available to the remote visitor.

Point clouds, as repositories of a large number of geometric data, are also the subject of experiments for the automatic extraction of 3D elements, destined for the world of digital twins in its various declinations (Thomson & Boehm, 2015; Macher et al., 2017; Ochmann et al., 2019). These systems exploit special algorithms to recognize surfaces and elements, which are then transformed into three-dimensional objects. Such systems, although at an early stage of development, are already opening up a new field for further development of digital models.

Net of this, the digital twins of existing architectures, traced in the bibliography, can be substantially divided into two groups, diffe-

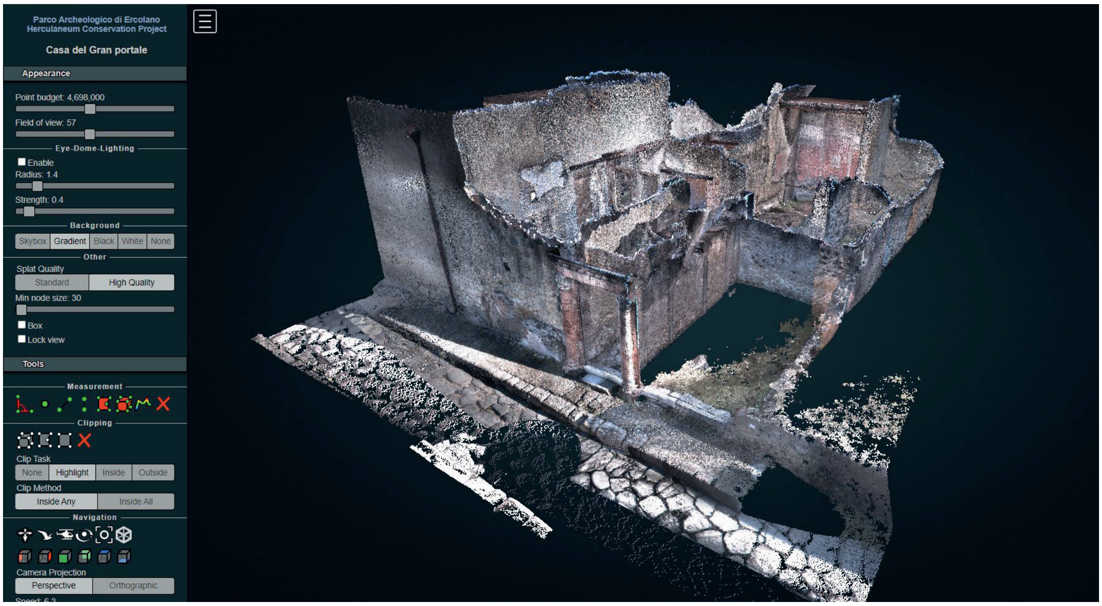


Figure 2.1.1.a View of the point cloud of the Casa del Gran Portale, present on the online platform for the virtual visit to the archaeological site of Herculaneum. On the left are the functions for managing the cloud.

Figure 2.1.1.b View of the point cloud of the archaeological site of Herculaneum, present on the online platform for the virtual visit. On the left are the functions for managing the cloud.

rentiated according to the approach used for their development.
On the one hand, there is the core of HBIM (Heritage/Historical Building Information Modeling) models. The paradigm mirrors the characteristics of BIM as used for new buildings, where each element that constitutes the architecture has a set of intrinsic information. As will be explored in the next section, this structure, which in some cases can be very useful and well-performing, in many others may not align with the particular needs of specific digital models in terms of information systems. In such instances, the information system has to be managed externally through other tools. As is widely known, BIM models are born to provide a digital and highly structured solution for handling buildings throughout their life cycle, from construction to demolition. This foundational approach, albeit subject to certain differences due to the intrinsic characteristics of an already existing asset with its historical fortunes, can also be replicated for architectural heritage and the management of its dynamics (Osello et al., 2018; Banfi et al., 2019.a). Other purposes associated to these digital copies are conservation (Chiabrando et al., 2017) and built environment enhancement (Barazzetti et al., 2015c; Banfi & Mandelli, 2021; Pulcrano, 2022).
A further case is experimenting with new ways to bypass the modelling difficulties of HBIM software. This initiative, programmed to offer generative modelling, often encounters obstructions due to the complex and irregular geometries of architectural cultural heritage. Traditional BIM software is created for digitising new and regular buildings, designed with relatively standard construction elements. While this issue is partly overcome with NURBS modelling, it still could prove to be an obstacle to the development of models with a high level of accuracy. Notwithstanding these challenges, the proliferation of this phenomenon and research on the subject is still flourishing.

The state of the art on the digitisation of existing architectures recorded the presence of a second ensemble of works with a further *modus operandi*. It abandons the world of HBIM, preferring geometric modelling to which, if necessary, could be associated, in several ways, the information necessary for the multiple purposes of the digital twin developed (Bolognesi, 2018; Santagati et al., 2018; Bolognesi & Aiello, 2019; Palma et al., 2019; Aiello et al., 2020).
The analysis showed a marked and general trend (also concerning HBIM models) towards the integration between digital twins and the world of modern communication technologies. In particular, the workflow for migrating these objects within augmented reality and virtual reality (and into the several applications and tools that support them) has been tested extensively, and its potential has been already validated. These are not only meant for dissemination purposes but also for the management and knowledge of the building itself. This further step does not deny the classic use of desktop hardware but is opening this world to greater interaction with the built environment.

Returning to the discourse of the initial classification, an additional facet of investigation opens up. After dealing with the reconstruction of lost architectures and the digitisation of those still present, the third group can be considered a subset of the one already cited. In particular, they are digital twins for the architectural palimpsest analysis. They identify the various historical stages still identifiable in the current state of the asset. These models develop following them and thus through different levels. Figures 2.1.1.c and 2.1.1.d show some examples.

Unlike the previous cases, the activities carried out on this issue are scarcer. Indeed, it is difficult to identify a consolidated and common framework (which was evident in the other procedures). This type of analysis, and subsequent digitisation work, requires knowledge of the building's historical events and mastery of existing documentation that describes changes in structure and layout. The cases featured are based on various processes and tools, from CAD modelling (Micoli et al., 2013) to BIM software (Barazzetti & Banfi, 2017). Moreover, the purposes of the digital models themselves are not always the same: dissemination (Stanga et al., 2017), structural analysis (Barazzetti et al., 2015.a) or support of site knowledge (Campi et al., 2017). This makes finding common solutions and processes even more complex. Despite the strong relationship between model and information (and sources), no explicit reference has been found to the possible management of this connection within digital twins.

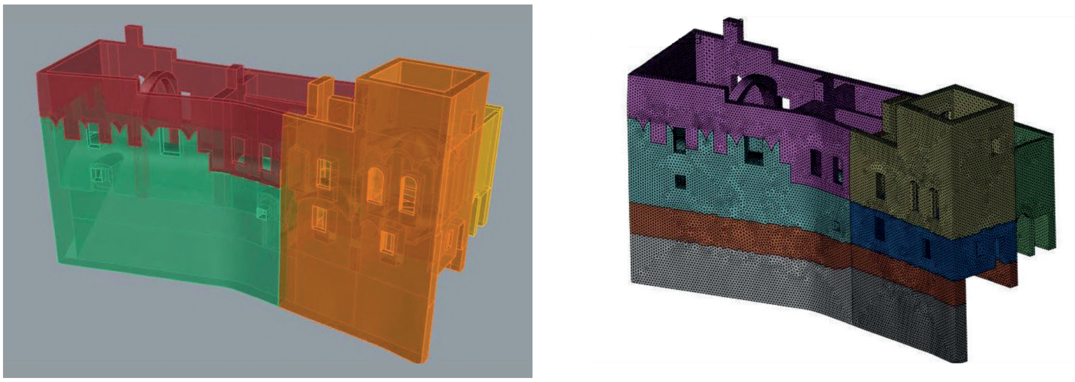


Figure 2.1.1.c "The BIM turned into a finite element model following construction stages and material properties". (Barazzetti et al., 2015.a).

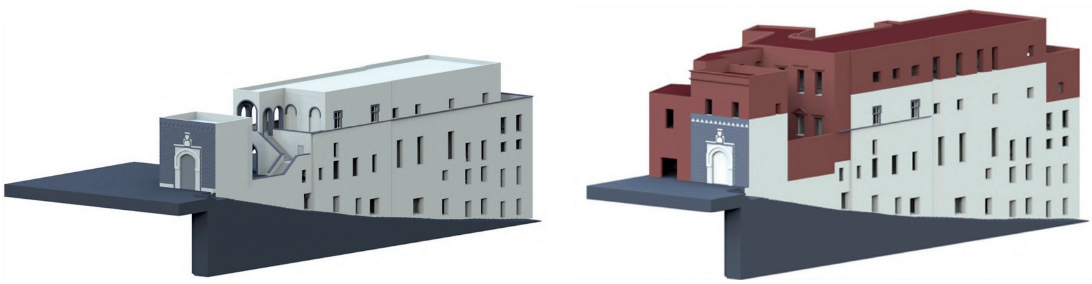


Figure 2.1.1.d Reconstruction of the original configuration of Palazzo Penne (left) and the second stage with the eighteenth-century additions. (Campi et al., 2017).

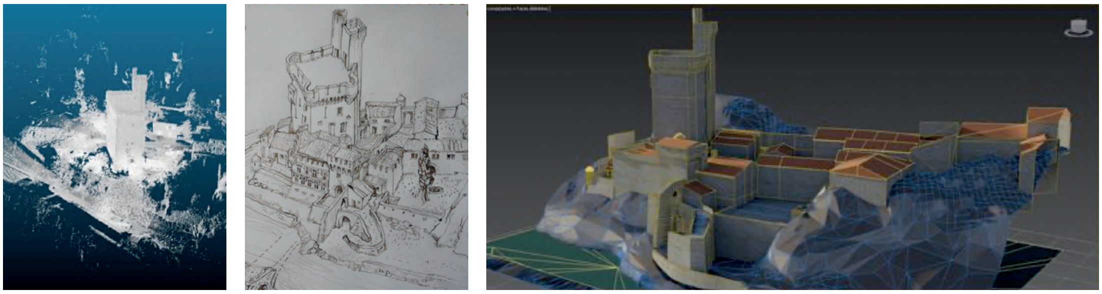


Figure 2.1.1.e The hypothetical reconstruction of the "Tour Philippe le Bel", made on laser scanner surveying and other historical sources. (Berthelot et al., 2015).

Lastly, there is a topic that has still to be fully covered by works and research, thus providing a few references to conduct some reflections. That is the digitisation of both the current state of architectural heritage and previous historical phases. These particular digital twins (Guidi & Russo, 2011; Mastronuzzi et al., 2013; Berthelot et al., 2015; Barrile et al., 2022) attempt to collect in a single place the digital copy of everything it is still visible, completed with the reconstructions of the elements no longer existing but deduced from the study of the documentation (Figure 2.1.1.e). These examples do not constitute a sufficiently populated group to identify a tested workflow. In these cases, the existing part, based on point clouds, is then completed with hypotheses for the lost portions. This field of work and research remains unstructured and even less aligned on common procedures, tools and systems. However, what emerges from these experiences, is the centrality of managing the relationship between geometric information obtained from modern surveys and that deduced from the study of historical documents.

Using different sources of geometric information, as for the last two groups of works, leads to reflection on the accuracy level the various components should present and how they can interact with each other (Rodriguez-Gonzalev et al., 2017) (Figure 2.1.1.f). Although the traced bibliography seems to treat the existing and digitally recorded structure and the reconstructed structure based on the documentation similarly, the question of the level of accuracy of the information is not new. The idea of combining elements, deriving from analyses and sources of different natures, into a single tool is quite diffused, although not exclusive to the built assets (Ferraretti et al., 2018), for which documentation has accumulated over time. Some works and research have dealt with the issue, finding different solutions. One approach simulates the pyramid structure proposed by GIS systems (Guidi et al., 2009): this approach works positively when general and broad information at near-territorial scales is added and overlaid with other detailed data in spotted zones. The information is thus redundant in some places. However, it allows both a general overview and detailed readings starting from individual areas. Additional studies (Banfi, 2019; Banfi, 2020) have developed a classification system to describe the degree of accuracy of the source information (on which model

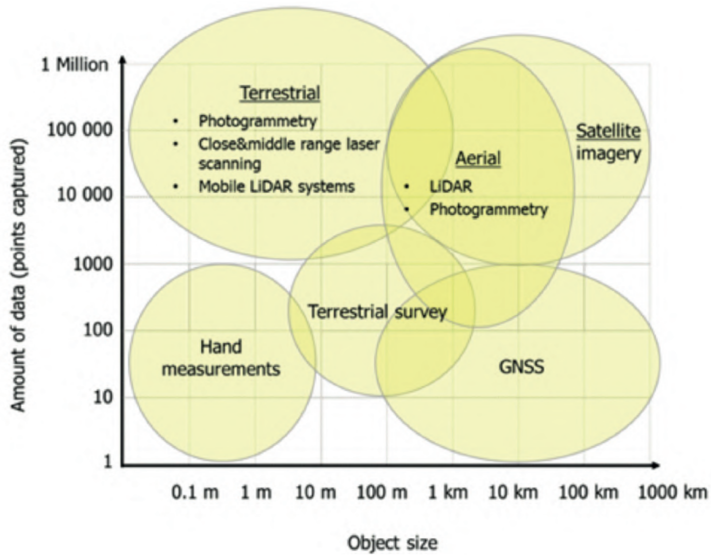


Figure 2.1.1.f Survey techniques scale and object size. (Rofriguez-Gonzalev et al., 2017).

development is based) and the resulting geometries. This approach allows a systematised modelling process. It starts by observing the nature of the reference data and then develops the corresponding three-dimensional components that match the sources in terms of the level of accuracy. According to the accuracy, the data is organised and stored. These classifications give the possibility, within the same system, to insert and retrieve both large-scale information and high-accuracy reference material such as point clouds.

Net that the whole field of cultural heritage digitization is constantly evolving due to a continuous digital transformation, the analysis showed that the areas of work dealing with existing assets digitisation and lost heritage reconstruction are well-established. It is equally clear that the other examples, those more related to the research question, do not yet have established and tested approaches for the digital transposition process.

The following section continues the discussion of the state of the art. It will move on to the topic of information management within digital twins.
Instead, the compendium on what is addressed in these two subsections will defer to Chapter 2.2. This final paragraph will describe the essential issues that emerged from this study, reporting the addresses for the subsequent work development.

02.1.2 _ Architecture and information assets: information technology for building management

A digital twin (Ildikó Leete, 2022) refers to a digital copy of an object or system, like a building, that simulates its processes and dynamics. These tools can manage and provide the information necessary for the specific function for which the digital twin is designed. In architecture, it can be declined in several areas: facility management, historical description, structural study, etc. With the consolidation of this type of tool, research has still begun to experiment on the merits of how to exploit these datasets at their best. It must also consider their connections with the components of the digital building.

This section critically reports the state of the art on this topic. It attempts to outline the methods used for information management of architectural heritage, emphasising their characteristics.

A first approach for the information management of built assets is certainly HBIM, introduced in the previous section. BIM is now a *de-facto* standard and a prerequisite in many areas of building design and management. Its great strength lies in the rigorous management of internal information: each element that composes the digital building has its set of data that describes every technical aspect such as materials, dimensions, specific characteristics, etc.
While this approach perfectly fits for new constructions, where it is correct to base the modelling and information system on the building's generative elements (wall, pillar, floor, etc.), this often clashes with the needs of built heritage assets. The interpretation of the latter cannot always be based on such components. Indeed, they can be more complex or deviate completely from this approach, for instance for conservative (based on stratigraphic units) or historical analyses (which reconstruct the various phases). All these necessities often involve difficulties in modelling, as requisites are in contrast with the default possibilities offered by the software. As already mentioned, a strand of research has developed a system to overcome this problem (Oreni et al., 2014; Barazzetti et al., 2015.b; Diara & Rinaudo, 2020). Once the three-dimensional objects have been developed outside the BIM environment, they are inserted into the dedicated software. The process involves making these elements parametric. It makes it possible to enter the necessary information linked to it. For the reasons mentioned above, there are also experimental works that develop new information structures within this software, customising the default solution (Pocobelli et al., 2018; Garcia Gaco et al., 2022). This tendency is often found in analyses of materials, architecture restoration, or dealing with the management of the built environment from the point of view of conservation and intervention history (Figure 2.1.2.a). As far as historical analysis is concerned, previous attempts exploited features already present within the software (although not designed for this specific use) to divide the model into several historical phases, succeeding in carrying out a palimpsest analysis (Godinho et al., 2020; Banfi, 2021) (Figure 2.1.2.b).

This study of the state of the art reveals an additional attitude towards the issue of information management for architectural heritage. In this new case, the dataset is managed subsequently to the development of the digital 3D model and outside the modelling environment (Battini & Landi, 2015; Agnello et al., 2019; Banfi & Previtali, 2021). This approach sees a starting point in what has just been explained in the analysis of HBIM models and provides the possibility to range widely over the information structure. These systems often can be more easily integrated to external communication and fruition technologies such

Figure 2.1.2.a BIM element modelled from a point cloud and correlated with a customised attribute table for conservation purposes. (García Gago et al., 2022).

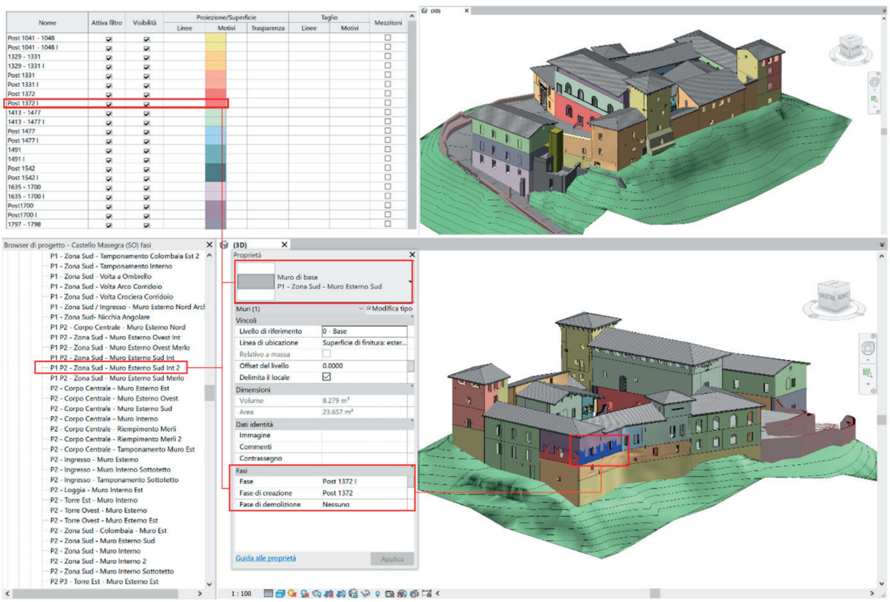


Figure 2.1.2.b "Management of historical phases in HBIM project of Masegra Castle" with work phase option in Autodesk Revit. (Banfi, 2021).

as AR and VR. Such digital twins are often more designed for communication and dissemination purposes rather than for building management. The approach, that is less technical and hierarchical compared to the working models seen above, allows the use of more modelling software, as it does not require an internal data system. Some experiments have also demonstrated the possibility of inserting and viewing historical documents, technical drawings, etc in VR (Banfi et al., 2019.b; Banfi & Oreni, 2020; Banfi et al., 2020). These solutions allow for a deeper understanding of the architecture, not only from a geometric point of view but also thanks to the sources loaded into the system. Nevertheless, documentation is not considered part of the digital twin but a communicative addon.

Another great area that is proving to be increasingly well-performing in information management is GIS (Geographic Information System). This system typology permits to control large quantities of data and perform various analyses on them. GIS information systems were created to work on a territorial scale and with various sub-systems included. For this reason, they very often intercept issues related to the built environment, managing information related to energy consumption, building characteristics, building services and more (Fabbri et al., 2012; Sánchez-Aparicio et al., 2020; Guzzetti et al., 2021.b; Guzzetti & Biolo, 2023).
Precisely because GIS was developed for large-scale databases, its basic visualisation is two-dimensional, which inhibited its use for digital twins of the individual building in the early days. In recent years, however, the tendency to encourage the integration of these systems with three-dimensional models is spreading strongly. It can be both for urban (Bertocci et al., 2014) and architectural (Avena et al., 2021), BIM (Wang et al., 2019; Carenzo, 2021) or geometric 3D (Moretti et al., 2014). This hybridisation makes it possible to think of digital twins of singular architectures that exploit the communication potential of 3D objects with the extensive and highly flexible data management functionalities of GIS systems. Solutions of this kind allow great freedom in the construction of the information system, making it easy to adapt to the needs of the particular case. Similar situations, although less powerful (they do not allow data analysis, which is fundamental for the study of the territory), are also found in some geometric modelling software. Rhinoceros, for example, allows the free construction of data tables for each element present in the modelling environment.
This third approach to digital twin information systems has still been little studied, as the combination of BIM/3D model and GIS is still a relatively new concept.

The management of the digital information model is a well-established issue and solutions to develop such systems are manifold and approach the different needs expressed within the specific uses.
Concerning research on this topic, there is little tendency to consider the reference sources within the datasets for architectural heritage digitisation. As previously mentioned, however, this documentation represents essential references for the digital transposition of these architectures and their complete knowledge and management. Some works have shown the desire to investigate this aspect, proposing solutions to link three-dimensional digital objects and documents necessary for asset knowledge. The state of the art on the subject has revea-

led experimentations that have customised BIM systems, in favour of external documents integration within the model (Bruno & Roncella, 2019) (Figure 2.1.2.c). Other works carried out similar activities using GIS systems (Stamnas et al., 2021). Finally, in further cases, the model is connected to external web storage systems that collect sources useful for the architecture's enhancement and the transmission of knowledge (Tommasi et al., 2019). These stimulating experiences open up additional points to address the studies on the theme of digital twins as a management tool and at the same time as a place to collect information sources to be connected with the model.

The next chapter reports a brief account of the directions and trends that emerged from the state of the art. The text then moves to the heart of the research with the proposed work and its implementation.

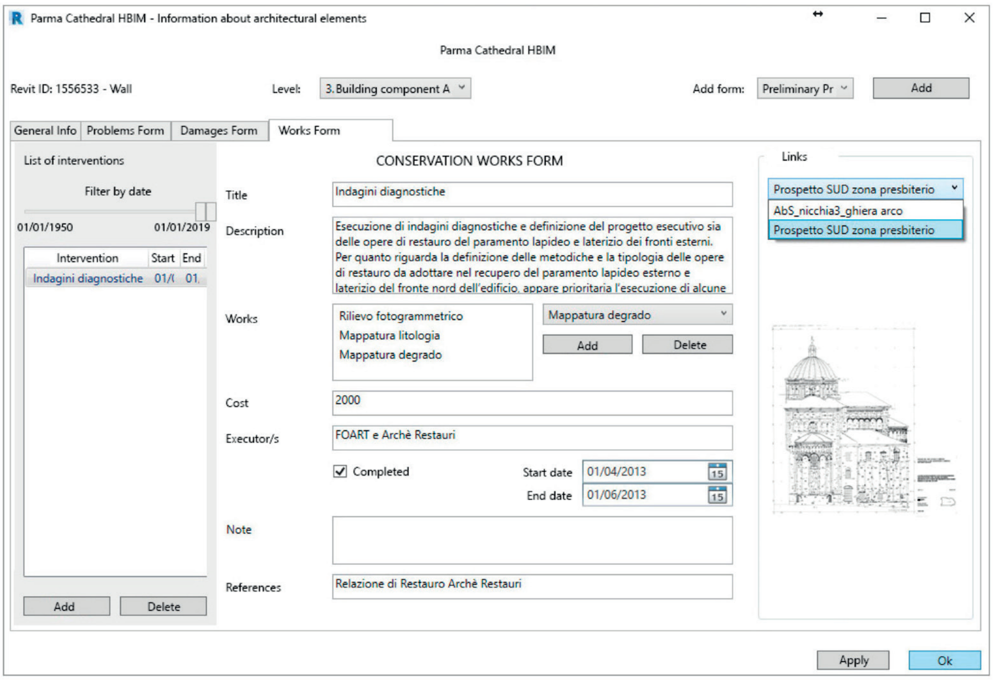


Figure 2.1.2.c "Example of Graphical User Interface. On the right, the links to external files can be visualised and opened". (Bruno & Roncella, 2019).

02.2 _ Directions for research work

The previous pages illustrated how the topic of digital twins has already been addressed within the architecture and architectural cultural heritage field until now. This analysis has demarcated the objectives achieved and the processes already settled in this field of research, both about the theme of the development of the digital object itself and the management of the pertaining information package.
The previous digression has also shown the directions for the development and structuring of the research work in terms of the research question itself and its objectives. The present work aims indeed to formulate a framework for developing digital twins in order to facilitate the spatial understanding of architectures and gather the necessary information for the knowledge process, indicating the related reference sources. This framework should allow a 360-degree understanding of the building thus considering the current state and the previous historical phases.

First, the research will have to work on the methodological structure underlying the model, which will have to gather both accurate restitution of the existing structures (based probably on survey products such as point clouds) and reconstruction of past and lost elements. Therefore, this involves considering the coexistence of the first two main cases outlined in Chapter 2.1.1. The objects will be both restitution of today's measurements and interpretations, sometimes hypothetical, of documents of past eras. The research does not concern the possibilities and methods of modelling but the handling, within the same object, of elements of different natures and with heterogeneous accuracy (since they are based on dissimilar reference sources). For this part of the work, it will be important to start from the experiences analysed, which have already dealt with the theme.

Since the work aims to develop a tool to support the knowledge of architectural heritage, the documentary sources used for its construction are a key focus of the work. In particular, given the historical nature of the sources, material has been quite hard to find and interpret (more frequent condition than for recent survey and study outputs). Nevertheless, these sources legitimise the three-dimensional representation, especially when dealing with purely hypothesised structures. For this reason, an important point to work on will be the integration of these sources within the digital twin. As we have seen, the existing bibliography does not yet present a univocal attitude and the possibilities for experimentation and deepening are diverse.

The desire for a system that also includes the reference material, and a connection system between it and the model itself, as well as the presence of elements with different characteristics (the model of the current and past configurations), will require the study of a well-structured information system that includes heterogeneous information that pertains to different elements: sources, geometric information and model components. The framework must be able to handle point cloud data, as well as for the identification and description of a historical text or a modelled object within the digital twin. The starting point must be the studies that have already addressed these issues, reported above, grasping the strengths and characteristics that can be re-proposed, and the aspects to be modified to better respond to the needs imposed by the purposes and features of the work.

Finally, a crucial attribute of a built heritage digitisation system is flexibility, namely, the ability to easily and naturally manage updates to the digital twin. The reference works seem to not treat such an issue. In the author's opinion, the research activity cannot neglect this theme. The study of the history of architectural heritage does not foresee a term. Knowledge evolves, expands and sometimes needs retractions and the digitisation system must consider these situations. The structure has to manage and assimilate them into the digital object.

The research work starts from these points, building upon the characteristics and current lines that emerged from the state of the art.

03

METHODOLOGY

03.1 _ Clarification of goals and targets

The origin of this research work lies in the observation of today's context, as well as in the unlimited possibilities offered nowadays by technological advancement and the increasingly predominant digitisation, which is a process strongly found within the world of architecture and cultural heritage. The analysis of the state of the art in the previous chapter illustrated many examples of how new digitisation technologies, as also information and communication ones, are transforming this sector and the approach to the built heritage. Therefore, the work carried out is part of this process, developing a new approach to the knowledge and management of architectural heritage supported by today's techniques and technologies for surveying, studying and digitally transposing information.

This PhD research proposes an approach for developing a complete digital model of an architectural asset and its geometric information. It is a digitisation method, capable of fully describing the complex architectures of our built heritage. Its application results in a 3D model of the currently available structures, of those no longer visible and eventually, of those that were once part of the building and no longer present now. Only a digital model of this kind can explain the processes still in progress and particular phenomena or junctures that can be traced within the building system. It is essential to analyse and understand the phenomena that have affected architecture with deep roots in the past and the spatial settings lost over the decades or centuries to fully understand them. This is why the inclusion, within the digital twin, of past historical-architectural layers that are no longer visible (due to demolitions or changes in layout) or no longer present, is considered crucial. Only the overall analysis of the structure understood as a sum of its transformation, elements and phenomena, can allow a complete knowledge of it, a prerequisite for correct interaction with the built heritage.

Therefore, this type of digital twin must be able to collect data from information sources of a different nature. Typically, architectures of this kind are linked to a vast heritage of documents, written works and information, accumulated throughout their existence. To these sources are added those closest to us, such as photographic material, traditional and modern surveys and so on. All this leads to geometric information with varying levels of accuracy. Moreover, the latter may cover the entire structure or only a part of the building, thus working in a complementary manner.

The devised system aims to collect in a well-structured manner all geometric information available on an architectural asset, as well as that which will be produced or traced in subsequent stages. The ultimate goal is to offer a tool that supports and facilitates the knowledge and understanding of complex structures and their architectural-spatial arrangements. The fundamental idea is that this system, favoured by the new techniques of three-dimensional representation and today's information technology, can make the narrative of these buildings, made complex by their historical and documentary stratification, easier and more accessible. The need for such tools emerges by observing the dynamics of projects in highly stratified areas. This is the case of urban interventions that too often intercept, or even affect, hidden portions of architectural heritage, whose presence had not been carefully evaluated. Digital tools, if well thought out and organised, can greatly facilitate these dynamics. In addition to being efficient catalysts for the knowledge process, they are potentially useful allies for the management of the asset itself and urban planning.

The figures to whom this system of digital transposition of geometric information is addressed are those that gravitate around the management of the architectural asset itself. These include, for example, individuals within the building's management-administrative apparatus, municipal and territorial planning bodies, professional figures operating on or adjacent to the structure, etc. This specific direction of the tool involves different approaches and characteristics compared to applications such as the touristic one. For this reason, it was considered appropriate to specify this information, to be able to correctly frame the proposal described in the next paragraph.

Before proceeding with the description of the approach proposed in this research work, the text outlines the main prerequisites for its development.

- The structure must be able to give rise to a model including the accessible structures, those known but not visitable and finally, those only hypothesised.
- The structure must be able to accommodate geometric information of different origins, nature and accuracy.
- The structure and its implementation must be able to link the sources used and the resulting 3D model, for a constant comparison with the original information.
- The structure must be flexible to incorporate changes affecting the 3D model and information system, even when new sources and information conflict with previously digitised data.

In summary, the approach just introduced, which will be detailed in the following sub-chapter, stems from the desire to obtain an adequate information tool supporting the management of built heritage. It is established on today's effective three-dimensional representation methods, as well as on an implementation and updating system that allows for a constant collection of new sources and information.

As anticipated, all that will be deepened with the following pages. The text will provide a detailed analysis of the proposed approach and then moves on to the methodology followed for experimentation with the case study, the Ghirlanda of the Castello Sforzesco in Milan.

03.1.1 _ Structure of the geometric and information model

This section of Chapter 3 provides an in-depth description of the framework designed for the digitisation of architectural assets and their geometric information.

The proposed methodology aims to furnish a comprehensive spatial configuration of complex constructions, based on an ensemble of data from different sources and analyses. The 3D model acts as a central hub where information about the buildings is connected and organised, in a functional way for their management.

The approach was based on the issues that emerged from the analysis of the cultural heritage world. Considering architectural assets in general, a salient issue that emerged was the inherently fragmentary nature of the extant geometric documentation. Comprehensive modern geomatic surveys of the entire building are infrequent. More often the geometric information on architectural assets comprises a mosaic of traditional surveys (performed by trilateration) in paper format, historical documentation and a few digital surveys of only small portions. From this observation emerges the urgency of structuring an approach to produce a correct 3D model of the building from different types of information and material. Another prerequisite is the development of a system that allows seamless updates as new detailed surveys or unpublished sources of geometric knowledge become available. The basic idea is to produce a 3D model that embodies multiple levels of accuracy, derived from the material available, often heterogeneous in terms of accuracy. The structure stems from the notion of LOGI: Level of Geometric Information. The digitisation method envisaged a tripartite division of the data into three distinct levels wherein the various elements of the building are then modelled. The differentiation is made according to whether they are spaces and structures investigated by the modern geomatic survey, whether they exist only as a documentary collection or they are only present as a hypothesis, since the original structure is no more existing. This differentiation derives from direct observation of the consistency of the geometric information of the case study but can be extended more generally to architectural heritage as a whole. The definition of these modelling levels takes its cue from the LODs associated with BIM processes (BIMForum, 2022) and other research work that has developed other systems to classify the level of detail in modelling. One research which has developed a system of levels of this kind is carried out by F. Banfi (Banfi, 2017; Brumana et al., 2018). He has introduced a series of GOG (Grade of Generation) within the process of developing BIM models for cultural heritage buildings.

The classification proposed with this research is as follows:

- LOGI 1. The first level pertains to the 3D modelling of the hypotheses deriving from historical documentation. The latter consists of graphics, cartography, iconography and photographic material. Therefore, the first tier of LOGI leads to simple three-dimensional elements that materialise structures that are no longer visible but that were probably present. This information, although often very approximate, is essential for intervention planning as it came clear during the planting project of Piazza Castello in early 2022. The project ignored the presumed presence of the Spanish Bastions ruins below ground level, leading to an abrupt halt of the operations, and the entire intervention was revised. The use of a comprehensive 3D model and an information system, bearing the geometry and data of these

structures, could have avoided that issue.
- LOGI 2. This level includes documents produced using traditional surveying methods, such as classic geometric surveying and trilateration. It is not uncommon that such documentation, as in the case of the Castello Sforzesco, is incomplete or does not fully describe the surveyed elements. In addition, the material may be paper-based, causing approximation errors in the digital transformation phase. Moreover, these surveying methodologies heavily struggle with absolute accuracy, while they guarantee relative accuracy as well. Thus, in complex environments, they risk misrepresenting the architectural corpus as a whole, even as they provide detailed insights.
- LOGI 3. It represents the highest level in terms of details and accuracy, and indeed information and material from modern geomatic surveys fall within this group. These materials are, for example, point clouds and surveys with a level of accuracy of a few millimetres. Unlike the two previous levels (LOGI 1 and LOGI 2) in which the modelled volumes respect the accuracy of the reference sources, in this case, the 3D modelling of the architectural elements involved a simplification factor. The model elements are led to have an accuracy of a few centimetres (not millimetres). Given that the approach aims to generate a support tool for asset knowledge and management, a simplified model has been considered sufficient. It does not mean obtaining a basic replica in terms of shapes but is somewhat simplified compared to the level of accuracy provided by this type of source. However, the result remains a correct model capable of transmitting the necessary information. In light of the character of the research issue, which is more holistic than technical, it was not considered essential within the work to further define this factor. It should also be emphasised that while exploring the model within the chosen software, it will always be possible to reconnect to the native reference information to consult the original data of the survey, without the metric and detail simplification introduced when switching to the 3D model.

For the time being, the system is developed on these three levels, defined based on the types of sources commonly found when studying and analysing this type of architecture. Nonetheless, it remains evident that as the technology progresses, this schema could conceivably be extended by inserting new levels with even greater accuracy.
A second specification concerns the association of a source, and its geometric information, to a specific LOGI. Such attribution cannot be based solely on the nature of the source and on the technology, more or less advanced, used for its determination. The discriminating factor lies in the degree of certainty relating to this information. An uncertain datum, although detected with state-of-the-art instrumentation, cannot be associated with LOGI 3. As a conjecture, it remains within the first level, those of hypotheses.

Net of these last considerations, the current structure permits the collection of both what is extracted from a survey such as the one carried out and information from historical sources. The result is an organic yet heterogeneous collection that encompasses all elements of the building, from those surveyed to those hypothesised because they are no longer visible or exist. Furthermore, by developing the digital twin in several blocks, and exploiting a rigorous use of georeferencing, each element of the 3D can

be updated whenever new material is available, either from surveys or found as a result of research activities. The system makes it possible to accumulate knowledge and update the object over time.
The representation of this method (Figure 3.1.1.a) shows that new data may lead to a seamless update of the geometric information or an upgrade of the block in terms of the Level of Geometric Information. In this case, the 3D object is modified by inserting a new partial model, built on the renewed information and it assumes the level of accuracy of the new source. The updating process could discard some portion of the digital twin. New data, discordant from that used previously and of a more accurate LOGI, may refute the current configuration of the digital twin. This situation, as we will see, happened during one of the phases of updating the model of the Ghirlanda of the Castello Sforzesco.
This paradigm, therefore, represents a cyclical system that accumulates knowledge and allows the collecting in a single place the contribution of individual works. This process allows increasingly setting up a complete reconstruction of the architectural asset.
The proposed digitisation method is vendor agnostic, since it does not give any indication of the specific software to be used. It comes earlier than the more pragmatic choices of 3D model development. Despite this, this hypothesis is based on the non-use of BIM modelling tools. The latter would have clashed with the geometric peculiarities typical of the architectural heritage. Software such as Revit and Archicad still struggles with modelling non-standard and non-regular elements, which are typically not part of the world of new construction (Guzzetti et al., 2021.a).

This framework for digitising architectural heritage consists of two parts. The first, just described, concerns the classification and modelling of geometric information. The second includes the organisation of reference sources and their connection to the 3D model.
The three-dimensional model of architecture is paired with an information management system (Gaiani & Martini, 2013; La Monica et al., 2013). It manages information related to model elements and reference sources, which are linked to the same elements, along with an online repository. These two elements, however, are not partitioned contexts: they intertwine mutual bonds, to develop a single organic and solid system, which also embodies the 3D model.
Moreover, the information system starts from the model and its three-dimensional elements. To develop a well-structured and connected system, the model, in the opinion of the author, must comply with certain conditions:

- The digital twin must be rigorously organised.
- There must be an association framework between model elements and the references within the 3D environment.
- Sources within the model must be linked to their files in the database.

These needs refer to the use of attribute tables for both the model (and its components) and the sources. This requirement could be met with many different software. One solution could be to enter the model into the GIS environment, organising the information through attributes tables and metadata management that reside in the software. A further hypothesis, the one used

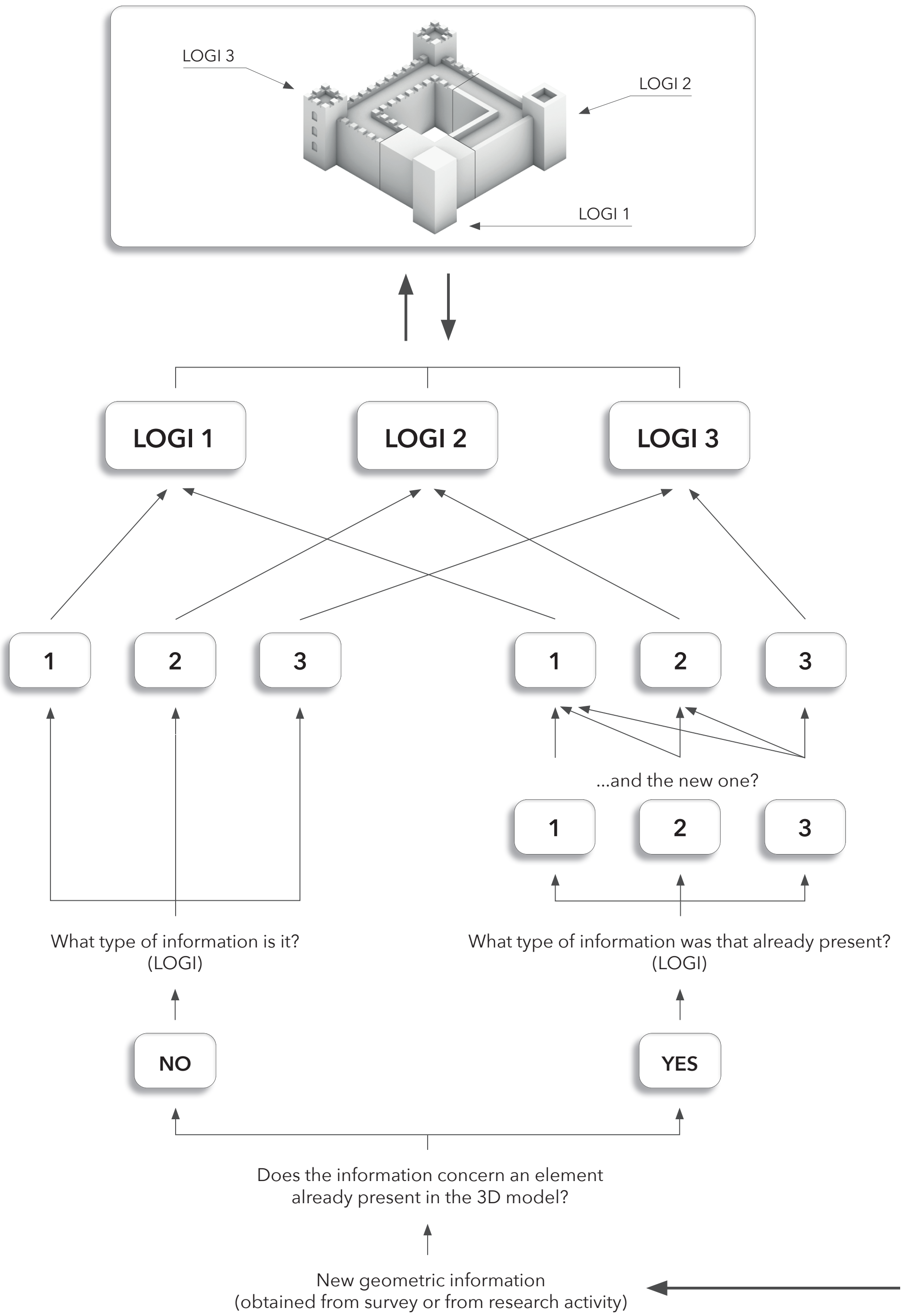


Figure 3.1.1.a Representation of the approach for developing and updating the 3D model.

during the verification stage, is Rhinoceros software. It provides functions for associating data with the modelled elements. Net of the chosen solution, the system assumes that all the modelled elements are associated, within the 3D environment, with attribute tables that describe them and report the essential data for the recognition of the object and its connections with the reference sources. The proposal outlined refers to existing information systems and their data management structures. In particular, it is the data structure used by the Topographical Database of the Lombardy Region for the organisation of information in the digital environment (Regione Lombardia, 2008; P.C.M. - Italian Government, 2011; Regione Lombardia, 2012).
The developed solution is structured as follows (Figure 3.1.1.b):

- IDENTIFICATION. It is a unique and progressive numerical code that involves all elements of the model (including sources). The ID_object allows unambiguous identification of each object within the modelling environment.
- OBJECT CLASSIFICATION. This group consists of three pieces of information: COD_component, COD_subject and COD_building. These numerical codes allow the modelled element to be classified within the building system, associating it with a particular structure and its component. Figure 3.1.1.c clarifies this classification. COD_building identifies the digitised architecture. The COD_subject is the identifier of the different recognisable structures of the building and therefore, it does not refer to the architecture as a whole. As it is possible to see, the diagram does not associate this code with the castle but with one of its four corner towers. The COD_component, finally, indicates the various parts of this structure, such as the red model of the inner space in the image. The system uses this fragmen-

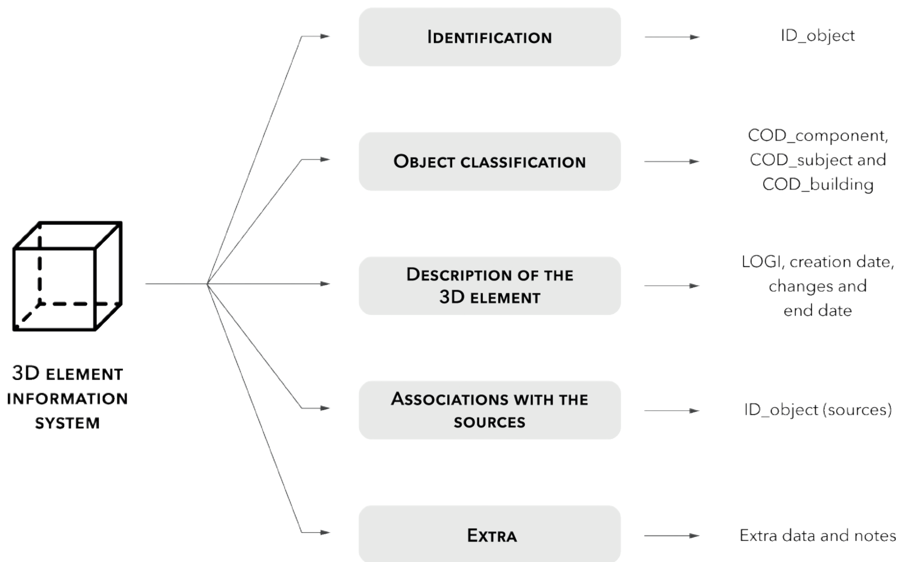


Figure 3.1.1.b Diagram of the information needed to compile the attribute tables of the 3D model elements.

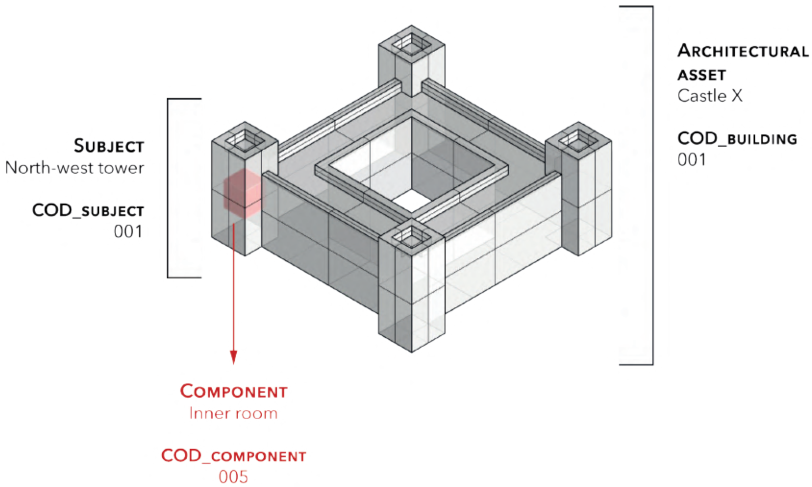


Figure 3.1.1.c Example of the classification system for 3D model elements.

tation to work more precisely with the associations between objects and sources. The latter often affect only some portions of the various structures, and it would therefore not be correct to indicate them as general references. It is the reason for which there is a description of the information used for each reference source. This breakdown of the digital twin into subjects and components does not base on a rigid and formal structure but on the particular experience of each architectural asset. It recognises the constituent elements of the building and works on them. The individual case study will allow the identification of these structures (COD_subject), which show themselves as elements with an autonomous character within the building narrative. A further discussion on it will be in the final phase. This solution requires a list of codes and referen-

COD_building		COD_subject		COD_component	
001	Castello Sforzesco, Milan	001	Torre della Colubrina	001	Connection route
				002	Casemate at 117,50m a.s.l.
				003	Casemate at 121,70m a.s.l.
				004	...
		002	Galleria di controscarpa	001	General route
				002	...
		003	Porta del Soccorso	001	Connection route
				002	Western staircase system
				003	...

Figure 3.1.1.d Classification according to the identification code system. It is also an example of a reference code list.

ce elements (for the three code levels), containing the subdivision. It can be constantly updated in case of changes or extensions to the digital twin (Figures 3.1.1.d).
- DESCRIPTION OF THE 3D ELEMENT. The third section of the data is for the LOGI of the object and the necessary information about its creation and following changes, to keep track of its updates. This group of data also presents a field to report the eventual end date of the validity of the three-dimensional object. It is important in the case when new, more accurate geometric information becomes available, which deprecates the previous one and the related 3D objects. The volume that must be replaced is historicised, inserting the end date. This operation allows the insertion of a new object, while keeping track of previous versions. This solution is already employed in some geographic information systems to keep track of changes to the countless elements that are often managed simultaneously. An example is the R3Trees application, developed by R3GIS s.r.l. (R3GIS, 2018). It is a tool for territorial scale management of green areas, also used by the Metropolitan City of Milan. Downstream of this, the previous source may also lose its validity. It will be indicated in the notes section of the source itself.
- ASSOCIATION WITH THE SOURCES. The system shall indicate the sources used for modelling the various three-dimensional elements. This information allows links to secondary sources in the online archive and to the information in the cataloguing document, which will be described shortly. It is in the form of ID_object, so as not to create ambiguity in the links.
- EXTRA. It may be useful to set up a separate section dedicated to notes and other collateral information, where there is a need to complete with additional data.

As the 3D model develops, the process inevitably considers new sources of information, which create a reference set for the model. This latter is considered complete only with the insertion of the main sources. Some references are crucial for the development of the model, and they must appear within the 3D environment to provide the possibility of an immediate comparison with the original information. Otherwise, the system only places secondary ones within the external archive, in the manner described below. As has just been mentioned, these are in any case linked to the model via the data tables of the modelled objects (section "association with the sources").

As for the sources within the model, the system also requires them, as in the case of volumes, to have a data table within the modelling environment. The proposed solution, shown in diagram 3.1.1.e, is similar to the previous one and consists of these data sets:

- IDENTIFICATION. It occurs through ID_object, as for model elements. This is a sequential number that is associated with all objects inside the model.
- OBJECT CLASSIFICATION. Similar to the previous section, this one aims to describe and classify objects systematically. Again, there are two numerical codes: the first one is the source number (COD_source), and the second one refers to the specific component of the source (COD_annex). This choice derives from the experience on the Castello Sforzesco. Some sources are sets of several documents, or the source material has been cut into multiple parts, as is the case for the cadastre sheets or the georadar

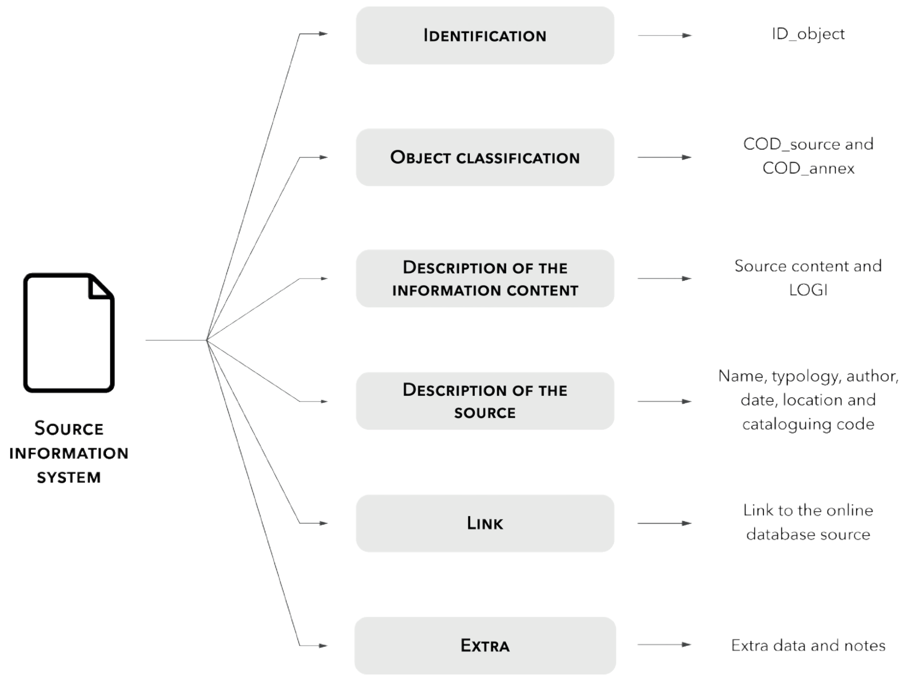


Figure 3.1.1.e Diagram of the information required to catalogue sources and compile their attribute tables.

outputs. It would not be correct to treat the individual parts as separate pieces of data. Furthermore, using this structure, it is easier to recognize different elements afferent of the same source, as their first numerical code will be the same. As in the case of 3D elements, a sheet will therefore be required in which all codes and their source and component references are listed. This additional document allows for keeping track of the dataset, providing a quick check of the codes used.

- DESCRIPTION OF THE INFORMATION CONTENT. The third part aims to describe the information contained in the various sources. There are two factors: on the one hand, there is a very brief description of the document's content, and on the other one the LOGI to which the source (and its information) is associated.

- DESCRIPTION OF THE SOURCE. This fourth section contains the basic data for recognising and describing the document. It is like typical archival cataloguing. The information required is document name, document type, author, date, location and cataloguing code (if present).

- LINK. It is the link to the source in the online database. It creates a bond within the archive. This link will also be present within the online archive, in the source catalogue file, to generate the necessary relationships for the global system to function.

- EXTRA. It may be useful to set up a separate section for notes and other collateral information, there should be a need to complete with additional data. This section may contain an annotation on the historicisation of the source itself, in favour of a more up-to-date or accurate reference.

Parallel to this internal information system in the model, the approach involves the creation of an archive in which to store information sources.
This component of the information system has been identified in an online database, ideally, a cloud repository accessible by the figures enabled to consult the reference material. The solution must connect the modelling environment with this online database by links. This kind of connection becomes a prerequisite for the cloud storage application choice. In this space, sources are organised as an archive, resulting in an always searchable reference database for the digital twin. This system consists of all the sources used and a file with the necessary information for their identification and description. Sources are renamed with their ID_object, for direct recognition and to better relate to the information in the model. However, the archiving and cataloguing file contains the information entered in the attribute tables of the model's internal references. This document differs only in the presence of extra data. It reports, for each source, the identification codes of the three-dimensional elements developed from them. For each ID_object, the structure also describes the specific information exploited (Figure 5.4.b). This additional data allows the model to be linked to the online archive, closing the network of connections.

The experimental phase of the work employed an Excel file for the classification operation, but it is only an example. What is described in this chapter, indeed, is an approach that can be adapted to different implementation choices in terms of software and tools.

The information system proposed connects sources, information and 3D elements, joining the LOGI-based digitisation method for geometric information. This approach allows for enriching and modifying the information system and the three-dimensional object simply and continuously. As a result, knowledge never starts from the beginning but accumulates and evolves progressively into an increasingly complete object, which supports the decisions and the management of the architectural asset.

03.2 _ Operating protocol

The approach for the digitisation of architectural heritage, including the information model, will be tested through the case study, the Ghirlanda of the Castello Sforzesco in Milan, to which the next chapter is dedicated.

The experimental work must adhere to the steps that would occur in the case of digitisation of an asset, proposing them in the same order.

The first step aims to frame and investigate the case study, working in parallel on the collection of sources and geometric information available. It will involve the analysis of previous studies and works, archival and other research.
Downstream of this initial phase, the missing data must be identified, on which to intervene with survey or study activities, if necessary. Concerning the case study, the work involved a modern geomatic survey, as none of the sources collected fell within the third Level of Geometric Information. In the absence of data relating to that LOGI, it would therefore have been impossible to completely test the structure.
Once the data collection will be complete, work will develop the initial version of the digital twin. Operations will use Rhinoceros software. This solution allows flexible geometric modelling, which meets the recurring needs of architectural assets. In addition, this software conveniently handles the import of external material (raster, point clouds, CAD files, etc.). Moreover, it allows the compilation of attribute tables for all elements in the project.
After the 3D modelling, the process must verify the information system. The model will have to be organised and completed by entering the principal sources and completing the multiple attribute tables, both for three-dimensional elements and the information sources. At this stage, the experimentation will check the attribute table's structure and make any changes. Regarding the online database, the work will exploit OneDrive for Business for cloud storage and Excel worksheets for cataloguing the sources. The links functionality for connecting the sources to the model will be tested.
Finally, the audit process will deal with the last piece of the submitted approach: the collection of new information and the geometric and information model update.

The result of the experimentation, which will be proposed in Chapter 5, was also possible thanks to the chosen case study: its complexity and richness in terms of documentation and information have made it possible to verify all aspects and mechanisms of the hypothesised structure fully and thoroughly.

04

THE CASE STUDY OF THE GHIRLANDA AND THE HIDDEN STRUCTURES OF THE CASTELLO SFORZESCO IN MILAN

04.1 _ Motivations and opportunities of the choice

The choice of the Castello Sforzesco in Milan (Figure 4.1.a-b) as the case study for this research work is based on multifarious considerations intrinsic to this architecture. Foremost, the castle is an exemplary case of architectural heritage.
Net of its monumental and symbolic value within the city and the surrounding territory, it shows a series of typical characteristics of the architectural heritage: it exhibits profound historical roots, intricate complexity and pronounced stratification.

Concerning the first aspect, the historical richness of the building, its story begins in the 14th century, although there are records of fortified settlements even in earlier times. Throughout its existence, and still today, architects, scholars, artists and many other figures have dealt with this complex structure in their artefacts: thousands of written documents, paintings and technical materials still survived history. Plenty of them concern the castle and the evolution of its architectural layout during the various dominations over the centuries, making the Milanese fortress still a building of great interest. This wealth of sources has provided an enormous amount of references, including geometric information, as a solid basis for the deve-

Figure 4.1.a Bird's eye view of the Castello Sforzesco from the city side.
Photo from the website https://www.comune.milano.it/.

Figure 4.1.b Bird's eye view of the Castello Sforzesco from Parco Sempione side.
https://upload.wikimedia.org/wikipedia/commons/8/8a/Castello_Sforzesco_da_alto.jpg

lopment of the digital twin. In addition, the variety of the sources has made it possible to structure a digitisation model and an information system capable of responding to the needs of the different sources that could be traced and their information.

Secondly, the castle is an architecturally complex construction, a testament of different phases and dominations that have brought changes to the layout of the fortification, of which the actual configuration is the resulting multiple stratification. History tells of various enlargements, demolitions, light and more extensive modifications. These metamorphoses can be attributed to different historical periods and the predominant function of the building in those phases: defensive structure, stately abode, barracks etc. These transformations have provided a wide range of scenarios to be analysed (structures remained unchanged, lost elements, others partially destroyed but visible, others probably hidden below ground level, etc.) and on which to test the digitisation method and its solutions. Furthermore, this architectural complexity allows access to the effectiveness of this framework in supporting the understanding of this kind of building.

Notwithstanding the countless research and investigations conducted on the Castello Sforzesco over the past decades, it is still notably unexplored, especially the underground structures. This condition provides the opportunity for future investigations and new geometric information to include within the digital model. This, in turn, paves the way for further long-term testing of the proposed digitisation system.

A final motivation is that the Castello Sforzesco is part of a consolidated urban fabric (Figure 4.1.c), as it intersects with various city systems, such as greenery, public transport infrastructure, surrounding buildings and many others. Considering future directions of the research, these interactions offer the possibility to investigate how this approach can aid in architectural asset management, in addressing conscious interventions and in spatial planning and coordination. An example is included in an academic paper developed from this doctoral research, which deals with the formulation of detailed three-dimensional constraint maps (Guzzetti et al., 2023).

These aspects are behind the choice of Castello Sforzesco as the case study for the digitisation approach. It proved, as it will be seen later, to be a tool for optimising the system.

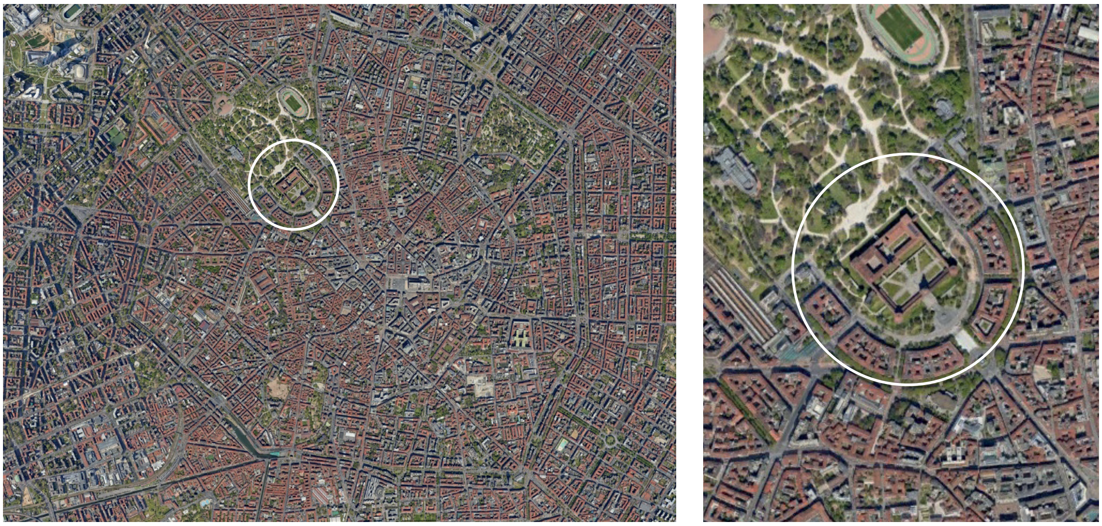


Figure 4.1.c Satellite image (and its zoom) of the centre of Milan with indication of the Castello Sforzesco.

04.2 _ A brief overview of the history of the Milanese fortress

The following pages provide a brief digression on the historical phases of the Castello Sforzesco and the evolution of the building in terms of its layout (Belloni, 1966; Mirabella Roberti et al., 1983). This research went in parallel with the collection of sources, a fundamental process for the experimental work. The analysis of the castle's history provided basic knowledge about the building and supported the understanding of its current arrangement and elements.

The document "Planimetria delle città di Milano colle curve di livello del terreno e delle acque di sottosuolo" of 1897 reports an interesting fact. Within its pages, it shows that the only modest upland present in the city of Milan matches exactly the area of the Castello Sforzesco. As an element of the city's defensive system, it had to take advantage of a higher elevation to effectively control its territory. Right on this small hill at 124,40 metre above sea level (at the time of the above plan, the city cathedral was at an altitude of about 119 m a.s.l.) begins the history of Milan's fortifications, the roots of which predate the Visconti. The first settlement, with its fortress, dates back to the period when the city was in Celtic hands (Padovan, 2014). This earliest version of Milan and its warlike structures slowly evolved as it passed through new dominations, such as that of the Lombards and Goths.

Subsequently, the city improved its fortifications during the battle with Federico I Barbarossa, emperor of the Holy Roman Empire. During this period the Visconti family was increasingly affirmed, which began the history of the Castello Sforzesco that we know. It was under this family that Milan was divided, firstly after the death of Azzone Visconti and then upon the death of Matteo II Visconti, among his two brothers: Bernabò and Galeazzo II. The first was entitled to the eastern part of the city, for whose defence he built, in 1368, a castle in the Porta Nuova district. Galeazzo II took possession instead of the western part and he built a new fortress. It was close to the walls erected under the government of Azzone Visconti. Around 1368 it was grafted in at Porta Giovia (Figure 4.2.a) taking the name of Castrum Portae Jovis (Figure 4.2.b) (Padovan, 2019). Although the found Visconti-era documents do not provide clear information about the interventions on the building, it is possible to say that Gian Galeazzo (who succeeded his father in 1378) continued the works, strengthening and enlarging it. The same happened with Giovanni Maria Visconti, another son of Galeazzo II. Filippo Maria, once Duke, decided to change the fortress vocation, making it his residency. In those years works were devoted to increasing the comfort and beauty of the castle, to make it a worthy home of the lord of Milan. It was Filippo

[1] Beltrami, L., *Il Castello di Milano*, cit., p. 35.

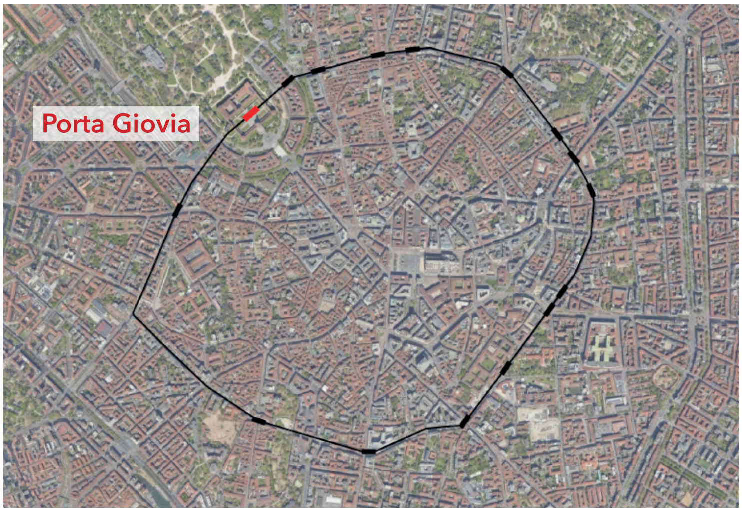


Figure 4.2.a Present-day plan of the city of Milan with indication of the walls (age of Barbarossa), in red Porta Giovia.

Figure 4.2.b Etching titled "Castello di Porta di Giove" (Castle of Porta Giovia). Filippo Biffi and Federico Agnelli, 1674. Document in the "Achille Bertarelli" Civic Collection of Print (Milan).

Maria himself who called Brunelleschi to his court, to have him work “al modello di una fortezza”[1]. Therefore, it is possible that he worked, to some extent, on the Ghirlanda. The architect L. Beltrami, following detailed research and surveys, associated the construction of the Ghirlanda with the Visconti period and not with the Sforza period, although in the latter phase, it was enlarged and improved. With the Visconti era, the castle assumed the square shape we see today, with the addition of the outer defensive structure of the Ghirlanda.

Figure 4.2.c Some areas where the castle shows signs of reconstruction, perhaps associated with the post-Republican period. The first one shows the transition from the use of stone to that of bricks, coinciding with the junction between the older and the later nucleus. In the second one there is an example of the reuse of stone blocks.

When Filippo Maria Visconti died, in 1447, Milan proclaimed the Ambrosian Republic, during which the population demolished part of the fortress, considered a symbol of oppression and tyranny. It is not easy to quantify the extent of such damage, but it is plausible that the outermost part was spared, and additionally, the side facing the countryside and the Ghirlanda itself (as it was beyond the city walls and not connected to them). The structure, as today, shows clear signs of renovations and rearrangements (Figure 4.2.c), not attributable to the restorations at the turn of the 1800s and 1900s. This evidence could be related to the reconstructions following the republican period, when the castle regained its centrality in the city system.

In 1450 the history of the fortress under the Sforza lineage began. Francesco I Sforza, the husband of Bianca Maria (daughter of Filippo Maria Visconti), reconquered the city of Milan, becoming its lord. Already in the same year, reconstructions and enlargement of the castle started, so much so that Bernardino Corio refers to such works with this enthusiasm: "Che ne i seguenti anni, non solamente come prima, ma più amplo il rifece; di sorte, che senz'alcun dubbio si può affermare essere il più superbo, e forte, che sia nel piano, per tutto l'Universo, & essere costato un milione di ducati"[2]. Due to the previous demolitions, the works focused a lot on the side towards the city, erecting the curtain, the circular corner towers and the central one. Among the military engineers who worked there was Antonio Averlino, known as "il Filarete", to whom is attributed the entrance tower, which, as it

[2] Corio, B.M., *L'Historia de Milano*, cit., p. 791. Traced in Padovan, G., *Castrum Portae Jovis Mediolani,* p. 63.

will be seen, would be destroyed in 1521. Francesco I Sforza made the ravelins of Santo Spirito and Porta Comasina to be built. At his death, the power went to his son Galeazzo Maria Sforza, who decided to reside at the castle. As before, the works in that period focused on embellishment activities, to make this fortified residence stately. On 26 December 1476, the Duke was assassinated. His young son Gian Galeazzo Maria Sforza came to power and his mother, Bona of Savoy, assumed the regency. The works of this period radically changed the destination of the structure, returning to a purely strategic type. The built complex increased the fortifications and the war works. In 1477 the Tower of Bona di Savoia, shown in Figure 4.2.d, was erected, and today is still in place between the area of Rocchetta and the great Piazza d'Armi. During those years, Leonardo da Vinci arrived in Milan, specifically around 1482 (Marani, 1982). Before him, however, Bramante had been at Sforza's court, leaving several contributions to the castle, including the famous "Ponticella", visible today on the east side (Figure 4.2.e). The structure aimed to connect the Corte Ducale with the area behind the Ghirlanda. Fortification works continued even with the last of the Sforzas: in this final phase, the castle oscillated between this domination and the French one, in a succession of acts of conquest and reconquest of the city. During one of these occupations, that of Louis XII of Valois-Orléans between 1499 and 1512, the entrances of the building were protected with two ravelins originally designed by Leonardo da Vinci (Pertot & Viganò, 2006). He had suggested such an intervention to Ludovico Maria Sforza, but without success. The one towards the city is still present, although topped and suffocated by the current entrance to the Piazza d'Armi (Figure

Figure 4.2.d Tower of Bona di Savoia today. Photo from the website https://www.flickr.com/photos/twiga_swala/2384011614.

Figure 4.2.e "Ponticella" of Ludovico il Moro, located on the east side of the castle.

Figure 4.2.f Lower part of the ravelin at the entrance to the castle (city side), built during French occupation.

Figure 4.2.g Woodcut of view of the Castello Sforzesco in Milan. C. 1552-1588. Document in the "Achille Bertarelli" Civic Collection of Print (Milan).

4.2.f). In this historical phase, in 1521, the southeast tower door, called "Torre del Filarete", collapsed due to lightning striking through one of its powder magazines. This period, characterised by uncertainty and different holders of the city, continued until 1535, the year Filippo Maria II passed away. The castle he left would have looked similar to the representation in Figure 4.2.g.

In that very year, Emperor Charles V annexed Milan, which therefore fell under Spanish control (Viganò, 1997; Istituto Italiano dei Castelli, 2005). Upon their arrival, the castle looked almost unchanged from its late Visconti layout. This new historical phase, instead, would have brought substantial changes, transforming the renaissance structure into a modern bastioned citadel.

The first new fortified works can be dated between 1550 and 1552, when, at the prompting of the governor Ferrante Gonzaga, the Tenaglia and the Galera (or Catena) were built (Figure 4.2.h). Both connect the central nucleus to the newly erected bastioned walls of the city.

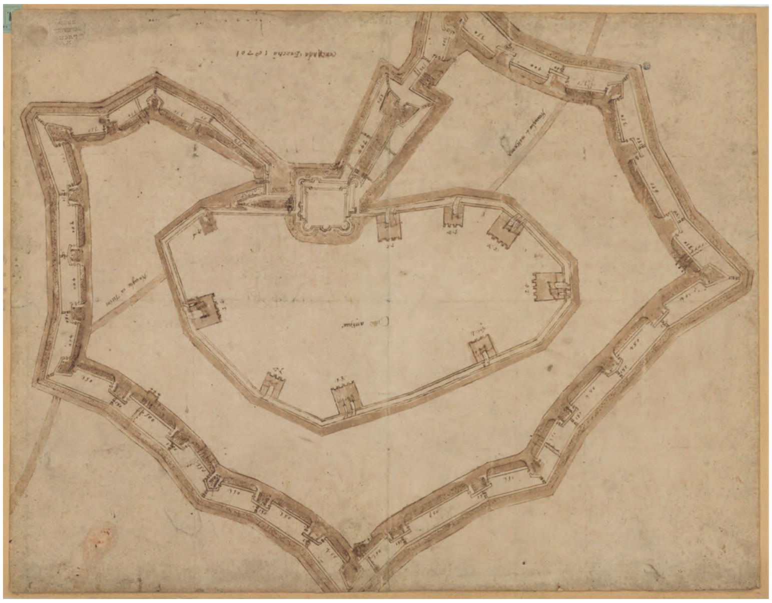


Figure 4.2.h Drawing showing the fortifications of Milan, including the Tenaglia and the Catena. C. mid 1500s. Document in the "Achille Bertarelli" Civic Collection of Print (Milan).

The most remarkable work of this period has been the bulwarks system around the fortress. The first project was by Giovan Giacomo Paleari Fratino (1560) (Viganò, 1996) who proposed to surround the castle with four bulwarks at the structure's corners. Two of these were built, those towards the city, adding a third facing the ravelin of Louis XII in a first construction phase that lasted from 1560 to 1569, the year when the three bastions were completed. The following twenty years were fraught with uncertainty and it became crucial to find a solution to harmonise the existing bastions with those that were to be erected on the opposite side. Driven by this, in 1590 the work resumed and all the ramparts were completed by 1599, as visible in Figure 4.2.i. The completion of these works towards the countryside required the sacrifice of the Galera, firstly damaged in 1583 due to the ongoing construction, and then finally demolished between 1593 and 1594. The Tenaglia structure was also destined to the same epilogue in 1597 when it was considered not only useless but even dangerous for the defensive dynamics of the citadel. Some documents report, in the same area, the construction of a massive structure (the Corona, Figure 4.2.l), although its actual existence still remains unclear.
A further phase of construction took place between 1600 and 1656. In this period, the castle proved unsuitable to accommodate the new war machines. Consequently, in 1646, the engineer Francesco Prestino proposed the construction of six ravelins in front of the bastions. The Milanese fortress had then grown to a star-shaped plan with twelve vertices (Figure 4.2.m), in an area six times larger than the one we can currently observe. Given this huge expansion, the Ghirlanda, which no longer played an acti-

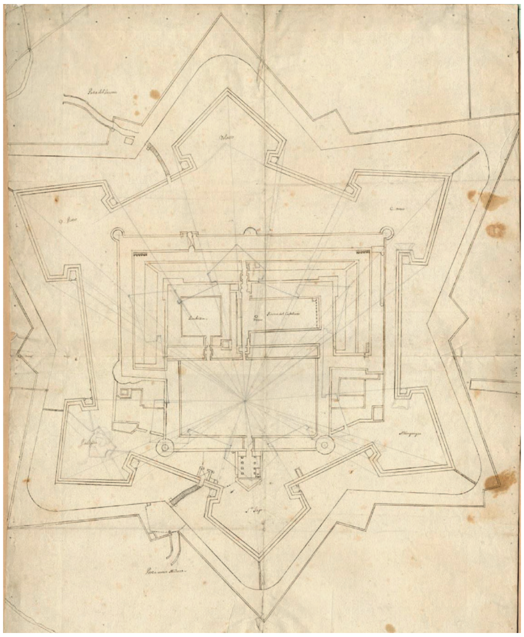


Figure 4.2.i Plan of the Castello Sforzesco after the construction of the six bastions but before the ravelins. C. late 1500s - mid 1600s. Document in the "Achille Bertarelli" Civic Collection of Print (Milan).

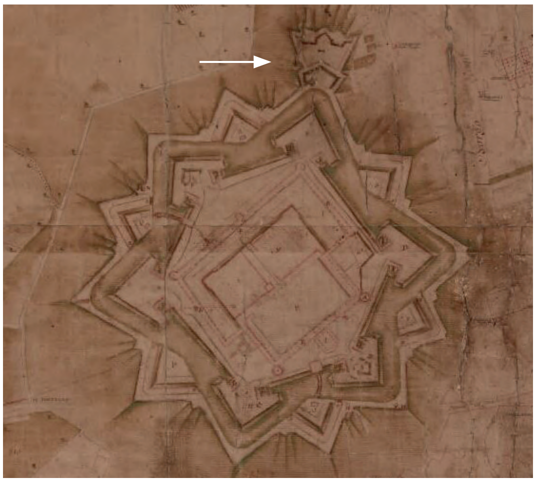


Figure 4.2.l Teresian Cadastre of 1722 bearing the Corona structure. Documents in the State Archives in Milan.

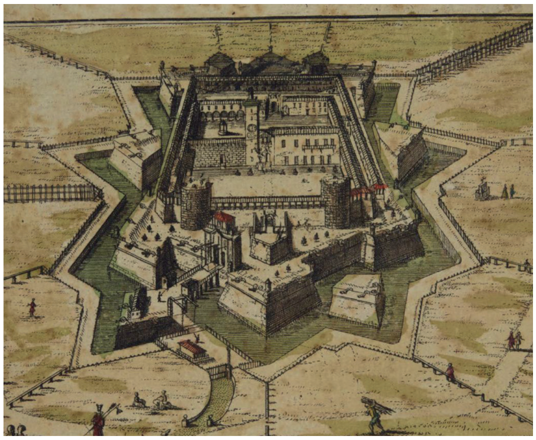


Figure 4.2.m A print entitled 'Real Castello', showing the fortress complete with bulwarks and its ravelins. Marcantonio Dal Re, 1743 - 1750. Document in the "Achille Bertarelli" Civic Collection of Print (Milan).

ve role in defence, changed its destination, accommodating the development of internal housing. The Spanish period, with later other minor works, gave the city the most complex and extensive form of the Castello Sforzesco.

Subsequently, Milan fell definitively subject to Austrian dominion (Viganò, 2006). In September 1706 the imperial army, under the command of Eugene of Savoy-Carignano, Prince of Soissons, entered the city and blocked the castle. They primarily engaged in the reconstruction of the portions that had incurred damage. Without any substantial alterations, control passed into the hands of the French, led by Napoleon Bonaparte in 1800. The leader ordered extensive demolitions at the citadel, which had endured significant impairment due to explosive mines. This operation largely destroyed the bastioned structure, although the lower part still remains. Figure 4.2.n depicts the situation at the time.

Figure 4.2.n Picture of the demolitions at the Castello Sforzesco ordered by Napoleon Bonaparte. C. first year of 1800. Document in the Civic Historical Collections (Milan).

Following the conclusion of the Napoleonic period, the castle takes on a new role. Under the control of the Engineers Corps, it was repurposed into a barracks. The Milanese fortress presented an unprecedented character, strongly linked to the military and other activities that took place inside. There were craft shops, granaries, warehouses, staff quarters and various spaces essential for the administration of the barracks. For this purpose, the Cavallerizza (Figure 4.2.o) was built on the east side between 1860 and 1864; however, no traces endure today.

Figure 4.2.o Photo framing the east tower and the Cavallerizza. Giulio Rossi, 1878. Document in the Civic Photographic Archive (Milan).

Witnesses of that historical period and the bad conditions that beset the castle prior to L. Beltrami's intervention, Giulio Rossi and Giuseppe Beltrami conducted extensive documentation of the building with two photographic campaigns, of which a limited selection of images is showcased here.

In 1893 the Castello Sforzesco passed from the military state property to the Municipality of Milan, which commissioned the architect Luca Beltrami for an in-depth study of the building and its history (Beltrami, 1894; Beltrami 1898). The fate of the Milanese fortress was doubtful for an extended period due to discordance about its destination. Numerous proponents advocated for its almost complete demolition, leaving only the nucleus of the Porta Giovia Castle, in favour of massive urbanisation (Figure 4.2.p). To settle the dispute, a detailed survey of the entire complex was undertaken, that also clarified the terms of building conservation (Istituto Italiano dei Castelli, 1997; Beltrami & Paoli, 2014; Pertot, 2019). Downstream of these studies, Luca Beltrami succeeded in safeguarding the Visconti square that we

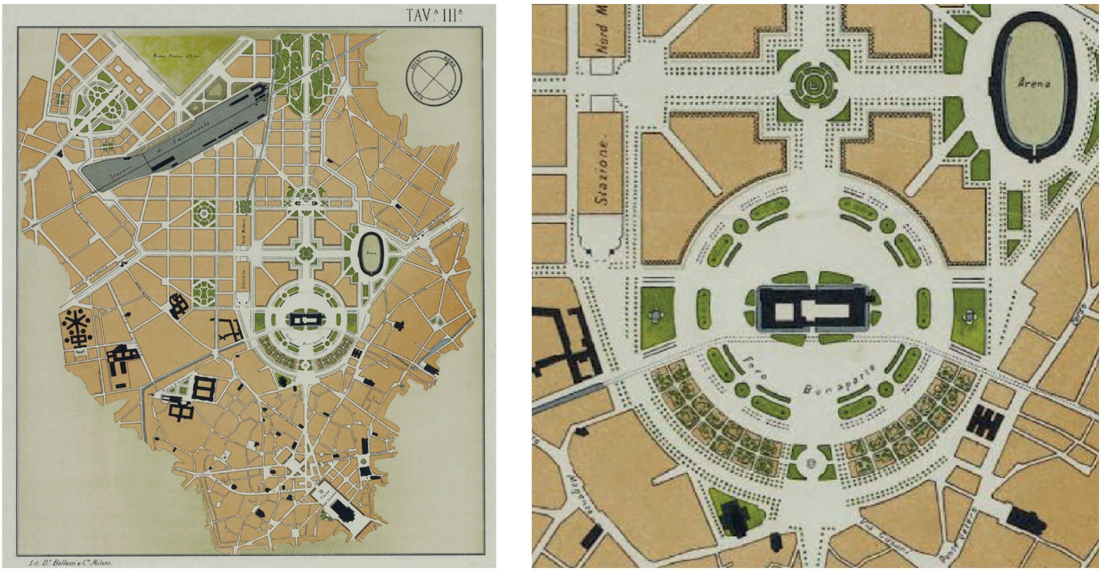


Figure 4.2.p Variant to the general land use plan (Piano Regolatore) for the area including Castello Sforzesco and surroundings. Cesare Beruto, 1884. Document in the "Achille Bertarelli" Civic Collection of Print (Milan).

still see today. The choice to return, with the intervention, to the unity of that historical moment involved many sacrifices and demolitions (Figure 4.2.q). The works eliminated the superfetations of more recent times, including the volumes leaning against the Piazza d'Armi enclosure and the Cavallerizza. A massive demolition operation also concerned the Ghirlanda, which was trimmed by the end of the century. Unfortunately, this operation damaged the underground infrastructure. Despite the demolition, some elements still remained, in particular those that are visible in Parco Sempione (i.e. Torre della Colubrina, Porta del Soccorso and Torre della Vittoria) because during the dismantling, arch. L. Beltrami made an intriguing observation: he noticed that Porta del Soccorso had a double stratification, suggesting that its original thickness was reduced than what he would expect. This discovery led him to affirm that these structures were from the Visconti period rather than the Sforza. Consequently, he halted the ongoing demolitions, which had already eliminated most of the defensive construction.

Intending to restore the castle to its first period, restoration involved the reconstruction of the four sides, up to the crenellations, and the two front towers in which during the project he positioned two water tanks in favour of the city's water system, as in Figure 4.2.r. Following detailed research, Beltrami designed the new Torre del Filarete, trying to rebuild in all respects the one lost in 1521. The Tower of Bona di Savoia was restored, and the Castello Sforzesco was largely destined for museum purposes. With this new (or rediscovered) configuration of the building, which assumed an unprecedented function within the city, the restorations ended in 1906.

Figure 4.2.q Photo of the demolition phase of the Ghirlanda, during the restoration of the castle. 1893. Document in the Civic Photographic Archive (Milan).

Figure 4.2.r Photo of the potable water tank being installed inside the east tower. 1893. Document in the Civic Photographic Archive (Milan).

A further phase pertains to World War II. During this period, the Ghirlanda included two anti-aircraft bunkers, which could shelter up to 2000 people (1000 for each bunker) (Breda, 2015). Positioned at the two lateral ends of the counterscarp path, these bunkers repurposed existing spaces through the erection of brick partition walls: 7 cells had been obtained for shelter 31/A (east side) and 8 for 31/B. The spaces, whose entrances were created during the restoration of the late 1800s (and still in use), had an electrical system and hygienic systems with disposable pits. Few traces remain from that period, just a few fragments of the electrical system.

Figure 4.2.s Work in progress at the Rivellino di Santo Spirito. March 1961. Photo from the website http://metromilano.biblio.arc.usi.ch/.

Finally, one last moment should be mentioned. It coincides with the construction of the two underground lines passing under the castle. Between 1957 and 1964, Milan saw the realisation of the M1 line, whose section between Cairoli and Cadorna intercepts the entrance to the Castello Sforzesco veering at 90° to the left and exits almost coinciding with Rivellino di Santo Spirito. These operations involved considerable demolition of the underground spaces of the Ghirlanda and of the fortress itself (Figure 4.2.s). The castle also had to face additional activities underground due to the second subway line, built between 1970 and 1978 that runs through the entire building.

The outlined historical narration provided here is a very concise version of the entire history of this architectural asset. While these pages are only a summary of the countless events that have shaped it, it is undeniable that navigating through the diverse dominations and structural changes can be an intricate endeavour. To facilitate the understanding, the various phases have been summarised and graphed in Appendix A.I. This result was then the basis for the operations carried out on the case study, reported in the next chapter.

04.3 _ The current state of the northwest corner of the Ghirlanda

The case study for the subsequent experimental phase is a portion of the Ghirlanda of the Castello Sforzesco that coincides with the northwest corner of the architectural ensemble (Figure 4.3.a).

The Ghirlanda was a defensive structure that surrounded the castle on three sides, leaving the one facing the city uncovered. The selected portion is an intersection zone between the fortress and Parco Sempione. In the basement, the rooms and paths of the Ghirlanda branch off, while at ground level there is just the urban greenery. This dicho-

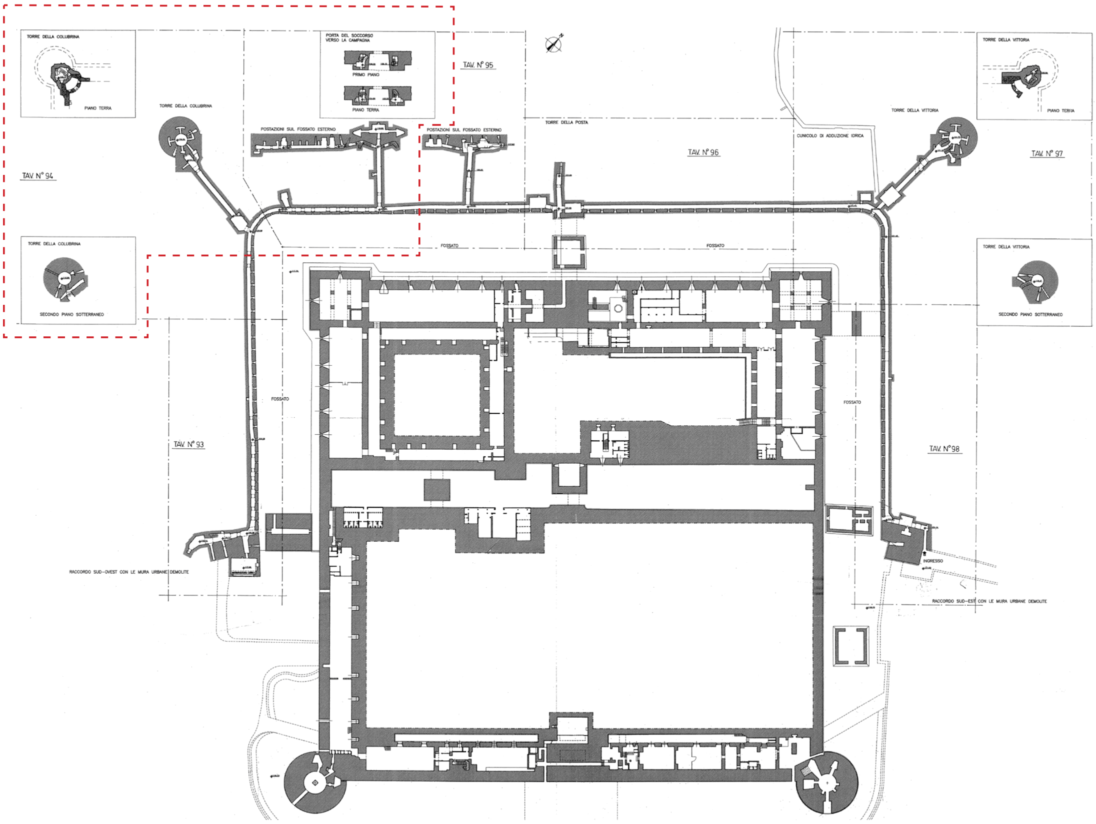


Figure 4.3.a The overall plan of the castle and the Ghirlanda. The elements investigated are highlighted in red. Survey by Gruppo Archeologico Milanese, 1994.

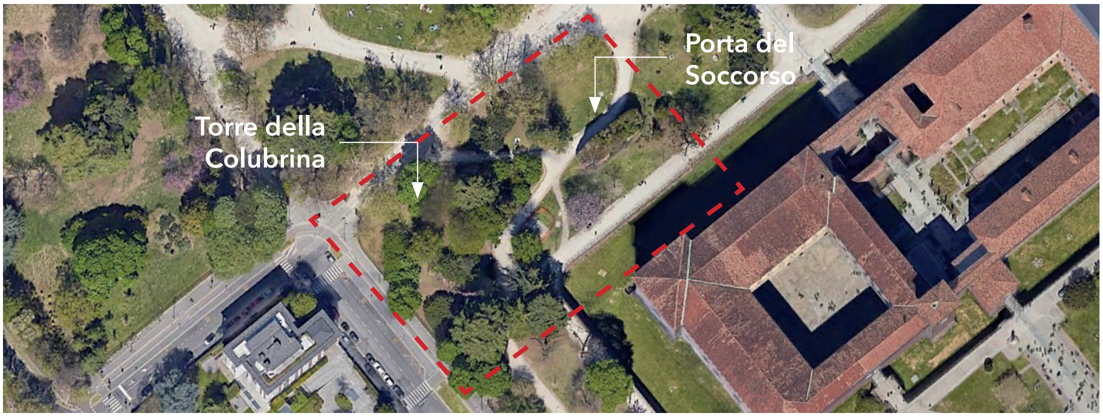


Figure 4.3.b Planimetric indication of the area chosen as a case study.

Figure 4.3.c-d The ruins of Torre della Colubrina (left). Photo from the website https://www.milanocastello.it/. The caponier of Torre della Colubrina (right).

Figure 4.3.e The current volume of Porta del Soccorso. Photo from the website https://www.milanocastello.it.

tomy is due to the partial destruction of this external defensive system, which left space for the subsequent project of the park.

Along the first axis, the area extends from Torre della Colubrina (corner tower of the Ghirlanda) to Porta del Soccorso. In the other direction, however, the boundaries coincide with the moat of the castle and the outermost limit of Porta del Soccorso (Figure 4.3.b).

Externally, there are only a few elements that survived the demolitions, defined by the architect L. Beltrami for the castle restoration project.
In addition to the counterscarp wall of the moat, there are only the ruins of Torre della Colubrina and Porta del Soccorso. The first, visible in Figure 4.3.c, looks like a small ruin compared to the original size but the corner capon on the Ghirlanda platform is still recognisable (Figure. 4.3.d). There is no external access to this structure, which covers the casemates below.
The current Porta del Soccorso (Figure 4.3.e) still shows a shape that can be associated with its past one, despite the destructive interventions. It encloses spaces that develop underground, and then reach a floor at its top.

Underground the dynamics are much more articulated and develop at different heights (Figure 4.3.f). There are two points of access, one coinciding with Rivellino di Santo Spirito and a further entry is located on the opposite, more easterly side.

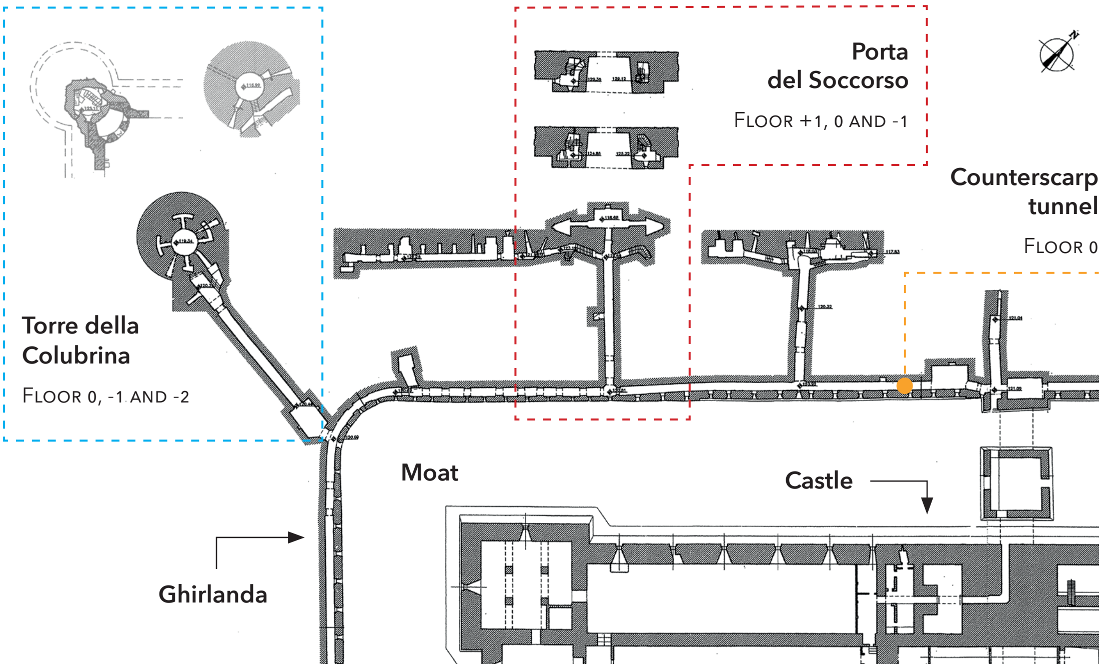


Figure 4.3.f Partial plan of the Ghirlanda. The Casamatta Celestino complex and the rooms of the lifting pumps are not present. Survey by Gruppo Archeologico Milanese, 1994.

Figure 4.3.g A section of the counterscarp tunnel.

To reach the studied area of the Ghirlanda infrastructure, the route runs along part of the counterscarp tunnel (Savoia, 2011), the main infrastructure of the Ghirlanda currently known (Padovan, 1996), which connects most of the spaces described. Its total development is approximately 500 metres long, with 101 small windows overlooking the inner moat. Compared to the entire infrastructure, this subject area covers a portion of 60 metres. It consists of a vaulted brick passage averaging 2,80 m high and about 1,60 m wide (Figure 4.3.g). Its floor level is 121,10 m above sea level (a.s.l.), constant in the case study. This elevation defines the first underground level, from which it is also possible to reach rooms placed both below and above.

Coming from the access at Rivellino di Santo Spirito (Comune di Milano, 2005), the first structure of the analysed area, which connects to the counterscarp, is Torre della Colubrina. As in the case mentioned above, this structure is also characterised by only vaulted brick structures. This tower consists of a first long corridor that leads to the three casemates inside the ancient cylindrical volume (Figure 4.3.h). The casemates have three separate entrances with a system of stairs, where present, that are autonomous (Figure 4.3.i-l).

These rooms are superimposed, although not aligned along the same vertical axis. The upper one, although covered by the masonry of the external ruin, is completely above ground. The middle casemate is located almost on the first underground floor (121,70 m a.s.l.) and the lower one reaches a height of about 117,55 m a.s.l. All known spaces of the tower are accessible and can be reached through this path.

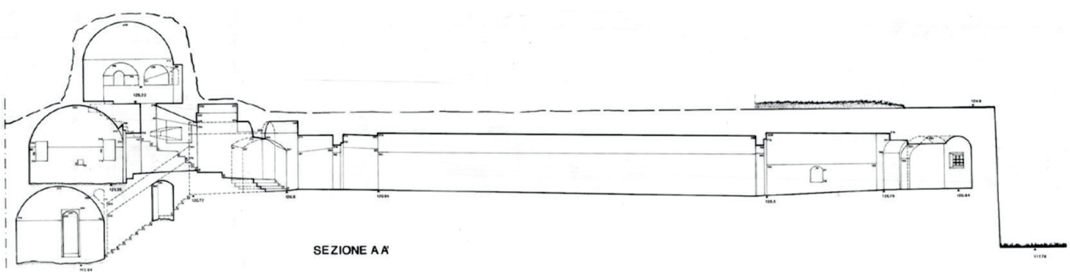


Figure 4.3.h Longitudinal section of Torre della Colubrina in which the non-alignment of the casemates along the z-axis is visible. Graphic design produced by the SCAM Association (1990 - SCAM Archive).

Figure 4.3.i-l The entrances to the three casemates inside Torre della Colubrina.
Photo from the website http://www.milanoneicantieridellarte.it.

Continuing along the counterscarp gallery and past the bend, there is a walled-in space on the left (Figure 4.3.n), which once led to the rooms now used for the water-lifting pump system. These spaces are now accessible from the outside, as indicated later.

The second structure intercepted is that of Porta del Soccorso, whose connection is placed at the end of the analysed section. The initial straight stretch leads to the opposite side of the Ghirlanda, crossing it transversely. The route has a considerable slope, ending at the head with a casemate (plus two small lateral and symmetrical ones) located at an altitude of 117,70 m a.s.l. (Figure 4.3.m), which coincides almost with the level of the lower casemate of Torre della Colubrina. Before descending to this space, the passage opens onto two specular stairways that ascend the volume of Porta del Soccorso visible from Parco Sempione. The stairs on the right lead to a casemate and then end abruptly with a recent closure. Its continuation is not known. On the other hand, the other system, the one on the western side, leads to the top, passing through two casemates, all communicating with the outside through loopholes.

Always on this side, continuing the trajectory and thus exiting the perimeter of Porta del Soccorso, it is possible to reach the Galleria delle Radici (Figure 4.3.m). The latter, after an uphill stretch and a subsequent slight downhill, reaches again level -1. This space, characterised by a succession of niches and loopholes, ends with a hint of a staircase, where it is promptly blocked. The rooms of the Casamatta Celestino and those dedicated to the water lifting system are not part of these routes. As mentioned in the previous lines, there was a connection between the counterscarp tunnel and this second system, which was closed. The project for the lifting pumps exploited and remodelled existing spaces, which have been isolated from the remaining Ghirlanda. The rooms of the lifting pumps are accessible from the park, where there are also trap doors. The-

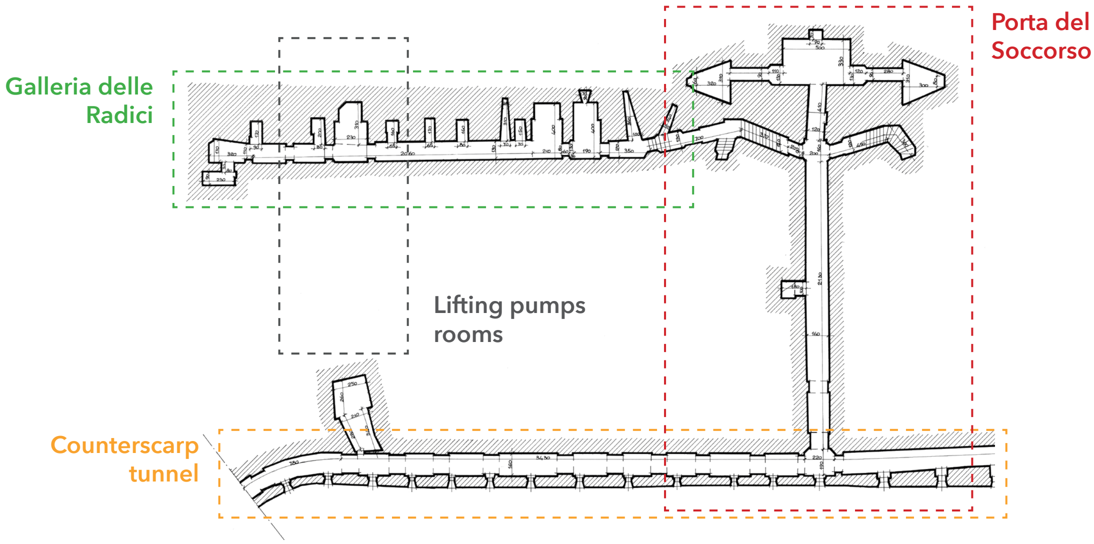


Figure 4.3.m Plan of the lower floor of Porta del Soccorso and Galleria delle Radici. The lifting pump rooms are not visible in the plan because they are part of a municipal system and are not accessible from the castle. Survey by Gruppo Archeologico Milanese, 1994.

se spaces are then connected to Casamatta Celestino (Figure 4.3.n), located below. It is from these structures, not only of modern times, that pipes branch off, running under the moat of the castle. The environment of Galleria delle Radici, although detached from this second system, is spatially intertwined with it. It is plausible that previously there were further connections between these spaces that are no longer practicable today.

Many other spaces and connections are present in the Ghirlanda's infrastructure. Those just reported are the structures that fall within the analysed area. This first and brief description hints at the comprehension difficulties encountered when dealing with complex architecture such as the castle, using only traditional communication tools.
A restoration project was carried out on some of these structures between May 2006 and August 2007 (Assolombarda, 1995). This intervention, supported by Fondazione Cariplo, made it possible to clean and reorganise the Ghirlanda spaces, making some of them accessible for tourism (Comune di Milano, 2007). The counterscarp path and part of the structures that are grafted onto it (the two corner towers and the access to the Porta del Soccorso) have been fitted with new facilities to allow visitors access. The existing ones installed during the Second World War, when the Ghirlanda was an anti-aircraft bunker, were removed for this purpose. The project also involved the cleaning of the walls, made entirely of bricks with rare stone elements. All rooms are therefore accessible, although part of them (those not included in the tourist visits) do not have a lighting system.

In addition to these well-known elements of the Ghirlanda, it is worth mentioning others, whose current presence is only presumed.

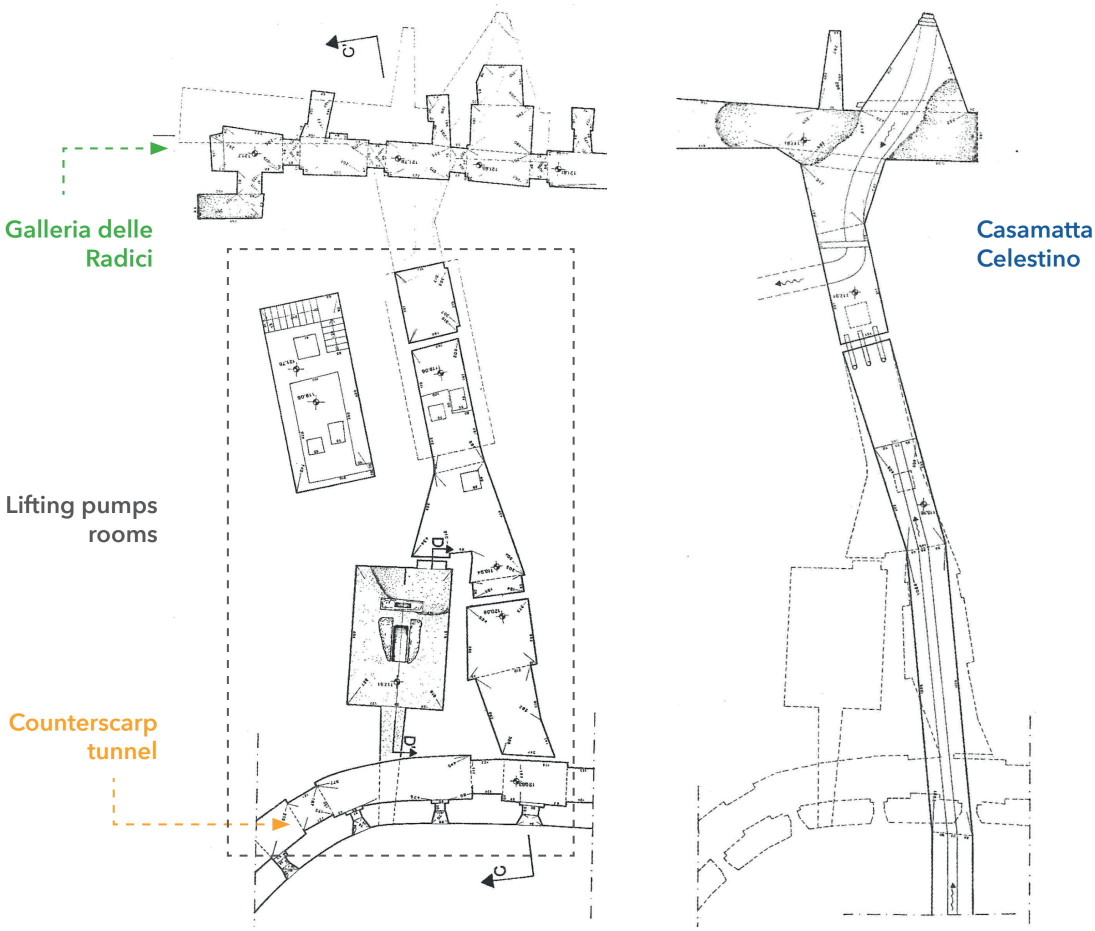


Figure 4.3.n Floor plans at different heights (left - 121,00 m a.s.l. and right - 116,30 m a.s.l.) of the lifting pump rooms and Casamatta Celestino. Graphic design produced by the SCAM Association (1990 - SCAM Archive).

The current layout of the case study must consider the presence of some massive structures, although they were destroyed in the various historical phases. The Ghirlanda consisted of a mighty structure, containing the spaces shown above. It implies that there may be substantial remains of such masonry and structures beneath the turf of Parco Sempione. A similar situation is that of the Spanish Bastions. The basement strips of "Baloardo D. Pietro" and "Mezza luna della Porta del Soccorso" (Figure 4.3.o) may still be present. Other hypotheses derive from the study and analysis of interior spaces: walls, for example, show several arches at their base, suggesting the presence of passages or structures at lower levels. A further basement level, with its spaces, could involve a route similar to the one already practicable, perhaps a second counterscarp pathway.

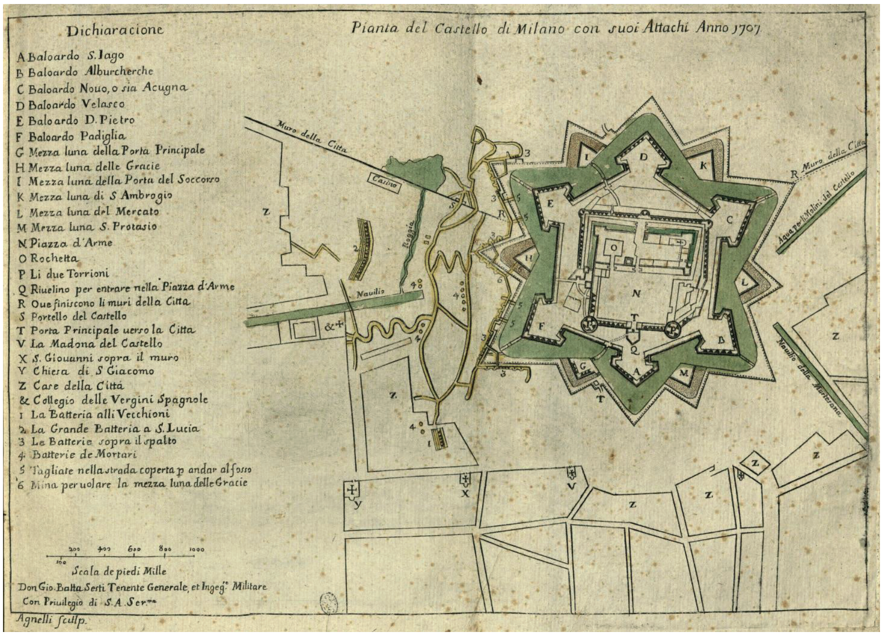


Figure 4.3.o Etching of the Castello Sforzesco indicating the names of the bastions and minor structures. Giovanni Battista Sesti and Francesco Agnelli, 1707. Document in the "Achille Bertarelli" Civic Collection of Print (Milan).

What emerges, observing this portion of the castle, is a general unawareness of its presence. Although there are many clues such as the windows of the moat wall and the ruins of Torre della Colubrina and Porta del Soccorso inside the park (few people are even aware of their presence, although they are well-visible structures), the idea of the Ghirlanda is not known by many people. The aim of the work is also to encourage the perpetuation of the knowledge of these places, developing a tool that might furtherly facilitate the process. At the base of the proper management of the heritage, there must always be adequate knowledge of its assets.

05

AN INFORMATION MODEL FOR THE GEOMETRIC KNOWLEDGE OF THE CASE STUDY

Chapter 5 of the research thesis delves into the experimental work conducted on the case study, the Ghirlanda of the Castello Sforzesco in Milan. This chapter serves to document the testing phase applied to the proposed digitisation system within the context of architectural heritage and it unfolds in six distinct sections, aligned with the chronological progression of the work phases.

Section 5.1 reports the first stage, involving the search for available and necessary material for the next steps thereby establishing the foundations for later work on the case study and for a global understanding of the area under analysis. This preliminary study also helped a great deal in preparing the subsequent survey operations.

Section 5.2 provides a detailed description of the first survey campaign at the Castello Sforzesco. This work ranged from the verification of the consistency of the available material to the laser scanner and photogrammetric survey, complemented by GPS measurements and a topographic network within the area, which also have been extended to all the underground branches of the Ghirlanda. The point clouds obtained in this phase were also used as reference material for the modelling of a wide part of the 3D of the Milanese fortress. The derived modern geomatic survey led to rich products in terms of information, which is difficult to capture with a traditional geometric survey by trilateration.

The third phase of the work, described in section 5.3, illustrates the development of the 3D model, following the approach described above. The model encompasses both the architectural complex and the Parco Sempione ground surface. The section concludes with a discussion on some circumstances that emerged during the modelling process: by gathering information of various kinds, the 3D model raised new issues and questions about the structure, which have opened up new possibilities for further investigation and analysis.

Section 5.4 describes the transposition in Rhinoceros of the framework designed for metadata management. The text outlines the difficulties encountered in this operation, illustrating all changes implemented according to the experimentation carried out. Thanks to its complexity and wealth of evidence and documentation, the Milanese castle allowed for comprehensive testing, ultimately yielding a functional and thought-out solution.

Finally, the last two sections of Chapter 5 describe the following two survey campaigns, one of which was conducted in collaboration with Codevintec s.r.l., using georadar technology. These supplementary investigations led to many model updates, which are also analysed in the text. This last part of the experimental work provided an opportunity to validate the broader approach proposed for the digitisation of architectural cultural heritage.

05.1 _ Collecting geometric information

The first phase of the experimentation carried out on the Castello Sforzesco in Milan coincided with its detailed study and the consequent identification of the sources of geometric information necessary for the subsequent 3D modelling. Therefore, the work involved the collection of geometric knowledge already available about the case study, concerning its architectural-spatial conformation and the history of architectural evolution. This initial phase of the process is the first and essential interaction when working with built heritage: knowledge of the building, its present state and previous phases are indeed fundamental for working consciously and for laying the proper foundations for the development of digital reproductions.

When approaching an architectural asset and the knowledge of its history, this process starts naturally: it is inevitable to come across documents, photos and notions that transmit geometric information. All these sources, plus those gathered through more structured research, represent the references for the digital transposition of the built complex. They, also and above all, legitimize the result obtained and endorse the choices made for the development of the three-dimensional object. As described in previous chapters, the main sources are present in the 3D model environment and are linked to their elements to provide a constant comparison with the original information.

The purpose of the research was twofold. On the one hand, it aimed to cultivate a comprehensive understanding of this architecture and the structures of the Milanese Castle, whether currently present or part of it in the past, in order to work properly with them. The material harvested was also employed to reconstruct the historical-architectural phases of the Milanese castle. On the other hand, the main objective was gathering reference sources that would serve to develop the 3D model of the case study. As a result, this process led to a large number of documents although the subsequent phases of the test used only a fraction of them. Some, as mentioned above, were still very valuable for further study and historical reconstruction. Note that the sources listed in Appendix A.II are only those identified as useful for the next steps and, therefore, part of the digitisation process of the architectural asset.

Searching and collecting was not a linear process, but rather iterative (Figure 5.1.a). The starting point was beginning from the figures who most worked and studied the Castello Sforzesco: L. Beltrami, M. Viganò, G. Pertot and G. Padovan etc. The information and cartographic/iconographic material reported in their texts served as a means for a series of archives, within which to search for further documentation, in addition to the one they mentioned. In particular, the work involved the interrogation of several foreign online archives that store information about

Figure 5.1.a Research scheme.

the castle, due to the numerous dominations that have affected the Milanese fortress. The French, Spanish and Austrians have contended for centuries for possession of the city of Milan and its war architecture, such as the Castello Sforzesco and therefore the consulted sources include the Archivo General de Simancas, the Kriegsarchiv, the Real Biblioteca del Monasterio de El Escorial and the Bayerische Staatsbibliothek. A major part of the materials have been searched in the archives of Milan, including the Civic Photographic Archive of Milan and the web portal "Grafiche in Comune", a meta archive that collects most of the documents of the Civic Historical Archive, the Trivulziana Library, the "Achille Bertarelli" Civic Collection of Prints, the Milan's Civic Art Library, the Library of Milan's Civic Historical Collections and the Cabinet of Drawings. Given the importance of the castle within the Milanese and Lombard architectural heritage, all the material was already accessible in digital format making it not necessary to consult the various collections on site.
The research has been conducted also at the State Archives of Milan, where various cadastres of different periods were found, in particular the ones between the 1722 Teresian Cadastre and the 1901 New Land Cadastre, to complete the cartography. Prof. Arch. G. Pertot also provided the vectorial outputs of the 2002 survey, carried out by him and other professionals for a redevelopment project at the castle. As for the terrain data, the DTM (1x1 metre grid) was requested by the Italian Ministero dell'Ambiente e della Tutela del Territorio e del Mare, according to the procedure described in Chapter 5.3.2.

The collection resulting from this research and selection process surpasses the scope that is necessary and feasible for the subsequent process of transforming the information in the three-dimensional model of the case study. As mentioned, not all of the compiled sources found utility in the subsequent phase. Certain sources contributed primarily to enhancing the knowledge of the historical evolution of the architectural site and gaining insights on its characteristics.

From this ensemble, the most suitable reference for modelling has been identified drawing from both primary and secondary sources. The work on the castle served to validate, once again, the methodology and general approach described in the previous chapters; there are essential documents for the geometric knowledge of architecture while others, on the contrary, supply only complementary aspects and notions.

About noted structures and spaces, there are two main references. The first is the previously mentioned survey carried out in 2002. The material of that survey describes the entire complex of the castle, but for the area selected for this research, there is only a plan of the basement of the Ghirlanda, as well as internal elevations and sections of the counterscarp pathway. A second block of sources is the output of the 1990 survey, carried out by the SCAM Association (Associazione Speleologica Cavità Artificiali Milano). The drawings have been traced in two publications by the speleologist G. Padovan ("La Fortezza Celata", 1996 and "Castrum Portae Jovis Mediolani", 2019). In both cases, these are traditional surveys, which can be associated with LOGI 2. This information concerns the underground infrastructure of the Ghirlanda, the current moat, the exterior and Porta del Soccorso. Finally, there is the DTM of the area, which describes the shape of the terrain, also classified in LOGI 2.

Concerning the hypothesised elements (the plan of the original moat, the second

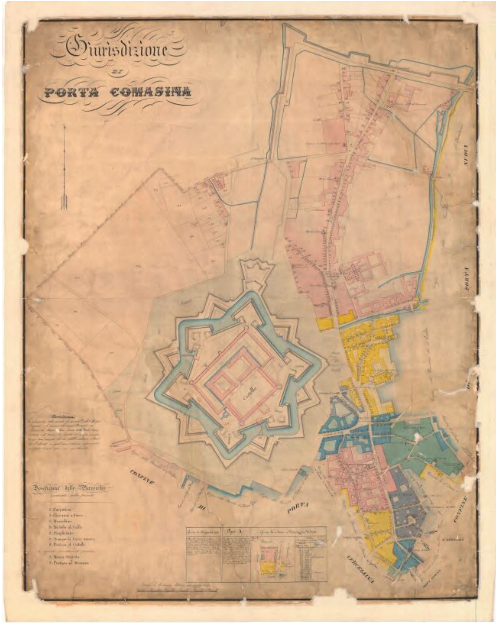


Figure 5.1.b-c Summary sheet of the Teresian Cadastre of 1751 (left). Summary sheet of the Lombardo-Veneto Cadastre of 1881 (right). Documents in the State Archives in Milan.

Counterscarp Tunnel and the volumes of the Ghirlanda and the Spanish Bastions), the sources are several. These include the 1751 updated Teresian Cadastre (Figure 5.1.b), the Lombardo-Veneto Cadastre of 1881 (Figure 5.1.c), photographs and iconographic material from various periods (Figures 5.1.d-e). Concerning these structures, precisely because they are hypotheses of elements no longer visible or present, the information used is classified in LOGI 1 and contributes to the formulation of the corresponding model.

Appendix A.II contains the complete list of the sources used for modelling, complete with ID, description, cataloguing and their use.

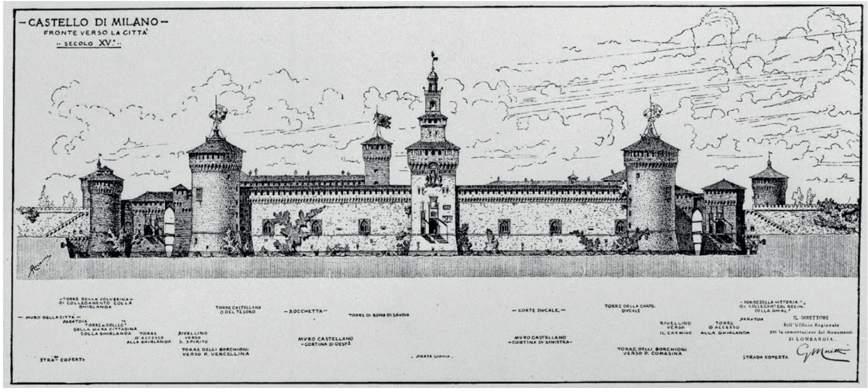


Figure 5.1.d Print with general view of the south-east front of Castello Sforzesco. C. 1900s. Document in the "Achille Bertarelli" Civic Collection of Print (Milan).

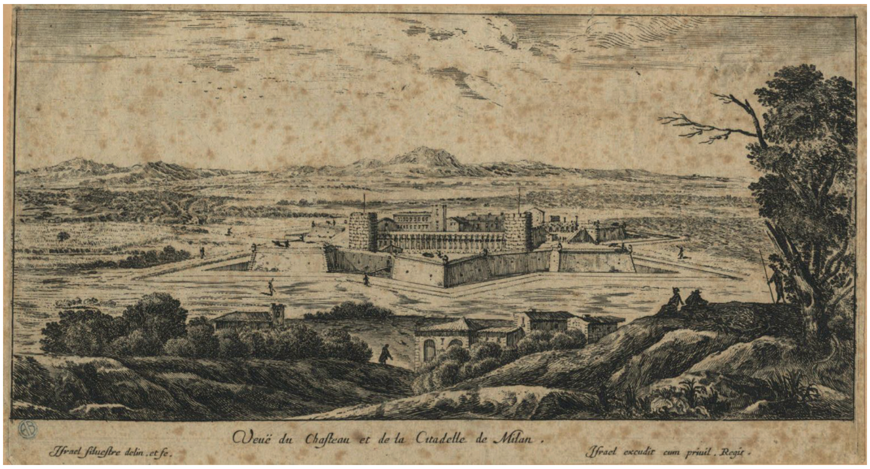


Figure 5.1.e Etching entitled "Veue du Chasteau et de la Cidatelle de Milan". Silvestre Israel, c. 1600s. Document in the "Achille Bertarelli" Civic Collection of Print (Milan).

It is important to underline that this work is not primarily engaged in historical research, except for the studies carried out to sufficiently contextualise and comprehend the Castello Sforzesco in order to carry out the activities. Consequently, the choice of sources has not to be considered a value judgment on the document itself. The chosen sources have been selected primarily based on their reliability, truthfulness and adherence to reality. That is because the aim is not to show, for example, project proposals (not realised) or imaginary illustrations. Subsequently, the amount of usable information in the document and the temporal source dating directed the choice. Relatively more recent ones have presumably a better chance of describing more accurately the state of affairs given the shorter temporal distance from the present day and improved surveying tools. This also applies, albeit in a lesser form, to the hypothesised structures.

It is evident that the data identified, despite its abundance, is not sufficient for developing a model that fully and accurately describes at least a portion of the case study. The underground environment is only partially represented in the sources traced. Moreover, a description of the ruins of Torre della Colubrina, which are present in the park, is completely missing. With the available data, which also do not contain any modern digital survey, it would not have been possible to thoroughly test the submitted digitisation method, precisely because sources and information of LOGI 3 are absent. This situation corroborates the necessity of the survey campaign described in the following chapter. This operation has thus allowed having a complete range of sources, from LOGI 1 to LOGI 3, providing the possibility of experimenting with the method. As will be seen later, the topographical, laser scanner and photogrammetric survey only concern a part of the case study, without replacing all the data collected belonging to LOGI 2. Although this survey changed part of the documentation collected, it was decided to work as if that was the state of affairs of the information at the beginning of the research. Therefore, the new material was not exploited for the first update of the model but as a starting point. This decision was taken also because the search for sources and the survey took place in close succession. Thus, it was not possible to develop the first version of 3D based only on external data. The verification of the update phase has been delegated to subsequent survey campaigns, as reported in Chapters 5.5 and 5.6.

05.2 _ The survey activities at the Ghirlanda of the Castello Sforzesco

This second section of Chapter 5 describes the survey activities carried out at the Castello Sforzesco, in particular the first survey operations performed on-site with different technologies, and the subsequent processing phase. These activities were preceded by a first collection and analysis of the recent available documentation, to better prepare and plan the subsequent survey.
The planning included both the design of the topographic network based on the known points and the organisation of the laser scanner survey (choice of scanning stations, positioning of references and realisation of the survey itself). Subsequently, she also was in charge of the elaboration of the collected material for the rest of the study.

The various subsections below describe the operations carried out for this first and largest survey campaign. The work consisted of a geomatic survey of the spaces chosen as the case study, the northwest corner of the Ghirlanda, trimmed in the late 1800s. The surveyed area, as described above, collects most of the rooms and paths collocated between Torre della Colubrina and Porta del Soccorso, including their connections and the counterscarp tunnel.

All these activities aimed to provide the necessary material for the subsequent phases, but also to deepen the comprehension of the built asset, in particular its geometries. The text aims to depict the survey not as a mere initial phase of a broader and more complex process but as an essential starting point (in the various forms in which it can be declined) and as a fundamental knowledge tool for the built heritage.

05.2.1 _ The preliminary framing steps

The Castello Sforzesco in Milan is one of the most remarkable and famous symbols of the Lombard city, if not also of the entire regional territory. For this reason, it often appears as a subject of research, inquiries and in various kinds of projects. Therefore, in order to optimally design the planned activities, it was necessary to analyse much of the already existing and recent material, produced in other contexts and for different purposes in order to verify the consistency of the geometric contents made available.

The .dwg files corresponding to the survey carried out in 2002 by the architects Elisabetta Michelini, Valeria Pracchi, Alberto Torsello and Marco Torsello have been the first to be examined. This work was conducted for the project intended for the new distribution of functions within the spaces of the Castello Sforzesco (Figure 5.2.1.a-b-c). The survey covers all portions of the main nucleus of the castle (all floors) and also presents a framing of the Ghirlanda infrastructure and some information on the topographic survey carried out. Despite the presence of point height data, the material delivered is not georeferenced. In order to

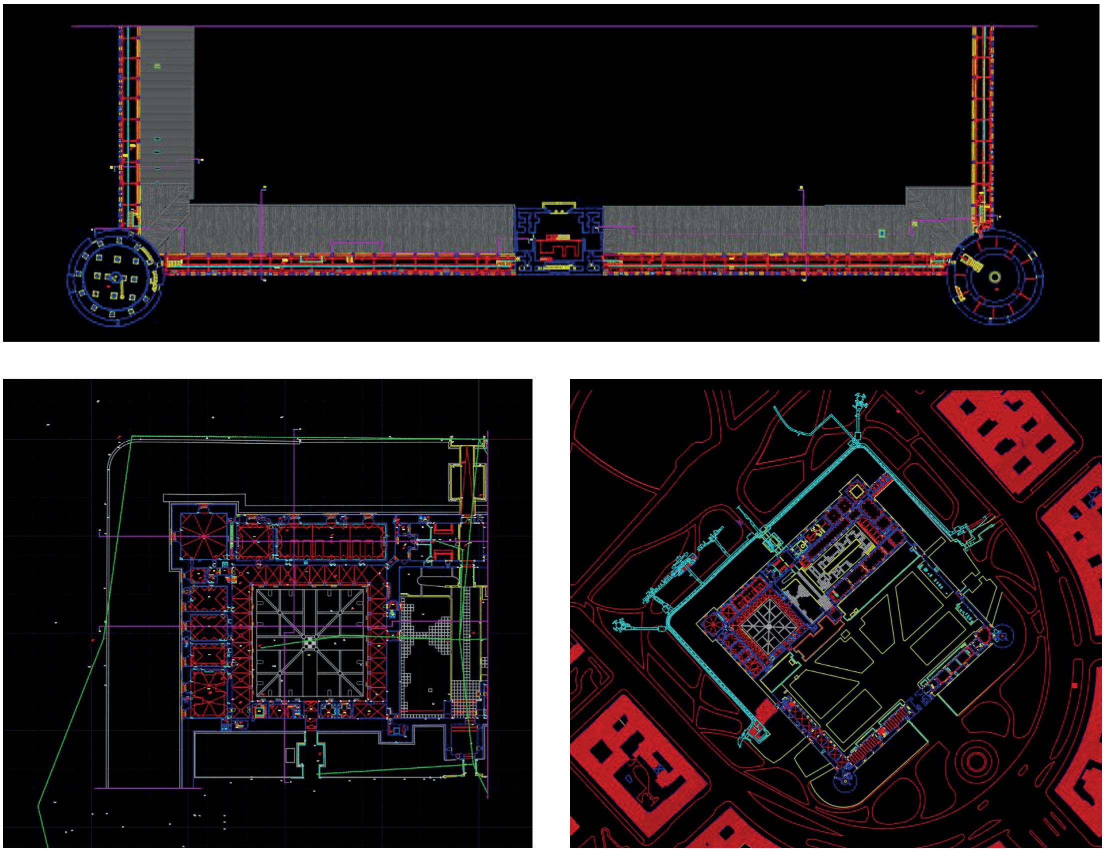


Figure 5.2.1.a-b-c Extracts from the 2002 survey in CAD environment.

integrate the new survey with the aforementioned CAD files, a preliminary inspection was carried out at the fortress in order to search for the polygonal vertices, therefore allowing measuring in a second phase. The monographs of these points were not present in the material made available: for this reason, their research was based on on-site inspection, on the basis of the relative position of these vertices to clearly recognisable elements.
The following points were identified and monographed to make their locationing easier and more immediate in the future (the nomenclature corresponds to the one used in the CAD drawings of the 2002 survey):

- Point S1. The point is located on the access ravelin to the castle, in front of Piazza del Cannone, along a joint of the stone pavement. Keeping Parco Sempione behind the observer, it can be found in the left portion of the path itself, before the tapering.
- Point S11. The point is located on the south-west side of the complex, close to the moat. It has been positioned on the edge of the cobblestone border overlooking the moat, near the corner tower of the Rocchetta.

- Point S12. This vertex is located on the north-west side, almost coinciding with the change of direction of the path. As in the previous case, it was positioned on the portion of cobblestone pavement near the moat.
- Point S15. The point is in Cortile della Rocchetta, near the access on the eastern side (towards Corte Ducale). It is inserted into the cobblestone paving.
- Point S16. As for the point S15, it is also located in the Rocchetta. Unlike the previous one, however, it is along the west side of the courtyard, near the vaulted covered walkway.
- Point S18. The vertex is located at Porta del Barcho, adjacent to the entrance to the administrative and management spaces. However, it is placed on the main public path, along a joint of the pavement.
- Point S21. The point is on the access bridge to the ancient architectural nucleus of Porta Giovia. Walking along the stretch from Piazza d'Armi towards Corte Ducale, it is traceable on the right-hand side of the route itself.

Figure 5.2.1.d shows the vertices of the polygon network that it was possible to trace. They are represented in red, while those in blue are the remaining points used for the 2002 survey. During the recon, it was verified that the points found were properly positioned for the survey operations that were being prepared.

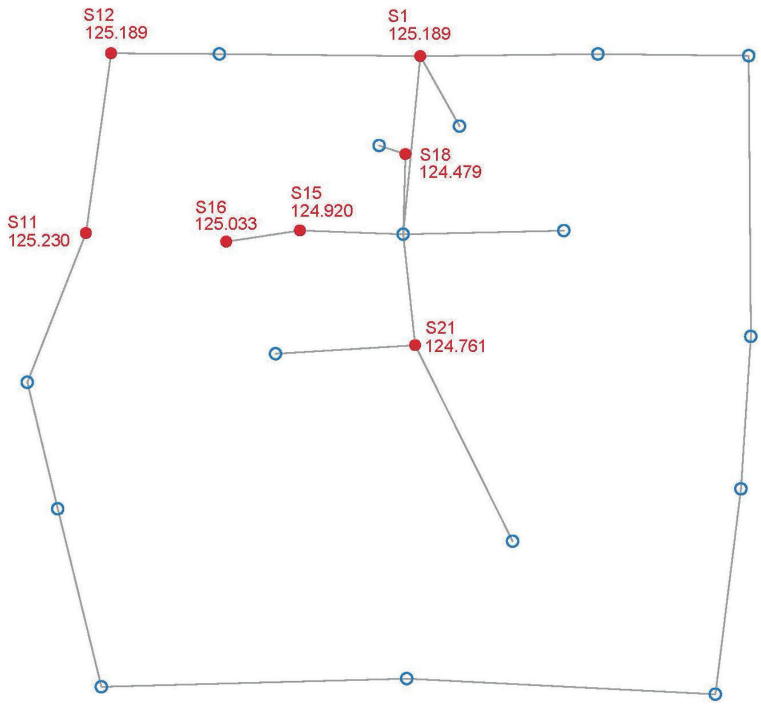


Figure 5.2.1.d Representation of the topographic polygon used for the 2002 survey. In red are the vertices identified.

05.2.2 _ GPS measurements

Once the preliminary framing phase was completed, the GPS survey activities of the identified points began. The process aims to obtain the necessary data to orient both the existing data and the new output material, which is the outcome of this work. This information was, therefore, necessary to perform a proper comparison of the material and for an appropriate management of the overall data package.
The actual survey started with a GPS operation to define the cartographic coordinates of these points in the official Italian national reference system: ETRS89 ETRF2000 (DM 10 November 2011) (Min. P.A.I. & Min. A.T.T.M, 2011). This reference system is mandatory for the entire public administration and in the EPSG documents it is referred to as RDN2008. Its identifier for coordinates projected on the map plane for zone 32, to which Milan belongs, is the 6707, to be used within the GIS software. The operations were carried out in April 2021 with a Topcon HiPer Pro receiver. The coordinates of the following points were measured:

- Point S1;
- Point S11;
- Point S12;
- Point S21;
- Point N1;
- Point N2;
- Point N3.

As can be seen, some of the points correspond to those in the 2002 survey, while others differ. Those marked with the letter 'N' were measured as an additional data check and they coincide with easily recognisable elements, present both on-site and in the documentation. A complete monograph of known points can be found in appendix A.III.I. It should be noted that it was not possible to measure all the points previously identified during the inspection due to external factors. In fact, the building's conformation and high facades limited the visible spectrum of the GPS receiver. In terms of accuracy, all this would not have allowed an adequate survey of the remaining vertices. For this reason, their coordinates were not collected. A second GPS survey was not planned as the coordinates of the available points were sufficient for the orientation process. Furthermore, the error reported by the software was in the range of a few centimetres for all the vertices, and it was considered acceptable.

As a first activity, the data was extracted from the survey software Mercurio to be processed on an external hardware. Subsequently, the initial geographical coordinates (in DMS format) were transformed with the Convergo software, obtaining the North and East coordinates used to geo-reference the output material of the subsequent survey campaigns.
The table (Figure 5.2.2.a) shows the results of these transformations. It also includes the differences in elevation between the GPS determination and the previous survey, as well as the residual deviations after normalisation.

After obtaining the coordinates of the vertices, the correctness of the material of the previous survey (that of 2002) was verified by ascertaining the congruence between the GPS coordinates obtained and the local topographic coordinates of the same vertices within the pre-existing CAD files. As can be seen in the comparison described in Figure 5.2.2.b, the differences (A-B') in the re-

Point ID	Latitude	Longitude	Ellipsoidal height		N UTM-ETRF89	E UTM-ETRF90	Geoid height	Prev. survey height	Difference	Residual deviation
S11	45°28'11,734827	9°10'40,691000	167.763		5035170.820	513911.605	125.161	125.230	0.069	- 0.008
S12	45°28'13,479170	9°10'38,954076	167.717		5035224.567	513873.771	125.112	125.189	0.077	0.000
S1	45°28'15,923324	9°10'42,760490	167.723		5035300.177	513956.253	125.115	125.189	0.074	- 0.003
S21	45°28'13,398391	9°10'45,981907	167.273		5035222.413	514026.374	124.671	124.761	0.090	+ 0.013
N1	45°28'14,362829	9°10'44,250758	167.281		5035252.092	513988.719	124.676			
N2	45°28'11,796928	9°10'44,069457	167.317		5035172.899	513984.958	124.717			
N3	45°28'11,665948	9°10'44,032187	167.295		5035168.855	513984.158	124.695			
								Average diff.	0.077	

Figure 5.2.2.a Processing of data obtained from GPS measurements.

Distance	Survey	Previos survey		B' = B*m	A-B'
S11-S12	65,728	65,767		65,744	- 0,017
S12-S1	111,893	111,958		111,919	- 0,025
S1-S21	104,710	104,728		104,692	0,018
S21-S11	125,832	125,919		125,874	- 0,042
			m	0,99965	

Figure 5.2.2.b Verification between the measured GPS coordinates and the local one of the vertices in the CAD file.

lative distances between these points, defined based on the coordinates measured by GPS with the coordinates of the CAD files, are of the order of a few centimetres.
Before carrying out this operation, preliminary calculations had to be performed: the first one led to the value of the linear deformation modulus for the area of the Castello Sforzesco, which turned out to be 0,99965. In the second step, this factor was multiplied by the various relative distances in the CAD files of the previous surveys. After taking the linear deformation modulus into account, discrepancies between related distances are being considered acceptable. This factor, therefore, implies that one km in reality is represented with a segment 999,65 metres long on the cartographic base, with a difference of 35 cm per km. Proportionally on points 152,59 metres apart (points S12 and S21), this difference should be 5 cm (from 152,64 metres in reality to 152,59 metres in cartographic representation).

Thanks to the GPS determination, it was possible to rototraslate the entire existing survey in the cartographic reference system. In addition, it allows to complete rigorously the overlapping procedures with other cartographic data, such as the Topographic Database (DBT) of the Municipality of Milan and orthophotos.

At the same time, this information allows unambiguous management of all subsequent produced materials, from point clouds to 3D models. All this work also lays the basis for the utilisation of the material in a GIS environment, where the knowledge of the absolute position represents a condition *sine-qua-non* for all operations.

05.2.3 _ The first survey campaign: the Ghirlanda basements

At the end of the previous two phases of framing and GPS surveying, the topographical and architectural survey of the Ghirlanda spaces began. Before proceeding, a site visit was necessary to better understand the spaces' extent and nature. This first inspection also clarified issues such as the accessibility to the survey area, lighting and available services, such as the presence of electricity connections for recharging instruments. This first approach to Ghirlanda's hidden infrastructure allowed for better organising the upcoming survey, in terms of timing, instrumentation (understanding the necessity for portable lighting sources) and planning of the actual activities (e.g., preparing the necessary for a polygonal vertex in the moat of the castle).

The first laser scanner survey took place over three days in November 2021 with the FARO CAM2 laser scanner. The processing of the recordings was performed with the FARO Scene software for a total of 57 scans, that were carried out according to the scheme described in Figure 5.2.3.a. As can be seen, the entire laser scanner survey occurred inside the Ghirlanda's underground passages, except for the last four. These latter concern the top floor of Porta del Soccorso and the strip of land near it. Starting from Torre della Colubrina, the survey also recorded the three overlapping casemates (partially above ground level), with also a laser scanner survey right up to the top of Porta del Soccorso, after climbing the narrow staircase leading outside, on top of the ruins of the structure itself.
The scans also covered the paths connecting these areas. These consist of a portion of the secret covered road overlooking the moat and the two stretches leading towards Parco Sempione that connected the outermost structures to the counterscarp path.

Special spheres and classic checkerboard targets were used to connect the scans to each other. They are automatically identified by the software in the different scanning scenes. The entire scanned route was in parallel served with a topographic polygonal, partly based on the points detected with GPS (in Appendix A.III.I there is the complete monograph of the polygonal vertices). The vertices were placed both outside the spaces and inside. The former (the outside ones) allowed the connection to the vertices of the previous survey and reached the internal station points by exploiting some of the 101 small windows dotting the counterscarp tunnel. The network made it possible to evenly distribute targets of known coordinates in the previously described reference system. The TOPCON ES-62 total station was employed for the topographic polygon. Figure 5.2.3.b depicts the course of the polygon, which is framed by the two points S12 (200, name in the polygon) and S1 (300) of known coordinates. There are 14 vertices. The measurements taken were least-squares-compensated using the Meridiana software. Appendices A.III.II.a and A.III.III.a contain the topography field book with all measurements and the polygonal processing, with the final three-dimensional coordinates of all points (celerimetric computation).

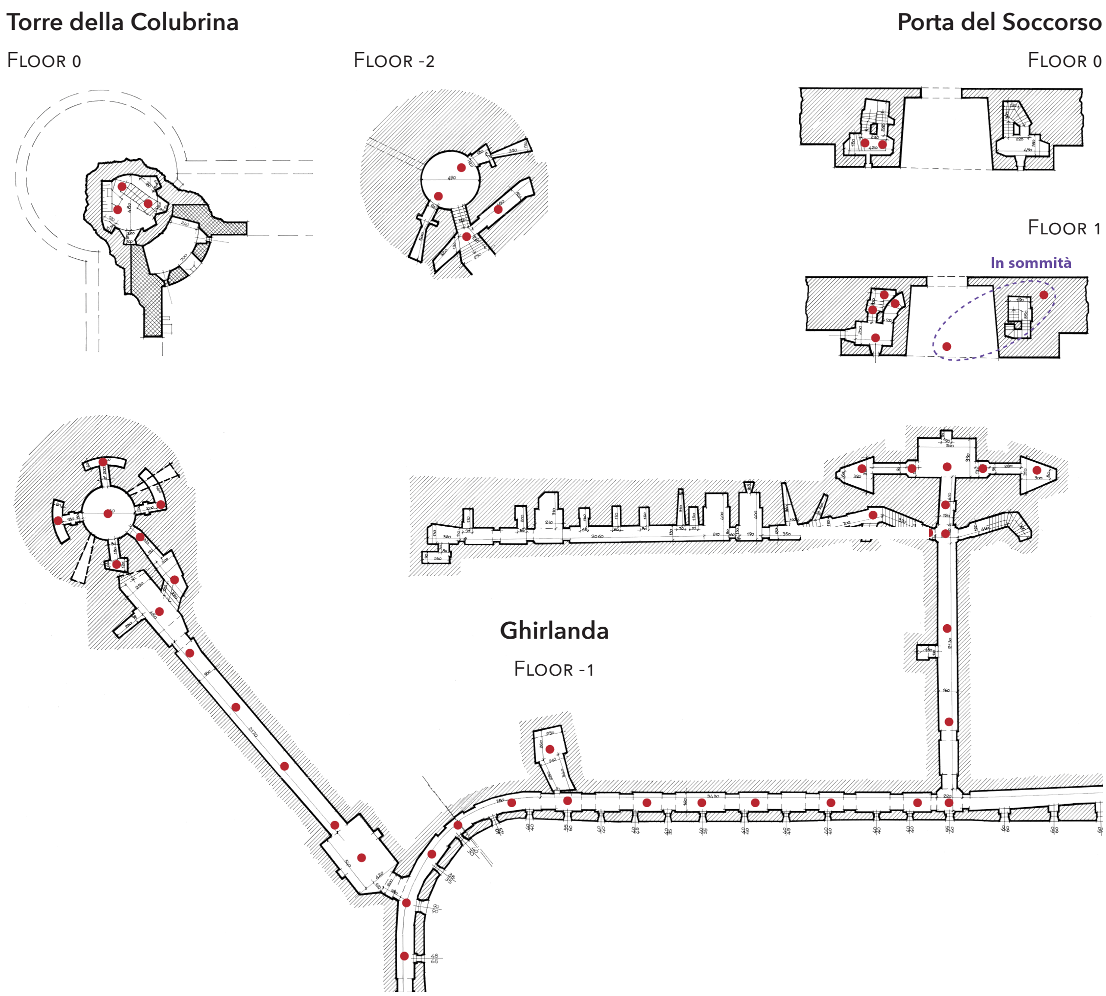


Figure 5.2.3.a Scheme of scanning points related to laser scanner activity. Above the plan at the height of the counterscarp tunnel. On the side those relating to the remaining floors of Torre della Colubrina and Porta del Soccorso.

The scans have different quality, and therefore density of points, depending on the space to be surveyed. In some cases, the wider ones, it operated with 44 million points, in others, the narrower ones, between 28 and 11 million points. This differentiation was also made with the aim of optimising survey times, where the conformation of the spaces allowed a smaller number of points without affecting the final reading of them. This choice was made right from the beginning due to the constant presence of tunnels, niches and narrow spaces that imposed greater redundancy in the scanning points.

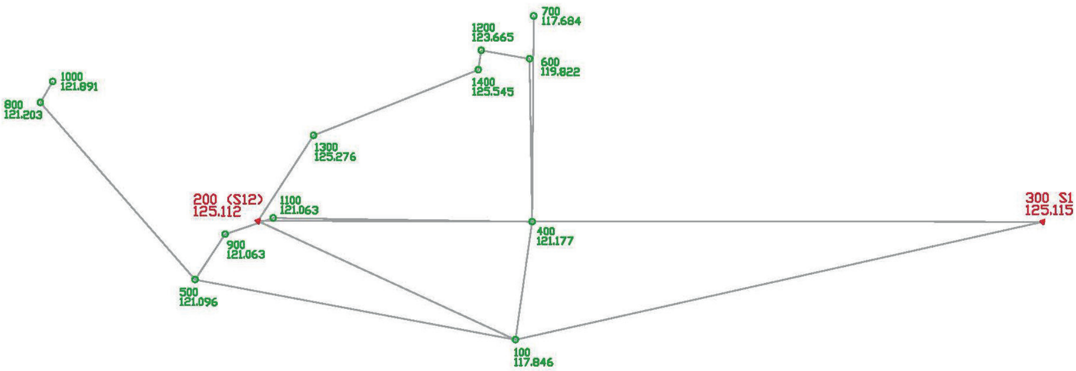


Figure 5.2.3.b Topographic polygonal created and used for the survey carried out at the Ghirlanda of the Castello Sforzesco.

The colour content has always been scanned. The lighting system present in the basement, however, has been designed according to the tourist fruition of these spaces, and for this reason, it only reaches some of the areas analysed, such as the secret covered road, which also has frequent views of the moat. In most cases, therefore, it was necessary to use an external light source (in this case some LED headlights) for scanning the RGB information. Despite several trials, the outcome was not satisfactory (Figure 5.2.3.c). Where no spotlights were used, scans were much sharper in colour content. The scans required four half-days of work, including all the time needed to prepare the various environments with the checkerboards and spheres.

The processing of the scans took almost a week of work. The first attempt was to align the scans into a single process. Considering the difficulties in placing them in the correct mutual position, the need for a new approach emerged. A new approach has been to carry out multiple processes, dividing the scans into five smaller sets.

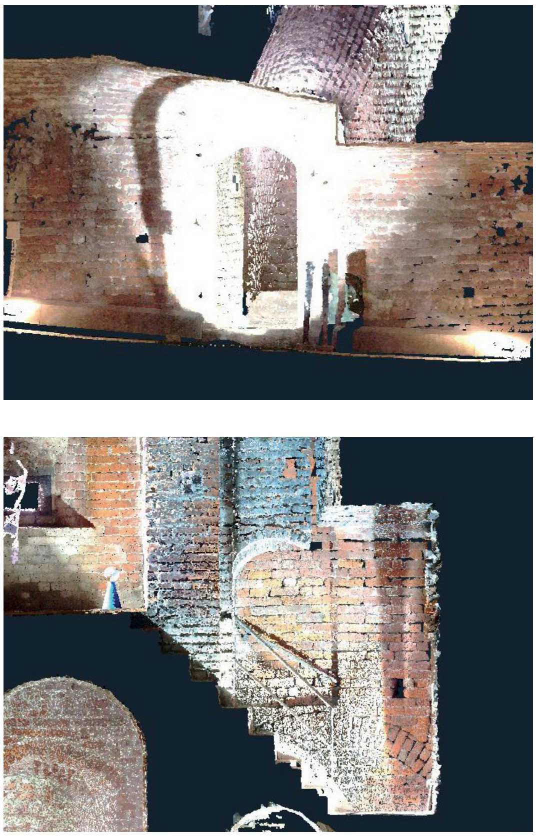


Figure 5.2.3.c Examples where the use of LED headlights led to unsatisfactory chromatic results.

The process for the first set generated the point cloud of Torre della Colubrina and the path connecting it to the counterscarp tunnel. It processed 21 scans, from n. 000 to n. 020. The error obtained for this first block averaged approximately 3,78 mm.
The second cycle processed scans of the secret covered path. There are 13 of these, from n. 020 to n. 032, with an average deviation of 4,97 mm. As can be seen, the scans corresponding to the intersection of multiple blocks were used more times. This choice was made to obtain a series of point clouds that completely cover the entire surveyed area, leaving no unresolved points.
For the third processing, scans regarding the spaces of the casemate at the head of Porta del Soccorso have been aligned. The recordings of the passage connecting it to the previous block, thus to the counterscarp tunnel, were also part of this group. The scans are 10, from n. 032 to n. 045, and the average error is 3,18 mm. Scans n. 034, 036, 037 and 040 are not present as they were eliminated during the survey phase due to errors incurred during the work.
The fourth group consisted of scans carried out along a staircase inside Porta del Soccorso, which connects the underground infrastructure to the two casemates inside the volume of the building itself, and the walkable roof placed at the top. Eleven elements were processed, from n. 050 to n. 061 (excluding 060). The error for this alignment is 3,09 mm.
A final small set of scans is the one that involves a portion of the exterior of the gate and the terrain surrounding it. There are only two scans (n. 062 and n. 063) because the activities were interrupted for technical reasons. Nevertheless, the material was still processed, although it shows a 6,28 mm deviation. As will be seen in the next section, the survey of the exteriors was completed at a later stage again using laser scanner technology.
For all these procedures, as mentioned above, different references were used. Spheres and checkerboard targets were arranged as basic tools for mutual alignment between the scans. In addition, to reinforce these connections and to georeference all material, all points typed with the total station, during the topographic survey, were entered. This data was imported into the software in the form of a .csv file, containing the point name, N coordinate, E coordinate and elevation.

Appendix A.III.IV.b provides a more detailed diagram of the scanning points, divided with respect to the processing blocks, and data on the deviation in the various processing. The images also show the elements used to align the scans, sorted by decreasing error. This means that the first terms in the tables are occupied by those checkerboards/points/spheres for which the software calculated a greater deviation between various scans. The elaborations were checked and the elements were handled in such a way that the first deviation (the largest one) was related to a point measured with the theodolite. That means all elements with an error greater than that shown of the first measured point in the list were manipulated, and the value of the error itself fell below the one of the first known point. This was achieved either by manually improving the positioning of the references or by eliminating, when there was no other way to improve the result, those too far away to be recognised correctly. This last solution was possible due to the great redundancy of elements used for the alignment of the scans. The outcome of the scanning and related processing is a

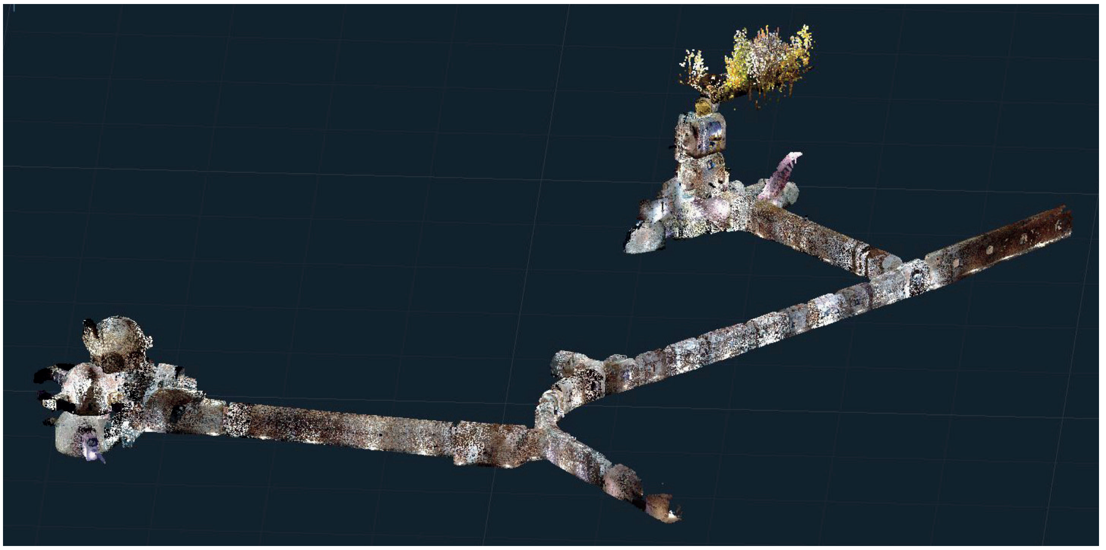


Figure 5.2.3.d Overview of the point cloud obtained by laser scanner survey.

dense georeferenced point cloud that defines the geometries of the detected spaces, as depicted as a whole in Figure 5.2.3.d.

Figure 5.2.3.e makes explicit the relationship between the point cloud and the topographic polygon used for georeferencing. As can be seen from the image, the network was taken deep into the Ghirlanda's paths to ensure good efficiency of the collimated points and greater rigidity of the cloud at the extremities.
Finally, some more detailed images of point clouds in a CAD environment are shown (Figure 5.2.3.f-g).

To support the laser scanner activities, a photogrammetric survey was also carried out during this first phase. This involved the northwest corner of the castle facade, the same portion of the moat wall face (to define the thickness of the wall in which the walkway is built) and the exterior of Porta del Soccorso (not completed with the laser scanner). These surfaces were surveyed with the photogrammetric technique precisely because of their simplicity. In contrast, the interiors of the Ghirlanda are presented as a huge number of spaces that follow one another, creating a very complex element, which requires the use of technologies such as laser scanning. By differentiating the work in this way, it was possible to optimise the working time, both by reducing the number of scans needed and by employing all the tools on different fronts.

A Canon EOS 700D digital camera at maximum resolution, with images of 18 MG pixel and a pixel size of 4.3 microns, was used to carry out this survey.
The photogrammetric survey is divided into the three parts listed but is oriented in a single reference system. This was possible by using some points typed by the theodolite from the vertex 100 of the polygonal

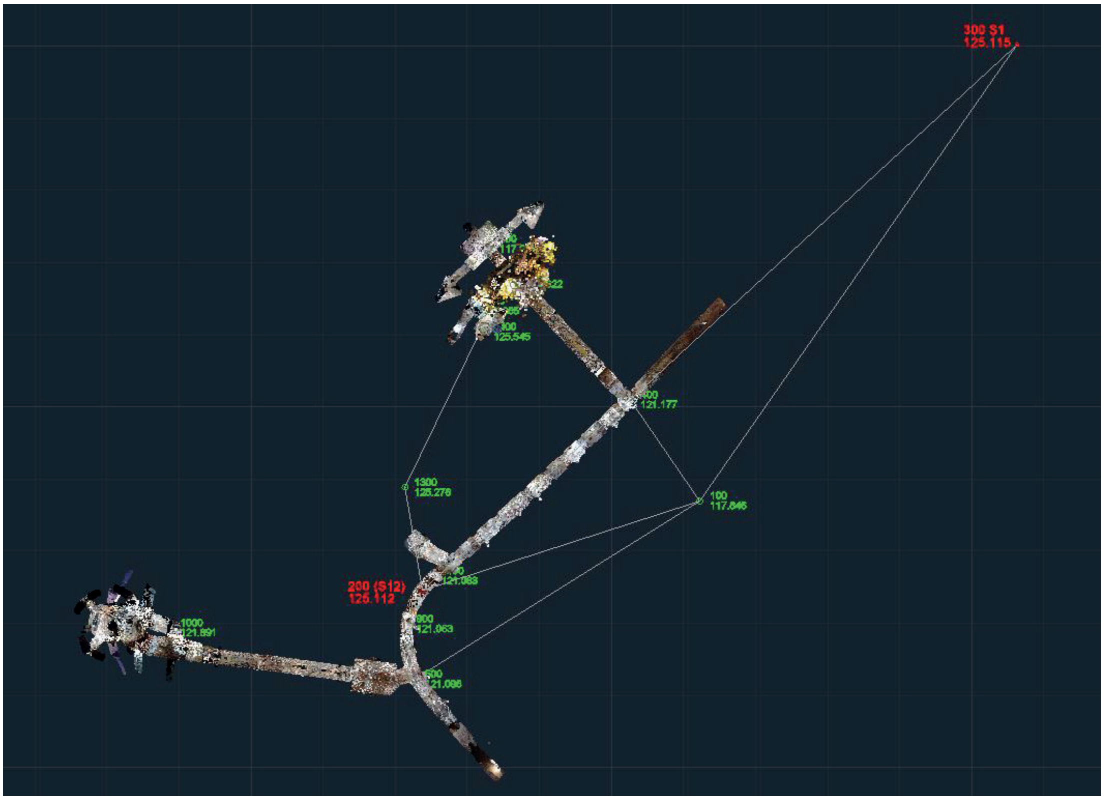


Figure 5.2.3.e Top view of the point clouds and topographic polygon developed for the survey.

Figure 5.2.3.f Interior spaces of Porta del Soccorso.

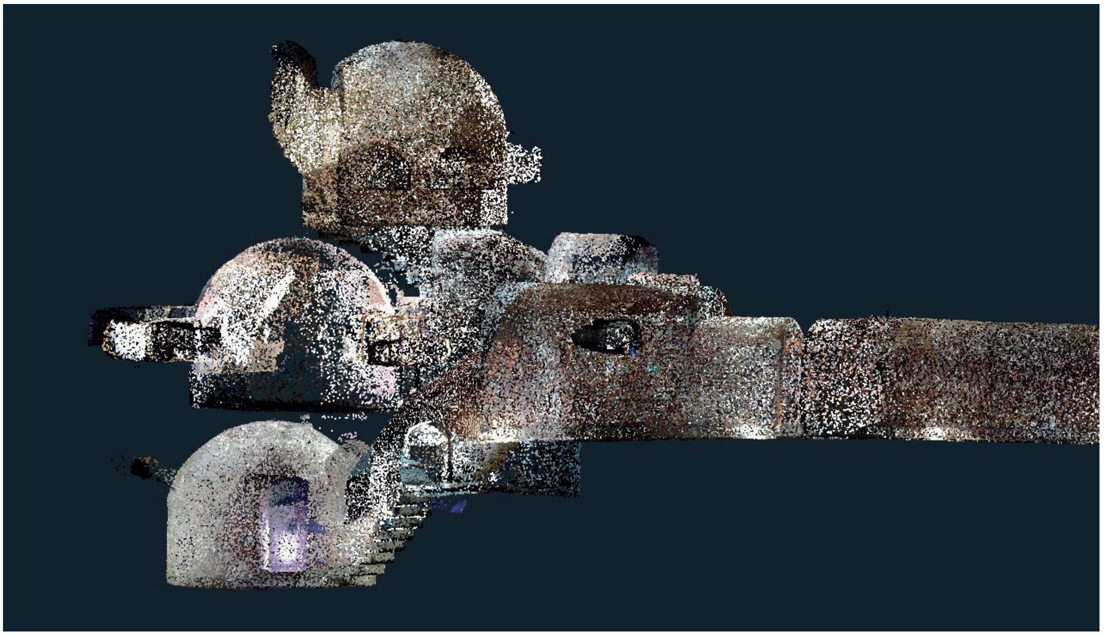


Figure 5.2.3.g The three casemates of Torre della Colubrina.

network. The materialised points refer to clearly recognisable elements in order to facilitate operations both in the survey phase and subsequently during processing with the Agisoft Metashape software. Markers, coinciding with the reference points, were then placed in the various photographic scenes.

The block of the fortress facade (Figure 5.2.3.h) consists of 60 frames oriented on 15 control points and its average deviation is 21 mm.
The second of the moat (Figure 5.2.3.i) contains 45 frames oriented on 17 points. The maximum deviation is 14 mm and the average one is 8 mm.
The third, that of Porta del Soccorso, (Figure 5.2.3.l) consists of 89 frames and 9 support points. The maximum error for this last photogrammetric process is 11 mm and the average error is 8 mm. Appendix A.III.IV.a shows a plan view of the involved surfaces and the data relating to the deviation in the various elaborations.
To obtain a good result using the software that processes the input material, frame sequences respected the canonical characteristics recommended for photogrammetry. As can be seen in the reported images (Figure 5.2.3.m-n), the photos were taken with a certain rigour, according to a constant scan, on several horizontal bands. In addition, a minimum percentage of overlap between the various frames has been ensured.

The three different photogrammetric blocks resulted in three point clouds that were placed in a single digital environment together with the clouds obtained with the laser scanning instruments (Figure 5.2.3.o). The development of this comprehensive object was

Figure 5.2.3.h Dense cloud obtained by photogrammetry of the facade of the Castello Sforzesco.

Figure 5.2.3.i Dense cloud obtained by photogrammetry of a portion of the moat.

Figure 5.2.3.l Dense cloud obtained by photogrammetry of the exterior of Porta del Soccorso.

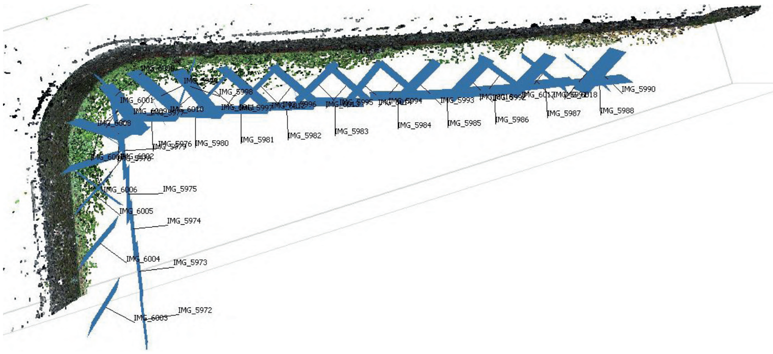


Figure 5.2.3.m The image shows the direction of the photos from above and thus the three different orientations: frontal, 45° to the right and 45° to the left.

Figure 5.2.3.n The image shows how several parallel horizontal strips were taken.

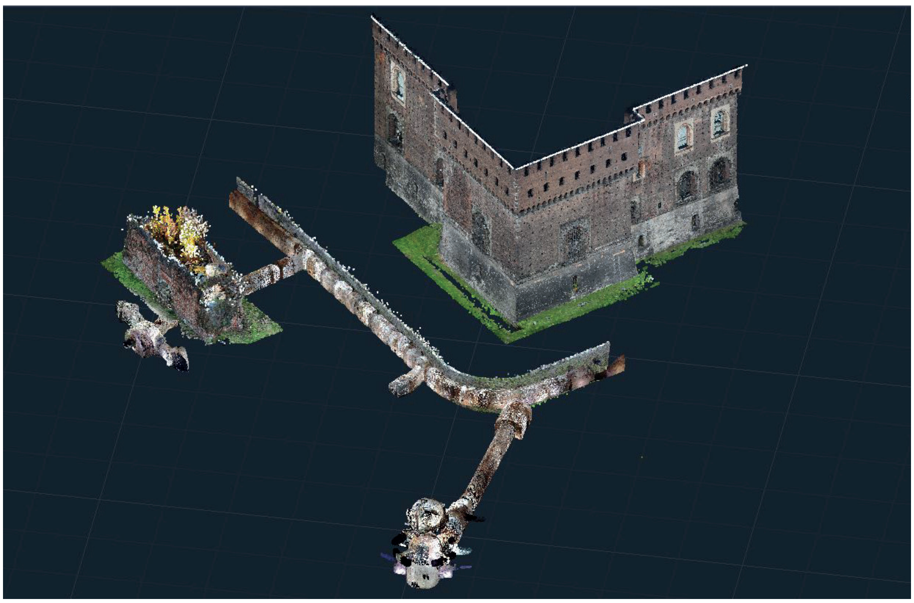


Figure 5.2.3.o Image of the overall point cloud obtained by both laser scanning and photogrammetric survey.

possible due to both the similar nature of the survey outputs and, above all, the precise use of the topographic information. This good base will make further comparisons with other materials in various digital environments and will also serve as a continuity tool for future work.

The last stage was comparing the point clouds with the pre-existing material: the 2002 survey and the available cartography. For that purpose, for the correct placement of the 2002 documentation, the GPS points newly surveyed have been used. Since this material is two-dimensional, a comparison of elevations was not possible. For this reason, the vector material lies in an arbitrarily chosen plane, roughly coinciding with the decking of the park near the moat.
Once these operations were completed, the new overall point cloud was compared with the previous survey, carried out using other methods and technologies. As can be seen in Figure 5.2.3.p, there are discrepancies that can arise up to several metres due to the heterogeneous levels of accuracy of the works, according to the different rigorousness of the surveying methods used.
This example corroborates the idea that today's laser scanner surveying technology, supported by a good topographical basis, can seamlessly handle the surveying of complex buildings and more delicate situations, which are often found within architectural cultural heritage. An example is visible in Figure 5.2.3.q, where the slightest error in the measurement of lengths or angles leads, over long stretches, to substantial discrepancies.

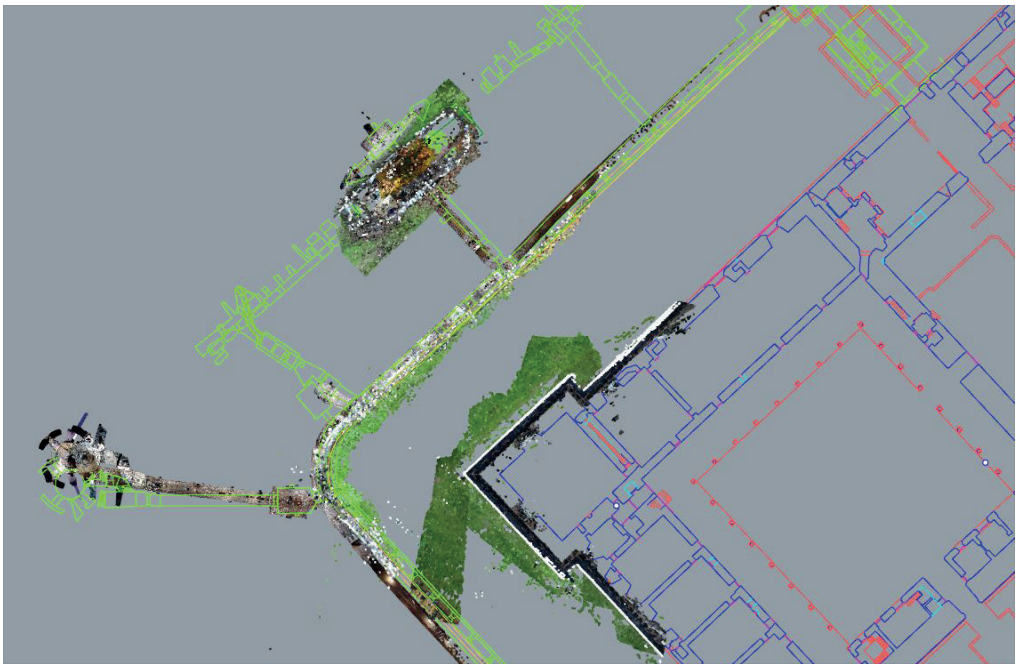


Figure 5.2.3.p Comparison between the 2002 survey and the point cloud.

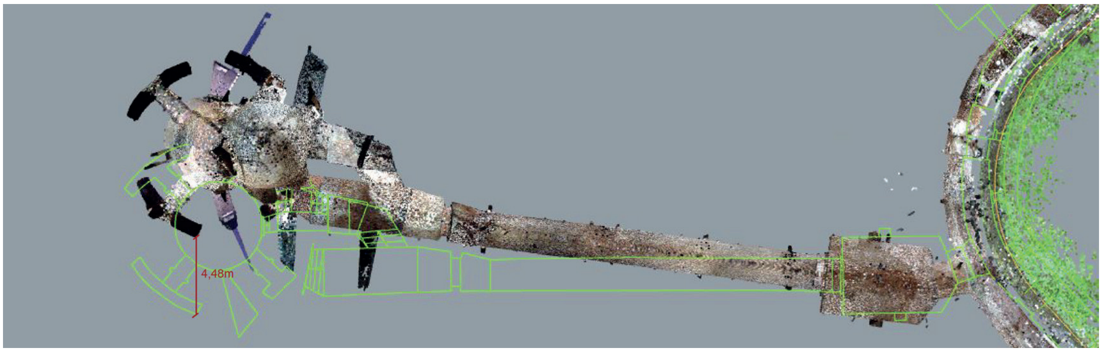


Figure 5.2.3.q Zoom of the point of maximum discrepancy between the 2002 survey and the point cloud.

Finally, there was a superimposition of the products: the survey and the DBT base of the area (downloaded from the Geoportal of the Lombardy Region). The objective, in addition to a second verification of the work, was to understand the position of the Ghirlanda underground infrastructure in relation to the elements present in the park.
The DBT was opened in a QGIS working file and set in the official national reference system: ETRS89 ETRF2000 (DM 10 November 2011). Once imported, the software exported only the Castello Sforzesco area in .dxf format (the base covers the entire city of Milan). The new file obtained was added to the point clouds within a CAD file, where, thanks to the previous management of the reference system in the GIS environment, it was positioned to coincide with the same clouds. Within the AutoCAD software, it was compared with the outcome of the survey carried out and the material of 2002 (Figure

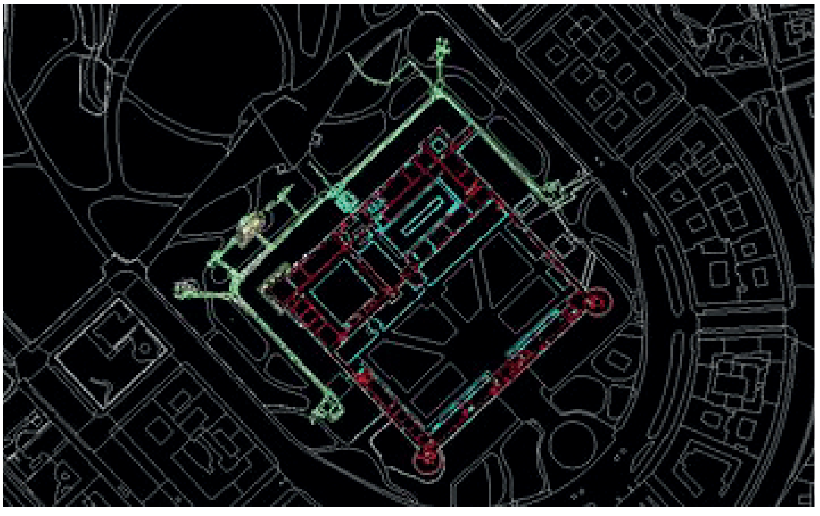


Figure 5.2.3.r Overlay of DBT, point clouds and CAD material from 2002.

5.2.3.r). As shown in the images below, the point clouds and the DBT (blue lines) coincide perfectly. The survey was checked on several points and in each of them, a good adherence to the Topographical Database was found (Figure 5.2.3.s-t-u). Previous surveys, on the contrary, cannot guarantee such a correspondence. The hypothesis of the position of the underground elements is in fact not compatible with the outside volume of Torre della Colubrina (Figures 5.2.3.q and 5.2.3.t read as a whole).

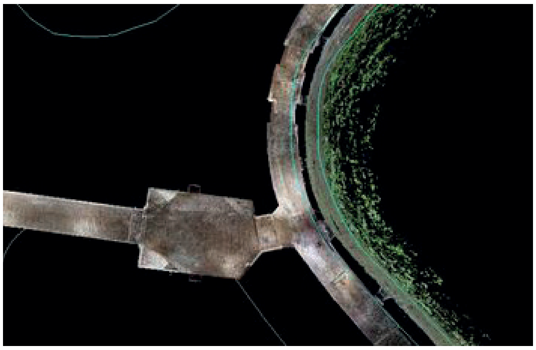


Figure 5.2.3.s Comparison between the DBT geometries (in blue) and the point cloud of the counterscarp tunnel.

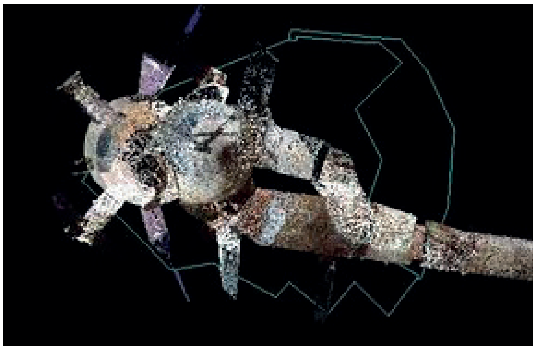


Figure 5.2.3.t Comparison between the volume of the ruins of Torre della Colubrina (in blue) and the internal casemates.

Figure 5.2.3.u Comparison between the DBT geometries (in blue) and the point cloud of Porta del Soccorso.

Since the sparse points in common correspond (the limit of the moat and the openings of the secret road, the ruins of Torre della Colubrina and the casemate at a higher elevation, the encumbrance of Porta del Soccorso), it is possible to state that the remaining portion of the survey is also correctly positioned.

05.3 _ The development of the 3D model

The third part of the chapter describes the development of the 3D model of the case study. The following subsections will report the modelling of the underground infrastructure studied, the above-ground elements and those parts whose presence is only a hypothesis. This first version of the three-dimensional object contains all the structures and spaces investigated in the study phase and with the first survey campaign. For the specific case of the Ghirlanda of the Milanese fortress, which is largely underground, the work also involved modelling the terrain in order to correctly read the correlations between what is below ground level and what is above.

As described in Chapter 3, the design of the 3D model involves the coexistence of objects at different Levels of Geometric Information (LOGI). The differentiation is made according to whether they are spaces investigated by the modern geomatic survey, whether they have only a documentary collection or whether they are present in the form of a hypothesis as they are no longer available. It is not uncommon to have several surveys and drawings, often concerning different portions of the building and with several levels of detail: in this way, it is possible to collect both data from a survey, such as the one carried out, and information from historical sources.
The result is a heterogeneous collection that encompasses all elements of the building, from those surveyed to those hypothesised because they are no longer visible or existent. Furthermore, thanks to the rigorous use of georeferencing, this approach permits the continuous update of the object over the years with novel information or additional research and survey activities.

The development of the geometric model in this phase involved Rhinoceros software since for this activity, it was not necessary to use BIM modelling tools. As already mentioned, the latter, would not have correctly handled all the geometric peculiarities typical of the architectural heritage. Software such as Revit and Archicad still struggles with modelling non-standard and non-regular elements, which are not part of the world of new construction. Rhinoceros software, in addition to its intuitiveness and wide possibilities in terms of geometric modelling, suits well also to import various types of reference materials, such as point clouds. Moreover, this software allows modelled objects to be enriched with a range of additional information. This set of capabilities allows users to organise data in customisable structures, similar to metadata in GIS environments. This solution, as will be described later, served perfectly to manage the data required to identify and catalogue the sources underlying the modelled objects.

The chapter ends with a series of analyses and considerations on the three-dimensional product, in particular on the potential for communication and understanding of complex architectures offered by these digitisation processes, citing some peculiar use cases extracted from the Castello Sforzesco digital twin.

05.3.1 _ The initial version of the model

The first version of the 3D of the Ghirlanda of the Castello Sforzesco derives both from the information gathered during the study and research phase (Chapter 5.1) and from the output data of the first survey campaign (Chapter 5.2.3). This initial step led to the digitisation of all known underground spaces that are part of the analysed area, the moat plan, some external structures and the ground surface. In addition to them, there are also some assumed elements such as the volume of the Ghirlanda and the Spanish Bastions and the second counterscarp passage.

The first elements realised are those related to LOGI 3, namely the spaces surveyed and described in the previous chapter. The modelling complied with the blocks created for scans and photogrammetry processing.
In particular, those blocks are described by six corresponding macro-areas:

- Torre della Colubrina and the stretch that connects it to the counterscarp tunnel.
- The counterscarp tunnel.
- The casemate below Porta del Soccorso and the stretch that connects it to the counterscarp tunnel.
- The casemates and the stairs inside Porta del Soccorso (west side).
- The exterior of Porta del Soccorso.
- The counterscarp wall and the moat ground surface.

All these blocks were modelled in Rhinoceros based on references prepared in a CAD environment and extracted from the point clouds. In order to work properly in that environment, point clouds had to be imported into Cloud Compare software to perform a decimation process. The obtained clouds, now containing one point every six centimetres, had greatly reduced their weight, making their management in the CAD environment easier. For each point cloud, multiple sections made it possible to extract all the reference elements necessary for modelling the structures of the Ghirlanda (Figure 5.3.1.a). This operation was carried

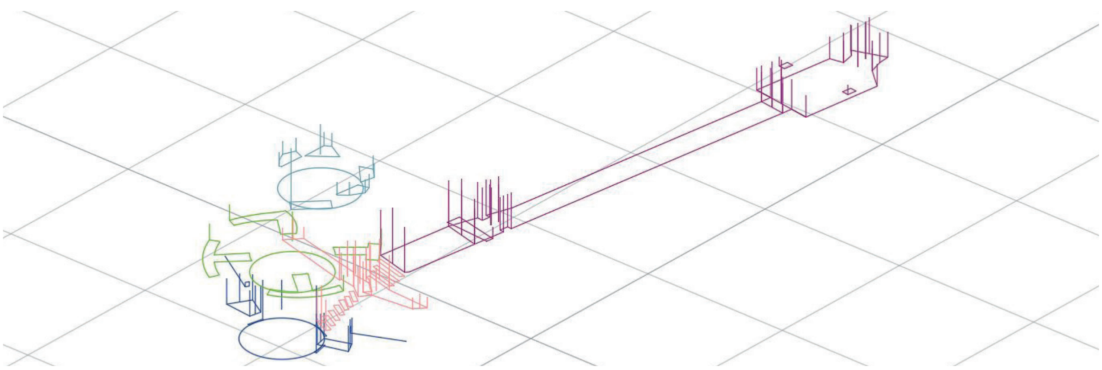


Figure 5.3.1.a Exemple of vector reference elements in AutoCAD environment (Torre della Colubrina).

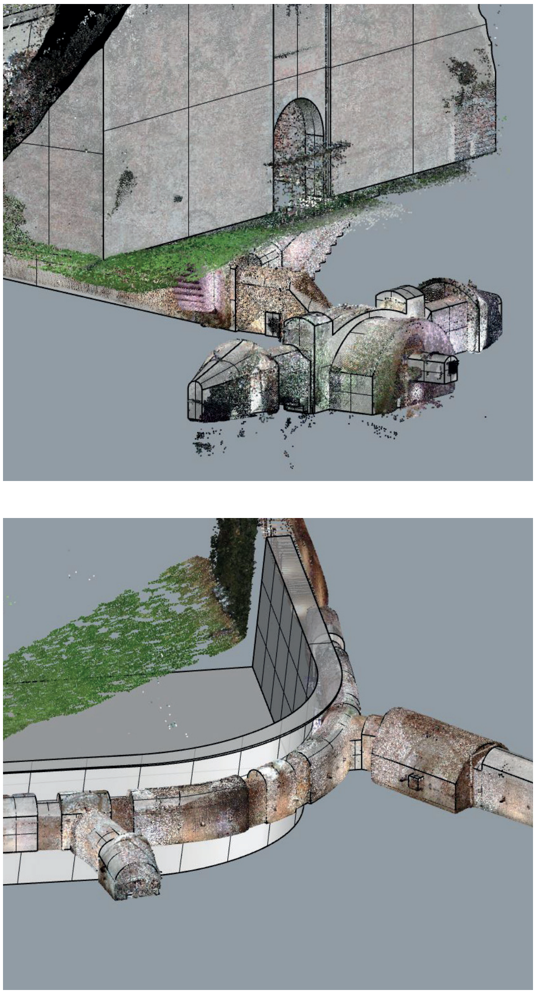


Figure 5.3.1.b-c Comparison between model and point clouds.

out using Autodesk AutoCAD to exploit its extensive point cloud manipulation capabilities. Having kept the position of the clouds unchanged, the CAD files, once imported into Rhinoceros, were placed in the correct position, both absolute and relative.
The result, therefore, consists of a georeferenced model. Based on these vector references, modelling was smoother and systematic. Importing the point clouds into the modelling environment also made it possible to verify the blocks created, comparing the adherence of the surfaces with the native geometric information (Figure 5.3.1.b-c).

Following the approach described in Chapter 3, all main sources were included within the modelling environment. Consequently, the digital twin of the cultural asset encompasses all the material necessary to legitimise the 3D model itself. Additionally, these sources facilitate comprehension of the shapes. In the context of the case study, this operation involves not only point clouds but also cartographic fragments and other necessary documentation for the modelling phase. In this way, as already mentioned, geometric information could be accessed both natively, through the visualisation of the leading sources, and in its three-dimensional reworking. The forthcoming sections and subsections will delve into the discussion about managing these sources in the 3D model.
The result obtained is visible in Figure 5.3.1.d: the model presents a minimal simplification factor to the level of precision of the survey output from which it was developed. However, this choice did not result in the loss of the information necessary for reading the spaces, their peculiarities and the data useful for its management.

The second modelling phase concerned the accessible spaces that do not have geomatic and digital surveys yet. For these rooms were only present paper graphics derived from a geometric survey by trilateration carried out in the 1990s, usable in low-resolution digital format only. There is also a CAD planimetry drawn in 1:200/1:500 scale detail. Considering these sources, the modelling of the blocks is in/with LOGI 2 and the blocks coincide with:

- The lift pump rooms;
- The Casamatta Celestino;
- The Galleria delle Radici;
- The casemates and the stairs inside Porta del Soccorso (east side).

The modelling process of these spaces still involved a preparation phase in the CAD environment, but only using the available material. Once the documentation was imported, the available reference points allowed the material to be scaled and positioned. The creation of these blocks involved a considerable approximation factor, given the consistency of the geometric information available. Figure 5.3.1.e shows the relationship between the model parts realised with LOGI 3 and those with LOGI 2.

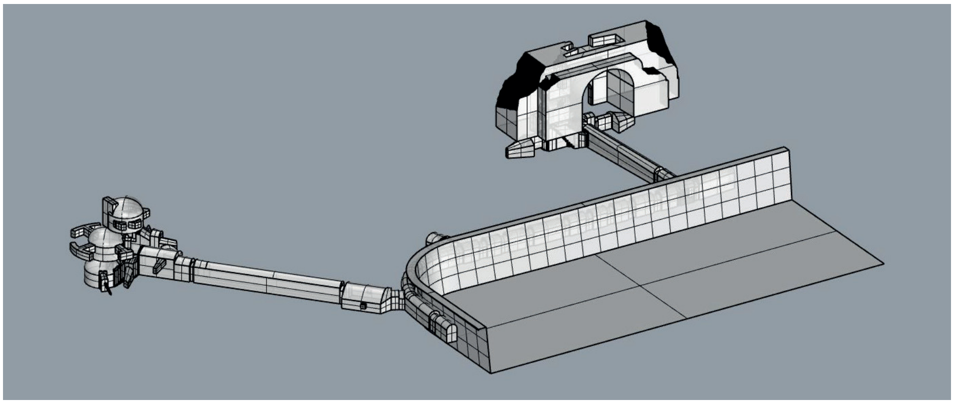


Figure 5.3.1.d Model of the structures pertaining to LOGI 3.

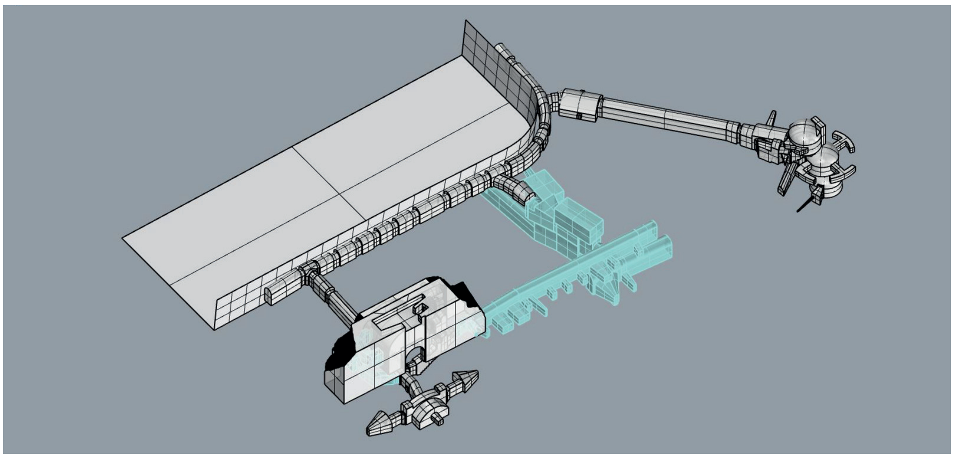


Figure 5.3.1.e Model of the structures pertaining to LOGI 3 and LOGI 2.

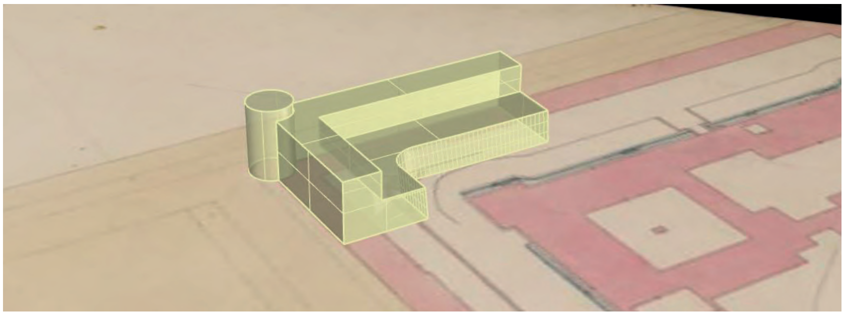


Figure 5.3.1.f Model of the original volume of the Ghirlanda on the reference of the Lombardo Veneto Cadastre (1881).

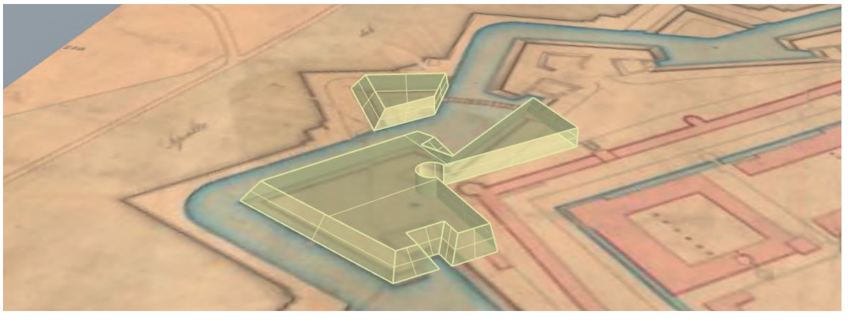


Figure 5.3.1.g Model of the original volume of the Spanish Bastions on the reference of the Teresian Cadastre (1751).

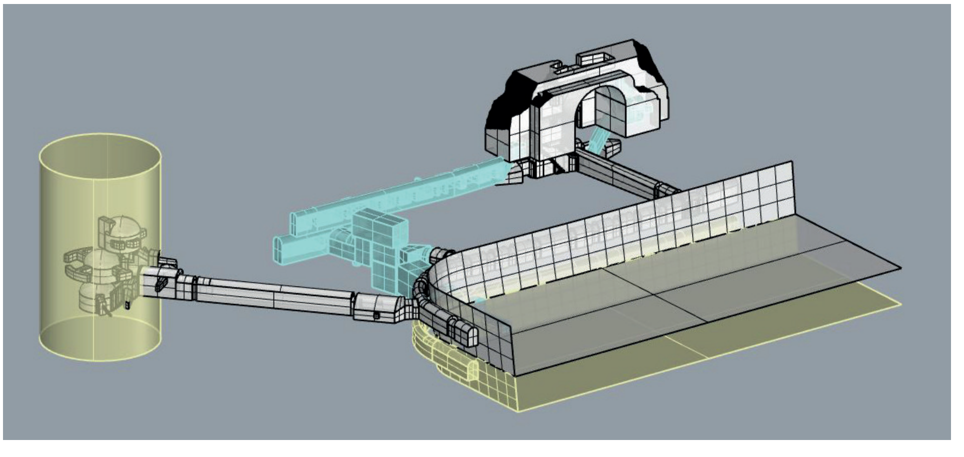


Figure 5.3.1.h Model of the structures included in the case study. The volumes of the Ghirlanda and the Spanish Bastions, which would have covered most of the other elements, are not present.

At last, the 3D was finalised with the introduction of elements assumed from the historical documentation. Therefore, these are the structures assimilated with LOGI 1.
These modelled elements are:

- The volume of Torre della Colubrina. Its geometries mainly derive from the depth of the narrow loopholes recorded by the laser scanner (Figure 5.3.3.b). The shapes reported in the Lombardo Veneto Cadastre of 1881 have supported the modelling of this volume.
- The other and deeper counterscarp tunnel. Historical records do not show information regarding this second underground path. The book Castrum Portae Jovis Mediolani (G. Padovan) reports early assumptions[1] about its existence. It refers to a drawing by Leonardo da Vinci to assume the presence of this additional infrastructure. The modelled volume draws inspiration from the reconstructions proposed in the book, providing some thoughts for its positioning within the 3D model. It should be on the second level underground compared to Parco Sempione. This was assumed to be equal in size to the one currently practicable. It is possible that the original height of the moat was five metres lower than the current one and that the second path should be located between the counterscarp tunnel and this level. Its keystone has been figured two metres from the floor level of the available principal way.
- The original level of the moat.
- The original volume of the Ghirlanda. It stands between the present moat wall and the outermost limit of the underground casemate at the head of Porta del Soccorso. The current elevation of Parco Sempione coincides with the level of the Ghirlanda's glacis. On the outer side, scholars hypothesise two or three more floors in elevation[2]. Again, the Lombardo Veneto Cadastre was very helpful in verifying the geometries, although in approximate terms (Figure 5.3.1.f).
- The Spanish Bastions. Their modelling was based substantially on the Teresian Cadastre of 1751, as well as on some iconographic documents for the estimation of vertical development (Figure 5.3.1.g).

All these elements, as described above, have simplified and approximate geometry, they coincide with overall dimensions. The modelling took place in Rhinoceros, without prearranging reference vector elements. Where possible, however, due to the presence of useful documents, the volumes have been developed directly on these sources. Due scaling and georeferencing had to be carried out in Autocad before their inclusion in the 3D modelling software environment. Figure 5.3.1.h shows the model as a whole.

05.3.2 _ The terrain modelling

This first version of the 3D model was completed with a surface describing the terrain trend. The modelling activities for this ele-

[1] Figures IV.31a (p. 168) and IV.33 (p. 169) are graphical representations of this hypothesis.

[2] Boccardo, E., Volpi, S., *Castello Sforzesco. Recupero della strada coperta della Ghirlanda, p. 8.* The text indicates that the Spanish lowered the structure to 8 metres from the redondone. This indicates that the Ghirlanda must have been taller.

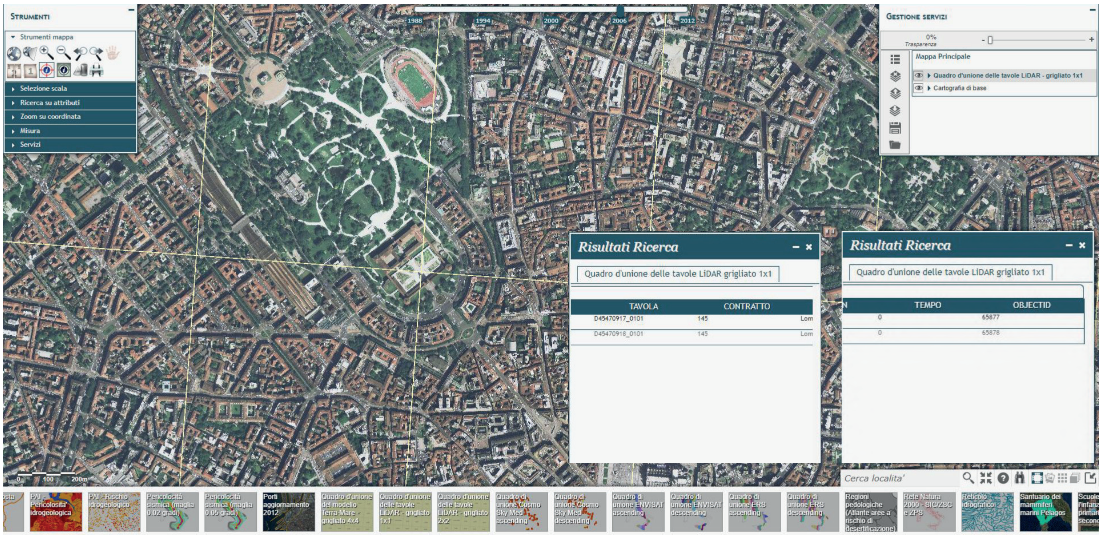


Figure 5.3.2.a Viewer of the National Geoportal and the information about DTM tables.

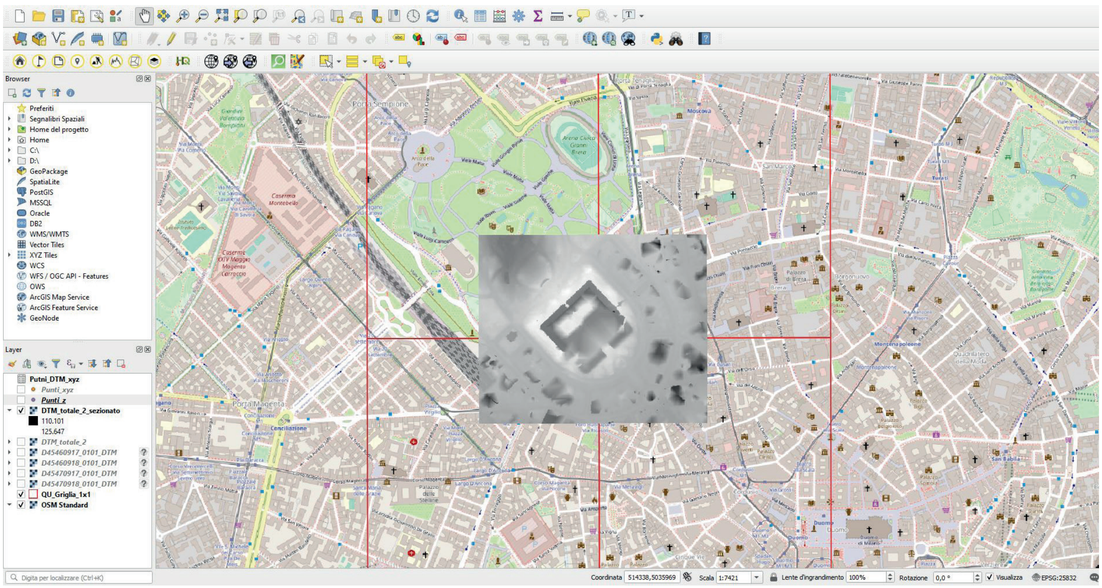


Figure 5.3.2.b Visualisation of the DTM of the Castello Sforzesco area in QGIS environment.

ment are different from the previous ones, requiring a more structured process. For this reason, the text reports this part separately.

To achieve the result, it was not possible to use the point cloud of the survey, as it was limited only to a portion of the area. Therefore, the model has been based on the Digital Terrain Model (DTM) data made available by the Italian Ministero dell'Ambiente e della Tutela del Territorio e del Mare.

The submission of a request for the digital material with a straightforward procedure (Corradeghini, 2017) has been the first step of the process. Using the viewer of the National Geoportal (http://www.pcn.minambiente.it/viewer/), it was possible to visualise the DTM union frame with a one-metre grid, obtained from the 2008-2009 LIDAR survey. Once the needed tables were identified, the application displayed all the information related to them, including the table number and its object ID (Figure 5.3.2.a). The request email sent to the Ministry reported these data that consented to receive a reply that contained all the indications for downloading the DTM files.

Once the files have been downloaded, it has been possible to start the procedure for organising the data for the terrain modelling. After opening a new project in QGIS software and setting the correct reference system for the area (ETRS89 ETRF2000), the DTM was imported into the working environment. The software displays these data as four rasters, according to the tables previously selected. For this reason, it was necessary to generate the overall datum, using the "Build Virtual Raster" command. This function allows the merging of several rasters, creating a single element. To better manage the file, the new layer was cropped, maintaining only the points of the Castello Sforzesco area (Figure 5.3.2.b).

The subsequent step was to proceed with data preparation: the aim was to obtain a .csv file containing a set of geographic coordinates derived from the 1x1 grid of the DTM. To achieve this, a shapefile was generated, transforming the pixels of the new raster into points. The "Raster pixels to points" command allowed the automatic extraction of the z-coordinate of the points created. However, the new layer had an attribute table containing only the elevation data. Once two new columns were added, the calculation functions of QGIS attribute tables made it possible to extract the missing data, inserting them directly into the empty cells. Upon completion of the process, the dataset looked as in Figure 5.3.2.c.

The final step in the GIS environment was to export the information in .csv format.
Before the surface terrain modelling, this data underwent some minor changes in Excel and Notes applications. Figure 5.3.2.d shows the result.

All the material required for modelling the terrain was ready. The following step was the modelling with Rhinoceros software. It was chosen both for coherence with the architectural part that was modelled in the very same environment and due to the available functionalities. For instance, Rhinoceros provides multiple options for developing a surface object from a set of points. In particular, for the present work, more tests were carried out, both using the "Patch" command and the Docofossor plugin within the Grasshopper platform (Hurkxkens & Bernhard, 2019; Michetti, 2020; D'Uva & Eugeni, 2021).
Despite having the same results, the first approach proved to be simpler and more manageable both in the data preparation phase and in the implementation of the 3D object. For this reason and given the absence of any particular requirements (which

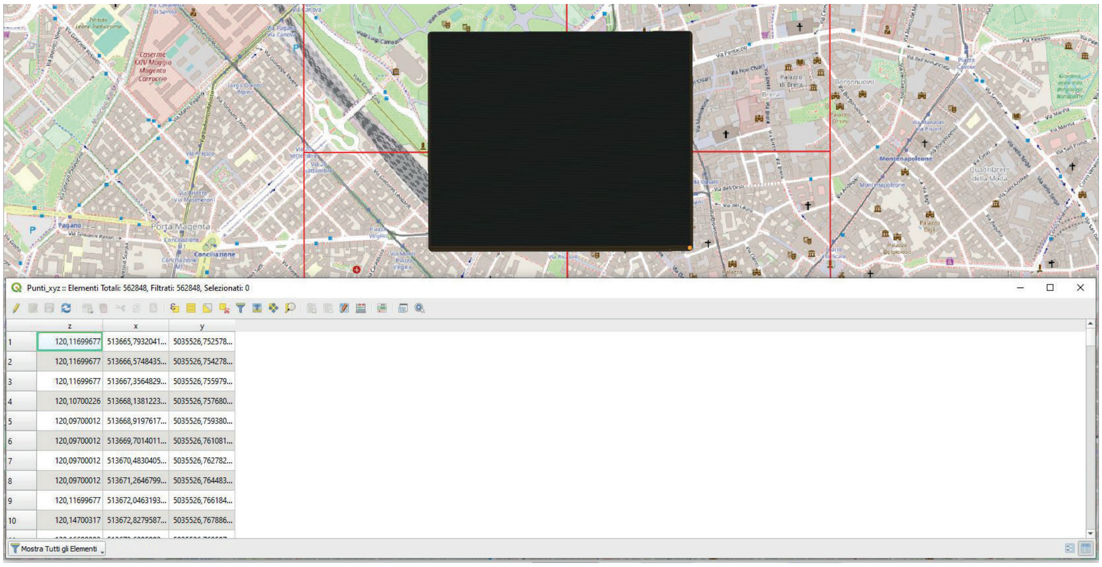


Figure 5.3.2.c Attribute table of points extracted from DTM file.

Putni_DTM_xyz_finale.csv - Blocco note di Windows

File Modifica Formato Visualizza ?

```
x,y,z
513665.7932041340,5035526.7525785044,120.11699677
513666.5748435410,5035526.7542789681,120.11699677
513667.3564829480,5035526.7559795324,120.11699677
513668.1381223550,5035526.7576801907,120.10700226
513668.9197617620,5035526.7593809497,120.09700012
513669.7014011690,5035526.7610818027,120.09700012
513670.4830405760,5035526.7627827553,120.09700012
513671.2646799828,5035526.7644838039,120.09700012
513672.0463193898,5035526.7661849493,120.11699677
513672.8279587966,5035526.7678861944,120.14700317
513673.6095982036,5035526.7695875354,120.16699982
513674.3912376106,5035526.7712889723,120.19699860
513675.1728770176,5035526.7729905080,120.19699860
513675.9545164244,5035526.7746921405,120.14700317
513676.7361558314,5035526.7763938708,120.11699677
513677.5177952382,5035526.7780956980,120.06700134
513678.2994346452,5035526.7797976220,120.06700134
513679.0810740520,5035526.7814996438,120.02700043
513679.8627134588,5035526.7832017625,119.98699951
513680.6443528658,5035526.7849039789,119.96700287
513681.4259922726,5035526.7866062922,119.89700317
```

Figure 5.3.2.d Final .csv file of the coordinates of the points.

would have justified the use of the Docofossor plugin, more articulated and feature-rich), it was decided to continue with only the internal commands of Rhinoceros software. The .csv file was then imported into the modelling environment, automatically generating the point cloud corresponding to the coordinates stored in the file (Figure 5.3.2.e). Thanks to the shared setting of the reference system during the initialisation in GIS, points were already in the correct position. Afterwards, the second selection was conducted, limiting the set to the investigated area only and improving the file fruition and the process performance.
Another modification of the point data affected the strip adjacent to the moat. The low density of the LIDAR survey caused an approximation of the DTM, which was inadequate for the level of detail of the present work. For this reason, points on the moat boundary that had an incorrect elevation datum have been replaced with the attribution of z-value comparable to the real one to the new elements. This value was assumed based on the attributes of neighbouring

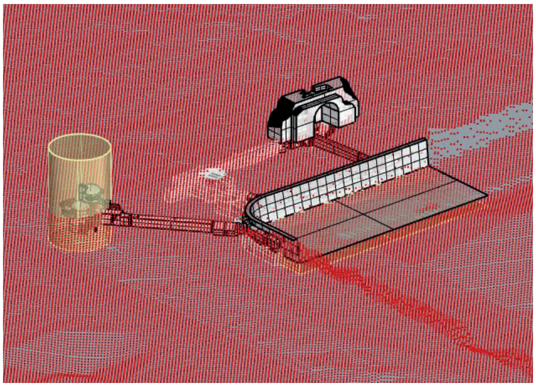


Figure 5.3.2.e Insertion of the points extracted from the DTM file.

points and information obtained from research and other material in possession and then placed on another level to keep track of the changes made (Figure 5.3.2.f).
A further change involved the removal of several points inside the perimeter of Porta del Soccorso (Figure 5.3.2.g): they were the result of the interpolation process and they do not correspond to the real conformation of the terrain, which is absent in that area due to the volume of Porta del Soccorso. For this reason, the modelling work didn't consider them for the surface. Tests were carried out, both with the complete set of points and the reduced one. The surface developed by this second attempt proved to be more adherent to reality, confirming the decision taken.
Finally, it was deemed necessary to add the perimeter lines of the area, similar to breaklines. These elements made it possible to force the behaviour of the generated surface, fixing its outer border and influencing the z-value interpolation along those lines. Figure 5.3.2.h makes explicit the differences between using or not using such elements for processing.

The set of data obtained, allowed the terrain surface extraction by developing the modelling with the "Patch" command. This tool generates a surface interpolating the available elements. This was processed several times, testing the command settings

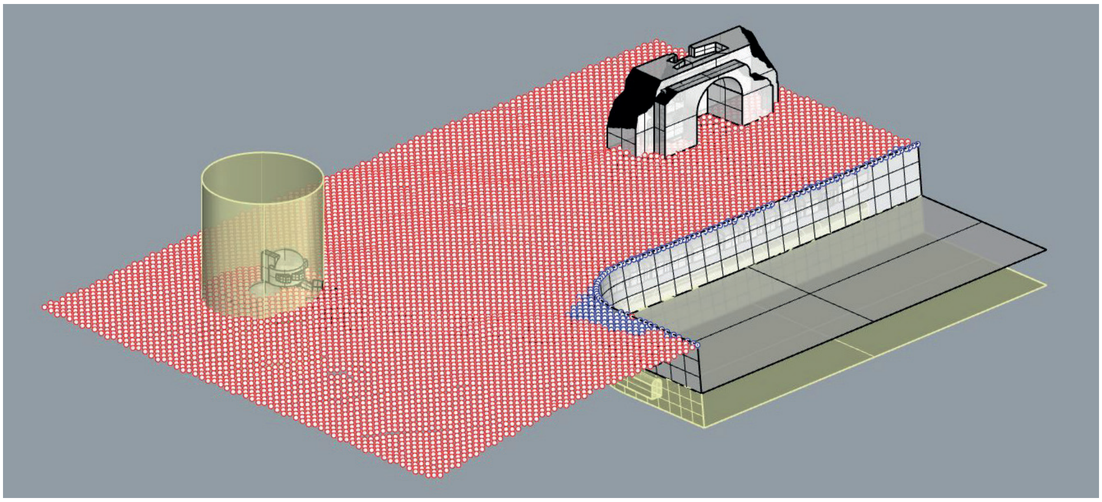


Figure 5.3.2.f New points inserted along the limit of the moat (in blue).

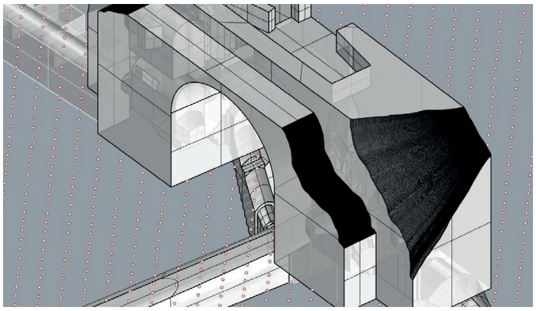


Figure 5.3.2.g Area of Porta del Soccorso without DTM points.

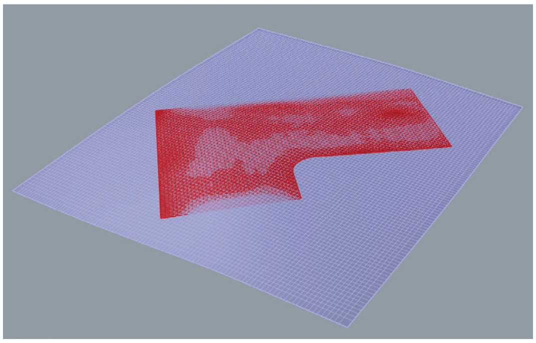


Figure 5.3.2.h Comparison of surfaces obtained with (red) and without (violet) breaklines.

(spacing between the points, number of subdivisions along the two directions and rigidity of the interpolating surface) to obtain a result that adhered as closely as possible to the reference points and reality. The final surface was then added and verified within the model of the architectural elements, which it complements by providing a reference for the above-ground context (Figure 5.3.2.i).

The implemented procedure led to an acceptable result. Nevertheless, the model denotes some approximations, due to the low point density of the DTM. These occur more often along the perimeter of the Ghirlanda ruins, in particular in the nearness of Torre della Colubrina and Porta del Soccorso. In these areas, the terrain shows pronounced variations due to the structures present a few centimetres below ground level (Figure 5.3.2.l-m). The one-metre grid of the LIDAR survey can't properly return these data due to the insufficient number of points collected on these small portions of the ground.

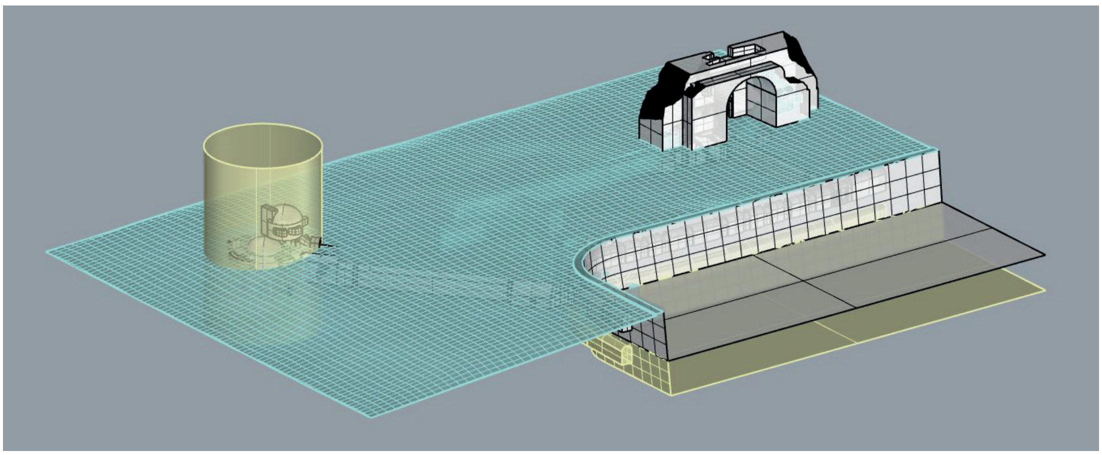


Figure 5.3.2.i The terrain surface inserted within the overall model.

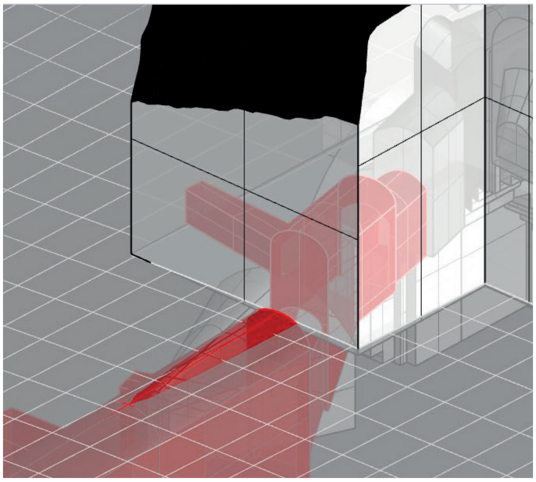


Figure 5.3.2.l-m Detail of the wrong surface processing, adjacent to Porta del Soccorso (l).
Image of the real shape of the ground in this area (m).

Despite the nature of the native data, the obtained model was, therefore, classified as LOGI 2, as it does not reach the level of accuracy for the highest class. The result is still acceptable and represents the first version of the terrain. However, as will be seen later, a second survey campaign investigated the whole area with laser scanner technology to obtain a denser point cloud. The latter served then to develop a more accurate three-dimensional description of the ground.

05.3.3 _ From the model new questions for knowledge

Understanding, analysing and critically re-examining the knowledge of an architectural asset and its spatial articulation is a very intricate process. This complexity is further amplified when undertaking such tasks exclusively relying on conventional tools, such as historical documentation, research and traditional graphic representations. It is in these phases that the great efficacy of three-dimensional representations becomes manifest, supporting the understanding of complex architectures and infrastructures, such as the one under scrutiny.

Presented below are the outcomes obtained from the observation of the 3D model. The analysis was carried out only for the case study. It is worth nothing that this process could be applied to another area, the whole structure or a different asset. The 3D not only facilitated the understanding of this asset but also introduced stimulating issues and insights for further study and research. This highlights the intrinsic potential of a digital object, such as this one, to achieve continuous improvement and enrichment. This, in turn, presents opportunities for deepening, for instance via updates and enrichment of the model with new information.

The first observations concern Torre della Colubrina. They address the mutual position of the three casemates and their relationship with the walking level of Parco Sempione. In Figure 5.3.3.a, the three rooms pre-

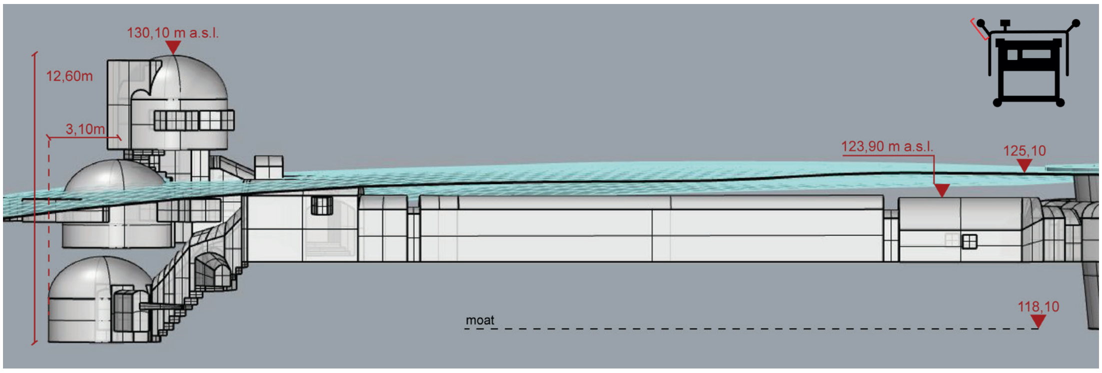


Figure 5.3.3.a Side view of the model of the underground spaces of Torre della Colubrina.

sent are staggered from the vertical axis of the structure. The casemate with the higher elevation has a misalignment of 3,10 metres compared to the lower one. Questions arise regarding this architectural and wartime choice.
Considering a hypothetical diameter of the tower, derived from the depth of the slits detected by laser recordings (Figure 5.3.3.b), it is possible to think about the presence of an additional environment or structure. The massive volume, which would otherwise be solid masonry, supports this theory. These assumptions, made on the survey material and information included in historical documents, might become a starting point for further studies or an important notion when working on the surrounding terrain. Leonardo Da Vinci, in some of his drawings (Figure 5.3.3.c), projected "secret" ascent systems within the wall mass of defensive towers, similar to Torre della Colubrina in terms of

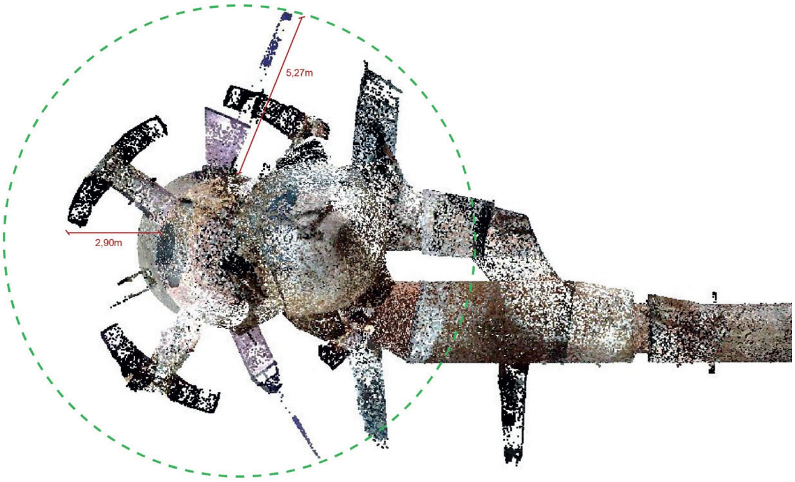


Figure 5.3.3.b Top view of the point cloud of Torre della Colubrina and indication of the hypothetical diameter.

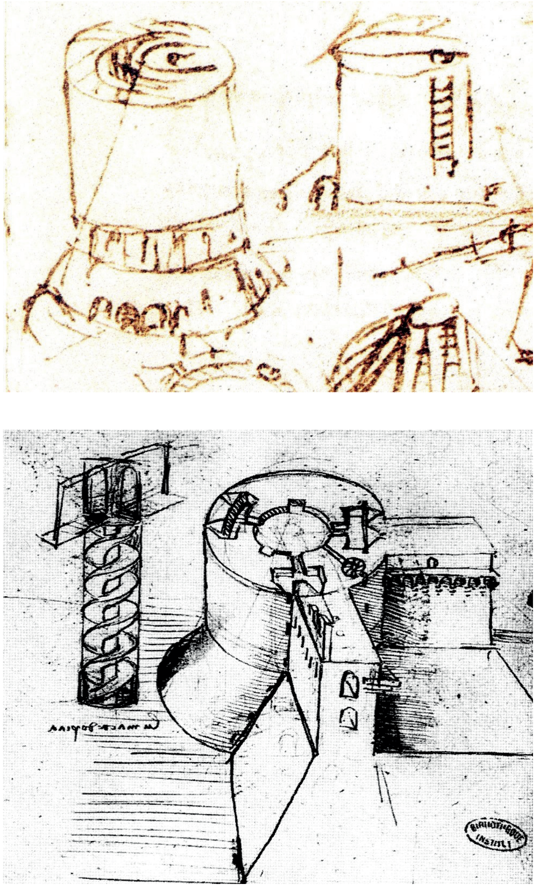


Figure 5.3.3.c Drawings bearing 'snail' scales. Leonardo Da Vinci, *Codice Madrid II, f. 37r.* and *Manoscritto B, f. 69 r.*)

space organisation and diameter.
Finally, again from Figure 5.3.3.a, it is possible to observe the relationship between the infrastructure of the Ghirlanda and the ground level. The proposed view reiterates and clarifies how much of the tower structure is above ground. It would be possible, with a survey specifically aimed at describing the terrain, to improve the precision level of the information could be even more precise, especially considering that using the surface from DTM the entire third casemate is above ground level, having a height of 4,55 metres (Figure 5.3.3.d).
Several pieces of evidence suggest other ruins of the tower beneath the surface of the Milanese park, extending beyond the planimetric boundaries of what is visible today. The aspect of the remaining masonry supports this observation because it certainly does not appear as an external finish of a facade (Figure 5.5.1.b). The 3D model suggests that this could be identified with simple non-invasive investigations or even discover what heritage could be unearthed within the park. From the point of view of the management of the built environment, this visualisation also supports a series of activities in these areas, from tree planting to possible underground interventions.

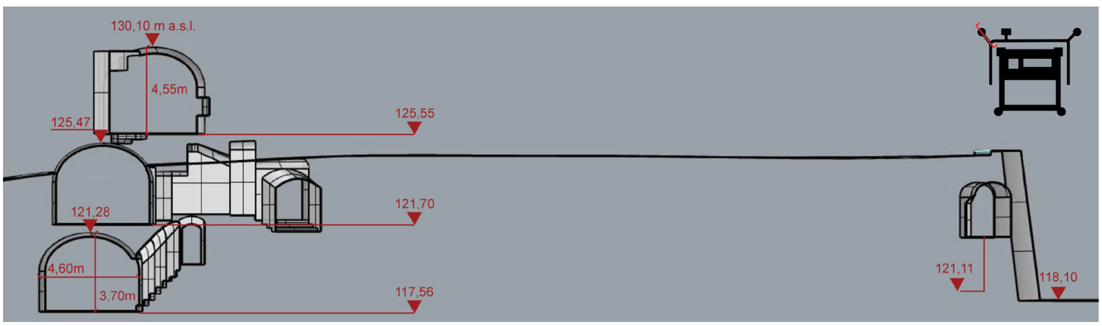


Figure 5.3.3.d Longitudinal section of the model of Torre della Colubrina (through the centre of the casemates).

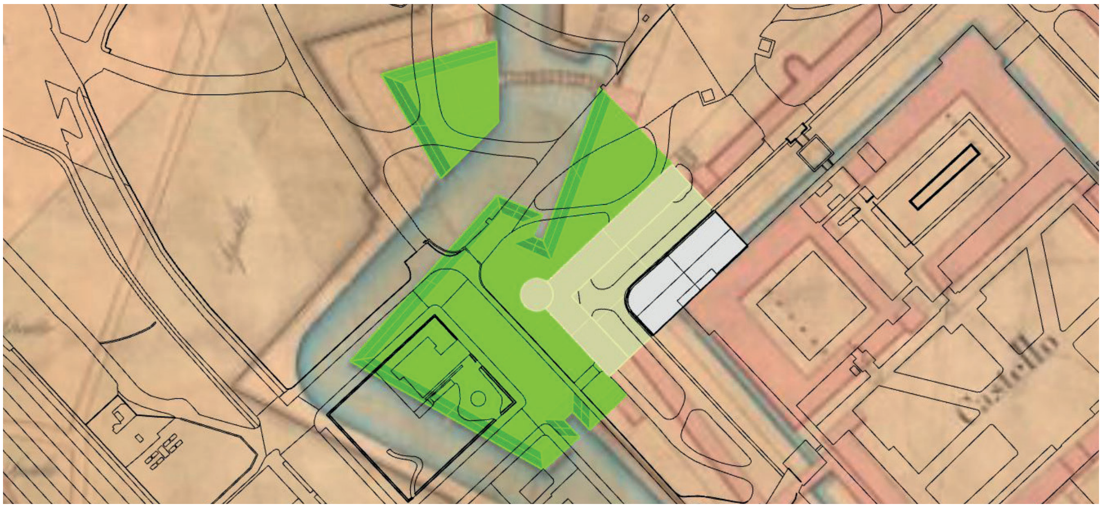


Figure 5.3.3.e Zenith view of the Spanish Bastions model (in green), superimposed on the Teresian Cadastre of 1751 and the DBT of the area.

Figure 5.3.3.f Spanish ramparts unearthed during excavations for the new pedestrianisation project of Piazza Castello. Photo from the website https://blog.urbanfile.org/category/milano/.

A second point concerns the architectural structures that are no longer visible as they were partly destroyed over the centuries with the succession of dominations. At this juncture, the analysis focused on the bastions of the Spanish era. Observing the DBT (Topographic Database) of the present state and the volumes in the model, reconstructed on the documentation, it is immediate to wonder how much of these structures are still present below the ground level of Parco Sempione or the neighbouring streets (Figure 5.3.3.e). A suggestion is given by the recent excavations carried out on the opposite side of the castle, in the context of the works for the new pedestrian area of Piazza Castello. Here the bulwarks were brought to light, lying a few centimetres below the urban green (Figure 5.3.3.f).

Another area observed was the covered walkway of the Ghirlanda, using transversal and longitudinal sections. The three-dimensional restitution in Rhinoceros and the point clouds made it possible to analyse the relationship between the main central part of the castle and the trajectory of the walkway, both in terms of profile and from the point of view of elevation and slope (Figure 5.3.3.g).

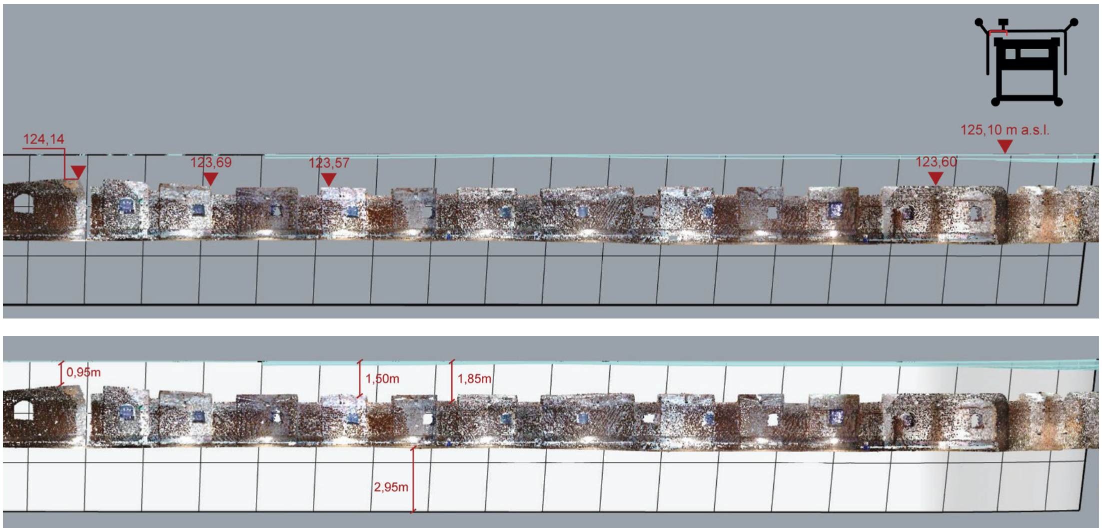


Figure 5.3.3.g Longitudinal sections of the counterscarp tunnel (point cloud and 3D model).

In the analysed section, variations in route height are easily visible. This also results in a varying thickness between the extrados of the vaults and the level of Parco Sempione with a difference of 0,50- 0,55 metres that creates a sort of hollow. The height of the floor level of the Ghirlanda, on the other hand, is constant, thus excluding the subsidence of the structure. This information can be precious for maintenance or safety, for instance the requested minimum heights to permit touristic use.
Observing the lower part of Figure 5.3.3.g, where the point cloud of the moat is in transparency, the distance between the floor level of the counterscarp path and the base of the moat is approximately three metres. Originally it was much deeper, at least five metres more than today. The height of the curtain wall was much greater than now. That generates immediate curiosity to discover if and what other structures are present below the counterscarp pathway and whether they can be compared with what is reported in the historical sources about the art of warfare in those centuries (Figure 5.3.3.h).
As already hypothesised above, there might exist a second counterscarp tunnel. The first version of the 3D has this hypothetical element. Nevertheless, the model reveals situations that contradict, or at least revise, the hypothesis itself. Within it, the second path was placed at a plausible height.
Considering the original depth of the moat and the position of the available walkway, its keystone at 119,10 m a.s.l. is two metres

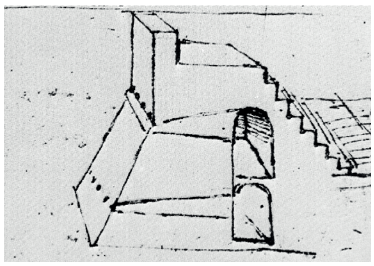


Figure 5.3.3.h Curtain wall with two tiers of casemates. Leonardo Da Vinci, *Manoscritto B, f. 69 r.*).

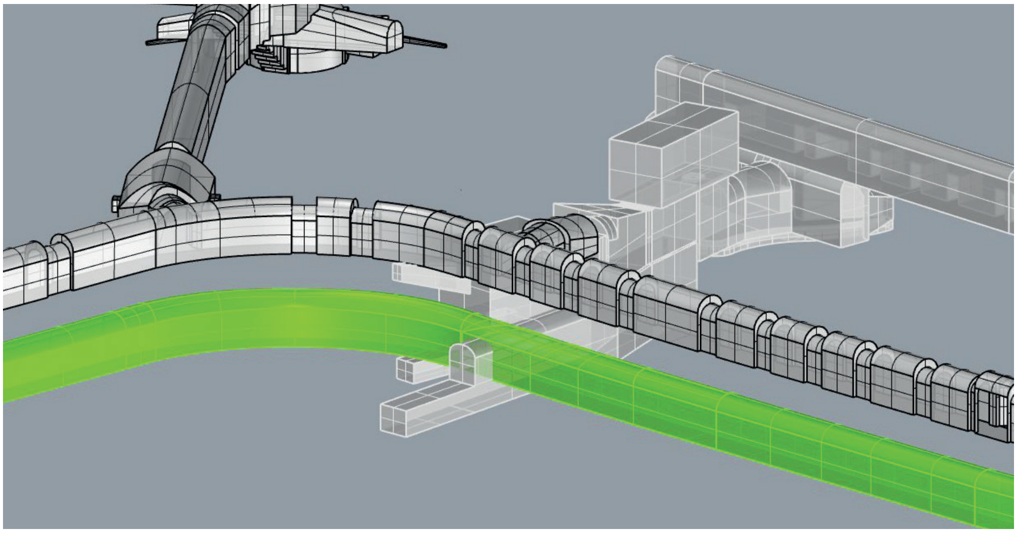


Figure 5.3.3.i View of the intersection between the Casamatta Celestino and the lower counterscarp tunnel (in green).

below its current walking level. At this elevation, it would intercept other known and currently walkable structures, such as the Casamatta Celestino (Figure 5.3.3.i). Therefore, this second infrastructure should be below, descending over 115,20 m a.s.l., the altitude of the canal coming out of the Casamatta itself.

A further issue concerns some existing elements, documented by traditional surveys, and their spatial relations. The relation between the surfaces of the moat and the canal exiting, in the direction of Cairoli, from the Casamatta Celestino, is unclear. It should be noted that the plan and the wall of the moat have been modelled on the information extracted from the recent digital survey and that the Casamatta complex derives from the 3D re-elaboration of the survey carried out by the SCAM Association (Speleologia Cavità Artificiali Milano), also reported in the book "La Fortezza Celata" by G. Padovan (Figure 5.3.3.l). The model shows that the spaces of the Casamatta Celestino should be visible to a small extent on the wall of the moat (Figure 5.3.3.m), even if only as an imprint on the masonry, which has not been identified on-site. Furthermore, the water infrastructure of the complex should be located between the height of the current moat and the original moat, without lying on the latter, as can be seen in Figure 5.3.3.n.
This information clashes with the functions of the structure. It was one of the two elements designed to bring water to the innermost moat of the fortress. The current altitude indicated by the documentation would have meant having a canal coming out of the moat boundary wall at about one-third of its height (from below). In addition, this choice would have meant dangerously exposing to enemies, whose first operation was to shut off the water to the moats, to facilitate siege operations. Therefore, the

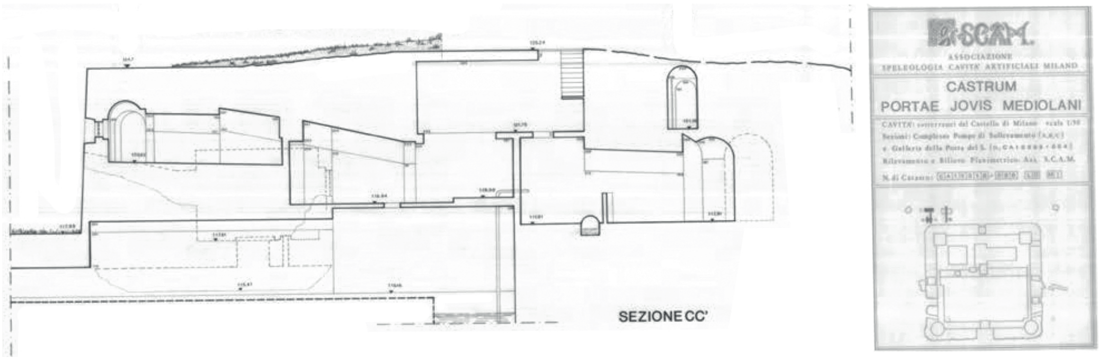


Figure 5.3.3.l Graphic design produced by the SCAM Association (1990 - SCAM Archive). The section covers the rooms of the lifting pumps and the Casamatta Celestino.

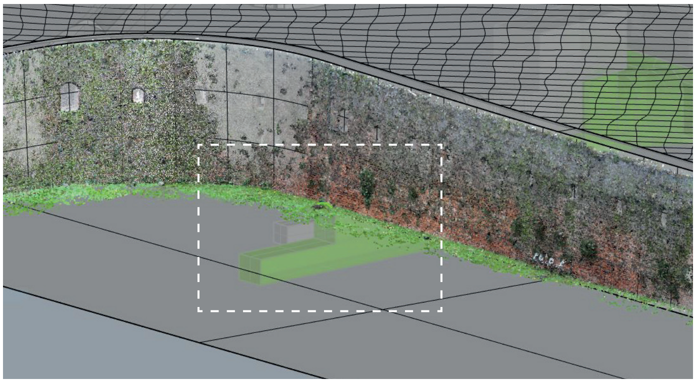


Figure 5.3.3.m Point of intersection between the Casamatta Celestino (in green) and the moat wall (point cloud).

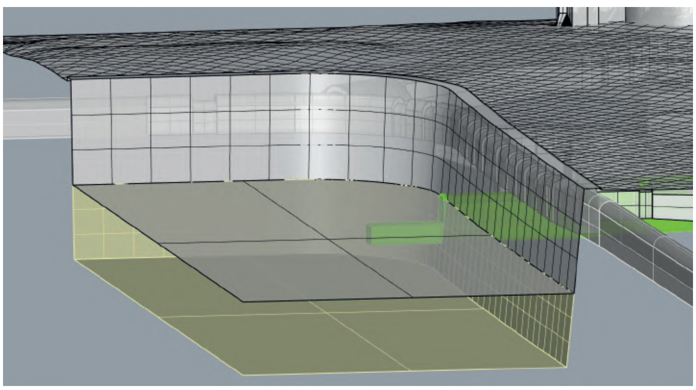


Figure 5.3.3.n Position of the water infrastructure (in green) in relation to the current and original moat plan.

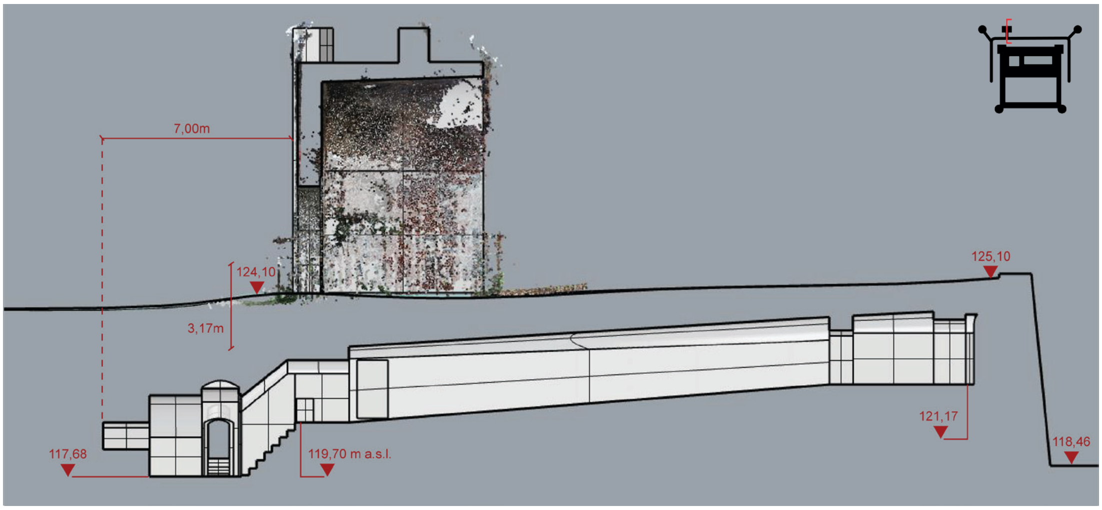


Figure 5.3.3.o Longitudinal section of the 3D model of Porta del Soccorso.

survey data should be verified with further investigations to understand the actual relationship between these elements.

The last element under analysis is Porta del Soccorso. The insight also comprehends the path that connects the latter to the covered road, and the internal stairs system leading to the top. In this case, too, the study of the slopes led to interesting results. The structure behaves very differently from what was observed for the rooms of Torre della Colubrina, with very accentuated slopes, especially in the basement, as in Figure 5.3.3.o. The slope brings the casemate to a lower height than the current moat.
The section also supports the comprehension of what now lies below the park level. The casemate, indeed, goes beyond the perimeter of Porta del Soccorso for 7 metres.
Similarly to Torre della Colubrina, it was also possible to identify a large volume that has not yet been surveyed. Observing the plan in Figure 5.3.3.p, stairs occupy only part of the total cubature (approximately 60-65%), the innermost and adjacent to the external vaulted passage. This simple observation of the plan brings up many questions and interests, related to the discovery of its most hidden and secret structures. It also lays the foundation for planning further surveys and studies. This information is also visible in section (Figure 5.3.3.q). The massive character and possible articulation of the blocks (the surveyed one and the 5,30 metres wide unexamined) are still in doubt.

The 3D model developed with the three layers of data allows the opening up of interesting questions about the architecture investigated but also about its context. Issues emerge about the position of structures, such as the outer wall of the Ghirlanda, beyond which was the second moat. Or even reflections on particular dynamics such as water flows (including meteoric ones).
All this is supported by today's technology offering, which facilitates our study and in-

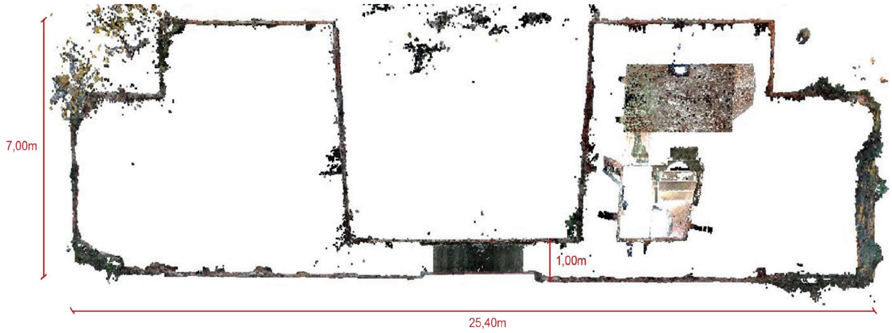


Figure 5.3.3.p Horizontal section of the point cloud of Porta del Soccorso at 129,65 m a.s.l.

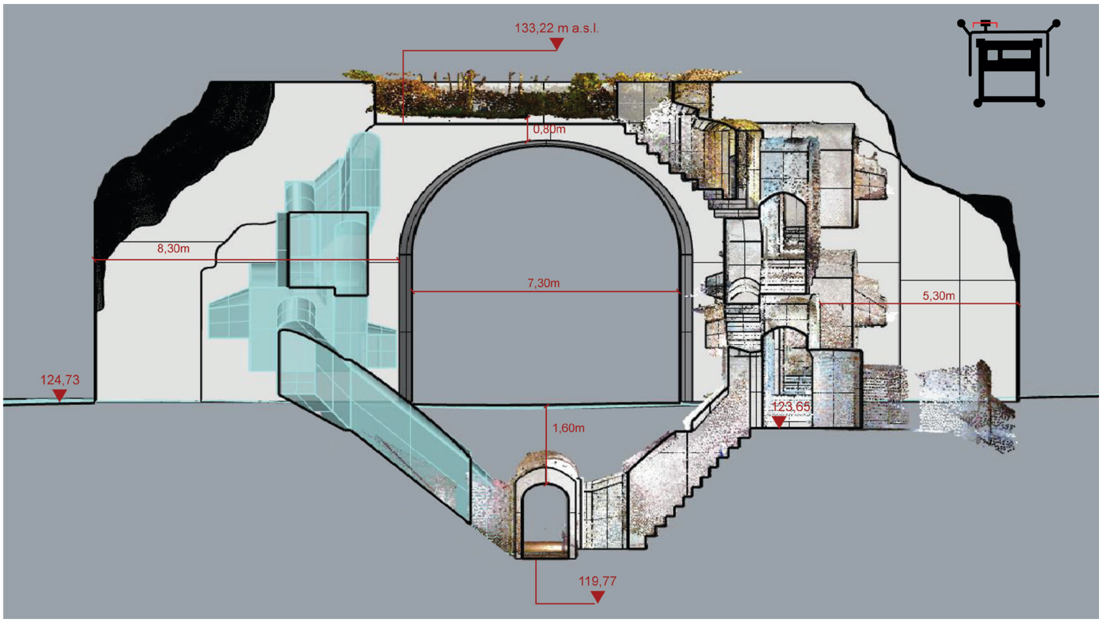


Figure 5.3.3.q Cross-section of Porta del Soccorso.

formation processes.
Modelling software, as seen in this section, allows the analysis and manipulation of the three-dimensional object. All these activities, that can be performed in several software, facilitate reading and deepening the spatial dynamics of structures. In this specific case, it has been used the Section Tools plug-in for Rhinoceros.
Additional inquiries, completed with the use of other techniques (such as georadar), are necessary to support and validate the different hypotheses made. Including this type of activities in the methodology presented in this doctoral work, would result in a cyclical system of continuous updating of

the three-dimensional model. This process would lead to a gradually completer and verified digital twin, gathering new sources and survey data.

05.4 _ Database of the digital twin of the Ghirlanda

The subsequent phase entailed the management of these records and the dataset of information related to the sources and the 3D model. The work involved the structuring of the online storage, the cataloguing of all sources and the formulation of the information system within the 3D in addition to the connection of the 3D environment with the online repository.

The activity started with the arrangement of the information system within the digital twin, utilising the user attribute management possibilities provided by the Rhinoceros software. This built-in capability allows assigning metadata to each object (modelled or imported), in the same way as in GIS software, albeit in a more limited form. Therefore, this framework facilitated the augmentation of the model and the information system, allowing the allocation of information to the volumes and creating links between them and the sources of geometric information.

The initial phase focused on the model's various components, their identification and their association with the sources. For this stage, data insertion was done directly in the Rhinoceros environment, without importing external .txt files as it was done with source importing. The data tables designed for the 3D volumes only partially trace those of the sources and the information that was deemed necessary is less. Figure 5.4.a shows, as an example, the attributes of the volume assumed for the Ghirlanda, which was partially destroyed in the late 1800s.

The first rows are for object identification, primarily utilizing the ID_object as the identifier of the element. Following this, there are classification codes for the object: COD_component, COD_subject and COD_building. To further illustrate this classification system, let's consider the example of Torre della Colubrina. The subject code (COD_subject) refers to the reference structure, the tower itself (as opposed to the Castello Sforzesco for which the identifying code is COD_building). The component code (COD_component) refers to several elements that are individual constituents of the structure. These components are therefore individually identified while being part of the same reference structure. For example, some elements identifiable as "components" are the three casemates or the path connecting them with the counterscarp tunnel. The model's deconstruction allows a more precise association between these and the several model components, giving support in sources management. That is helpful because different objects belonging to the same structure may have been generated from slightly different documents.
Subsequent data in the table are information about the LOGI, the creation date, the last modification and the end date. The last lines are for the input of the source codes used for the development of each 3D object being filed. As a source can refer to multiple

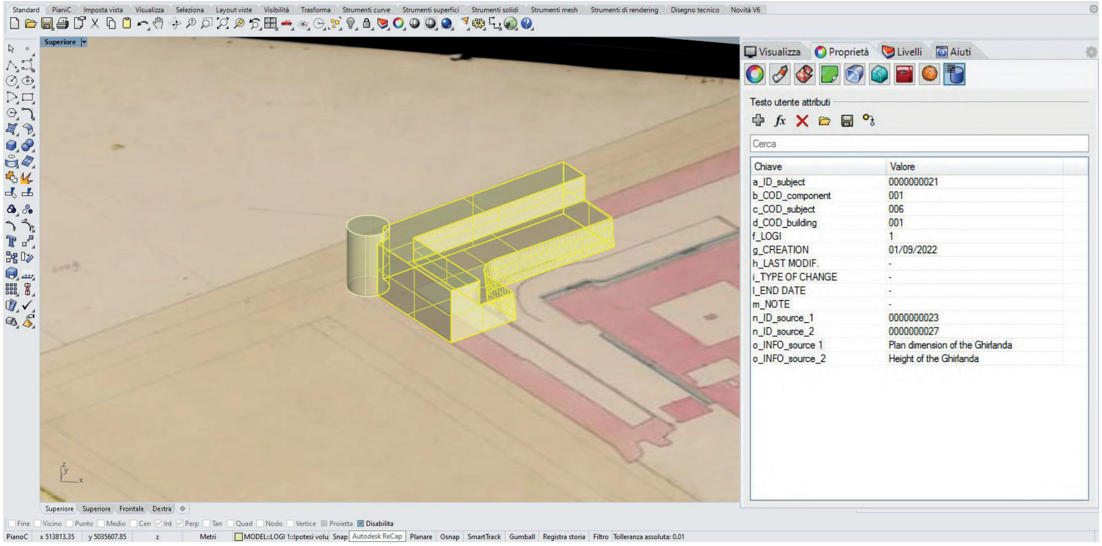


Figure 5.4.a Rhinoceros attribute table for the hypothetical original volume of the Ghirlanda.

elements in the model, a three-dimensional object can be based on different documents.

In order to prevent potential complications in terms of data management, such as the case of selection based on attribute terms in these tables, the rows containing links and notes were therefore placed at the end of the tables. This decision ensured that any variation of key names or in the number of links to the sources would not lead to as many variable slippages of the last two terms (links and notes) within alphabetical indexing.

This was also made possible by changing the position of these terms, all the rest of the rows remain, instead, unaltered. In addition, all rows linking the sources and the model had the same letter.

This operation of consistent naming across all rows linking sources facilitated selection operations even here, as will be explained in the following paragraphs.

Multiple spaces for possible reference links have been provided. While testing the structure in Rhinoceros, it was necessary to make some adjustments to the last rows. This was due to the way the software recognises as an attribute the entire text contained in the cell but not the individual elements that compose it. For this reason, it was not adequate to propose a single row for the ID_subject of the reference sources. Each code occupies its own row, allowing the software to recognise all of them. This change, therefore, enables the selection within the model of all the volumes that have used a specific source or, vice versa, all the sources that have contributed to the definition of a volume. Achieving this goal would have been challenging if all the IDs were confined in a single table cell. Therefore, splitting the various identification codes into several lines, eased the automatic selection of all those elements (volumes and sources) that have multiple links.

Parallel to these operations carried out on the 3D elements, the work also involved the sources, completing the structure of the information system.
As described in Chapter 3, the source management approach also encompassed an online database to host all reference material, both primary and secondary. This external repository serves as an organised catalogue for all sources used for modelling, accessible whenever it proves necessary to consult the entire set of information used in the development of the digital twin. This external archive is related to 3D through links that are part of the sources' attributes within the modelling environment.
The experimentation activity carried out through the case study was based on OneDrive for Business. This platform facilitated document sharing via links, supporting the proposed method, and with a great amount of cloud storage space (up to 1TB per user). This last characteristic is very important when working with data-intensive elements like point clouds, which might require many GB of storage each.

After creating a dedicated folder and uploading all the sources used for modelling (Appendix A.II), it was necessary to organise all this material.
First of all, the files have been renamed with their ID_object. This renaming allows correspondence with both sources within the model as with information in the cataloguing file (Excel document). The latter completed

ID_object	0000000007	0000000010	0000000011	0000000023	00000000045	0000000048
COD_source	001	001	002	003	004	005
COD_annex	001	002	001	001	001	002
CONTENT	Point cloud of Torre della Colubrina	Point cloud of counterscarp tunnel	Point cloud of the moat	Cadastre of Milan - Castle area	View of the Castello Sforzesco	Plan of the basements of the Ghirlanda
LOGI	3	3	3	1	1	2
NAME_source	Rilievo della Ghirlanda del Castello	Rilievo della Ghirlanda del Castello	Rilievo del fossato del Castello	Catasto Lombardo Veneto	Veuë du Chasteau et de la Citadelle de Milan	Rilievo dei sotterranei del Castello
TYPE	Laser scanner point cloud	Laser scanner point cloud	Photogrammetric point cloud	Cartography	Print	Graphical drawings
AUTHOR	F. Biolo	F. Biolo	F. Biolo	-	S. Israel	SCAM Association
DATE	23/11/2021	23/11/2022	23/11/2023	1881	1600 ca.	1990
LOCATION	DABC - Politecnico di Milano	DABC - Politecnico di Milano	DABC - Politecnico di Milano	Archivio di Stato di Milano	"Achille Bertarelli" print collection, Milan	SCAM archive
COD_cataloging	-	-	-	155100	P.V. p. 2-54	-
ID_mod_1	M_001_001	M_002_001	M_004_001	M_001_005	M_007_001	M_008_001
INFO_1	Geometry of the lower casemate	Geometry of the counterscarp path	Geometry of the moat	Original floor plan of the T. Colunbrina	Height of the bastions	Floor plan of Galleria delle Radici
ID_mod_2	M_001_002	-	-	M_006_001	M_007_002	M_009_001
INFO_2	Geometry of the middle casemate	-	-	Plan dimension of the Ghirlanda	Height of the bastions	Floor plan of Casamatta Celestino
ID_mod_3	M_001_003	-	-	-	-	M_010_001
INFO_3	Geometry of the upper casemate	-	-	-	-	Floor plan of lift pump rooms
ID_mod_4	M_001_004	-	-	-	-	-
INFO_4	Geometry of the pathway	-	-	-	-	-
ID_mod_5	-	-	-	-	-	-
INFO_5	-	-	-	-	-	-
LINK	http://polimi365-my.sharepoint.com	http://polimi365-my.sharepoint.com	http://polimi365-my.sharepoint.com	http://polimi365-my.sharepoint.com	http://polimi365-my.sharepoint.com	http://polimi365-my.sharepoint.con
NOTE	-	-	-	-	-	-

Figure 5.4.b Extract of the Excel file containing the cataloguing of all resources in the online storage.

the online folder and it aimed at collecting the necessary data for all the sources. This information is analogous to that within the model, to create complete parallelism. Figure 5.4.b shows an excerpt from this document.
It contains all essential information about the sources present in the database, including also their classification codes: COD_source and COD_annex. These show the numerical code assigned to the source and that one indicating the specific part of the reference material. If it consists of a single product, the COD_annex will always be equal to 001. In addition, there is the LOGI of the information and its source. The table then describes the nature and origin of the material. In this section, data such as author, type of reference material, date and others are reported. Another group of rows indicates the volumes modelled on the basis of that reference, reporting their ID_object. The following rows, instead, indicate the specific information used for that three-dimensional object. A source, indeed, may be used in its entirety or may be exploited for precise detail. For example, the file "0000000045" is a print showing a view of the Castello Sforzesco from the countryside but it served only for the height of the bastions, although the subject of this work is much wider. These last indications are not present in the attribute tables of the model's internal sources. This is because the 3D elements, instead, contain the ID of their information references, creating sufficient connections for the system to function. It was also found that this solution optimises the structure of the otherwise excessively long source tables. Finally, the last two rows contain the link to the source on OneDrive and a section for notes. Complementing this file, there is a list of the codes of the modelled element on a separate sheet. This supplementary list clarifies which structures were based on the different sources, as well as provides a reference for the classification of 3D elements.

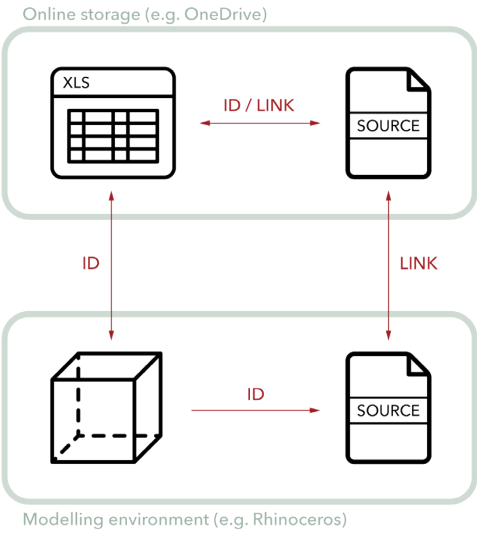


Figure 5.4.c Diagram of relationships between 3D model elements and online storage documents.

The system just exposed (Figure 5.4.c), completed with the sources' attribute table, provides a structured and complete system of geometric information, allowing a solid and continuous comparison between the original data (the sources that contain it) and the 3D model of the architectural asset.

During the digitisation process, the organisation of the online archive is carried out

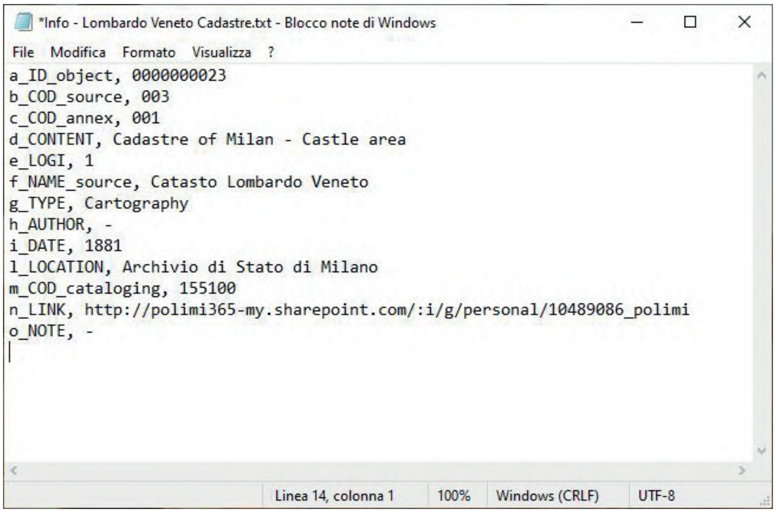


Figure 5.4.d Attribute .txt file to be linked to the Lombardo Veneto Cadastre (source) within the model.

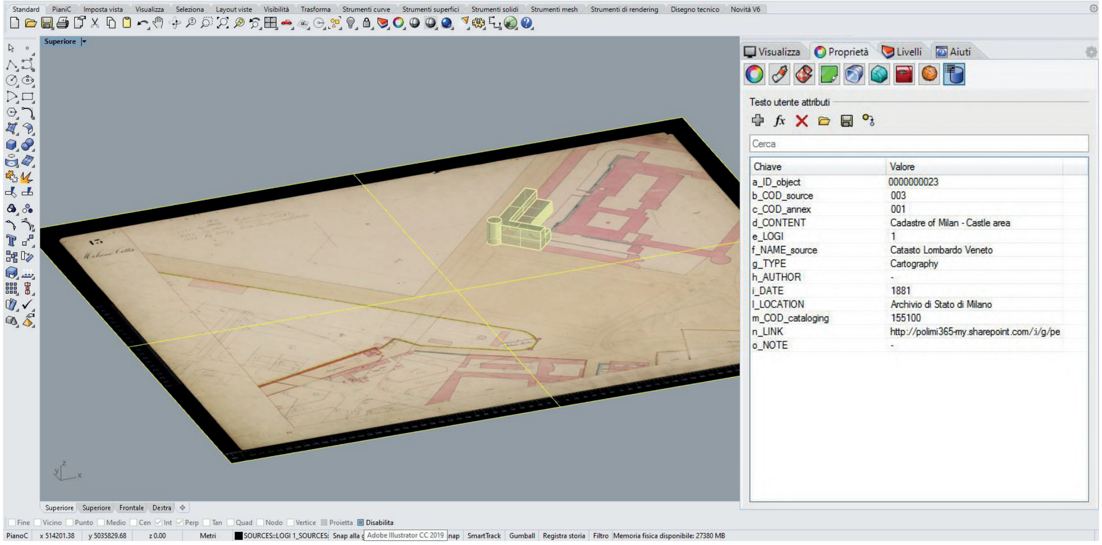


Figure 5.4.e Rhinoceros attribute table for the Lombardo Veneto Cadastre extract.

simultaneously with the management of sources and their data within the modelling environment.
Starting from this overall file, it was then simple to arrange many .txt files (with comma-delimited values). They contained keys and attributes for each source. Thanks to these .txt files, it was then possible to enrich the sources attribute within the model. Rhinoceros allows attributes to be loaded through .txt or .csv files, speeding up the process. The imported .txt files look like the ones in Figure 5.4.d.
Notably, the setup in this illustration slightly differs from that presented in Figure 5.4.a as rows have alphabetical indexing. This alignment serves to maintain the established order. Rhinoceros forces the reorganisation of the attributes so that the table keys are in alphabetical order. Thus, in this way, the data remain in the order chosen and are also present in the online filing.
The result of the .txt file import is shown in Figure 5.4.e, with the example featuring the Lombardo Veneto Cadastre of 1881.

By arranging the source information within the digital environment of the model, the information system and the digital twin are effectively completed.

The activity carried out on the Castello Sforzesco about the sources management, the information system framework, and linkage with the model was very interesting. It yielded several reflections and implementations of the initial hypothesised structure. The latter underwent some purely operational changes to adapt the initial (and more theoretical) layout to the chosen software and its specific characteristics. Nevertheless, the test confirmed the validity and effectiveness of the method described in Chapter 3. However, it is not intended that studies on the framework are exhaustive. It would be very useful, with future insights, to test this system with other cloud storage systems and with different modelling software. These tests would be functional in modifying the current set-up in favour of a version responsive to the needs of more tools and applications on which to base the process of digitising and managing sources and information.

05.5 _ The first update of the 3D model

This chapter, along with the subsequent one, focuses on testing the last stage of the digitisation process. It coincides with the gathering of new geometric information and the consequent updating of the three-dimensional model. This phase can sometimes be time consuming, especially when dealing with smaller architectures or assets of lesser impact within its territory and the historical-social dynamics. In the case of the Castello Sforzesco and more precisely within the project stipulated with its Superintendence body, there was the opportunity to carry out further surveys and in-depth studies. These endeavours offered a chance to finalise the workflow by taking advantage of the availability of this new data.

The following pages, including Chapter 5.6, represent a kind of ultimate validation of the approach proposed for the digitisation of the geometric knowledge of architectural cultural heritage.

It includes the report on the second survey campaign that has been carried out. This campaign entailed a laser scanner survey of the above-ground elements that have not been measured yet, specifically the external surface of the ruin of Torre della Colubrina and the terrain of the studied area. Subsequently, section 5.5.2 delves into the process of updating the 3D model, verifying the feasibility of the process and reporting eventual issues and reflections of particular interest inherent to the method used.

05.5.1 _ The second survey campaign: the land shape and the ruins of Torre della Colubrina

Upon developed the first version of the 3D model, it became evident that a second survey campaign was necessary.
In particular, the purpose of this second phase was to complete the survey of the elements within Parco Sempione, namely the ruins of Torre della Colubrina. As described in previous sections and clearly evident below, the development of the model of the information available online (DTM) for ground surface digitisation proved to be suboptimal. For this reason, the additional work also included a series of scans to complete the terrain shape data, allowing the development of a more accurate object.
The survey encompassed these two elements, with scans concentrated between Torre della Colubrina up to circumnavigate Porta del Soccorso, to cover the external surface corresponding to the underground area investigated in the previous phase.

Laser scanner technology, employing the FARO CAM2 laser as the instrument and FARO SCENE as the software, was used for the survey. There were 21 scans, and their positions in Parco Sempione are shown in Figure 5.5.1.a. As will be discussed in more detail later, the records were conceived in two autonomous blocks, one linked to the area of the tower and a second one further to the east and, therefore, related to Porta

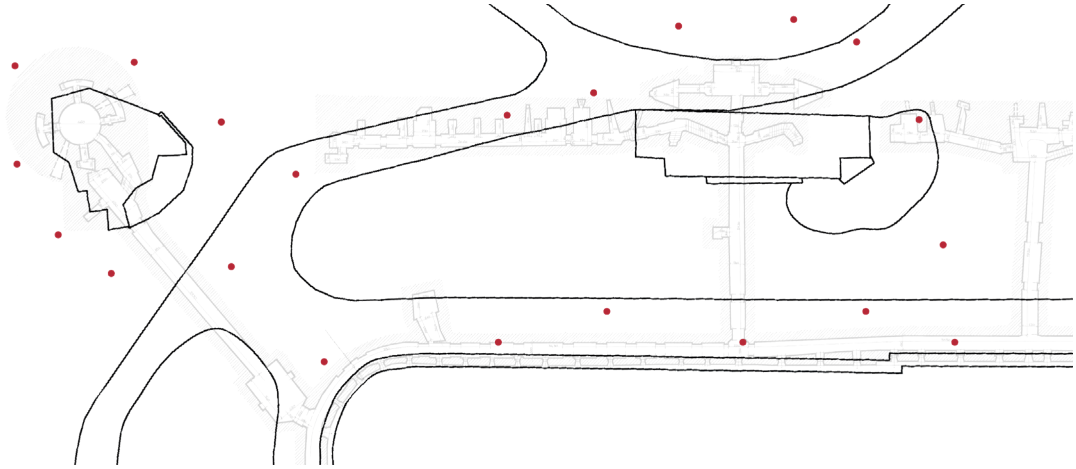


Figure 5.5.1.a Scheme of scanning points related to the second survey campaign.

del Soccorso. The acquisition process took approximately half a day of work and involved the use of special spheres and traditional checkerboard targets for alignment and scene connection.
Similar to the previous survey, topographical data enabled the positioning of the processed product within the appropriate coordinate system. This operation utilised some of the vertices of the polygonal network created for the first survey campaign, the monograph of which is reported in Appendix A.III.I. The text will simply recall this information since topographical measurements have already been described on the previous pages. To collimate the points useful for the orientation of the point cloud, the station with the theodolite was at a single vertex, the 200 (S12 in the name of the 2002 relief), aligning with the 300 (S1) positioned at the same altitude. Due to its central position in the investigated area, it was sufficient for the collimation of a suitable number of points. Appendices A.III.II.b and A.III.III.b, respectively, report the field booklet and the celerimetric computation of the topographic survey.
Each scan consisted of around 28 million points. While for outdoor surveys often are preferred denser point clouds, it was decided to operate in this way for two reasons. Where it was necessary to detect an architectural artefact (Torre della Colubrina), due to the characteristics of the area, the survey position has always been close to the element itself. The second reason arises from the very purpose of the activity, obtaining the necessary data for terrain modelling.
This kind of operation does not require a point cloud as dense as those for building knowledge. On the contrary, it was necessary to thin out the product before the modelling phase. Considering these two factors, it was deemed sufficient to operate with such settings of the laser scanner, which also detected the RGB data.

As already mentioned, the survey project led to two groups of autonomous scans, processed separately. Appendix A.III.IV.c shows the diagram with the subdivision of the scans and the screenshots from the

software with the information on process deviation. The organisation of the survey stems from the nature of the place. It was preferred to circumscribe the survey areas to better manage the reference elements, such as spheres and checkerboards, and their positions within the scans.
The acquisitions from n. 000 to n. 010 focused on the ruins of Torre della Colubrina and the adjacent land, with a deviation for this first block of 5,84 mm. The second group of scans, which covered the easternmost portion, handled scans from no. 012 to no. 023, with a final error of 5,98 mm. The resulting point clouds are in the same (global) reference system as those obtained in

Figure 5.5.1.b Point cloud of the ruins of Torre della Colubrina.

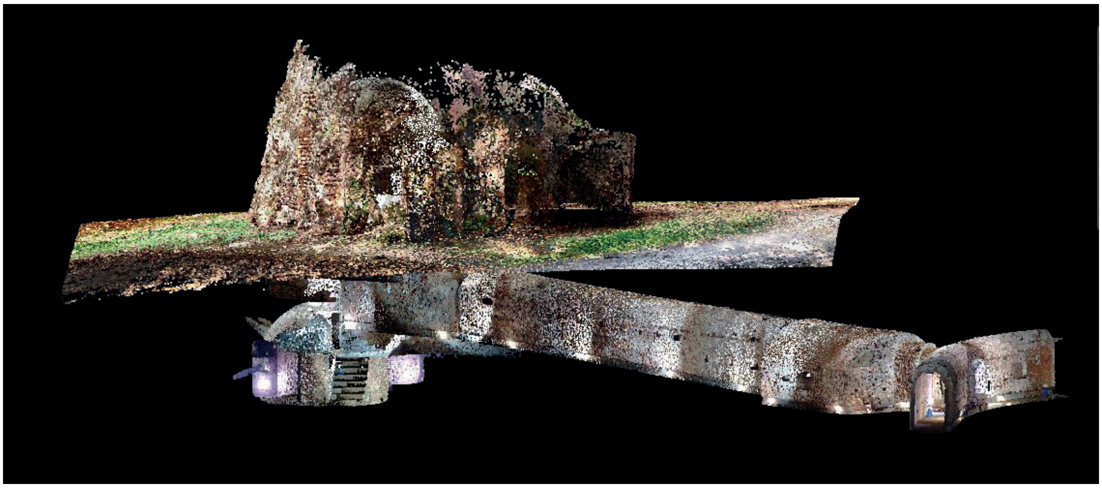


Figure 5.5.1.c Position of the ruins of Torre della Colubrina in relation to the underground apparatus.

the first survey campaign, thanks to the topographic measurements carried out and their inclusion into FARO SCENE software during the processing phases of laser scanner recordings.

The result of the work consists of three point clouds. The first represents the external volume of Torre della Colubrina (Figure 5.5.1.b), obtained from the first block of scans by purifying the initial cloud of unnecessary elements, such as all the surrounding terrain. As can be seen in Figure 5.5.1.c, it is correctly above the three casemates, once the point cloud has been imported into Autodesk AutoCAD environment.
The other two point clouds are those of the terrain. In order to obtain the appropriate data for the modelling phase it had been necessary to carry out some extra steps in addition to the usual processing, leaving only the points referring to the ground. For this reason, the work involved a substantial cleaning of the point clouds, taking advantage of the functionality of Cloud Compare software. This tool is specific for the management and manipulation of point clouds. Once the file, exported from FARO SCENE, was opened, the point clouds looked as in Figure 5.5.1.d.

The resulting point clouds still included the vegetation and the surrounding elements. Cloud Compare allowed a thorough cleaning of files using the "Cross section" command, making it possible to delete excess points, section by section (Corradeghini, 2018). The first step involved merging the scans, still divided in the file, using the "Merge" command. Once a single scan was obtained, the command "Cross section" was applied.
The sectioning system was rotated so that it was parallel to the area-defining elements.

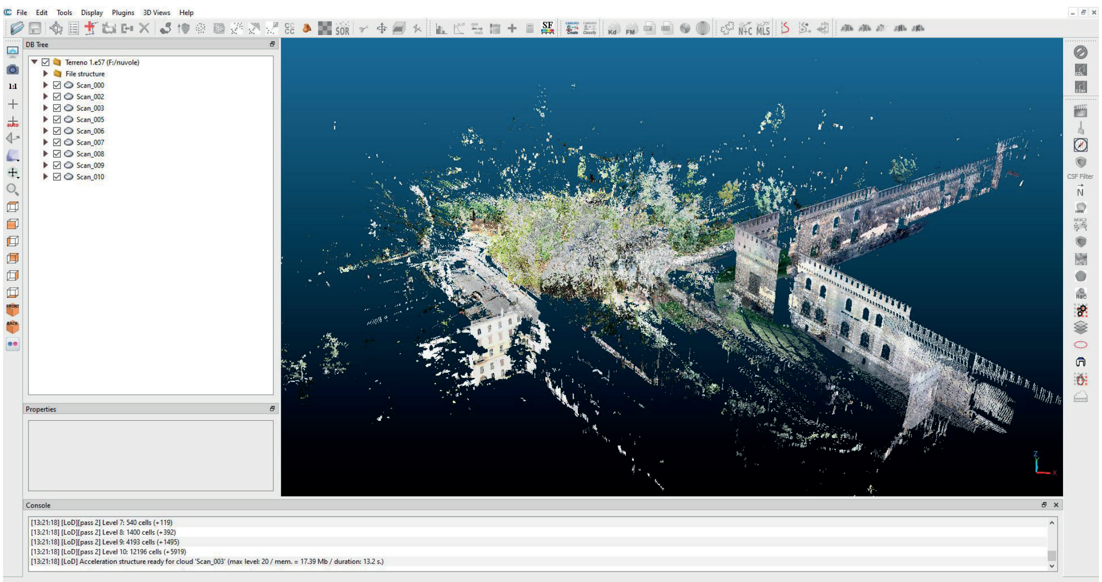


Figure 5.5.1.d One of the terrain point clouds within Cloud Compare software.

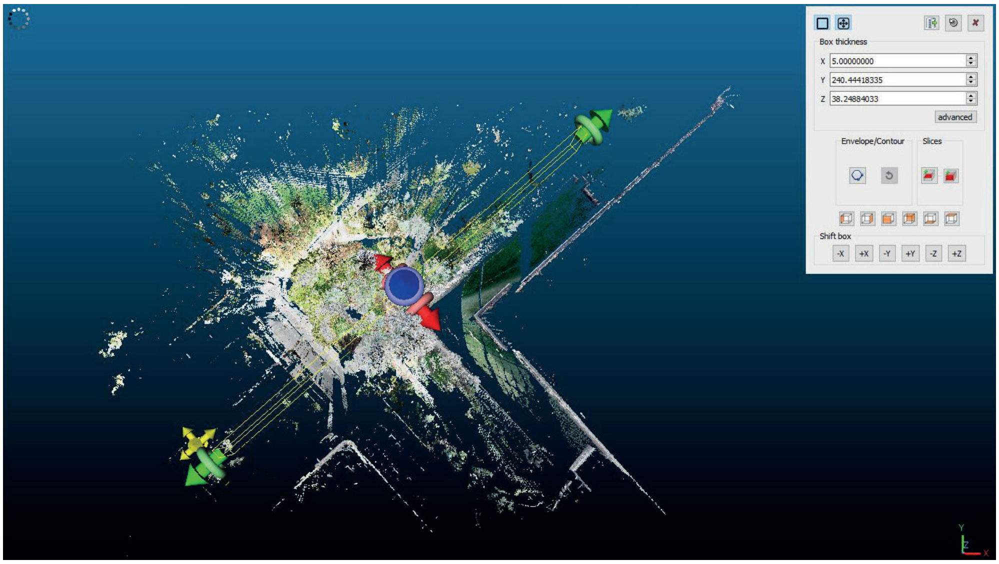


Figure 5.5.1.e Application of the “Cross section” command.

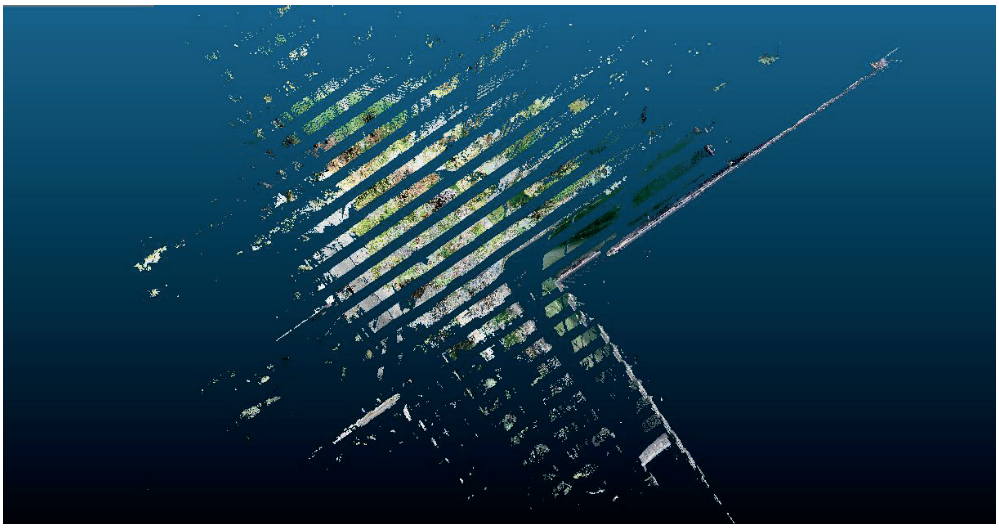


Figure 5.5.1.f View of some sections of the point cloud, obtained with “Cross section” command.

The functionality also required the choice of section thickness, which was set to 5,00 metres (Figure 5.5.1.e). This value was chosen as a good compromise to obtain a manageable number of sections and to allow proper cleaning of the point clouds. The resulting cloud is represented in Figure 5.5.1.f. Cleaning operations involved each slice,

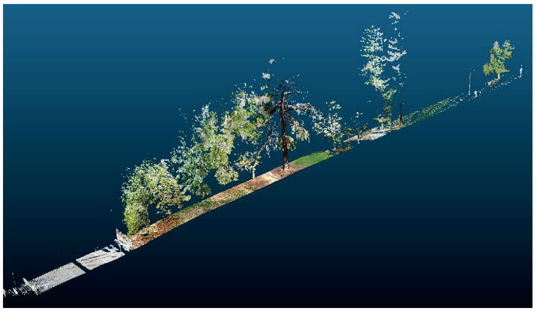


Figure 5.5.1.g View of a section of the point cloud, before and after cleaning.

working meticulously on all the points not forming part of the ground surface. Figure 5.5.1.g shows the comparison between a section before and after treatment.
At the end of this operation, the various portions were brought together into a single point cloud, thus obtaining the result shown in Figure 5.5.1.h. It was saved in .E57 format for use in Rhinoceros software.

05.5.2 _ The development of the new three-dimensional elements

As mentioned in the previous section, the revised version of the castle model included the last visible above-ground element and the updated landform. With the new survey data, the model was expanded.
These pages describe the modelling and updating phases, as well as considerations of the product's potential.

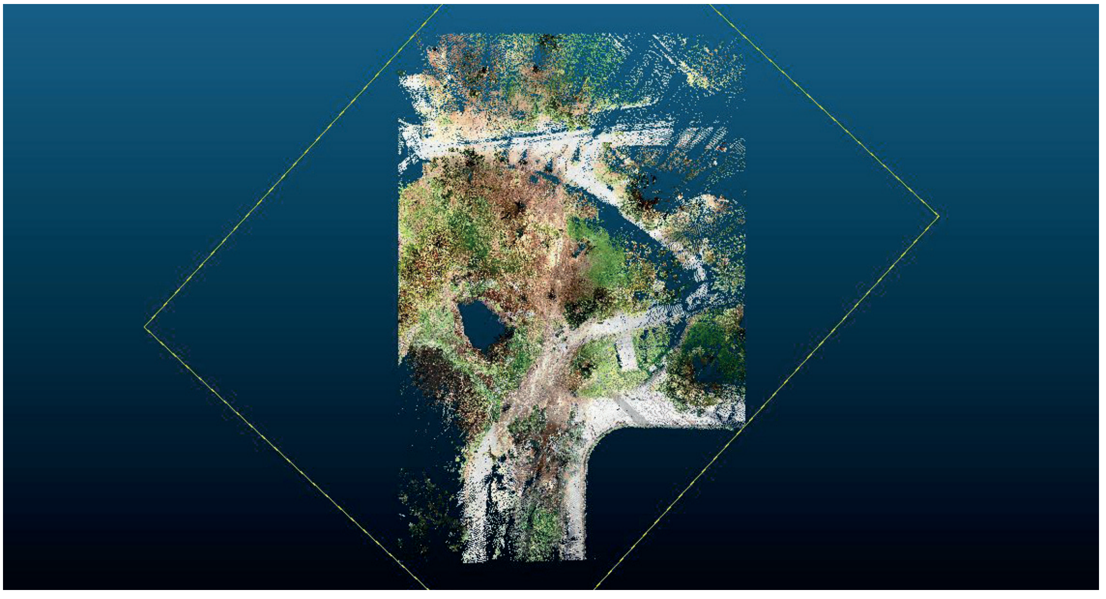
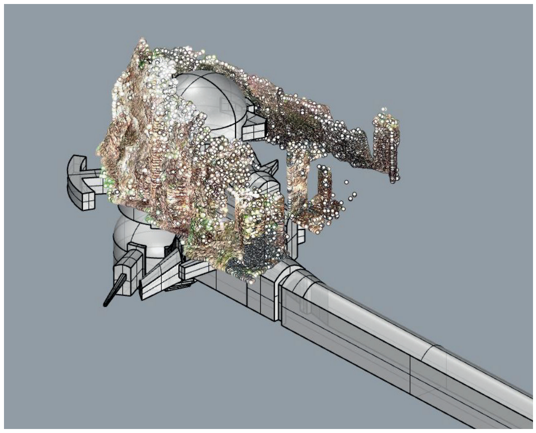


Figure 5.5.1.h Zenith view of the final result, the cloud shows only the points on the ground surface.

As described in Chapter 5.5.1, the second survey campaign involved the above-ground ruins of Torre della Colubrina. This structure had not been investigated at the previous stage. For this reason, measuring the ground form proved to be an opportunity to complete the scanning of the architectural elements of the site.
Similarly to the other point clouds, the process began with a contained lightening of the data. This operation allows to make data more manageable within the various software, without losing the necessary information for a complete and exhaustive understanding of the subject and its characteristics. Given the delicate joints with the casemates below, the first step was to verify the relative position of the cloud to the others, especially the ones relating to the underground spaces of the tower. This verification process was conducted within the Rhinoceros environment, to compare the data both with the other reference clouds and the previously modelled volumes. The outcome, as depicted in Figure 5.5.2.a, demonstrate the precise alignment of the survey data both in an absolute and relative way. Further verification was carried out by superimposing the digitised volume with the perimeters proposed by the DBT (Topographic Database), which confirmed the accurate alignment. This first verification demonstrates the potential offered by today's survey products, especially in combination with a proper topographical basis and systematic management of reference systems.
The modelling phase was not straightforward due to the irregularities of the object. Only a few ruins of the original vertical structure remain visible, and it shows only some intact or at least recognisable elements and surfaces. Most of the exterior, indeed, is the result of the demolition



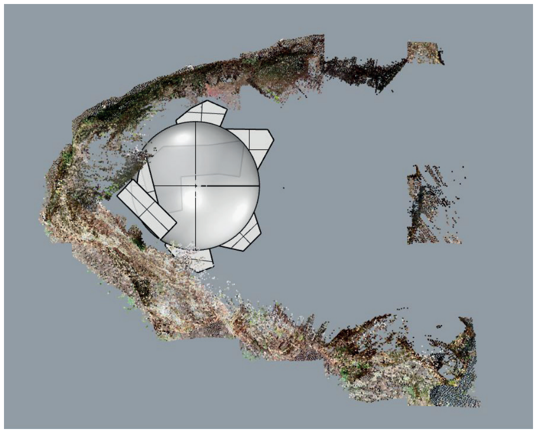


Figure 5.5.2.a Verification of the position of the point cloud compared to the undergrounds of Torre della Colubrina.

wanted by architect L. Beltrami during the castle's restoration in the late 1800s. The proposed approach aims to develop a digital twin capable of supporting the user in the knowledge and understanding of the spatial dynamics of complex architectures. However, given the complexity of the element under analysis, the operations mediated the need for an accurate representation of the current state with the optimisation of the modelling process. To model this sha-

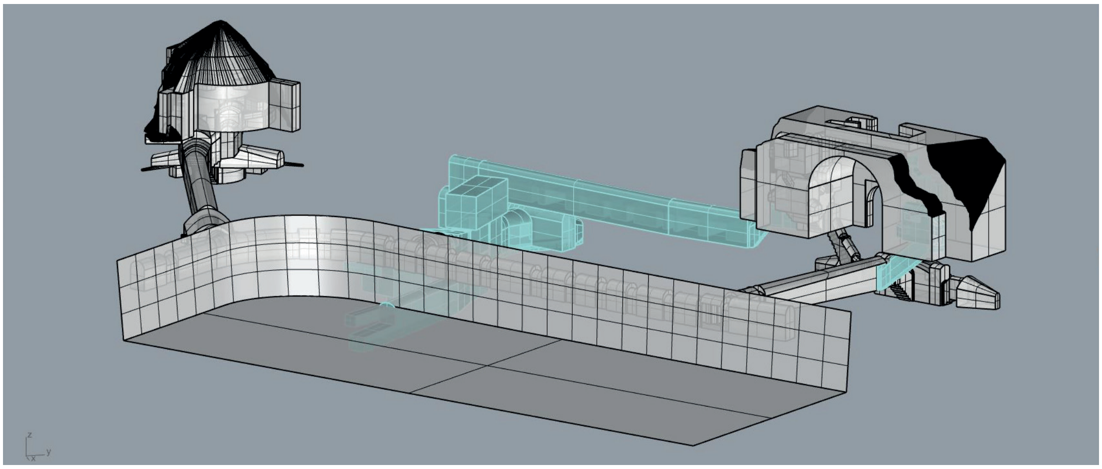


Figure 5.5.2.b View of the exterior of the tower in the overall 3D model.

peless volume, the work started from the development, in Rhinoceros software, of the few portions that were traceable to clear and preserved geometries, working directly on the point cloud. It was then necessary to visualise multiple horizontal sections of the cloud at different heights for completing the surface. This made it possible to extract perimeters on which to base the vertical development of the wall. The procedure required the use of Autodesk AutoCAD, to import these curves into the modelling software when completed. The different curves were then connected with surfaces. By completing the overlapping horizontal bands with multiple surfaces for each level, it was possible to respect and adapt the model more closely to the morphological variations that the structure has along its perimeter. Figure 5.5.2.b shows the new object within the complete model.

The obtained result serves as another important example of how a digital three-dimensional object can significantly enhance the understanding of complex and intricate situations. This is the case of Figure 5.5.2.c, which shows the relationship between the current configuration of Torre della Colubrina and the hypothetical original volume. This visual representation helps to figure out what may still be present under the grassy surface of Parco Sempione. Its lower part might be preserved, protected by the ground, or there might only be remnants of it, as with the visible volume. Moreover, their mutual position confirms the still recognisable curvilinear portion is the corner caponier, that was placed at the height of the rampart of the Ghirlanda, to control this area. It was not a part of the tower and that is why it protrudes from the yellow volume in the model. The opposite case is the one illustrated by Figure 5.5.2.d. In this case, the tower does not compare with assumed geometries but with widely investigated spaces. This scenario is equally intriguing since it facilitates the quantification of spatial proportions, otherwise challenging to discern (e.g. the thickness of the structure near the upper casemate, where there could be a staircase, as shown in Da Vinci's sketches (Figure 5.3.3.c).

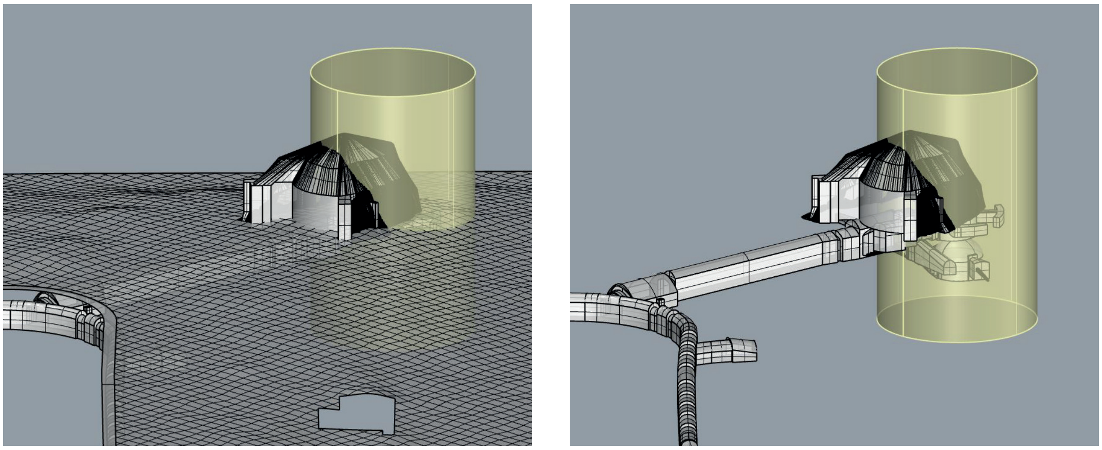


Figure 5.5.2.c Comparison of the current Torre della Colubrina with the original volume. The corner caponier protrudes.

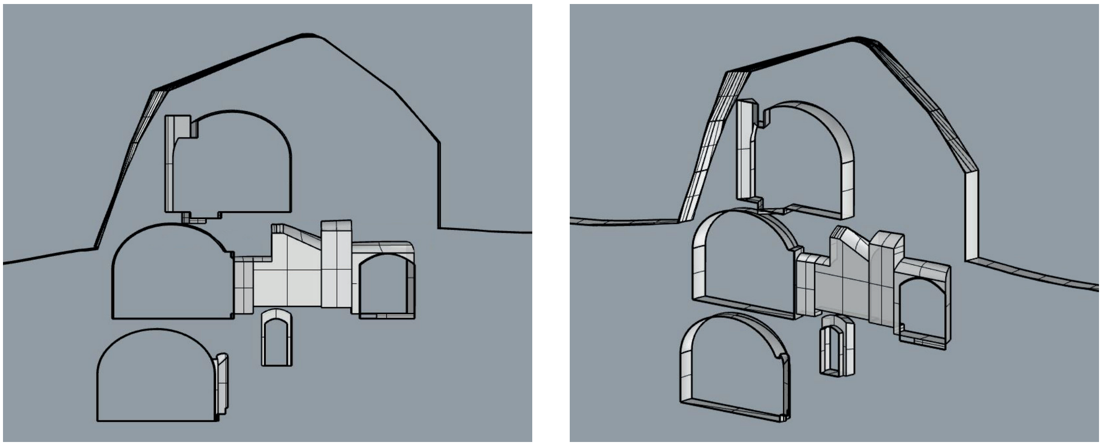


Figure 5.5.2.d Section of the tower model showing the relationships between the elements.

Supported by the presence of the reference sources, linked to the volumes and organised as described above, this object is an alternative and functional way of knowledge and speculation on architectural assets.

In contrast to the aforementioned scenario where the digitisation of the tower was not present yet, the terrain digital model was instead upgraded by taking elements from LOGI 2 to LOGI 3 through the process. The initial version of the surface was derived from a 1x1 metre grid DTM. However, the data in the grid was too sparse to generate an object with the level of accuracy needed to be associated with the highest level of accuracy in the methodological framework. In contrast, the newly acquired geometric

information, provides what is necessary to develop a shape that sufficiently approximates reality, thus enabling the level transition, given the nature of the survey made.
The development of the 3D element partly follows that carried out for its first version. The starting point, instead, was the two clouds obtained from the cleaning process in Cloud Compare. Before migrating to the digital modelling environment, the points were thinned out using the "Subsample" functionality of Cloud Compare, as for other cases described above. Using the "Space" sampling mode, the program generated a new version of clouds characterised by a minimum space between points of 0,20 metres. Working on the shape of the terrain and not on an architectural element, this density was considered sufficient to describe its shape accurately, even where there are circumscribed variations.
This adjustment significantly facilitated interpolation operations within the software, which otherwise could have been challenging to complete with the huge number of starting points.

Once the .E57 files were into Rhinoceros, the work process involved two main steps: exploding the two point clouds to clean them in the overlapping areas and creating a copy (by merging the punctiform elements) to be kept as an internal source.
The 'Patch' command carried out the interpolation of the split points. Several tests were necessary with different combinations of the stiffness index and the subdivisions in the two directions (U and V), to obtain the most accurate result possible. The stiffness value governs the smoothness of the surface. Higher values result in smoother surfaces because when the programme reads high values, once it has calculated an ideal first plane, prevents the element from nearing the generating points. On the other hand, when a value is very low, the system tends to exasperate certain tendencies on the surface. The combination that best describes the shape of that terrain has the following values: subdivisions U, 110; subdivisions V, 110 and stiffness, 15. Figure 5.5.2.e shows the element obtained, which replaced the initial proposal for the terrain shape.

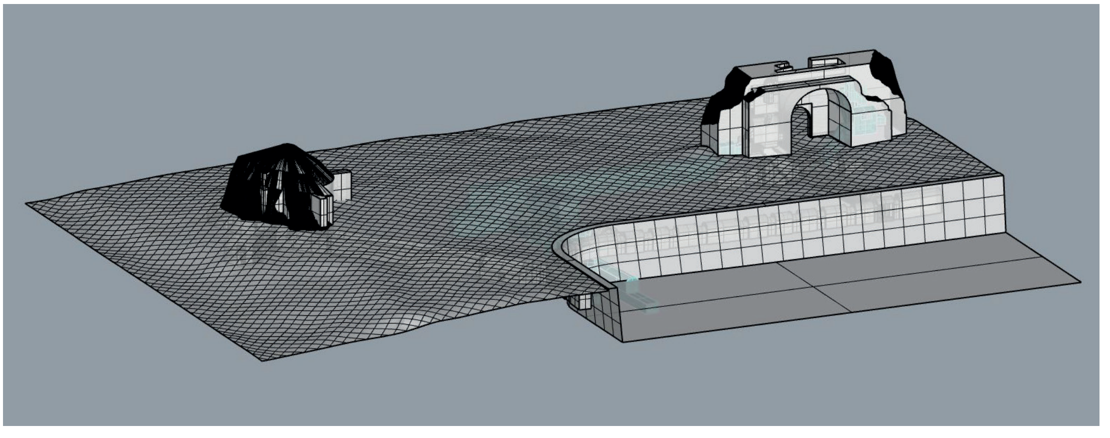


Figure 5.5.2.e View of the model with the new version of the terrain surface, obtained from the laser scanner survey.

In this case of expansion and updating the model, there was no opportunity to test the information system within the 3D environment. It is because the latest records for the new 3D elements are analogues to some of those used for the first version of the model. The information derives from an additional laser scanner survey, whose identification and descriptive data are already well-suited to the structure used.
The structure, obtained from the sources available for the case study (including the surveys carried out), can be furtherly tested and corrected when additional material is acquired.

Despite this, the first test of modifying and extending the system has led to a substantially positive comment. As seen above, the model itself often suggests how to proceed for its completion, highlighting uncertain situations and areas. The flexibility of the system for the collection of geometric information proved to be fundamental for the continuous process of gathering novel knowledge, typical of architectural heritage.

05.6 _ The second update of the 3D model

This section concludes the chapter about the work on the case study by reporting a further data collection process and a second update of the 3D model. As in the case of the previous chapter, the text describes the survey phase in the first sub-chapter. The second one then moves to the 3D transposition of what has been collected in terms of geometric information.

In this third survey campaign the data collection was carried out by an external entity, Codevintec s.r.l, rather than Politecnico di Milano. The company provided the data acquired during this campaign to be integrated in this PhD research.

As previously discussed, these final parts of the chapter, which pertain to the experimentation on the case study, focus on validating the last step of the digital transposition process. This involves the integration of new information within the three-dimensional object, and the updating of both the model and the reference resource system underpinning it.

05.6.1 _ The third survey campaign: the georadar analysis

As mentioned above, the third survey campaign was conducted by Codevintec s.r.l., a private company specialised in providing high-tech instrumentation for land and sea sciences. On the occasion of the 50th anniversary of its foundation, the company expressed the wish to carry out a free survey as a tribute to the city of Milan, where its headquarters are located. This opportunity led to the establishment of a collaborative relationship that allowed further analyses at the Castello Sforzesco. As part of this work, the Politecnico group provided support with its expertise of the site and in the definition of the sensitive areas where the survey should be conducted. The work described in this text corresponds to the initial phase of the campaign, to detail the interest areas. For these, a second survey will be planned in the near future. The new survey will be designed based on the information gathered, in order to carry out a more in-depth survey, supported by the specific instrumentation suited to the specific conditions of the site.

The initial phase of collaboration with Codevintec s.r.l., led by Ing. Maurizio Porcu, focused on identifying the areas for the survey, based on the data collected in the previous stages, the created model of the castle and the several questions emerged concerning the structure of the castle and the apparatus of the Ghirlanda. Following this first visit to the spaces, Ing. Porcu was able to verify the proposals, thus defining a program for the survey. Most of the issues dealt with the verification of underground structures that had only been hypothesised or were no longer visible, due to destruction and modifications. To investigate these issues and to map the area, georadar instru-

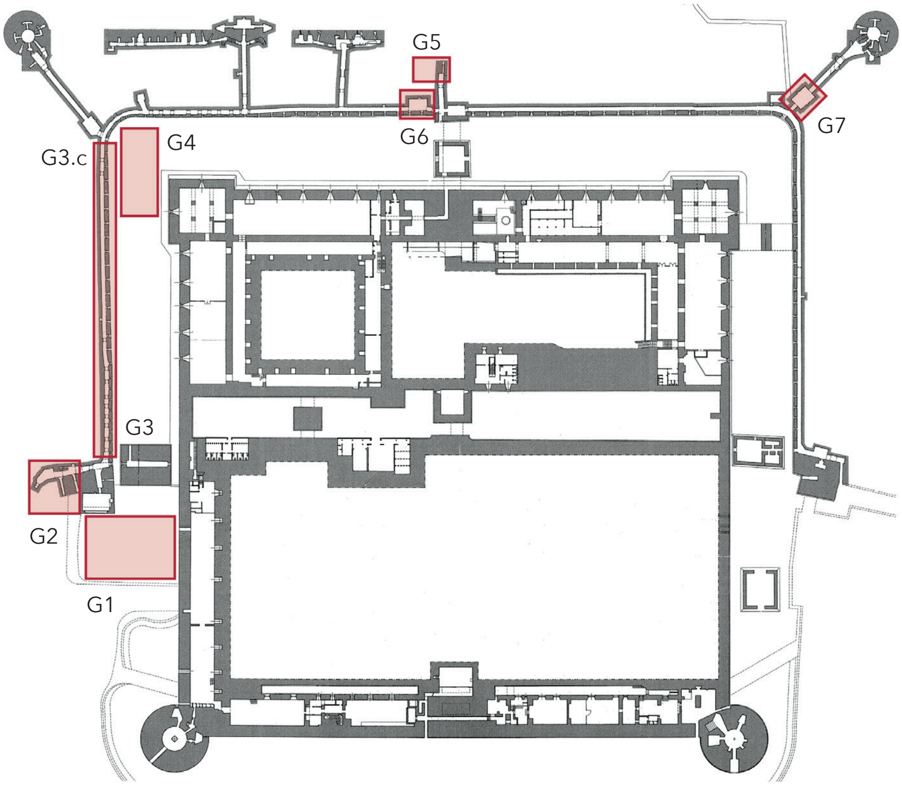


Figure 5.6.1.a Scheme of the areas analysed during the survey with georadar technology.

mentation was employed (Regli et al., 2002; Tomecka-Suchoń, 2012; Barba et al., 2018; Welc et al., 2022). Due to its expeditious nature, the activity covered many sites related to the Ghirlanda. Figure 5.6.1.a shows the zones, studied with this instrumentation, that showed attractive responses. Specifically, the instruments used were GSSI UtilityScan RLT3 and UtilityScan 200 HS. The two georadars are systems equipped respectively with 350 MHz and 200 MHz antennas, both with HyperStacking technology. This allowed effective investigations within the underground spaces, where the thicknesses of the structures are relatively small, as well as extensive external analysis when needed.

In cases where the sizeable thickness of the soil or the conditions of the ground (greater conductivity or heterogeneity of the same) could reduce the depth analysable, the work has been executed with the lower frequency instrumentation. The choice of frequencies involves a trade-off between resolution and depth: higher frequencies offer higher resolution of data but shallower penetration. On the other hand, with lower frequencies, the datum has less resolution, but greater survey penetration.

During the processing phase, the radar data was processed with the GSSI RADAN 7 software. The procedure involved time calibration or zero time determination, back-

ground removal, IIR filter, gain adjustments and the calculation of the dielectric to have the correct depth.
It's worth noting that during the two days of surveying, Engineer Porcu and his colleague Dr. Geol. Nicola Catalano carried out some verifications with the Carlson C-ALS Gyro laser borehole scanner inside Rivellino di Santo Spirito and at the Ghirlanda spaces. The use of this particular laser scanner made it possible to survey inaccessible spaces with the accuracy of the laser scanner. These spaces are located far away from the area on which the 3D modelling is being tested, so the results of these surveys have not been included in this work. However, the instrument proved suitable to carry out further metric surveys in future, even in the underground part that has only been modelled.

The survey output data yielded stimulating information from all surveyed areas, in some cases providing very distinct and clear results. Indeed, Appendix A.III.V shows at least one significant radargram for each area surveyed.

One of the outdoor areas investigated is the one adjacent to Rivellino di Santo Spirito. In this area, the Codevintec team conducted two different analyses. The first (G1 in Figure 5.6.1.a) aimed to verify the presence of underground remains of the ravelin connecting the Ghirlanda and the city walls[3]. Rivellino di Santo Spirito has two brackets of different widths on its south side, suggesting a mobile connection with another adjacent structure 5.6.1.b. This no-more-present ravelin is visible in some documents, such as in the sixteenth-century woodcut in Figure 5.6.1.c. The georadar survey rigorously analysed the entire area, but no elements that could lead to structures hidden underground can be deduced from the data collected. On the other hand, the radargram shows the presence of a large reinforced concrete slab. Therefore, it is possible that, during the construction of the city's two metro lines, everything present below the park level may have been lost.

Figure 5.6.1.b The two shelves of Rivellino di Santo Spirito.

Adjacent to this area, there is the G2, analysed to search for traces of the southwest tower of the Ghirlanda. Despite the complex composition and conformation of the soil that prevents the desired results, the survey showed the presence of two tunnels that develop for tens of metres in the direction of the Cadorna train station.

Another outdoor analysis took place on the moat plane, in the north-west corner, near

[3] Figure IV.35 (p. 171) indicates with the number '5' the ravelins connecting the city walls and the Ghirlanda.

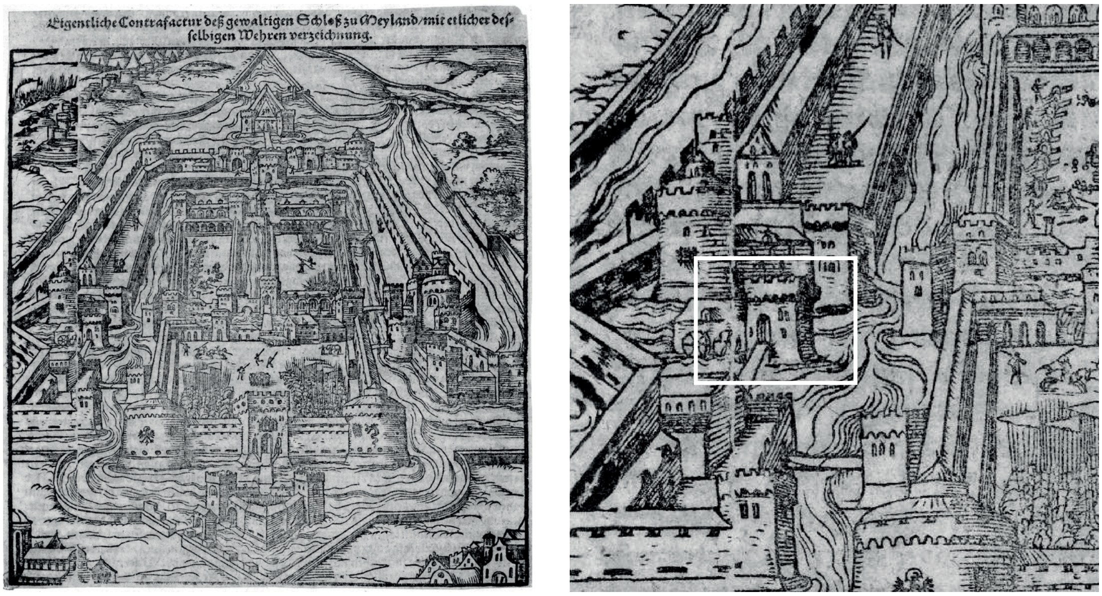


Figure 5.6.1.c Xylograph showing the lost ravelin. C. late 1600s. Document in the "Achille Bertarelli" Civic Collection of Print. (Milan).

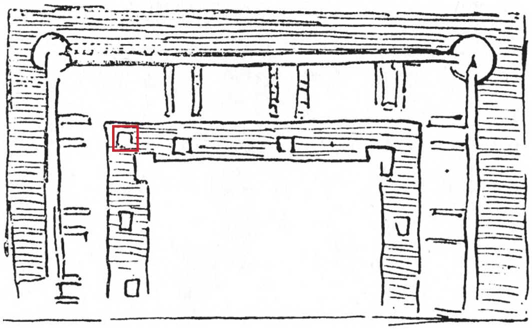


Figure 5.6.1.d Drawing of the Porta Giovia Castle showing the ravelin of the north-west corner investigated during the survey (Leonardo da Vinci, Manoscritto B,f. 15 r.).

Torre della Colubrina. Similar to the previous case, case G4 was also studied to find traces of a ravelin, which Leonardo da Vinci places in this position (Figure 5.6.1.d). As in the previous case, the results did not clearly show the desired information, but georadar analysis showed the presence of elements in the subsoil.

Area G3, which consists of the first side of the counterscarp path, showed a mix of clear and less distinct information.
A first overall scan, conducted from south to north (from the Rivellino di Santo Spirito towards Torre della Colubrina), showed several responses at different positions along the route. It is possible to assume that there are pathways at a lower height, perpendicular to the counterscarp tunnel. The georadar was used in correspondence with ascertained voids to get an idea of a similar signal response. The hypothesis is sustained by the presence of multiple arches along the wall of the counterscarp path (Figure 5.6.1.e). In the G3.c site a second analysis of this area was performed, in the opposi-

Figure 5.6.1.e One of the arches on the inner wall of the counterscarp passageway.

te direction and to a smaller extent. This recording showed a very evident finding, marked in red in Figure 5.6.1.f. This answer indicates the presence of a vaulted structure, perhaps one of the galleries mentioned above. Unlike previous signals, and in analogy to those that follow, this signal leaves no room for doubt. The 3D representation of this structure is proposed in the following section, with Figure 5.6.2.a.

The georadar survey also involved the central area of the defensive infrastructure, located near the ravelin towards the park. Zone G5 was analysed externally to identify the development of a tunnel below, whose presence was directly verified. On inspection, the structure appeared completely obstructed, leaving no possibility of verifying its dimensions. The radar data confirmed the presence of the first segment, whose signal then faded as the scans were made to the west side.

The georadar analysis of Point G6, was instead carried out internally because this area was not initially part of the survey project. During radar examination in this area for possible additional counterscarp tunnels on the lower levels, a clear signal emerged at the Galleria verso il Parco, a space located along the main path of the Ghirlanda. The georadar scanned the entire surface of this widening. The radar data show two small

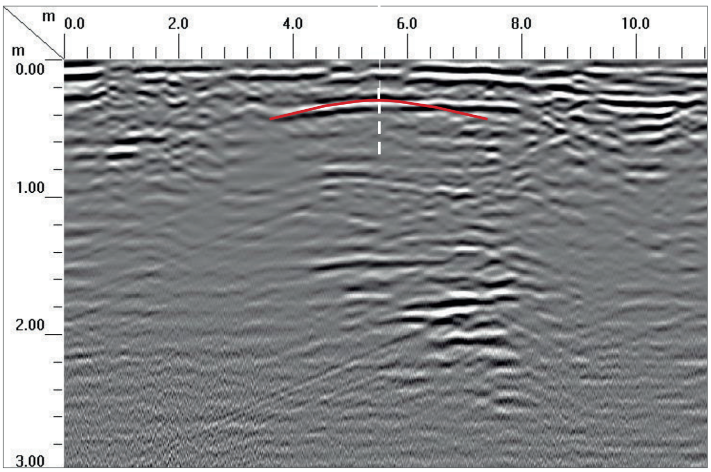


Figure 5.6.1.f Radargram of area G3.c bearing the signal of a vaulted structure (in red). The dotted line indicates the mid-line of the arch in the masonry.

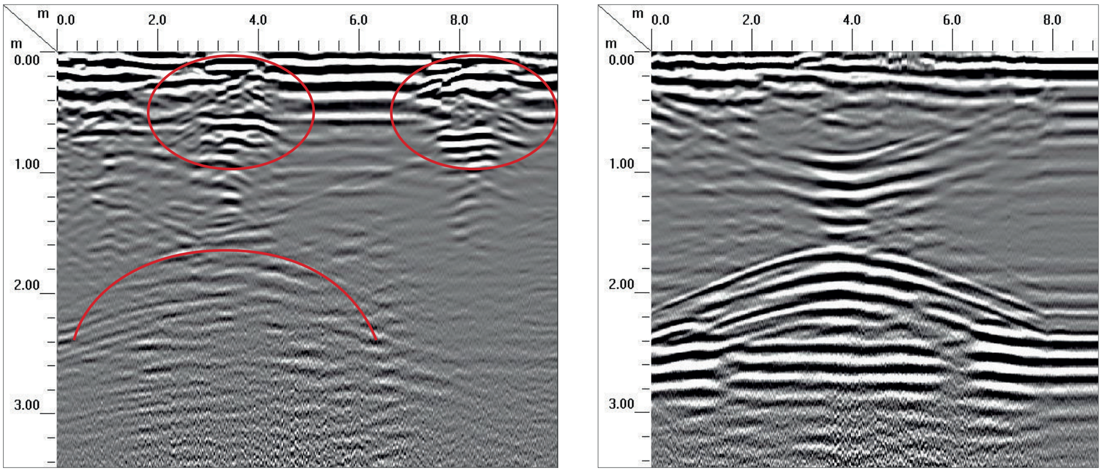


Figure 5.6.1.g Two of the scans carried out at Galleria verso il Parco. On the left, the outermost one presents all the three elements described. On the right the radargram shows only the strong signal of the vaulted structure below.

structures just below the floor level and a large, vaulted structure even deeper (Figure 5.6.2.c). The first two elements coincide with the two windows in the moat wall and develop up to the limit of the width of the counterscarp path. The third structure has to be clearly defined yet, but with a good degree of certainty, can be identified as an actual room, likely of similar size to the currently accessible one above. Figure 5.6.1.g shows two significant radargrams. In the first, all the objects are present and in the second, relating to a more internal scan, only the vaulted structure with its vertical supports.

The last area of scanning includes Torre della Vittoria (G7), located in the northeast corner of the structure. Similarly to the previous case, the radar signal showed a room on the lower level. Even in this case, the element seemed to trace the dimensions and features of the space currently walkable on a different level. It is possible to affirm this as the signal fades when investigating

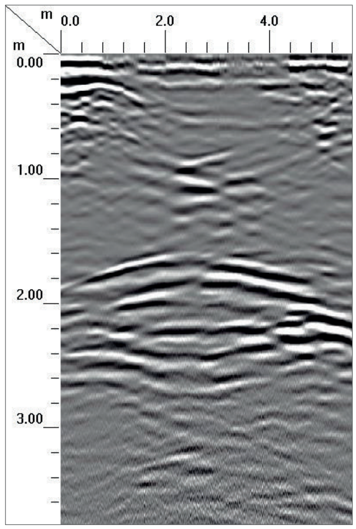


Figure 5.6.1.h Radargram of the G7 area showing the clear signal of a vaulted structure 1,60 m below ground level.

the adjacent corridor of the tower. Figure 5.6.1.h shows something very similar to the G6 site, namely a large vault (as present in all the spaces of the Ghirlanda) and hints of the vertical support structures. The following pages show the 3D of this element (Figure 5.6.2.d).

This third important campaign provided this PhD research with the opportunity to validate the proposed framework for digitising the geometric information of an architectural cultural asset. This further investigation is an example of the continuous collection and, notably, the evolution of the digital information available for this kind of building. The two previous campaigns provided the necessary information for the first two versions of the 3D model even though those are non-discordant forms of the same three-dimensional object, providing more or less complete versions of the area. This third survey has instead introduced partially discordant data compared to the previous ones and additional types of sources. These two conditions allowed both to test the process of updating the three-dimensional model and to verify the management and cataloguing structure of the 3D sources.

05.6.2 _ New discoveries in the castle basements

The second and final update of the model carried out following the georadar survey campaign, expanded the 3D with new elements and partly revised it following the new information.

Not all the scans yielded clear answers for the subsequent development of three-dimensional objects. For this reason, the modelling work involved only some areas of the Ghirlanda, those whose scanning provided clear evidence. These responses leave little room for interpretation. The spaces certainly exist, yet it has not been possible to access and measure them with higher accuracy. Potentially, coring procedures using a borehole laser scanner could be employed to carry out the survey. Further investigations are indeed planned for the near future. Since these spaces have not yet been certified and inspected, the new 3D volumes are still considered in the LOGI 1 level. Despite the high technology used, in fact, these discoveries remain hypotheses. While their presence is indisputable, their conformations and characteristics are not. This second revision of the geometric information collector has provided an opportunity to reflect on the digitisation and categorisation system initially developed. This last phase of the experimentation has introduced new variables regarding the definition of the Levels of Geometric Information. As it has just been described, it cannot be only the technology used to define the level of the sources, the data and the three-dimensional elements. Tools used, although modern and avant-garde, do not guarantee the accuracy of the data collected. These factors, the working method, and the general structure of digitisation, also derive from what emerged in this final phase of the experimentation. Indeed, the observations that emerged allowed the parameters of the approach to be revised.

As far as the purely operational part of the 3D model is concerned, the work led to the development of volumes relating to:

- the tunnel towards Cadorna (G3.c);
- the pathway adjacent to the facilities room (G5);
- the room below Galleria verso il Parco (G6);
- the room below Torre della Vittoria (G7).

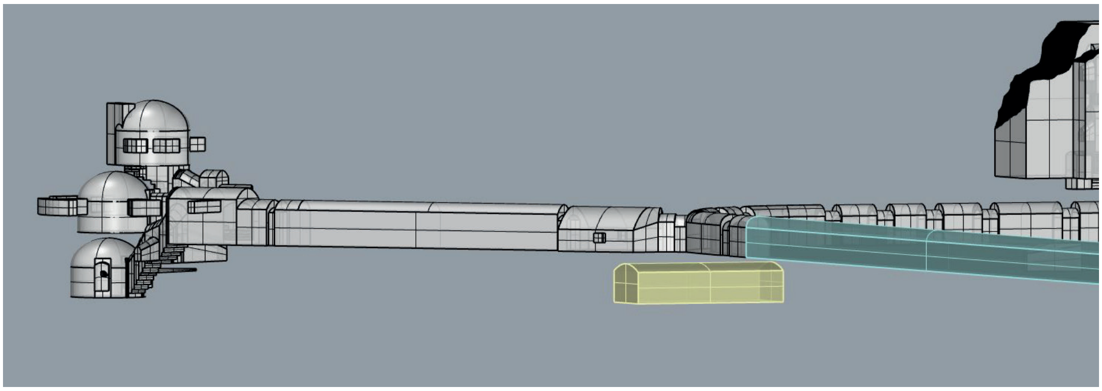


Figure 5.6.2.a View of the volume relating to area G3.c (the Cadorna side of the Ghirlanda).

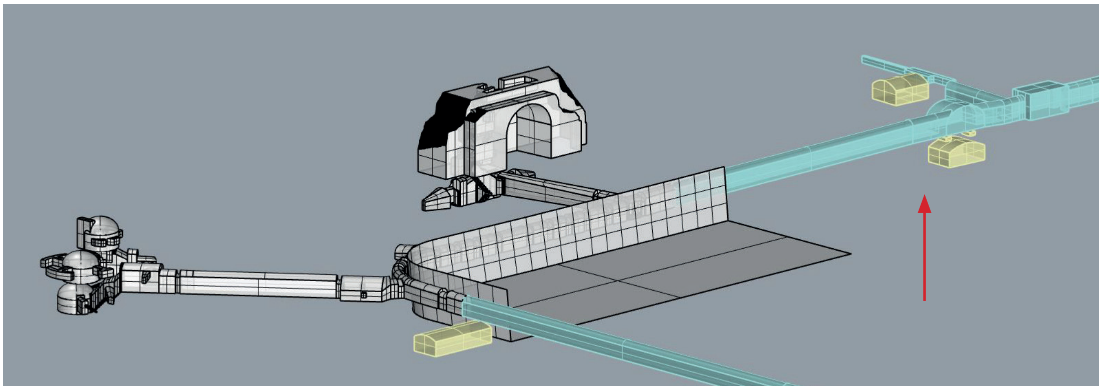


Figure 5.6.2.b General view of the model with the new volumes in the central area of the Ghirlanda (G5 - G6), indicated by the arrow.

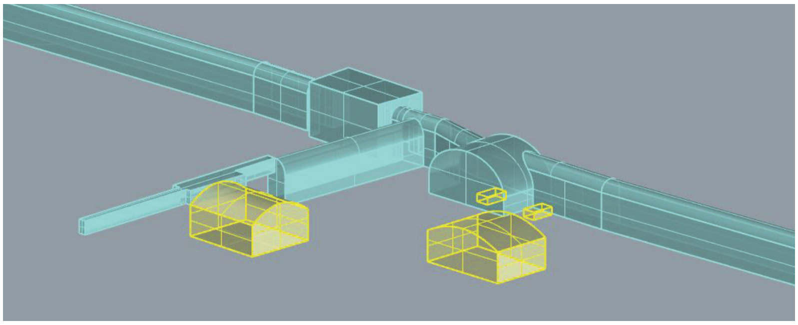


Figure 5.6.2.c Zoom on the developed volumes near the facilities room (left) and below the Galleria verso il Parco (right).

The three-dimensional reproductions are derived from the geometric information present in the radargrams, which are complete with a metric reference both along the x-axis (planimetric development) and the y-axis (height). The images show the volumes, referred to as the LOGI 1 (yellow), within the general model. Since the areas move away from the nucleus studied in the previous phases, it was necessary to model some reference structures, to understand their relationship with the newly identified spaces. The continuation of the counterscarp path was modelled, based on the existing documents mentioned above (LOGI 2), as well as the facilities room and the first portion of Torre della Vittoria. Figure 5.6.2.a shows the infrastructure towards Cadorna. It is interesting to note that it is only a few centimetres below the floor level of the main route. Not having complete information on its development towards the west side, the model reports only the first portion of this element, which could also extend for many more metres.

The following images (Figure 5.6.2.b-c) depict areas G5 and G6, namely what was found in the proximity of the facilities room and below the Galleria verso il Parco. The heights of the modelled structures are hypothetical and derive from similarities with neighbouring or similar structures. The graphs extracted from the georadar survey do not show the complete vertical development of these spaces (which could be obtained in the future with a second survey with different and/or more performing instrumentation), but only the upper structures, in this case, the vaults.
Finally, Figure 5.6.2.d shows what has been found below the east tower. Given the similar position of the findings regarding the rooms already known, the new space was hypothesised with the same height.

The survey also investigated a major part of the counterscarp in search of evidence of a second, similar path at the lower level. The investigation yielded no clues, refuting this hypothesis. It is logical to state that if there

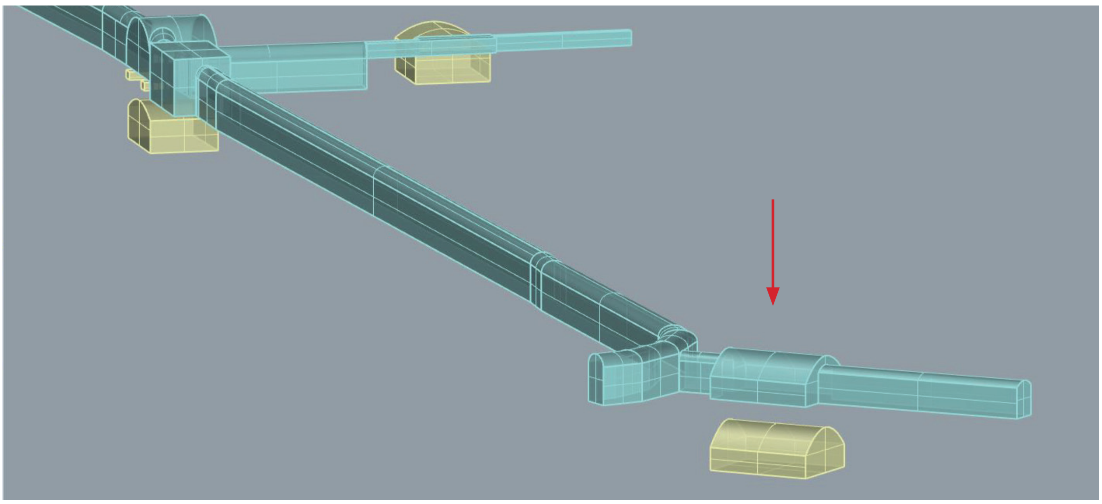


Figure 5.6.2.d View of the volume modelled for the traced space under Torre della Vittoria.

had been a second path, it would have been visible in the various scans carried out, like what happened with the other structures just mentioned. Considering this information, during the second update of the model, this part of the 3D was historicised, rejecting this hypothesis. The attributes table now shows an end date for the previous volume. Since no trace has been found of the second route of counterscarp, the model invites to reflect on the possible ways of connection between these new spaces and the remaining apparatus of the Ghirlanda. As mentioned above, they are all very superficial spaces, and a hypothetical connecting corridor (placed at the same altitude) would have been detected during the investigations.

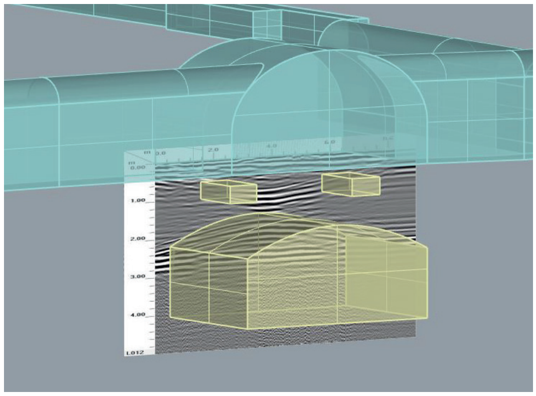


Figure 5.6.2.e One of the radargrams included within the model as a source of geometric information and reference for modelling process.

Consistently with the general approach, the new version of the 3D object also includes the original information and, therefore, the source from which the geometries shown in the model were deduced. The radargrams were also imported into Rhinoceros environment and placed in the correct position. In this case, the survey and processing did not also manage the geographical information, requiring a manual insertion of the sources, which were scaled concerning the metric references. Figure 5.6.2.e shows the graphs within the modelling environment.
This new category of reference material had not been used and managed within the digitisation system yet. This introduction created the chance to update the overall cataloguing of the sources. During the survey, as we have seen previously, several scans were carried out at different points of the castle and the Ghirlanda. Each scan consists of several records, carried out one after the other. This set of scans, altogether, forms a georadar analysis. These several records are a single survey and thus a single source. Often, however, for the modelling, only some of these data were used and not the entire ensemble. For this reason, in the structure the "COD_annex" data has been added, which contributes to the source classification. Although this new line is present in the general approach described in Chapter 3 and is also visible in Chapter 5.4, it arises from the reflections conducted during this last process of implementing the model. Following this 3D update, all the attribute tables, previously developed, were then modified to the version described in the previous pages. This change to the structure of data also facilitates the management of point clouds. In this way, the latter has been imported into the model, and loaded into OneDrive, according to the processing blocks and not as a single cloud, simplifying their fruition. The system then catalogued these point clouds as complementary components of the same source, which is essentially the laser scanner cloud as a whole. This new formula has established a better match between the various parts of the model and their references. Torre della Colubrina is connected to its

specific point cloud, as is also the case for the other structures detected.

This last updating process was very useful, both in general terms considering the discoveries made in the basement of the castle, and about the verification of the proposed digitisation model.

06

CONCLUSIONS

This doctoral research stems from an initial issue: how today's technologies in architecture and communication fields can interact with cultural heritage. This intersection is investigated within the context of digitisation methodologies aimed at enhancing the knowledge of that type of asset, its management and planning processes.

To formulate a thoughtful and informed proposal, an analysis of the state of the art on the issue was necessary. As detailed in the second chapter, this analysis evolved into a range of studies and trials to identify tools and solutions previously employed or currently in use. This study makes it possible to evaluate the pros and cons of the various approaches, clarifying what has been tested before and what has not, establishing indeed the boundaries within which this research could be conducted.

The urgency of structuring a system to simplify the transmission of the available knowledge about an architectural asset, taking advantage of current technologies, has been recognised. Such an approach also had to be capable of fully describing the built heritage from a geometric point of view and collect sources and information of different nature and accuracy in the same object, making it possible to exploit the heterogeneous documentary and information heritage of these buildings. The result is a digitisation framework based on several Levels of Geometric Information supported by an information system to manage the data linked to the reference information sources.

Within the experimental phase with the case study, the Ghirlanda of the Castello Sforzesco in Milan, the outcome underlined positive notes. The system proved to be efficient and functioning and the framework successfully achieved the objective of making the geometric information more easily intelligible, simplifying the understanding of the complex spatial dynamics of the building under analysis. This accomplishment was possible thanks to the inherent communication capabilities of 3D modelling, harnessed for the development of the digital twin.
The data schema, which was designed as a tool for gathering heterogeneous information, has proven its effectiveness. It facilitated the aggregation of sources and information of different natures, which are usually not considered jointly and managed in the same manner. The described solution grouped these sources into several LOGIs, from which 3D elements, with the same accuracy, were derived. The work process thus levelled the source information and its language, a crucial transformation to create a model capable of encapsulating all the existing data, despite its inherent heterogeneity.
The structure based on multiple Levels of Geometric Information in combination with the information system also proved to be a good solution for the digital twin update process. By operating in blocks, the expansion and modification of the model are streamlined and faster, all while working on the same digital twin, which evolves in incremental steps with the information dataset. In addition, the choice of incorporating the creation date, all the modifications and the end date for each element has proven to be a valuable tool for keeping track of model updates.

It has been presented the first version of the digitisation and information model. The structure demonstrated its efficacy and the experimentation conducted on the Milanese case study revealed some potential themes for possible future directions.

A first insight could concern the abstraction of the system. The experimental phase utilised Rhinoceros software, as it enabled all stages of the digitisation process to be carried out. As illustrated above, thanks to its attribute management functions, it has been possible to complete the information system implementation. However, the objective is to develop an approach that transcends specific tools and remains effective regardless of the chosen technological platform. The possible subsequent step could therefore deal with experimenting with the framework by implementing it in the GIS environment. In recent years, GIS has been developing a lot of integration with geometric and BIM models. Developing the 3D model externally and then inserting it into a GIS software (such as ArcGIS Pro, for example) for the information system development would greatly expand the options in terms of modelling software.
Furthermore, GIS platforms were created for large dataset management, thus offering advanced tools for the information system. Given its territorial scale, there are several possibilities to manage multiple models within the same digital environment. The COD_building data in the information model, described in the previous chapters, was designed with this potential scenario in mind. This approach would enable better management data concerning a single building. The presence of several models within the same environment is facilitated by the georeferencing of sources and models.

A second issue is the historicisation of model components. While the solution adopted is basically correct, it would be worth experimenting with additional cases and even more heterogeneous situations. This exploration would permit the identification of further possible improvements. Such a system is already in use within geographic information systems where the analysed elements require constant monitoring and tracking of changes. In these cases, the historicisation system (and therefore the insertion of an end date) makes it possible to control the many alterations made to the several elements present, while keeping track of past configurations. This information could be also very useful for the architectural digital twin as it allows a critical reassessment of the previous versions of the 3D model. For this reason, it would be worthwhile dedicating additional tests on the subject.

The proposed information system proved to be, in its structure, well-articulated and functioning, validated with Castello Sforzesco's sources. However, this does not detract from the fact that developing an information model is a complex and very difficult task. The version presented here is a first step in the right direction towards a complete and solid solution.

The possible research developments, which have emerged during the experimental phase, are both manifold and stimulating. In light of this, stepping back from possible improvements to the specific system in favour of more general reasoning, it is possible to report a final consideration. The process of development and verification undertaken for the proposed approach to the digitisation of the architectural heritage has made increasingly evident that the potential of the digitisation is not limited to the mere collection and hierarchisation of information sources. While communication and understanding of the built environment

are fundamental to managing and properly operating on it, the resulting digital twin opens the way to other possible uses and development.
By integrating further information, the digital twin could become a critical basis for the reading and interpretation of processes and phenomena, thus supporting an even more targeted and specialised knowledge. As a model for understanding the architectural asset, its spaces and its evolution over time, the newly proposed structure could be tested in the future to provide a holistic model. The three-dimensional object would become a neutral base on which to read and then interpret different levels of information, methodologically organized. The various information subsets, complete with documents and sources, could then span a range of topics: material degradation and preservation, structural elements and related instabilities and interventions, facilities, attentional elements and previously investigated areas, or even monitoring systems, artworks and their management, etc. The study and management of a complex architecture inevitably involve cross-cutting analyses in multiple areas, which would be smarter and more immediate in a framework of this kind. The model developed with the present doctoral research is a valuable piece within this broader perspective and application, allowing critical analysis of the object and its components. What has also been achieved in terms of the information system lays the foundations for a general approach, to be extended (and tested) to all the elements of the different information levels and the various reference sources, to set up an organized and functioning structure. This perspective inevitably brings with it reflections on the management of such amounts of data. Referring to the previous lines, the GIS world could be the answer to this need, thus organizing the thematic information groups on levels and then in different shapefiles, treating the model (complete with its system of reference sources) as a three-dimensional map to be characterized from time to time with the pertinent information, to be read individually or even in a stratified way, as is typical of Geographic Information Systems. This is referred to as a BIM-GIS approach. This shift from modelling software such as Rhinoceros to GIS software would also make larger-scale readings possible, making the data of the architectural asset interact with those of the urban systems that usually surround and intercept this type of building. This approach would succeed in opening up more in-depth analyses. Taking into consideration the Castello Sforzesco in Milan, it is very strategic to visualize the interactions between the building, its basement and neighbouring systems: the subway lines, the network of underground irrigation ditches (which also fed the moat of the fortress), technological tunnels and infrastructures, the urban green area ecosystem, public surface transportation and many others.
Structuring such a digital twin, organised in thematic information packages that link to a model developed for Levels of Geometric Information, certainly requires the integration of additional skills and tools. These necessities stem from the immense volume of information and intricate networks that need to be managed, as well as to establish a solid and extensive internal framework.

However, this suggestion points towards possible implications and developments of this inaugural attempt on the subject. Importantly, these possible insights do not invalidate the results achieved so far, but rather indicate the way forward. To borrow from the first chapters of this text, such a digital twin could thus become a new place aimed at new knowledge and useful for multiple in-depth studies, based on the specific data package connected to the critical geometric base, also in continuous evolution.

The migration towards the digital world and digital twins is undoubtedly transforming the landscape of architecture and cultural heritage. Its declinations are multiple, spanning beyond issues addressed within this text, towards themes such as education, tourism and more.
The approach describes in a peculiar interpretation the digitisation of architectural assets and their information heritage. As repeated several times, the work aims to develop a method to make geometric information, otherwise scattered in historical documents, graphic designs or products of some modern digital survey, easily accessible within the same digital tool. Achieving this goal has not only meant testing the countless possibilities of today's technological advancement. It has been about delivering a solution that, by leveraging on these technologies, supports the preservation and transmission of knowledge of the built heritage, which is too often forgotten in archives or between the pages of books. Only knowledge, which in turn allows for a critical understanding of conditions and phenomena, makes it possible to manage, safeguard and enhance the architectural heritage.
As the digital landscape continues to evolve, this work tries to be marked as a significant contribution to ensuring that architectural assets are not only preserved but also made accessible and comprehensible.

ACKNOWLEDGEMENTS

This work would not be possible without the financial support of Digitarca s.r.l.s and the ABC department of Politecnico di Milano: especially thanks to Professor M. Scaioni, head of the ABC PhD program, for his great willingness, and Professor C. Rossi for her active tutoring of my work.

My sincere thanks go also to all professors that spent time on my work revision, proving precious hints and advice. Special remembrance goes to Professor M.P. Iarossi for her unwavering faith.

This research was supported by Soprintendenza Castello, Musei Archeologici e Musei Storici. I thank Professor C. Salsi for his collaboration as former Superintendent and Director of Castello Sforzesco, Dott. G. Mori for the resources' coordination and both technical and administrative staff.

I would like to mention Codevintec s.r.l. for the valuable and stimulating collaboration during the surveys. A special thanks to engineer Maurizio Porcu for the availability and passion he puts into his work.

My heartfelt thanks go to Professor Franco Guzzetti and my deep gratitude for his everlasting support. In these three demanding years, he has proved to be an irreplaceable guide as a researcher, professor, and person.
Finally, I would like to thank all the people, relatives and friends that sustained me in this challenging experience.

REFERENCES

Agnello, F., Avella, F., Agnello, S. (2019). Virtual Reality for historical architecture. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W9*, 9-16. https://doi.org/10.5194/isprs-archives-XLII-2-W9-9-2019.

Aiello, D.A., D'Agostino, G., Galizia, M. (2020). Virtual Baroque: digitization experience of the ecclesiastical heritage in Acireale. In C. Bolognesi & C. Santagati (Eds.), *Impact of Industry 4.0 on Architecture and Cultural Heritage* (pp. 137-158). IGI Global. https://doi.org/10.4018/978-1-7998-1234-0.ch006.

Assolombarda (1995). *Il castello di Milano. Una proposta di valorizzazione e rilancio*. Il Sole 24 Ore Management.

Autorità per le garanzia nelle comunicazioni (AGCOM) (2018). Rapporto sul consumo di informazione. https://www.agcom.it/documents/10179/9629936/Studio-Ricerca+19-02-2018/72cf58fc-77fc-44ae-b0a6-1d174ac2054f?version=1.0.

Avena, M., Colucci, E., Sammartano, G., Spanò, A. (2021). HBIM modelling for an historical urban centre. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLIII-B2-2021*, 831–838. https://doi.org/10.5194/isprs-archives-XLIII-B2-2021-831-2021, 2021.

Aveta, C., Salvatori, M., Vitelli, G.P. (2017). The complex point cloud for the knowledge of the architectural heritage. Some experiences. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-5/W1*, 235–244. https://doi.org/10.5194/isprs-archives-XLII-5-W1-235-2017.

Baek, F., Ha, I., Kim, H. (2019). Augmented reality system for facility management using image-based indoor localization. *Automation in Construction, 99*, 18-26. https://doi.org/10.1016/j.autcon.2018.11.034.

Banfi, F. (2017). BIM orientation: grades of generation and information for different type of analysis and management process. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W5*, 57-64. https://doi.org/ 10.5194/isprs-archives-XLII-2-W5-57-2017.

Banfi, F. (2019). *Holistic generative modeling process for HBIM* [Doctoral dissertation, not accesible online]. Politecnico di Milano.

Banfi, F. (2020). HBIM, 3D drawing and virtual reality for archaeological sites and ancient ruins. *Virtual Archaeology Review, 11(23)*, 16-33. https://doi.org/10.4995/var.2020.12416.

Banfi, F. (2021) The evolution of interactivity, immersion and interoperability in HBIM: digital model uses, VR and AR for built cultural heritage. *ISPRS International Journal of Geo-Information, 10(10):685*. https://doi.org/10.3390/ijgi10100685.

Banfi, F., Brumana, R., Aljishi, A., Sayeh, N., Quintero, M., Cuca, B., Oreni, D., Midali, C. (2019.a). Generative modeling, virtual reality and HBIM interaction: immersive environment for built heritage: case study of Shaikh isa Bin Ali House, Bahrain. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W11*, 149-157. https://doi.org/10.5194/isprs-archives-XLII-2-W11-149-2019.

Banfi, F., Brumana, R., Stanga, C. (2019.b). Extended reality and informative models for the architectural heritage: from Scan-to-BIM process to virtual and augmented reality. *Virtual Archaeology Review, 10(21)*, 14-30, https://doi.org/10.4995/var.2019.11923.

Banfi, F., Mandelli, A. (2021). Computer vision meets image processing and UAS photogrammetric data integration: from HBIM to the eXtended Reality project of Arco della Pace in Milan and its decorative complexity. *Journal of Imaging, 7*. https://doi.org/10.3390/jimaging7070118.

Banfi, F., Oreni, D. (2020). Virtual Reality (VR), Augmented Reality (AR), and Historic Building Information Modeling (HBIM) for built heritage enhancement: from geometric primitives to the storytelling of a complex building. In C. Bolognesi & C. Santagati (Eds.), *Impact of Industry 4.0 on Architecture and Cultural Heritage* (pp. 111-136). IGI Global. https://doi.org/10.4018/978-1-7998-1234-0.ch005.

Banfi, F., Oreni, D., Bonini, J. (2020). The Arch of Peace of Milan and its historic memory: from 3D survey and HBIM to mixed reality (VR-AR). Proceedings of the 2th International Conference of Representation Disciplines Teachers Congress of Unione Italiana per il Disegno, 1669-1677. https://doi.org/10.3280/oa-548.92.

Banfi, F., Previtali, M. (2021). Human–computer interaction based on Scan-to-BIM models, digital photogrammetry, visual programming language and eXtended Reality (XR). *Applied Sciences, 11(13):6109*. https://doi.org/10.3390/app11136109.

Barazzetti, L., Banfi, F. (2017). Historic BIM for mobile VR/AR applications. In M. Ioannides, N. Magnenat-Thalmann, & G. Papagiannakis (Eds.), *Mixed reality and gamification for cultural heritage*. Springer, Cham. https://doi.org/10.1007/978-3-319-49607-8_10.

Barazzetti, L., Banfi, F., Brumana, R., Gusmeroli, G., Oreni, D., Previtali, M., Roncoroni, F., Schiantarelli, G. (2015.a). BIM from laser clouds and finite element analysis: combining structural analysis and geometric complexity. *Int. Arch. Photogramm. Remote Sens. Spatial*

Inf. Sci., XL-5/W4, 345–350. https://doi.org/10.5194/isprsarchives-XL-5-W4-345-2015, 2015.

Barazzetti, L., Banfi, F., Brumana, R., Previtali, M. (2015.b). Creation of parametric BIM objects from point clouds using NURBS. *The Photogrammetric Record, 30*, 339-362. https://doi.org/10.1111/phor.12122.

Barazzetti, L., Brumana, R., Banfi, F., Lostaffa, F., Piraino, F., Previtali, M., Oreni, D., Roncoroni, F., Villa, L. (2015.c). BHIMM e Augmented Information: il rilievo per la conoscenza e la valorizzazione di Castel Masegra. Proceedings of Asita Conference, Lecco (Italy), 2015.

Barba, L., Blancas, J., Pecci, A., Miriello, D., Cura, M., Crisci, G., Cappa, M., De Angelis, D., Yavuz, H.B. (2018). Georadar investigations in the central nave of Hagia Sofia, Istanbul (Turkey). *Archaeol. Anthropol. Sci., 10*, 259–268. https://doi.org/10.1007/s12520-016-0351-y.

Barone, Z., Nuccio, G. (2017). For a consciuos fruition of the cultural heritage of ancient Noto (Sicily). EFIAN project as opportunity for valorisation. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-5/W1*, 89-97. https://doi.org/10.5194/isprs-archives-XLII-5-W1-89-2017.

Barrile, V., Bernardo, E., Bilotta, G. (2022). An experimental HBIM processing: innovative tool for 3D model reconstruction of morpho-typological phases for the Cultural Heritage. *Remote Sensing, 14(5)*. https://doi.org/10.3390/rs14051288.

Battini, C., Landi, G. (2015). 3D tracking based augmented reality for cultural heritage data management. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XL-5/W4*, 375–379. https://doi.org/10.5194/isprsarchives-XL-5-W4-375-2015.

Belloni, G.G. (1966). *Il Castello Sfrozesco di Milano*. Bramante.

Beltrami, L. (1894). *Guida storica del Castello di Milano: 1368-1894*. Hoepli.

Beltrami, L. (1898). *Il castello di Milano*. Dante Alighieri.

Beltrami, L., Paoli, S. (2014) Luca Beltrami, 1854-1933: storia, arte e architettura a Milano. Silvana.

Berthelot, M., Nony, N., Gugi, L., Bishop, A., Luca, L. (2015). The Avignon bridge: a 3D reconstruction project integrating archaeological, historical and geomorphological issues. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XL-5/W4*, 223-227. https://doi.org/10.5194/isprsarchives-XL-5-W4-223-2015.

Bertocci, S., Bua, S., Parrinello, S., Picchio, F. (2014). Montepulciano 3D virtual models for urban planning and development of the urban environment. *DISEGNARECON, 7*. https://doi.org/10.6092/issn.1828-5961/4152.

BIMForum (2022, June 28). *Level of development specification*. BIMForum. https://bimforum.org/resource/level-of-development-specification/.

Bolognesi, C. (2018). Digital workflow for virtual and augmented visit of architecture. Proceedings of 7th International Conference, EuroMed 2018, Nicosia (Cyprus), October 29 – November 3 2018. https://doi.org/10.1007/978-3-030-01765-1_15.

Bolognesi, C., Aiello, D. (2019). The secrets of S. Maria delle Grazie: virtual fruition of an iconic milanese architecture. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W15*, 185–192. https://doi.org/10.5194/isprs-archives-XLII-2-W15-185-2019, 2019.

Bolognesi, C., Aiello, D. (2020). 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). IGI Global. https://doi.org/10.4018/978-1-7998-1234-0.ch003.

Breda, M.A. (2015). *Milano 5 Ottobre 1940. I rifugi antiaerei pubblici del Comune di Milano*. Lo Scarabeo.

Brumana, R., Della Torre, S., Previtali, M., Barazzetti, L., Cantini, L., Oreni, D., Banfi, F. (2018). Generative HBIM modelling to embody complexity (LOD, LOG, LOA, LOI): surveying, preservation, site intervention — the Basilica di Collemaggio (L'Aquila). *Applied Geomatics, 10*, 545-567. https://doi.org/10.1007/s12518-018-0233-3.

Bruno, N., Roncella, R. (2019). HBIM for conservation: a new proposal for information modeling. *Remote Sensing, 11(15):1751*. https://doi.org/10.3390/rs11151751.

Campi, M., di Luggo, A., Palomba, D., Palomba, R. (2019). Digital surveys and 3D reconstructions for augmented accessibility of archaeological heritage. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W9*, 205–212. https://doi.org/10.5194/isprs-archives-XLII-2-W9-205-2019.

Campi, M., di Luggo, A., Scandurra, S. (2017). 3D modeling for the knowledge of architectural heritage and virtual reconstruction of its historical memory. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W3*, 133–139. https://doi.org/10.5194/isprs-archives-XLII-2-W3-133-2017.

Canciani, M., Conigliaro, E., Grasso, M., Papalini, P., Saccone, M. (2016). 3D survey and augmented reality for cultural heritage. The case study of Aurelian Wall at Castra Praetoria in Rome. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLI-B5*, 931-937. https://doi.org/10.5194/isprs-archives-XLI-B5-931-2016.

Carenzo, U. (2021). *Verso un digital twin urbano: integrazione fra BIM e GIS nel settore edilizio*

[Degree thesis, Politecnico di Milano]. https://www.politesi.polimi.it/handle/10589/176248.

Carrión-Ruiz, B., Blanco-Pons, S., Duong, M., Chartrand, J., Li, M., Prochnau, K., Fai, S., Lerma, J. (2019). Augmented experience to disseminate Cultural Heritage: House of Commons windows, Parliament Hill National Historic Site (Canada). *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W9*, 243-247. https://doi.org/10.5194/isprs-archives-XLII-2-W9-243-2019.

Chang, Y.L., Hou, H.T., Pan, C.Y., Sung, Y.T., Chang, K. (2015). Apply an augmented reality in a mobile guidance to increase sense of place for heritage places. Educational Technology & Society, 18, 166-178.

Chiabrando, F., Turco, M., Rinaudo, F. (2017). Modeling the decay in an HBIM starting from 3D point clouds. A followed approach for cultural heritage knowledge. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W5*, 605-612. https://doi.org/10.5194/isprs-archives-XLII-2-W5-605-2017.

Chianese, A., Piccialli, F. (2015). The TrUST project: improving the fruition of historical centres through smart objects. *Procedia Computer Science, 63*, 159-164. https://doi.org/10.1016/j.procs.2015.08.327.

Cirulis, A., Brigis Brigmanis, K. (2013). 3D outdoor augmented reality for architecture and urban planning. *Procedia Computer Science, 25*, 71-79. https://doi.org/10.1016/j.procs.2013.11.009.

Comune di Milano, Zone 1 Council (2005). *Rivellino, una sentinella in ascolto*. Boniardi Grafiche.

Comune di Milano (2007). *Castello Sforzesco. Recupero della strada coperta della Ghirlanda*. Comune di Milano.

Corradeghini, P. (2017, July 31). *Un LIDAR ad alta risoluzione*. 3d metrica. https://3dmetrica.it/un-lidar-ad-alta-risoluzione/.

Corradeghini, P. (2018, July 13). *Pulire una nuvola di punti in Cloud Compare*. 3d metrica. https://3dmetrica.it/pulire-una-nuvola-di-punti-in-cloud-compare/.

Council of Europe (2017). *European cultural heritage strategy for the 21st century*. https://www.coe.int/en/web/culture-andheritage/strategy-21.

D'Uva, D., Eugeni, F. (2021). DTM to NURBS—A parametric approach to landscape modeling for an environmentally-conscious design. *Sustainability, 13(4)*. https://doi.org/10.3390/su13042379.

Dhanda, A., Reina Ortiz, M., Weigert, A., Paladini, A., Min, A., Gyi, M., Su, S., Fai, S., Quintero, M. (2019). Recreating cultural heritage environments for VR using photogrammetry. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W9*, 305-310. https://doi.org/10.5194/isprs-archives-XLII-2-W9-305-2019.

Diara, F., Rinaudo, F. (2020). Building archaeology documentation and analysis through open source HBIM solutions via NURBS modelling. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLIII-B2-2020*, 1381–1388. https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-1381-2020, 2020.

Direzione Generale Musei (MiBACT) (2019). *Piano Triennale per la Digitalizzazione e l'Innovazione dei Musei*. http://musei.beniculturali.it/wp-content/uploads/2019/08/Piano-Triennale-per-la-Digitalizzazione-e-l%E2%80%99Innovazione-dei-Musei.pdf.

European Commission (2011). *Raccomandazione della Commissione del 27 Ottobre 2011 sulla Digitalizzazione e l'Accessibilità in Rete dei Materiali Culturali e sulla Conservazione Digitale*. https://eur-lex.europa.eu/LexUriServ/LexUrServ.do?uri=OJ:L:2011:283:0039:0045:IT:PDF.

Fabbri, K., Zuppiroli, M., Ambrogio, K. (2012). Heritage buildings and energy performance: mapping with GIS tools. *Energy and Buildings, 48*, 137-145. https://doi.org/10.1016/j.enbuild.2012.01.018.

Ferraretti, E., Mai, A., Seiti, Y. (2018). *Dalla nuvole di punti al modello BIM: conservazione e divulgazione dei dati dei beni storico-culturali. Caso studio: la Villa medicea di Poggio a Caiano* [Degree thesis, Politecnico di Milano]. https://www.politesi.polimi.it/handle/10589/142124.

Flavián, C., Ibáñez-Sánchez, S., Orús, C. (2019). The impact of virtual, augmented and mixed reality technologies on the customer experience. *Journal of Business Research, 100*, 547-560. https://doi.org/10.1016/j.jbusres.2018.10.050.

Gaiani, M., Martini, B. (2013). Processi e temi per una smartculturalcity. *SCIRES-IT, 3(2)*. https://doi.org/10.2423/i22394303v3n2p1.

García Gago, J.M., Sánchez-Aparicio, L., Soilán, M., González-Aguilera, D. (2022). HBIM for supporting the diagnosis of historical buildings: case study of the Master Gate of San Francisco in Portugal. *Automation in Construction, 141*. https://doi.org/10.1016/j.autcon.2022.104453.

Godinho, M., Machete, R., Ponte, P., Falcão, A.P., Gonçalves, A.B., Bento, R. (2020). BIM as a resource in heritage management: an application for the National Palace of Sintra, Portugal. *Journal of Cultural Heritage, 43*, 153-162. https://doi.org/10.1016/j.culher.2019.11.010.

Guidi, G., Remondino, F., Russo, M., Menna, F., Rizzi, A., Ercoli, S. (2009). A Multi-resolution methodology for the 3D modeling of large and complex archeological areas. *International Journal of Architectural Computing, 7(1)*, 39-55. https://doi.org/10.1260/147807709788549439.

Guidi, G., Russo, M. (2011). Diachronic 3D reconstruction for lost Cultural Heritage. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XXXVIII-5/W16*. https://doi.org/10.5194/isprsarchives-XXXVIII-5-W16-371-2011.

Guzzetti, F., Anyabolu, K.L.N., Biolo, F., D'Ambrosio, L. (2021.a). Considerations and questions derived from the application of a Scan-to-BIM modeling process of a historical public building. Proceedings of the event 9th ARQUEOLÓGICA 2.0 & 3rd GEORES, Valencia (Spain). 26–28 April 2021. https://doi.org/10.4995/arqueologica9.2021.12093.

Guzzetti, F., Anyabolu, K.L.N., Biolo, F., D'Ambrosio, L. (2021.b). BIS—Management of energy consumption data for companies and public administration. In: D. La Rosa & R. Privitera (Eds.), *Innovation in Urban and Regional Planning, INPUT 2021*. Lecture Notes in Civil Engineering, Springer, Cham. https://doi.org/10.1007/978-3-030-68824-0_25.

Guzzetti, F., Anyabolu, K.L.N., Biolo, F., D'Ambrosio, L. (2023). From the digital twin of architectural heritage to the definition of the constraint maps. The case study of the Castello Sforzesco in Milan. *ISPRS Ann.. Photogramm. Remote Sens. Spatial Inf. Sci., X-M-1-2023, 101–108, https://doi.org/10.5194/isprs-annals-X-M-1-2023-101-2023*.

Guzzetti, F., Biolo, F. (2023). Il BIS per il monitoraggio dei consumi e l'ottimizzazione degli interventi di riqualificazione. *Techne*. Under publication.

Hurkxkens, I., Bernhard, M. (2019). Computational terrain modeling with distance functions for large scale landscape design. *Journel of Digital Landscape Architecture, 4*, 222-230. https://doi.org/10.14627/537663024.

Ildikó Leete, R. (2022, January 22). *What is a digital twin?*. Archdaily. https://www.archdaily.com/975256/what-is-a-digital-twin.

IPER - ICT to Promote Cultural Heritage (2018). *Summary report on the actual situation of promotion of cultural heritage through digital tools and according to accessible tourism principles*. https://iperproject. eu/files/2021/08/IPER_SummaryReport_Aggiornato-1.pdf.

Istituto Italiano dei Castelli (1997). *Luca Beltrami e il restauro dei castelli 1893-1993. Nel centenario dell'acquisizione del Castello da parte del Comune. Atti del seminario, Milano, 11 Dicembre 1993*. Istituto Italiano dei Castelli.

Istituto Italiano dei Castelli (2005). *Milano città fortificata. Vent'anni dopo: atti del convegno, Milano, Castello Sforzesco, 1 Ottobre 2003*. Comune di Milano.

Istituto nazionale di statistica (ISTAT) (2018). *Cittadini, imprese e ICT - anno 2018*. https:/www.istat.it/it/files//2019/01/Report-ICT-cittadini-e-imprese_2018_PC.pdf.

Istituto nazionale di statistica (ISTAT) (2019). *Cittadini e ICT - anno 2019*. https://www.istat.it/it/files/2019/12/Cittadini-e-ICT-2019.pdf.

Istituto nazionale di statistica (ISTAT) (2020). *Digitalizzazione e tecnologia nelle imprese italiane*. https://www.istat.it/it/files/2020/08/REPORT_DIGITALIZZAZIONE_CENSIMPRESE_PC.pdf.

Istituto nazionale di statistica (ISTAT) (2022.a). *Cittadini e ICT - anno 2022*. https://www.istat.it/it/files//2023/03/REPORT_CITTADINIEICT_2022.pdf.

Istituto nazionale di statistica (ISTAT) (2022.b). *Imprese e ICT - anno 2022*. https://www.istat.it/it/files//2023/01/REPORTICTNELLEIMPRESE_2022.pdf.

La Monica, D., Martinelli, M., Salvetti, O., Signore, O., Tampucci, M., Botarelli, L., Costa, S., Pace, G., Papa, C., Bargagliotti, S., Franchi, L., Casa, G. (2013). Thesaurus: un sistema per la conoscenza del patrimonio sommerso. *SCIRES-IT, 3*. https://doi.org/10.2423/i22394303v3n1p57.

Lee, W., Lee, D.H. (2019). Cultural Heritage and the intelligent Internet of Things. *J. Comput. Cult. Herit., 12(3)*. https://doi.org/10.1145/3316414.

Lerario, A., Varasano, A. (2020). An IoT smart infrastructure for S. Domenico church in Matera's "Sassi'': a multiscale perspective to built heritage conservation. *Sustainability, 12(16): 6553*. https://doi.org/10.3390/su12166553.

López, F.J., Lerones, P.M., Llamas, J., Gómez-García-Bermejo, J., Zalama, E. (2018). A review of Heritage Building Information Modeling (H-BIM). *Multimodal Technologies and Interaction, 2(2):21*. https://doi.org/10.3390/mti2020021.

Luna, U., Rivero, P., Vicent, N. (2019). Augmented reality in heritage apps: current trends in Europe. *Applied Sciences, 9(13):2756*. https://doi.org/10.3390/app9132756.

Macher, H., Landes, T., Grussenmeyer, P. (2017). From point clouds to Building Information Models: 3D semi-automatic reconstruction of indoors of existing buildings. *Applied Sciences, 7(10):1030*. https://doi.org/10.3390/app7101030.

Marani, P. C. (1982). Tre disegni d'architettura militare di Leonardo dal Codice Atlantico. *Arte Lombarda, 62 (2)*, 66–80. http://www.jstor.org/stable/43105339.

Mastronuzzi, G.A., Boccardi, L., Candela, A.M, Colella, C., Curci, G., Giletti, F., Milella, M., Pignatelli, C., Piscitelli, A., Ricci, F., Sansò, P. (2013). *Il Castello Aragonese di Taranto in 3D nell'evoluzione del paesaggio naturale*. Digilabs di Fiore G. & C.

MiBACT - Ministero dei beni e delle attività culturali e del turismo (2017). *Piano Strategico di Sviluppo del Turismo - 2017 2022*. https://www.ministeroturismo.gov.it/wp-content/uploads/2021/11/Piano-Strategico-del-Turismo-2017-2022.pdf.

Michetti, M. (2020). *Rhino: terreno in 3D*. Samilolab. https://www.samilolab.it/portfolio/tutorial-rhino-3d-modellare-un-terreno/.

Micoli, L., Guidi, G., Angheleddu, D., Russo, M. (2013). A multidisciplinary approach to 3D survey and reconstruction of historical buildings. Proceedings of Digital Heritage International Congress (DigitalHeritage), Marseille (France), 2013, 241-248, https://doi.org/10.1109/DigitalHeritage.2013.6744760.

Ministero dell'Economia e delle Finanze (M.E.F.) - Italian Government (2021). *Piano nazionale si ripresa e resilienza*. https://www.governo.it/sites/governo.it/files/PNRR.pdf.

Ministero per la Pubblica Amministrazione e l'Innovazione (Min. P.A.I.), Ministero dell'Ambiente e della Tutela del Territorio e del Mare (Min. A.T.T.M.) (2011, November 10). *Decreto 10 Novembre 2011. Adozione del Sistema di riferimento geodetico nazionale. (12A01799) (GU Serie Generale n.48 del 27-02-2012 - Suppl. Ordinario n. 37)*. Gazzetta Ufficiale della Repubblica Italiana. https://www.gazzettaufficiale.it/eli/id/2012/02/27/12A01799/sg.

Mirabella Roberti, M., Tabarelli, G.M., Vincenti, A. (1983). *Milano città fortificata*. Istituto Italiano dei Castelli.

Moretti, E., Bertozzi, S., Baratin, L. (2014). Cultural Heritage: restituzione reale di prospetti e piante in ArcScene. Proceedings of the 15th ESRI Italian Conference, Rome (Italy). 9-10 April 2014.

Ochmann, S., Vock, R., Klein, R. (2019). Automatic reconstruction of fully volumetric 3D building models from oriented point clouds. *ISPRS Journal of Photogrammetry and Remote Sensing, 151*, 251-262. https://doi.org/10.1016/j.isprsjprs.2019.03.017.

Oreni, D., Brumana, R., Banfi, F., Bertola, L., Barazzetti, L., Cuca, B., Previtali, M., Roncoroni, F. (2014). Beyond crude 3D models: from point clouds to historical Building Information Modeling via NURBS. *Lecture Notes in Computer Science, 8740*, 166-175. https://doi.org/10.1007/978-3-319-13695-0_16.

Osello, A., Lucibello, G., Morgagni, F. (2018). HBIM and virtual tools: a new chance to preserve architectural heritage. *Techne, 13*, 21-26. https://doi.org/10.3390/buildings8010012.

Padovan, G. (1996). *La fortezza celata: i sotterranei del Castello Sforzesco di Milano*. Diakronia.

Padovan, G. (2014). *Milano celta: le tre fortezze*. Lo Scarabeo.

Padovan, G. (2019). *Castrum Portae Jovis Mediolani. Dai disegni di Leonardo Da Vinci all'Archeologia del Sottosuolo*. BAR Publishing.

Palma, V., Spallone, R., Vitali, M. (2019). Augmented Turin baroque atria: AR experiences for enhancing cultural heritage. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W9*, 557–564, https://doi.org/10.5194/isprs-archives-XLII-2-W9-557-2019.

Pertot, G. (2019). Restauri e stratigrafia nel Castello di Milano. Limiti e potenzialità delle letture archeologiche dell'architettura in un contesto radicalmente restaurato. *Archeologia dell'Architettura, 24*, 217-231.

Pertot, G., Viganò, M. (2006). "…nouo reuelino quante ala porta del Castello". Una probabile opera di Leonardo. In: Settore Musei e Biblioteche del Comune di Milano (Eds.), *Rassegna di Studi e di Notizie. Vol. XXX - Anno XXXIII* (pp. 241-302). Comune di Milano.

Pescarin, S., Fanini, B., Ferdani, D., Baldassari, G., Calori, L. (2011). Archeologia virtuale, realismo, interattività e performance: dalla ricostruzione alla fruizione on line. *DisegnareCon, 4*. https://doi.org/10.6092/issn.1828-5961/2570.

Petrucco, C., Agostini, D. (2016). Teaching our cultural heritage using mobile augmented reality. Je-LKS : Journal of e-Learning and Knowledge Society, 12, 115-128. https://doi.org/10.20368/1971-8829/1180.

Pierleoni, P., Belli, A., Palma, L., Valenti, S., Raggiunto, S., Incipini, L., Ceregioli, P. (2018). The Scrovegni Chapel moves into the future: an innovative Internet of Things solution brings new light to Giotto's masterpiece. *IEEE Sensors Journal, 18(18)*. https://doi.org/10.1109/JSEN.2018.2858543.

Pocobelli, D., Boehm, J., Bryan, P., Still, J., Grau-Bové, J. (2018). BIM for heritage science: a review. *Heritage Science, 6*. https://doi.org/10.1186/s40494-018-0191-4.

Portalés, C., Lerma, J., Pérez, C. (2009). Photogrammetry and augmented reality for cultural heritage applications. *The Photogrammetric Record, 24*, 316 - 331. https://doi.org/10.1111/j.1477-9730.2009.00549.x.

Presidenza del Consiglio dei Ministri (P.C.M.) - Italian Government (2011). *D.P.C.M. 10 /11/2011 - Annex 1. Regole tecniche per la definizione delle specifiche di contenuto dei database geotopografici*. https://www.gazzettaufficiale.it/eli/id/2012/02/27/12A01800/sg.

Pulcrano, M. (2022). Cloud-to-BIM-to-VR: an operative approach for the construction of interactive and information models for the cultural heritage. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLVI-2/W1-2022*, 443–449. https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-443-2022.

R3GIS (2018, October 5). *R3 TREES - la gestione efficiente e responsabile del verde urbano*. Slideshare. https://www.slideshare.net/r3-gis/r3-trees-la-gestione-efficiente-e-responsabile-del-verde-urbano.

Regione Lombardia (2018). *Deliberazione giunta regionale n. 8/6650 20/02/2008. Aggiornamento delle specifiche tecniche in materia di Data base topografico a supporto del sistema informativo territoriale integrato*. https://www.consultazioniburl.servizirl.it/pdf/2008/03171.pdf#Page=3.

Regione Lombardia (2012). *Regional decree n. 3870 07/05/2012 - Annex B. Specifiche tecniche del Database Topografico regionale (DBT)*. https://www.geoportale.regione.lombardia.it/en-GB/specifiche-tecniche.

Regli, C., Huggenberger, P., Rauber, M. (2002). Interpretation of drill core and georadar data of coarse gravel deposits. *Journal of Hydrology, 255 (1–4)*, 234-252. https://doi.org/10.1016/S0022-1694(01)00531-5.

Rodríguez-Gonzálvez, P., Muñoz-Nieto, A., Del Pozo, S., Sánchez-Aparicio, L., González-Aguilera, D., Micoli, L., Gonizzi Barsanti, S., Guidi, G., Mills, J., Fieber, K., Haynes, I., Hejmanowska, B. (2017). 4D reconstruction and visualization of cultural heritage: analyzing our legacy through time. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W3*, 609-616. https://doi.org/10.5194/isprs-archives-XLII-2-W3-609-2017.

Sánchez-Aparicio, L.J., Masciotta, M.G., García-Alvarez, J., Ramos, L.F., Oliveira, D.V., Martín-Jiménez, J.A., González-Aguilera, D., Monteiro, P. (2020). Web-GIS approach to preventive conservation of heritage buildings. *Automation in Construction, 118*. https://doi.org/10.1016/j.autcon.2020.103304.

Santagati, C., Noto, V., La Russa, F. (2018). A project for Museo Civico Castello Ursino in Catania: breaking through museum walls and unlocking collections to everyone. Proceedings 7th International Conference, EuroMed 2018, Nicosia (Cyprus), October 29 – November 3 2018. https://doi.org/10.1007/978-3-030-01765-1_10.

Savoia, D. (2011). La “Strada Coperta Segreta” del Castello Sforzesco di Milano. *AUT (archeologia uomo territorio), 30*, 83-93.

Stamnas, A., Georgoula, O., Patias, P. (2021). Development of a protocol for a GIS related to the restoration of cultural heritage buildings and sites through documentation stage.

Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLVI-M-1-2021, 705–712. https://doi.org/10.5194/isprs-archives-XLVI-M-1-2021-705-2021, 2021.

Stanga, C., Spinelli, C., Brumana, R., Oreni, D., Valente, R., Banfi, F. (2017). A N-D virtual notebook about the Basilica of S. Ambrogio in Milan: information modeling for the communication of historical phases subtraction process. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W5*, 653-660. https://doi.org/10.5194/isprs-archives-XLII-2-W5-653-2017.

Tarani, F., Manganelli del F'a, R., Riminesi, C. (2020). Towards IoT monitoring of street-side monuments: the Florentine Dietrofront as a case study. *IOP Conf. Ser.: Mater. Sci. Eng., 949*. https://doi.org/10.1088/1757-899X/949/1/012005.

Thomson, C., Boehm, J. (2015). Automatic geometry generation from point clouds for BIM. *Remote Sensing, 7(9)*, 11753-11775. https://doi.org/10.3390/rs70911753.

Tomecka-Suchoń, S. (2012). Georadar studies on St. Benedict's Church on Lasota Hill, Kraków, Poland. *Acta Geophysica, 60*, 386–398. https://doi.org/10.2478/s11600-011-0019-z.

Tommasi, C., Fiorillo, F., Jiménez Fernández-Palacios, B., Achille, C. (2019). Access and web-sharing of 3D digital documentation of environmental and architectural heritage. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W9*, 707–714. https://doi.org/10.5194/isprs-archives-XLII-2-W9-707-2019.

United Nations (2015). *Agenda 2030 per lo Sviluppo Sostenibile*. https://unric.org/it/agenda-2030/.

Viganò, M. (1996). Il Castello di Milano (1559-1599). L'opera di Giovan Giacomo e Giorgio Paleari Fratino. *Arte Lombarda, 117(2)*, 71-79. http://www.jstor.org/stable/43106956.

Viganò, M. (1997). Iconografia del Castello Sforzesco nell'epoca delle grandi fabbriche (1551-1656). *Arte Lombarda, 120 (2)*, 44–54. http://www.jstor.org/stable/43106294.

Viganò, M. (2006). Iconografia del Castello Sforzesco dalla prima alla seconda età Austriaca (1707-1859). *Arte Lombarda, 146/148(1-3)*, 167-176. http://www.jstor.org/stable/43133225.

Wang, H., Pan, Y., Luo, X. (2019). Integration of BIM and GIS in sustainable built environment: A review and bibliometric analysis. *Automation in Construction, 103*, 41-52. https://doi.org/10.1016/j.autcon.2019.03.005.

Welc, F., Rabiega, K., Brzostowska, I., Wagner, A. (2022). From field survey to 3D model. Application of ground-penetrating radar for studies of historical architecture: a case study of the Wyszyna Castle in Poland. *International Journal of Conservation Science, 13, (3)*, 793-804.

LIST OF FIGURES

AA

APPENDICES

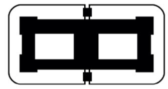
AA.I _ Timeline of the evolution of the Castello Sforzesco layout

This first appendix provides a timeline of the evolution of the layout of the Castello Sforzesco in Milan. It contains both a synopsis of the changes and a planimetric scheme of the architecture in the various phases identified. The appendix complements the historical digression in Chapter 4 and the description of the events that affected the case study. The diagrams are partly based on the graphic re-elaboration carried out by A. Vincenti and C. Vincenti (based on the historical documentation by M. Viganò) and published in the text "Milano Città Fortificata. Vent'anni dopo". The dates delimiting the various phases of the timeline do not always coincide with the historical phases. These periods are the temporal gaps within which a given layout has developed and been preserved.

1

1368 - c. 1390
Early Visconti period

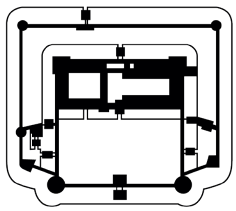
Galeazzo II Visconti has the castle of Porta Giovia built at the homonymous gate. The fortress roughly coincides with the current nucleus of Corte Ducale and Rocchetta.



2

c. 1390 - 1499
Visconti - Sforza period

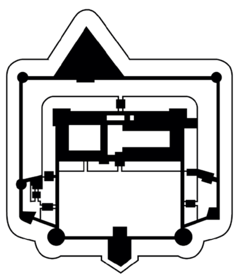
The castle expands to a square shape with the Piazza d'Armi.
The Ghirlanda infrastructure, with its moat, is built.



3

1499 - 1535
French period

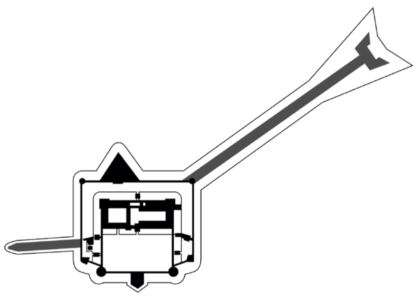
The castle has two new ravelins at the two entrances. They are derived from Leonardo Da Vinci's drawings.



4

1535 - 1560
Early Spanish period

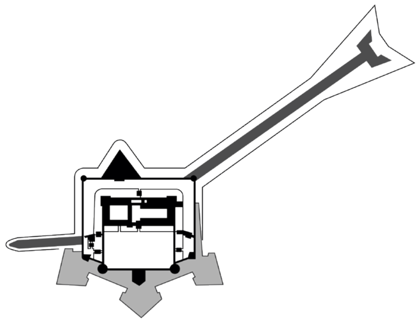
During the first phase of Spanish domination, the Tenaglia and the Catena are erected, which are connected to the new city walls, also built by the Spanish.



5

1560 - 1590
Second Spanish period

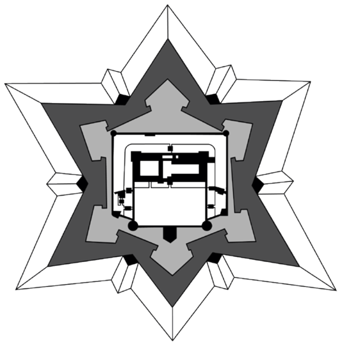
Work begins on the construction of the Royal Fortress. During this period, the first bastions towards the city are completed and then there are years of stalemate.



6

1590 - 1599
Third Spanish period

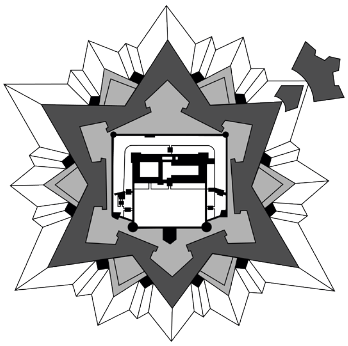
The bastioned circuit around the castle is completed. The Tenaglia and the Catena are demolished, which are considered unnecessary or even dangerous within the new defensive system.



7

1599 - 1800
Last Spanish period

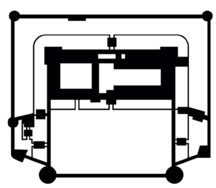
The defensive system is completed with six ravelins placed between as many bastions. Although it is not certain, there are reports of the construction of a Corona structure, placed in front of the Acuna bastion. The layuot remained unchanged even with the transition to Austrian rule.



8

1800 - 1860
The Napoleonic Conquest

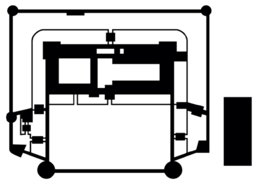
With Napoleon Bonaparte's entry into Milan, the castle underwent extensive demolition, which decimated the entire bastioned structure erected by the Spanish.



9

1860 - 1893
The military barracks

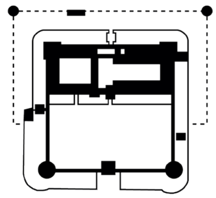
In this period, the only substantial planimetric change is the construction of the Cavallerizza. The complex in general falls into a period of decay.



10

1893 - 1940
The restoration by Luca Beltrami

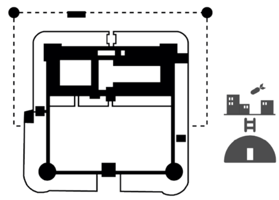
The castle become municipal property and the extensive work on Luca Beltrami's project begin immediately. Many elements are demolished, including the Ghirlanda. This layout remained unchanged until the Second W.W.



11

1940 - 1957
The Second World War

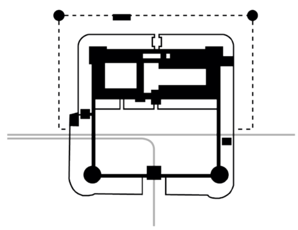
During these years, the Ghirlanda take on the function of an anti-aircraft bunker, offering asylum to 2,000 people. The facilities and elements built during this period will remain even beyond the end of the conflict.



12

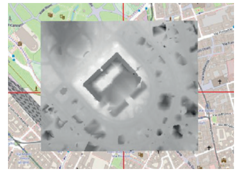
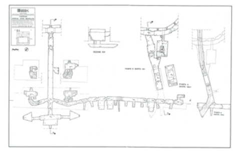
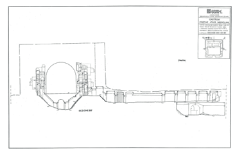
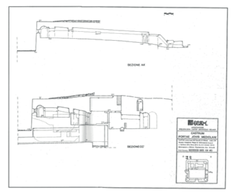
1957 - today
MM - Metropolitane Milanese

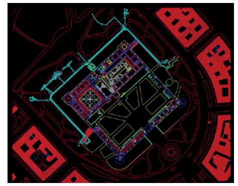
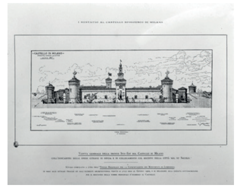
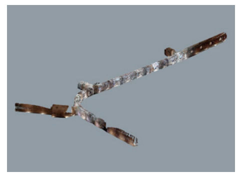
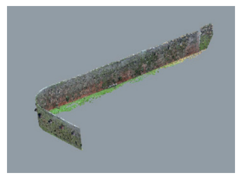
In the second half of the 20th century, sections of two metro lines are built under the castle's site, causing substantial demolitions.

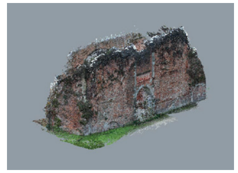
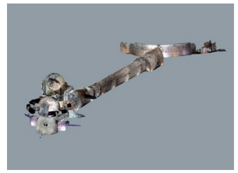


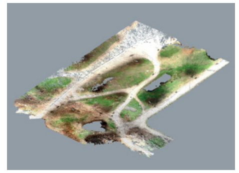
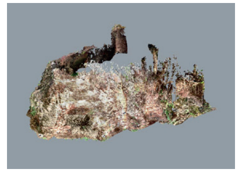
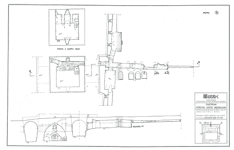
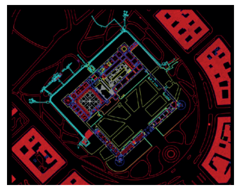
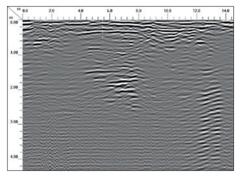
AA.II _ The complete catalogue of the sources for the development of the 3D model

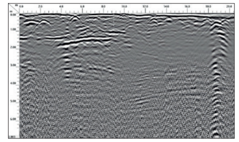
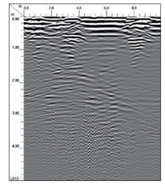
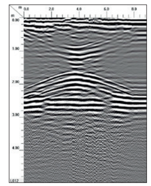
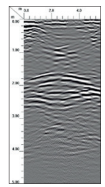
The appendix provides a list of all sources used for the development of the 3D model and its two updates. The table reports information on the reference material. Some data are for identification purposes, others aim to describe their nature and content. The cataloguing follows the order of use of the sources during the process. In the first rows are those exploited for the initial version of the 3D model, followed by those for the first and second updates. Within these three sections, the material follows an alphabetical order base on the name.

N°	Name	Author	Date	Source typology	Description	Location	Cataloguing code	ID_source	LOGI	Use phase (model version)	Preview
1	"Castello di Milano. Torre del palazzo ducale prima del restauro e costruzioni sulla Ghirlanda antica verso il parco demolite nel 1893"	G. Rossi	1878 - 1884	Phograph	The photo shows Torre Falconiera of the Castle and the Ghirlanda in its last configuration before demolition.	Civic Photographic Archive of Milan	RLB02665	S_009_001	1	1	
2	DTM of the Castle area	Italian Ministero dell'Ambiente e della Tutela del Territorio e del Mare	-	Measurements, data point	The source consists of a set of known coordinate points describing the landform of the Castello Sfrozesco area. The DTM has a 1x1 metre grid.	National Geoportal	-	S_011_001	2	1	
3	Geometric survey of the basements of the Ghirlanda - Casamatta Celestino, Galleria delle Radici and lifting pump room	SCAM Association	1990	Graphic work	The document shows plans of three structures inside the Ghirlanda: the Casamatta Celestino, the Galleria delle Radici and the water pump room.	SCAM archive	-	S_005_001	2	1	
4	Geometric survey of the basements of the Ghirlanda - Galleria delle Radici	SCAM Association	1990	Graphic work	The document shows the longitudinal section of the Galleria delle Radici.	SCAM archive	-	S_005_003	2	1	
5	Geometric survey of the basements of the Ghirlanda - lifting pump room	SCAM Association	1990	Graphic work	The document shows the longitudinal section of the rooms used for the water lifting system.	SCAM archive	-	S_005_002	2	1	

N°	Name	Author	Date	Source typology	Description	Location	Cataloguing code	ID_source	LOGI	Use phase (model version)	Preview
6	Geometric survey of the Castello Sforzesco and the Ghirlanda	G. Pertot	2002	Vector file (CAD)	The survey shows the plan of the Ghirlanda as a whole, within the Castle complex and part of Parco Sempione. In the first phase, it was used for modelling the Galleria delle Radici, the Casamatta Celestino and the water lifting rooms.	-	-	S_007_001	2	1	
7	"Veduta generale della fronte Sud-Est del Castello di Milano coll'indicazione delle opere esterne di difesa e di collegamento col recinto della città nel XV Secolo"	-	post 1900	Print	The print shows the city-facing front of the Castello Sforzesco. The side ravelins and one of the towers of the Ghirlanda are visible.	"Achille Bertarelli" Print Collection	P.V.m 76-1	S_004_001	1	1	
8	Lombardo Veneto Cadastre	-	1751	Cartography (cadastre)	Original map of the territory of jurisdiction of Porta Comasina.	State Archive of Milan	217373	S_008_001	1	1	
9	Survey of the basements of the Ghirlanda - counterscarp tunnel	F. Biolo	23/11/21	Laser scanner point cloud	The point cloud describes the section of the pathway that is part of the case study (from Torre della Colubrina to Porta del Soccorso). Point cloud with RGB content.	DABC - Politecnico di Milano	-	S_001_002	3	1	
10	Survey of the moat wall	F. Biolo	23/11/21	Photogrammetric point cloud	The cloud returns a portion of the moat wall, the one analysed with the case study. Point cloud with RGB content.	DABC - Politecnico di Milano	-	S_002_001	3	1	

N°	Name	Author	Date	Source typology	Description	Location	Cataloguing code	ID_source	LOGI	Use phase (model version)	Preview
11	Survey of Porta del Soccorso - exterior surfaces	F. Biolo	23/11/21	Photogrammetric point cloud	The cloud returns the fronts of Porta del Soccorso. Point cloud with RGB content.	DABC - Politecnico di Milano	-	S_006_001	3	1	
12	Survey of the basements of the Ghirlanda - Porta del Soccorso (interior spaces)	F. Biolo	23/11/21	Laser scanner point cloud	The point cloud covers all the rooms and underground spaces of Porta del Soccorso. The survey also affects the external floor at the top. Point cloud with RGB content.	DABC - Politecnico di Milano	-	S_001_003	3	1	
13	Survey of the basements of the Ghirlanda - Torre della Colubrina (interior spaces)	F. Biolo	23/11/21	Laser scanner point cloud	The point cloud covers all rooms and underground spaces of Torre della Colubrina. Point cloud with RGB content.	DABC - Politecnico di Milano	-	S_001_001	3	1	
14	Teresian Cadastre	-	1881	Cartography (cadastre)	Original cadastral map of Milan - sheet 13	State Archive of Milan	155100	S_003_001	1	1	
15	"Veuë du Chasteau et de la Citadelle de Milan"	S. Israel	1600 ca.	Etching	View from the countryside of the Castle, including the Ghirlanda and Spanish Bastions.	"Achille Bertarelli" I	P.V.p. 2-54	S_010_001	1	1	

N°	Name	Author	Date	Source typology	Description	Location	Cataloguing code	ID_source	LOGI	Use phase (model version)	Preview
16	Survey of the above ground elements of the Ghirlanda - ground surface	F. Biolo	12/10/22	Laser scanner point cloud	The point cloud describes the terrain of the analysed portion. The cloud only shows the terrain points as it has been cleaned of unnecessary elements. Point cloud with RGB content.	DABC - Politecnico di Milano	-	S_012_001	3	2	
17	Survey of the above ground elements of the Ghirlanda - Torre della Colubrina (esterior surfaces)	F. Biolo	12/10/22	Laser scanner point cloud	Point cloud the ruins of Torre della Colubrina in Parco Sempione. Point cloud with RGB content.	DABC - Politecnico di Milano	-	S_012_002	3	2	
18	Geometric survey of the basements of the Ghirlanda - the facilities room	SCAM Association	1990	Graphic work	The document shows a plan and section of the facilities room and the ravelin towards the park.	SCAM archive	-	S_005_004	2	3	
19	Geometric survey of the Castello Sforzesco and the Ghirlanda	G. Pertot	2002	Vector file (CAD)	The survey shows the floor plan of the Ghirlanda as a whole, within the Castle complex and part of Parco Sempione. In this third phase, it served for the realisation of the remaining extension of the counterscarp gallery.	-	-	S_007_002	2	3	
20	Georadar survey at the Ghirlanda - cave towards Cadorna Station	Codevintec s.r.l. (Ing. Maurizio Porcu)	01/12/22	Radargram	The radargram presents the data extracted from the analysis carried out along the counterscarp tunnel and shows the presence of a vaulted structure below the path floor.	Codevintec s.r.l.	-	S_013_002	1	3	

N°	Name	Author	Date	Source typology	Description	Location	Cataloguing code	ID_source	LOGI	Use phase (model version)	Preview
21	Georadar survey at the Ghirlanda - facilities room tunnel	Codevintec s.r.l. (Ing. Maurizio Porcu)	01/12/22	Radargram	The radargram is one of the scans carried out during the study of the path close to the facilities room.	Codevintec s.r.l.	-	S_013_003	1	3	
22	Georadar survey at the Ghirlanda - Galleria verso il Parco_1	Codevintec s.r.l. (Ing. Maurizio Porcu)	01/12/22	Radargram	The radargram is one of the scans carried out during the study of the structure below Galleria verso il Parco. This data comes from the recording carried out along the counterscarp tunnel and shows three elements.	Codevintec s.r.l.	-	S_013_004	1	3	
23	Georadar survey at the Ghirlanda - Galleria verso il Parco_2	Codevintec s.r.l. (Ing. Maurizio Porcu)	01/12/22	Radargram	The radargram is one of the scans carried out during the study of the structure below Galleria verso il Parco. This data comes from the recording made in the innermost part and shows only one element.	Codevintec s.r.l.	-	S_013_005	1	3	
24	Georadar survey at the Ghirlanda - Torre della Vittoria	Codevintec s.r.l. (Ing. Maurizio Porcu)	01/12/22	Radargram	The radargram is one of the scans carried out during the study of the first section of Torre della Vittoria. The file shows a large vaulted structure below the floor.	Codevintec s.r.l.	-	S_013_001	1	3	

AA.III _ The survey activities: complete data and additional documents

The third section of the appendices contains addictional material about surveying activities. The following pages report complete topographic and celerimetric data, information on scanning positions and on elaborations as well as a complete monograph of known points.

AA.III.I *Point monograph*
AA.III.II *Topography field book*
- *AA.III.II.a* *First survey campaign*
- *AA.III.II.b* *Second survey campaign*

AA.III.III *Celerimetric computation*
- *AA.III.III.a* *First survey campaign*
- *AA.III.III.b* *Second survey campaign*

AA.III.IV *Photogrammetry and laser scanning: survey position and process data*
- *AA.III.IV.a* *Photogrammetric survey*
- *AA.III.IV.b* *Laser scanning: the first set of scans*
- *AA.III.IV.c* *Laser scanning: the second set of scans*

AA.III.V *The radargrams*

AA.III.I _ Point monograph

The monograph includes both the points surveyed with GPS and the vertices of the topographic polygon, some of which coincide. For the second campaign, some of the vertices of the polygon previously created for the first survey phase were used.

Point S11

N: 5035170,820
E: 513911,695
Elev: 125,161 m a.s.l.

Point S21

N: 5035222,413
E: 514026,374
Elev: 124,671 m a.s.l.

Point N1

N: 5035252,092
E: 513988,719
Elev: 124,676 m a.s.l.

Point N2

N: 5035172,899
E: 513984,958
Elev: 124,717 m a.s.l.

Point N3

N: 5035168,855
E: 513984,158
Elev: 124,695 m a.s.l.

Point 100

N: 5035236,951
E: 513912,244
Elev: 117,846 m a.s.l.

Point 200 (S12)

N: 5035224,567
E: 513873,771
Elev: 125,112 m a.s.l.


Point 300 (S1)

N: 5035300,177
E: 513956,253
Elev: 125,115 m a.s.l.


Point 400

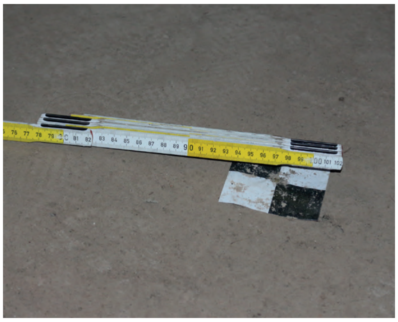
N: 5035250,922
E: 513902,638
Elev: 121,177 m a.s.l.




Point 500

N: 5035212,341
E: 513872,799
Elev: 121,096 m a.s.l.

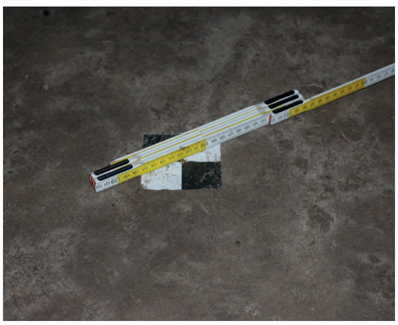





Point 600

N: 5035267,736
E: 513886,664
Elev: 119,822 m a.s.l.






Point 700

N: 5035272,639
E: 513882,974
Elev: 117,684 m a.s.l.

Point 800

N: 5035215,968
E: 513839,507
Elev: 121,203 m a.s.l.

Point 900

N: 5035220,002
E: 513871,575
Elev: 121,063 m a.s.l.


Point 1000

N: 5035219,360
E: 513838,763
Elev: 121,891 m a.s.l.



Point 1100

N: 5035226,331
E: 513875,076
Elev: 121,063 m a.s.l.


Point 1200

N: 5035263,980
E: 513880,783
Elev: 123,665 m a.s.l.

Point 1300

N: 5035238,896
E: 513871,349
Elev: 125,276 m a.s.l.

Point 1400

N: 5035261,644
E: 513882,352
Elev: 125,545 m a.s.l.

AA.III.II _ Topography field book

The tables show, from left to right, the following data: point code, point name, prism height, inclined distance, vertical angle, horizontal angle, horizontal distance, the relative height of the points, relative north coordinate and relative east coordinate.

AA.III.II.a _ First survey campaign

File: CASTELLO_211130_corretto.fw1
N.Lavoro: 1
Nome Lavoro:
Operatore:
Strumento: ES-62 Ver.1-8.01E1_04
Data:

Nome Stazione: 100
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,468

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	200	1,800	41,117	88,1656	332,5748	40,409	7,267	19,786	-35,233
	200	1,800	41,117	311,8284	132,5786	40,409	7,264	19,788	-35,233
	101	0,000	26,396	98,6088	343,4622	26,390	2,045	16,649	-20,475
	102	0,000	15,307	90,2748	0,8938	15,129	3,797	15,127	0,212
	103	0,000	18,918	93,1824	364,1824	18,810	3,490	15,910	-10,033
	104	0,000	44,222	100,1050	312,9768	44,222	1,395	8,952	-43,306
	105	0,000	44,929	94,7486	317,2358	44,776	5,170	11,975	-43,145
	106	0,000	43,291	100,0478	322,8682	43,291	1,435	15,218	-40,528
	107	0,000	42,539	94,1822	326,5958	42,361	5,350	17,187	-38,718
	108	0,000	39,531	99,6010	329,9418	39,530	1,716	17,914	-35,238
	109	0,000	28,936	91,4180	340,7580	28,673	5,357	17,129	-22,995
	110	0,000	22,240	99,9782	351,8570	22,240	1,476	16,178	-15,261
	111	0,000	17,331	99,9026	371,3654	17,331	1,495	15,607	-7,535
	112	0,000	17,577	86,0360	373,9378	17,156	5,293	15,738	-6,829
	113	0,000	15,687	100,4142	22,3790	15,687	1,366	14,727	5,401
	114	0,000	16,853	83,4648	25,7830	16,288	5,796	14,970	6,418
	115	0,000	7,958	95,6542	192,6642	7,939	2,011	-7,887	0,913
	116	0,000	4,916	112,3814	235,3538	4,823	0,518	-4,098	-2,543
	117	0,000	24,593	101,7130	293,4774	24,584	0,806	-2,514	-24,455

Nome Stazione: 100
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,563

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	200	1,800	41,118	88,3120	191,7888	40,427	7,270	-40,091	5,200
	200	1,800	41,117	311,6854	391,7904	40,426	7,268	-40,091	5,199
	300	2,000	77,479	93,6610	350,3344	77,095	7,265	54,800	-54,227
	300	2,000	77,478	306,3334	150,3366	77,095	7,258	54,802	-54,225
	400	1,625	17,288	87,4154	273,2970	16,951	3,333	-6,904	-15,482
	400	1,625	17,287	312,5814	73,2982	16,951	3,332	-6,903	-15,481
	500	1,800	46,634	95,2332	176,1018	46,503	3,252	-43,265	17,050
	500	1,800	46,631	304,7628	376,1034	46,501	3,248	-43,263	17,048

Nome Stazione: 200
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,488

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	100	1,500	41,065	111,3032	196,5612	40,419	-7,265	-40,360	2,182
	100	1,500	41,064	288,6926	396,5678	40,418	-7,267	-40,359	2,178
	201	0,000	30,638	87,4188	221,1308	30,042	7,503	-28,402	-9,789
	202	0,000	26,713	83,0252	234,0118	25,769	8,527	-22,178	-13,122
	203	0,000	32,916	83,0646	217,3880	31,758	10,141	-30,581	-8,567
	204	0,000	40,363	89,0538	206,0522	39,768	8,394	-39,588	-3,775
	205	0,000	39,235	77,4284	207,7336	36,795	15,109	-36,523	-4,459
	206	0,000	28,317	67,8120	234,2304	24,774	15,203	-21,278	-12,688
	207	0,000	35,044	100,9716	212,1330	35,040	0,953	-34,405	-6,638
	208	0,000	31,238	100,6244	241,1706	31,236	1,182	-24,929	-18,822
	209	0,000	27,953	76,9172	235,6010	26,136	11,403	-22,154	-13,866
	210	0,000	37,365	81,2568	244,9776	35,757	12,331	-27,198	-23,213
	211	0,000	32,896	112,9900	215,4590	32,214	-5,178	-31,268	-7,746
	212	0,000	36,043	111,8122	245,6126	35,424	-5,161	-26,714	-23,264
	300	1,800	111,945	99,8290	169,1522	111,945	-0,011	-99,058	52,146
	300	1,800	111,945	300,1674	369,1540	111,945	-0,018	-99,059	52,143
	1300	1,800	14,539	97,9474	105,7272	14,531	0,157	-1,306	14,473
	1300	1,800	14,539	302,0502	305,7272	14,531	0,156	-1,306	14,473
	P213	0,000	36,344	100,8464	119,4570	36,341	1,005	-10,935	34,657
	P214	0,000	36,748	100,4248	134,4860	36,747	1,243	-18,947	31,486
	P215	0,000	50,093	99,9644	144,2908	50,093	1,516	-32,106	38,451
	P216	0,000	30,093	102,3914	159,3452	30,072	0,358	-24,145	17,925
	P217	0,000	22,186	100,9432	152,1694	22,184	1,159	-16,211	15,143

Nome Stazione: 400
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,624

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	100	1,563	17,283	112,5616	51,8584	16,948	-3,327	11,629	12,328
	100	1,563	17,283	287,4336	251,8628	16,947	-3,328	11,628	12,329
	1100	1,800	36,941	99,8824	143,7940	36,941	-0,108	-23,455	28,540
	1100	1,800	36,938	300,1166	343,7922	36,938	-0,108	-23,452	28,538
	600	1,800	23,227	296,7708	41,8042	23,197	-1,354	-18,373	-14,161
	600	1,800	23,228	103,2280	241,7984	23,198	-1,353	-18,375	-14,160
	700	1,800	29,485	107,1642	243,3292	29,298	-3,487	-22,770	-18,437
	700	1,800	29,486	292,8308	43,3334	29,299	-3,490	-22,770	-18,439

Nome Stazione: 400
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,340

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	1100	1,273	36,930	100,3064	125,0998	36,930	-0,111	-14,186	34,096
	1100	1,273	36,930	299,6874	325,1058	36,930	-0,114	-14,189	34,095
	401	0,000	11,653	96,9484	120,4678	11,640	1,898	-3,678	11,043
	402	0,000	4,349	89,9638	115,9416	4,295	2,023	-1,064	4,161
	403	0,000	5,392	90,3190	220,2554	5,330	2,157	-5,062	-1,667
	404	0,000	24,087	101,2058	224,4386	24,083	0,884	-22,330	-9,019
	600	1,223	23,236	104,0278	223,1176	23,190	-1,352	-21,677	-8,237
	600	1,223	23,235	295,9700	23,1202	23,188	-1,353	-21,676	-8,237

Nome Stazione: 500
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,632

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	800	1,800	33,492	300,5274	54,6764	33,491	0,109	-21,880	-25,356
	800	1,800	33,491	99,4692	254,6766	33,490	0,111	-21,879	-25,355
	900	1,800	7,760	98,8210	337,6760	7,759	-0,024	4,328	-6,439
	900	1,800	7,761	301,1740	137,6830	7,760	-0,025	4,330	-6,440
	100	1,563	46,612	104,5310	12,2582	46,494	-3,246	45,635	8,897
	100	1,563	46,612	295,4642	212,2636	46,494	-3,249	45,634	8,901
	501	0,000	8,565	100,1518	261,3496	8,565	1,612	-4,886	-7,034
	502	0,000	6,540	102,2056	330,2322	6,536	1,405	2,989	-5,813
	503	0,000	1,289	92,8440	372,0748	1,281	1,777	1,160	-0,544
	504	0,000	8,230	107,3384	235,0078	8,175	0,685	-6,970	-4,272
	505	0,000	11,669	100,4816	248,2900	11,669	1,544	-8,470	-8,026
	506	0,000	11,670	100,4810	248,2832	11,670	1,544	-8,471	-8,026

Nome Stazione: 600
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,223

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	400	1,340	23,236	95,9548	243,9038	23,189	1,358	-17,890	-14,754
	400	1,340	23,236	304,0422	43,9056	23,189	1,357	-17,889	-14,755
	601	0,000	1,620	75,5880	206,4738	1,502	1,829	-1,495	-0,153
	602	0,000	1,404	141,7630	189,2264	1,113	0,367	-1,097	0,187
	603	0,000	8,873	123,1266	52,2136	8,294	-1,930	5,657	6,065
	604	0,000	1,916	81,1232	337,2442	1,832	1,783	1,012	-1,528
	1200	1,472	8,090	66,2332	356,0950	6,978	3,844	5,384	-4,440
	1200	1,472	8,089	333,7672	156,0904	6,978	3,843	5,383	-4,440
	605	0,000	4,271	89,0618	129,7430	4,208	1,953	-1,895	3,757
	606	0,000	7,424	71,5146	128,9030	6,693	4,435	-2,935	6,015
	607	0,000	3,824	92,0554	356,9210	3,794	1,699	2,958	-2,376

Nome Stazione: 700
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,616

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	400	1,900	29,539	91,8260	170,2688	29,296	3,498	-26,159	13,190
	400	1,900	29,538	308,1722	370,2692	29,295	3,497	-26,158	13,189
	701	0,000	9,019	98,3210	269,2000	9,016	1,854	-4,194	-7,981
	702	0,000	7,481	98,0730	69,5750	7,478	1,842	3,439	6,640

Nome Stazione: 800
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,484

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	500	1,800	33,489	99,5966	91,9334	33,488	-0,104	4,232	33,220
	500	1,800	33,488	300,4036	291,9426	33,487	-0,104	4,227	33,219
	1000	1,496	3,544	87,2884	371,2856	3,474	0,691	3,126	-1,514
	1000	1,496	3,543	312,7052	171,2862	3,473	0,690	3,125	-1,514
	801	0,000	3,770	79,5134	394,5910	3,576	2,676	3,564	-0,304
	802	0,000	4,719	84,9904	374,2842	4,588	2,586	4,219	-1,803
	803	0,000	1,001	87,6044	243,9700	0,982	1,678	-0,757	-0,626
	804	0,000	4,122	125,5708	306,3044	3,794	-0,128	0,375	-3,775
	805	0,000	13,566	122,3216	309,5562	12,741	-3,176	1,905	-12,597

Nome Stazione: 900
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,513

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	500	1,800	7,763	97,3078	261,3834	7,756	0,041	-4,421	-6,372
	500	1,800	7,764	302,6902	61,3880	7,757	0,041	-4,422	-6,374
	901	0,000	8,114	101,8134	268,7334	8,111	1,282	-3,825	-7,152
	1100	1,273	7,237	102,0920	103,6450	7,233	0,002	-0,414	7,221
	1100	1,273	7,236	297,9048	303,6464	7,232	0,002	-0,414	7,220

Nome Stazione: 1000
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,496

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	800	1,484	3,543	112,6148	162,6192	3,474	-0,685	-2,892	1,924
	800	1,484	3,543	287,3808	362,6272	3,474	-0,686	-2,892	1,924
	1001	0,000	5,014	87,0854	285,4698	4,911	2,506	-1,111	-4,784
	1002	0,000	10,544	99,8364	282,9456	10,544	1,523	-2,791	-10,168
	1003	0,000	8,729	69,7698	295,0204	7,763	5,487	-0,607	-7,739

Nome Stazione: 1100
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,273

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	900	1,513	7,237	97,8612	287,2126	7,233	0,003	-1,443	-7,087
	900	1,513	7,236	302,1394	87,2110	7,232	0,003	-1,443	-7,086
	1101	0,000	17,117	95,8942	110,3912	17,081	2,376	-2,776	16,854
	1102	0,000	24,133	97,2432	109,8276	24,110	2,318	-3,707	23,824
	400	1,340	36,930	99,6798	108,6568	36,930	0,119	-5,006	36,589
	400	1,340	36,929	300,3166	308,6624	36,929	0,117	-5,009	36,587

Nome Stazione: 1200
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,439

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	600	1,272	8,047	133,1982	365,1200	6,977	-3,842	5,956	-3,634
	600	1,272	8,046	266,7956	165,1288	6,976	-3,842	5,956	-3,633
	1201	0,000	1,163	67,7660	308,8662	1,017	2,003	0,141	-1,007
	1202	0,000	4,430	74,9058	49,6596	4,090	3,140	2,908	2,877
	1400	1,539	3,443	60,9238	63,6702	2,815	1,883	1,520	2,369
	1400	1,539	3,442	339,0798	263,6658	2,814	1,883	1,520	2,368

Nome Stazione: 1300
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,648

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	1400	1,539	25,270	300,4104	20,2954	25,269	0,272	-23,996	-7,920
	1400	1,539	25,270	99,5878	220,2910	25,269	0,273	-23,997	-7,918
	200	1,800	14,535	100,0524	380,9540	14,535	-0,164	13,889	-4,284
	200	1,800	14,534	299,9464	180,9550	14,534	-0,164	13,888	-4,283
	1301	0,000	20,978	102,3224	209,6296	20,964	0,883	-20,725	-3,159
	1302	0,000	25,178	105,8408	184,3682	25,072	-0,659	-24,320	6,095

Nome Stazione: 1400
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,539

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	1200	1,439	3,440	138,9858	245,3650	2,815	-1,877	-2,130	-1,840
	1200	1,439	3,440	261,0040	45,3748	2,815	-1,878	-2,129	-1,840
	1401	0,000	2,904	119,8164	362,4196	2,764	0,650	2,297	-1,539
	1300	1,648	25,270	100,3962	111,6850	25,270	-0,266	-4,612	24,845
	1300	1,648	25,269	299,5998	311,6906	25,269	-0,268	-4,614	24,844

AA.III.II.b _ Second survey campaign

File: Castello_terreno.fw1
N.Lavoro: 1
Nome Lavoro:
Operatore:
Strumento: ES-62 Ver.1-8.01E1_04
Data:

Nome Stazione: 200
Identificativo:
Temperatura:
Pressione:
Altezza strum: 1,593

Codice punto	Nome punto	Altezza Prisma	Distanza incl.	Angolo vert.	Angolo orizz.	Distanza orizz.	Quota rel.	Co.Rel. Nord	Co.Rel. Est
	300	1,700	111,955	99,9396	316,3116	111,955	-0,001	28,372	-108,300
	300	1,700	111,954	300,0586	116,3136	111,954	-0,004	28,376	-108,298
	T201	0,000	19,552	98,8804	96,1760	19,549	1,937	1,174	19,514
	T202	0,000	24,099	103,0972	137,2230	24,070	0,421	-13,286	20,072
	T203	0,000	32,596	101,3662	141,3362	32,588	0,894	-19,704	25,957
	T204	0,000	35,000	99,8202	173,2096	35,000	1,692	-31,946	14,298
	T205	0,000	24,886	100,0532	162,7294	24,886	1,572	-20,742	13,751
	T206	0,000	42,544	101,5150	253,6304	42,532	0,581	-28,312	-31,740
	T207	0,000	35,496	100,1318	267,9714	35,496	1,520	-17,114	-31,098
	T208	0,000	71,587	101,5866	263,8558	71,565	-0,191	-38,483	-60,337
	T209	0,000	13,940	106,9362	112,7336	13,857	0,077	-2,753	13,581
	T210	0,000	14,826	105,8992	133,0068	14,762	0,221	-7,316	12,822
	T211	0,000	11,136	108,0570	143,2014	11,047	0,187	-6,934	8,599
	T212	0,000	36,925	100,7630	281,8296	36,922	1,150	-10,396	-35,429
	T213	0,000	50,297	100,1356	291,0450	50,297	1,486	-7,052	-49,800
	T214	0,000	18,625	103,8368	193,0996	18,591	0,471	-18,482	2,011
	T215	0,000	53,744	101,4678	299,7624	53,730	0,354	-0,201	-53,729
	T216	0,000	69,285	101,1508	309,6118	69,274	0,341	10,419	-68,486

AA.III.III _ Celerimetric computation

The tables show, from left to right, the following data: point name, identification code, height, north coordinate, east coordinate, azimuth and reduced distance.

AA.III.III.a _ First survey campaign

	Nome	Codice identificativo	Quota	Coordinata Nord	Coordinata Est	Corr. Az. / Azimut	Distanza ridotta
Stazione	**100**		**117,846**	**5035236,951**	**513912,244**	**88,3855**	
Punto	101		119,891	5035233,258	513886,114	291,0606	26,390
Punto	102		121,643	5035247,392	513901,296	348,4922	15,129
Punto	103		121,336	5035240,412	513893,756	311,7808	18,810
Punto	104		119,241	5035211,282	513876,235	260,5752	44,222
Punto	105		123,016	5035213,456	513874,127	264,8342	44,776
Punto	106		119,282	5035217,581	513873,529	270,4666	43,291
Punto	107		123,196	5035220,246	513873,316	274,1942	42,361
Punto	108		119,562	5035223,292	513875,149	277,5402	39,530
Punto	109		123,203	5035231,736	513884,049	288,3564	28,673
Punto	110		119,322	5035236,761	513890,005	299,4554	22,240
Punto	111		119,341	5035242,038	513895,677	318,9638	17,331
Punto	112		123,139	5035242,645	513896,061	321,5362	17,156
Punto	113		119,212	5035250,926	513905,118	369,9774	15,687
Punto	114		123,642	5035251,836	513905,631	373,3814	16,288
Punto	115		119,857	5035232,258	513918,648	140,2626	7,939
Punto	116		118,364	5035232,300	513913,521	182,9522	4,823
Punto	117		118,653	5035217,309	513897,460	241,0758	24,584
Stazione	**200**		**125,112**	**5035224,567**	**513873,771**	**-116,3876**	
Punto	201		132,615	5035222,331	513903,729	104,7432	30,042
Punto	202		133,639	5035217,524	513898,559	117,6242	25,769
Punto	203		135,253	5035224,068	513905,525	101,0004	31,758
Punto	204		133,506	5035230,995	513913,016	89,6646	39,768
Punto	205		140,221	5035229,553	513910,226	91,3460	36,795
Punto	206		140,315	5035217,714	513897,578	117,8428	24,774
Punto	207		126,065	5035226,907	513908,733	95,7454	35,040
Punto	208		126,294	5035212,712	513902,670	124,7830	31,236
Punto	209		136,515	5035216,798	513898,725	119,2134	26,136
Punto	210		137,443	5035209,043	513905,983	128,5900	35,757
Punto	211		119,934	5035225,037	513905,981	99,0714	32,214
Punto	212		119,951	5035208,870	513905,528	129,2250	35,424
Punto	P213		126,117	5035260,866	513875,522	3,0694	36,341
Punto	P214		126,355	5035259,839	513884,078	18,0984	36,747
Punto	P215		126,628	5035269,925	513895,031	27,9032	50,093
Punto	P216		125,470	5035248,048	513892,558	42,9576	30,072
Punto	P217		126,271	5035243,338	513885,593	35,7818	22,184

Stazione	**400**	**121,177**	**5035250,922**	**513902,638**	**128,5105**	
Punto	401	123,075	5035242,561	513894,541	248,9783	11,640
Punto	402	123,200	5035247,632	513899,877	244,4521	4,295
Punto	403	123,334	5035254,617	513898,797	348,7659	5,330
Punto	404	122,061	5035268,722	513886,416	352,9491	24,083
Stazione	**500**	**121,096**	**5035212,341**	**513872,799**	**52,2310**	
Punto	501	122,707	5035214,154	513864,428	313,5806	8,565
Punto	502	122,501	5035218,631	513871,021	382,4632	6,536
Punto	503	122,872	5035213,530	513873,276	24,3058	1,281
Punto	504	121,781	5035210,713	513864,788	287,2388	8,175
Punto	505	122,639	5035212,437	513861,131	300,5210	11,669
Punto	506	122,640	5035212,435	513861,130	300,5142	11,670
Stazione	**600**	**119,822**	**5035267,736**	**513886,664**	**-92,2748**	
Punto	601	121,651	5035267,403	513888,129	114,1990	1,502
Punto	602	120,189	5035267,789	513887,775	96,9516	1,113
Punto	603	117,892	5035274,441	513881,782	359,9388	8,294
Punto	604	121,605	5035266,342	513885,475	244,9694	1,832
Punto	605	121,775	5035271,236	513889,000	37,4682	4,208
Punto	606	124,257	5035273,351	513890,306	36,6282	6,693
Punto	607	121,521	5035265,735	513883,440	264,6462	3,794
Stazione	**700**	**117,684**	**5035272,639**	**513882,974**	**-17,1136**	
Punto	701	119,538	5035266,477	513876,393	252,0864	9,016
Punto	702	119,526	5035277,719	513888,462	52,4614	7,478
Stazione	**800**	**121,203**	**5035215,968**	**513839,507**	**14,9695**	
Punto	801	123,879	5035219,504	513840,042	9,5605	3,576
Punto	802	123,789	5035220,491	513838,736	389,2537	4,588
Punto	803	122,880	5035215,377	513838,722	258,9395	0,982
Punto	804	121,075	5035217,212	513835,923	321,2739	3,794
Punto	805	118,027	5035220,755	513827,700	324,5257	12,741
Stazione	**900**	**121,063**	**5035220,002**	**513871,575**	**-71,4748**	
Punto	901	122,345	5035211,899	513871,924	197,2586	8,111
Stazione	**1000**	**121,891**	**5035219,360**	**513838,763**	**23,6322**	
Punto	1001	124,397	5035220,060	513833,902	309,1020	4,911
Punto	1002	123,414	5035220,448	513828,275	306,5778	10,544
Punto	1003	127,378	5035221,603	513831,331	318,6526	7,763
Stazione	**1100**	**121,063**	**5035226,331**	**513875,076**	**-55,0424**	
Punto	1101	123,439	5035237,353	513888,126	55,3488	17,081
Punto	1102	123,380	5035242,051	513893,357	54,7852	24,110
Stazione	**1200**	**123,665**	**5035263,980**	**513880,783**	**98,6937**	
Punto	1201	125,668	5035264,990	513880,904	7,5599	1,017
Punto	1202	126,805	5035261,164	513883,749	148,3533	4,090
Stazione	**1400**	**125,545**	**5035261,644**	**513882,352**	**116,9917**	
Punto	1301	126,159	5035259,026	513877,203	18,0165	20,964
Punto	1302	124,617	5035263,806	513868,502	392,7551	25,072
Stazione	**1400**	**125,545**	**5035261,644**	**513882,352**	**116,9917**	
Punto	1401	126,195	5035262,522	513884,973	79,4113	2,764

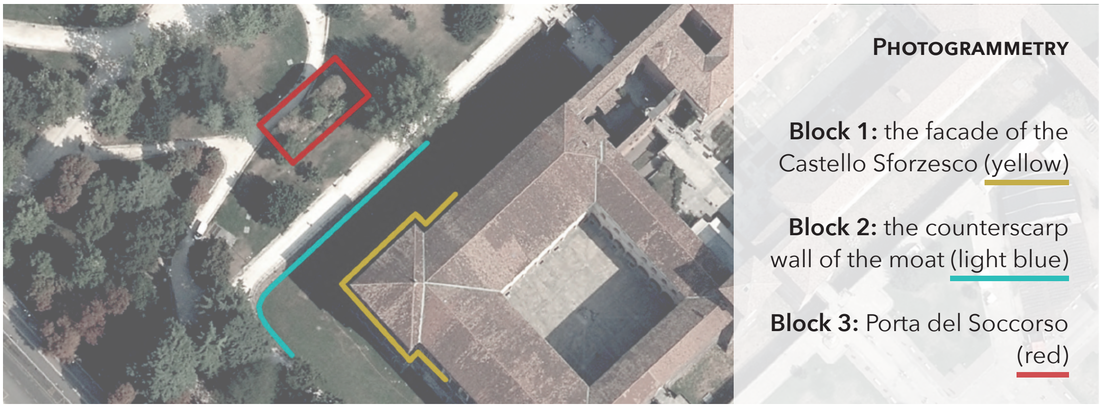
AA.III.III.b _ Second survey campaign

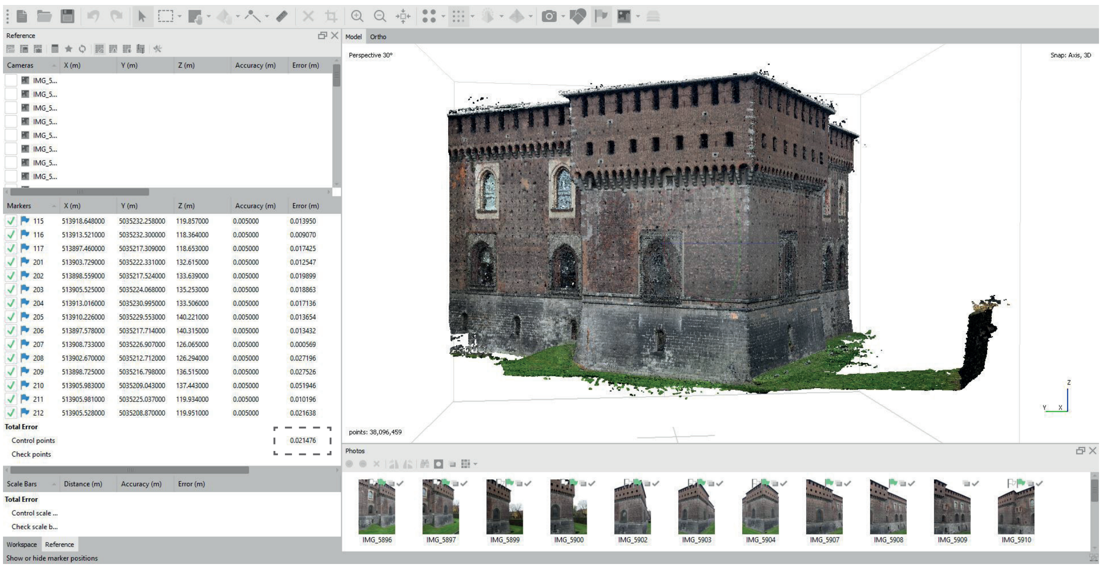
	Nome	Codice identificativo	Quota	Coordinata Nord	Coordinata Est	Corr. Az. / Azimut	Distanza ridotta
Stazione	**200**		**125,112**	**5035224,567**	**513873,771**	**136,4529**	
Punto	T201		127,049	5035207,530	513864,184	232,6289	19,549
Punto	T202		125,533	5035214,895	513851,729	273,6759	24,070
Punto	T203		126,006	5035213,427	513843,146	277,7891	32,588
Punto	T204		126,804	5035229,859	513839,174	309,6625	35,000
Punto	T205		126,684	5035224,247	513848,887	299,1823	24,886
Punto	T206		125,693	5035266,584	513867,173	390,0833	42,532
Punto	T207		126,632	5035259,977	513876,236	4,4243	35,496
Punto	T208		124,921	5035296,131	513874,118	0,3087	71,565
Punto	T209		125,189	5035214,644	513864,098	249,1865	13,857
Punto	T210		125,333	5035217,754	513860,675	269,4597	14,762
Punto	T211		125,299	5035221,096	513863,283	279,6543	11,047
Punto	T212		126,262	5035259,977	513884,229	18,2825	36,922
Punto	T213		126,598	5035270,244	513894,827	27,4979	50,297
Punto	T214		125,583	5035232,891	513857,147	329,5525	18,591
Punto	T215		125,466	5035269,835	513902,714	36,2153	53,730
Punto	T216		125,453	5035276,483	513919,635	46,0647	69,274

AA.III.IV _ Photogrammetry and laser scanning: survey position and process data

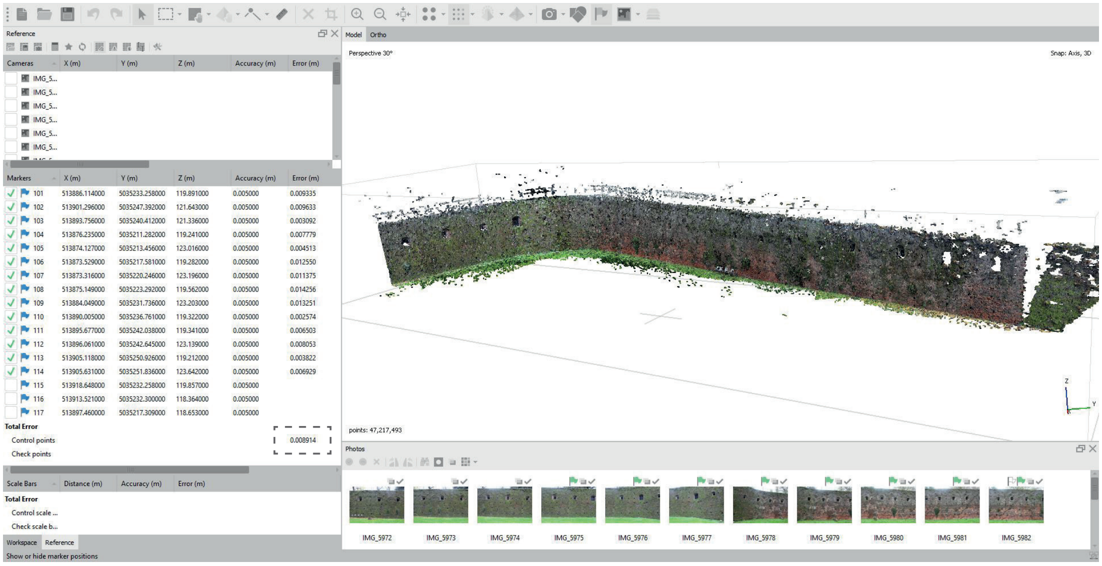
The portions of the building surveyed by photogrammetry and the scanning positions are shown in diagrams. For each processing (both the photographs in Agisoft Metashape and the scans in FARO Scene) the resulting error data are also present.

AA.III.IV.a _ Photogrammetric survey

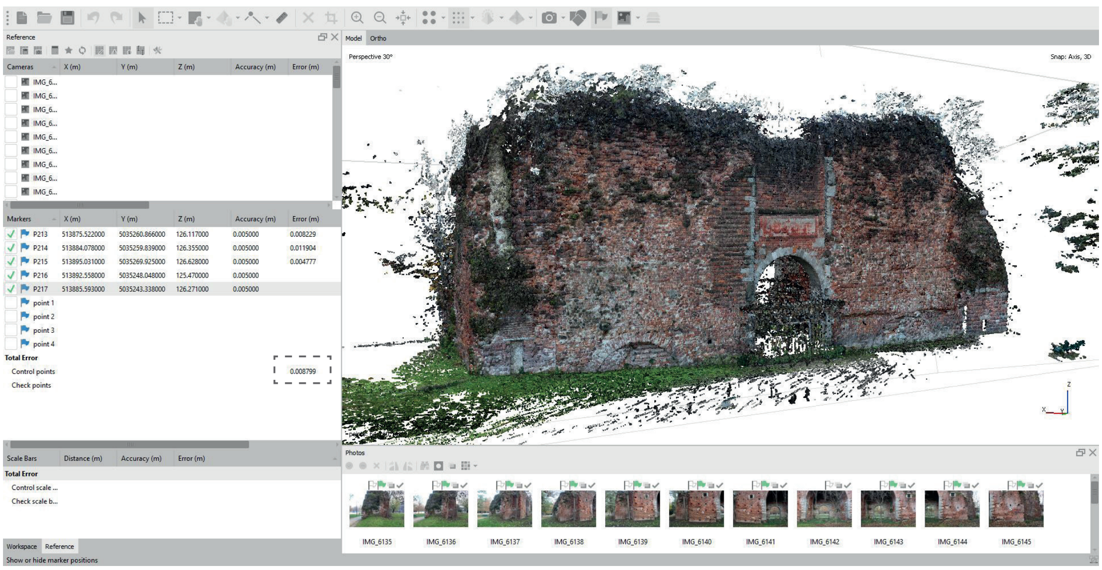




Block 1: the facade of the Castello Sforzesco
Error: 21,50 mm

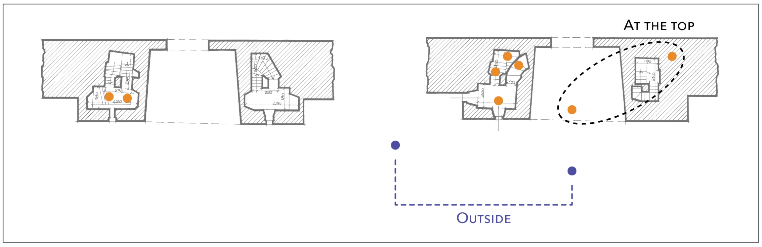


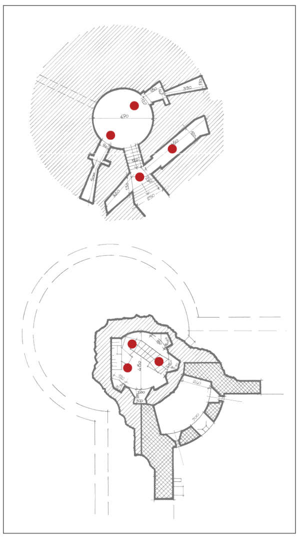
Block 2: the counterscarp wall of the moat
Error: 8,90 mm



Block 3: Porta del Soccorso
Error: 8,80 mm

AA.III.IV.b _ Laser scanning: the first set of scans





Laser scanning

Processed scan sets

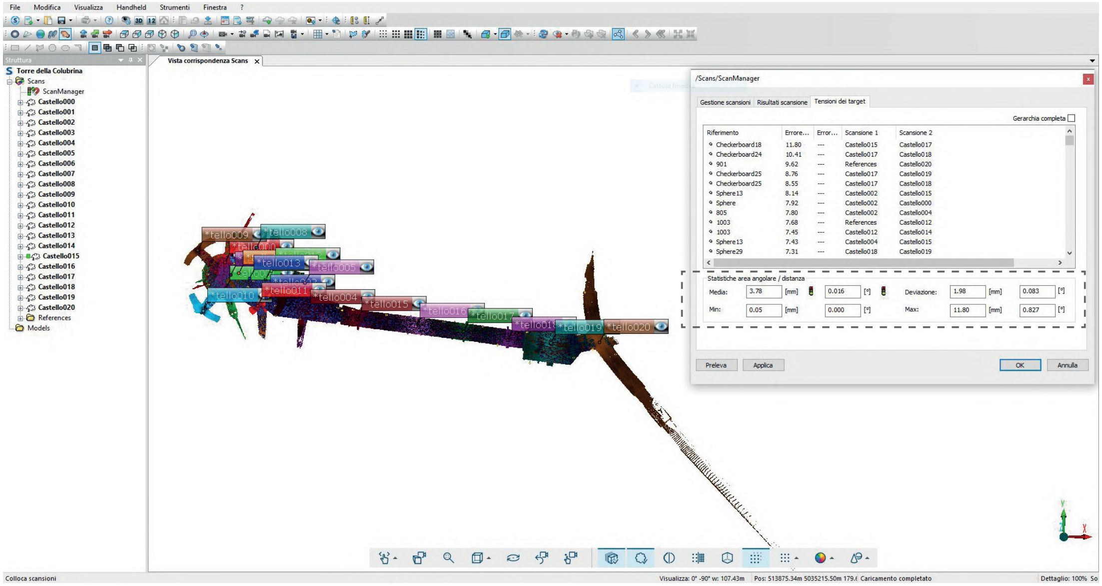
Block A: Torre della Colubrina (red)

Block B: the counterscarp tunnel (green)

Block C: Porta del Soccorso - underground (blu)

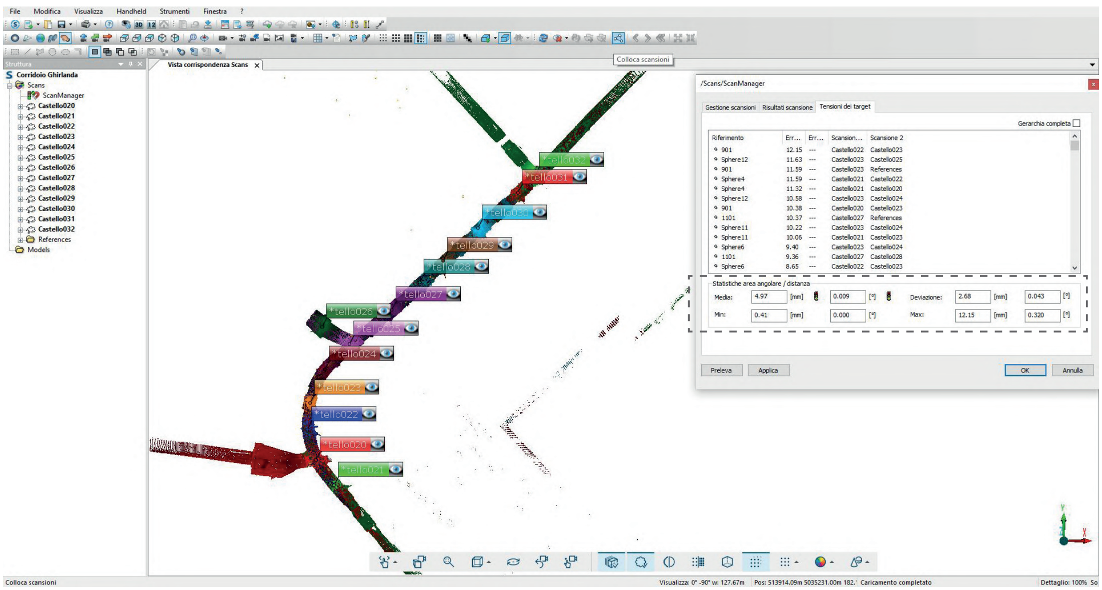
Block D: Porta del Soccorso - stairs (orange)

Block E: Porta del Soccorso - facades (purple)



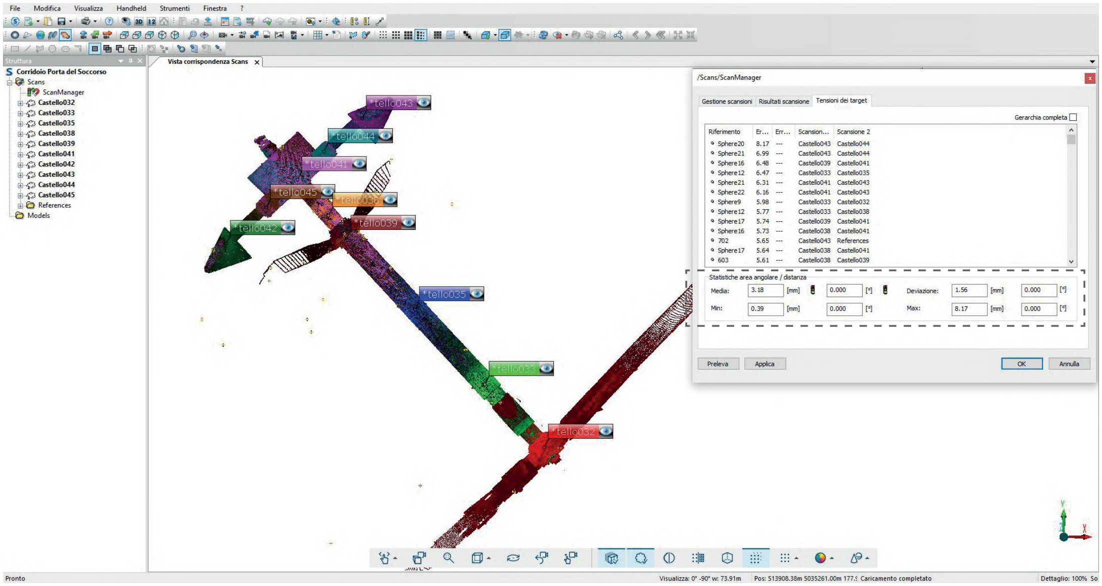
Block A: Torre della Colubrina

Error: 3,78 mm **Error (MAX):** 11,80 mm **Error (MIN):** 0,05 mm



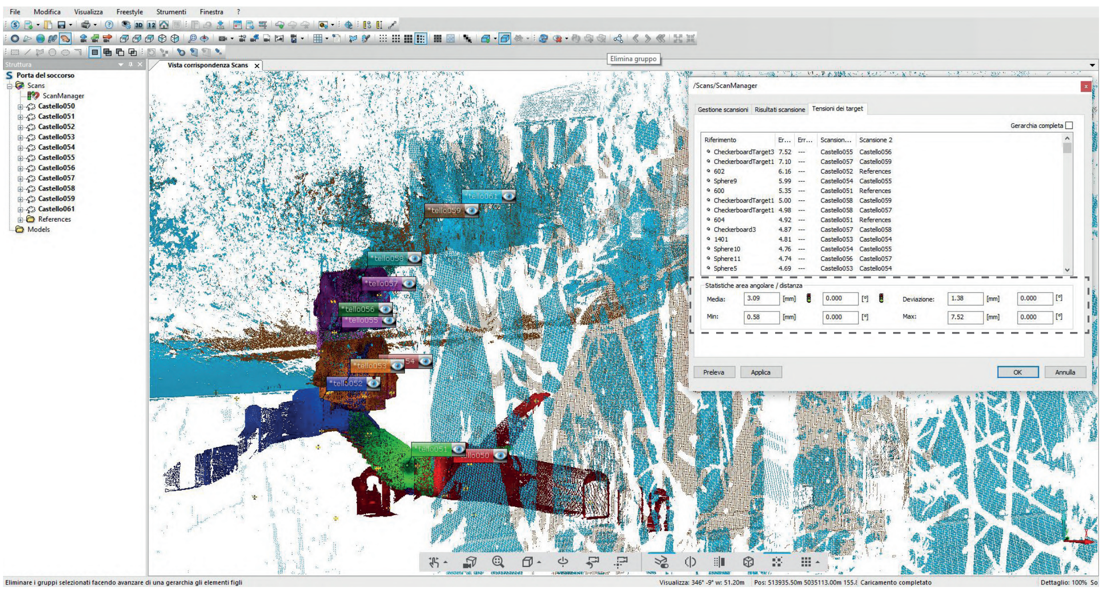
Block B: the counterscarp tunnel

Error: 4,97 mm **Error (MAX):** 12,15 mm **Error (MIN):** 0,41 mm



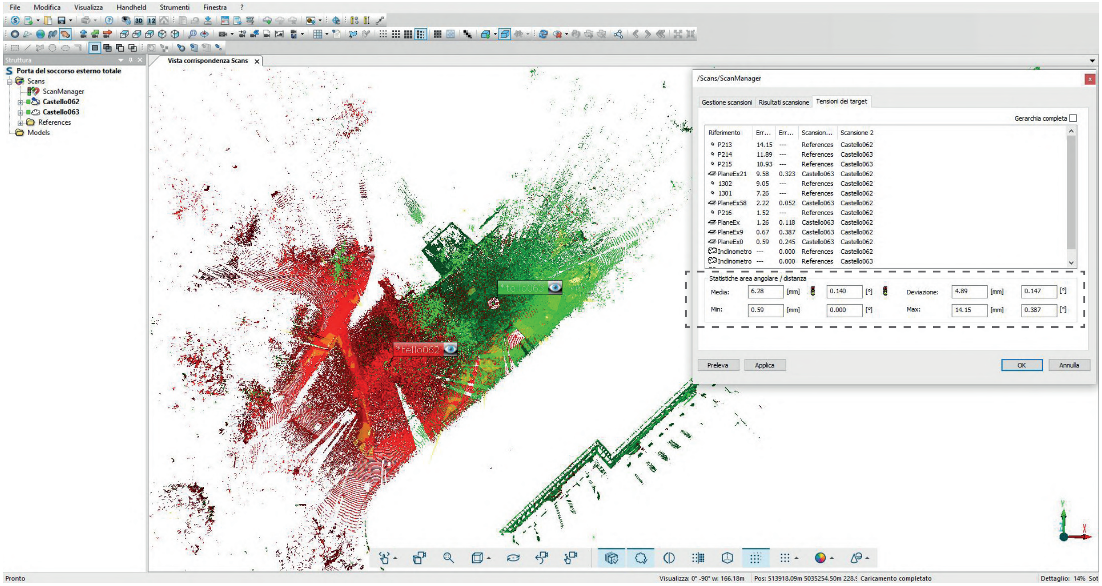
Block C: Porta del Soccorso - underground

Error: 3,18 mm **Error (MAX):** 8,17 mm **Error (MIN):** 0,39 mm



Block D: Porta del Soccorso - stairs

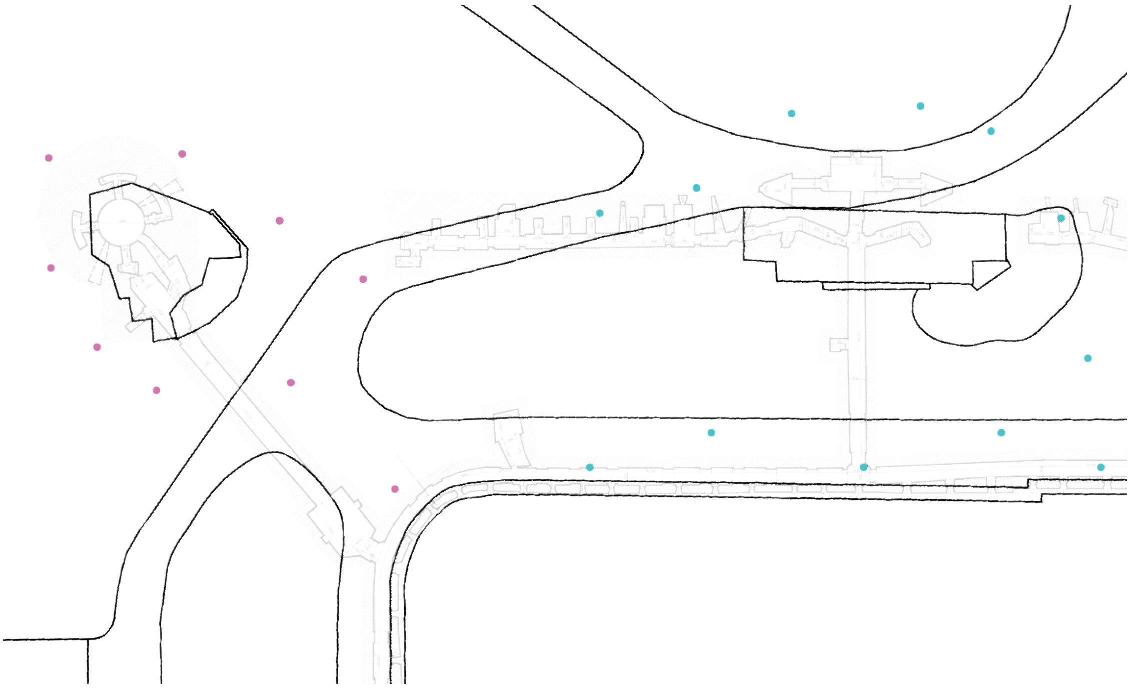
Error: 3,09 mm **Error (MAX):** 7,52 mm **Error (MIN):** 0,58 mm



Block E: Porta del Soccorso - facades

Error: 6,28 mm **Error (MAX):** 14,15 mm **Error (MIN):** 0,59 mm

AA.III.IV.c _ Laser scanning: the second set of scans

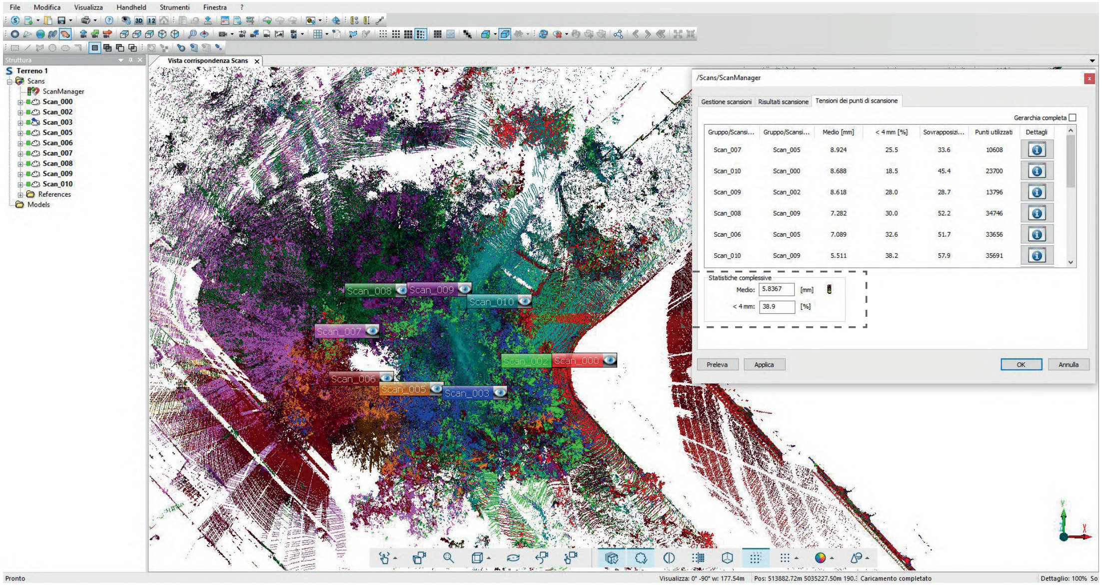


Laser scanning

Processed scan sets

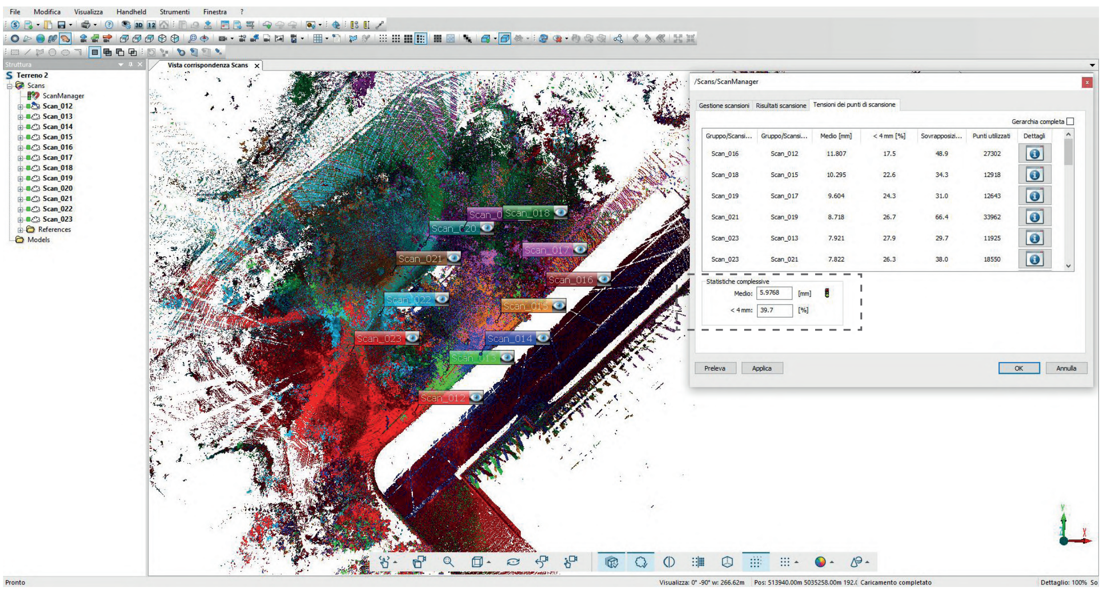
Block GS1: ground surface - part one (pink)

Block GS2: ground surface - part two (light blue)



Block GS1: ground surface - part one

Error: 5,84 mm **< 4 mm:** 38,9 %

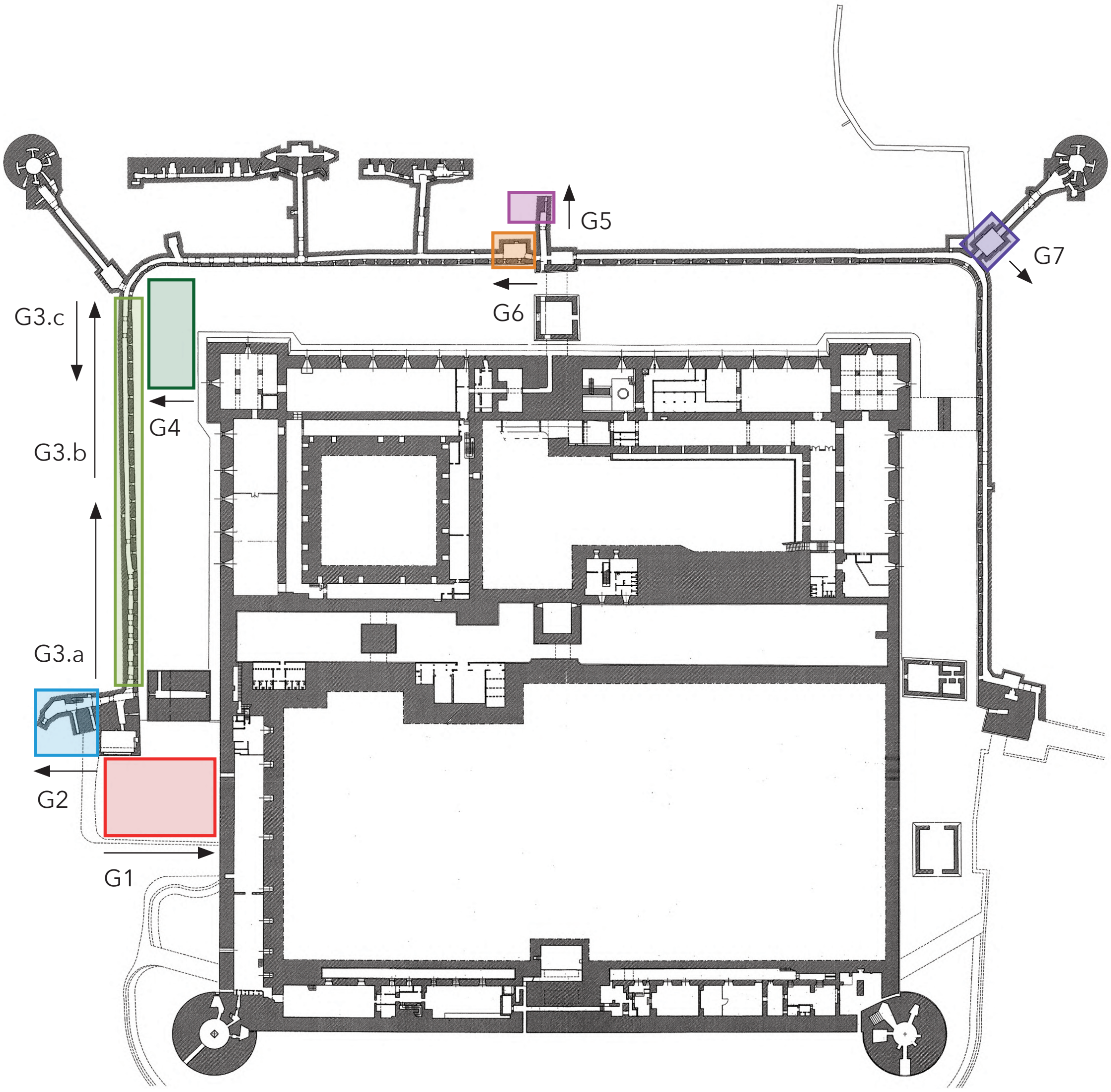


Block GS2: ground surface - part two

Error: 5,98 mm **< 4 mm:** 39,7 %

AA.III.V _ The radargrams

The appendix does not report the entire sets of scans but only the significant radargrams for each of the areas studied.



The black arrows next to the georadar survey areas indicate the direction of the scans.

Georadar

Block G1: Rivellino di Santo Spirito - part 1
(red)

Block G2: Rivellino di Santo Spirito - part 2
(light blue)

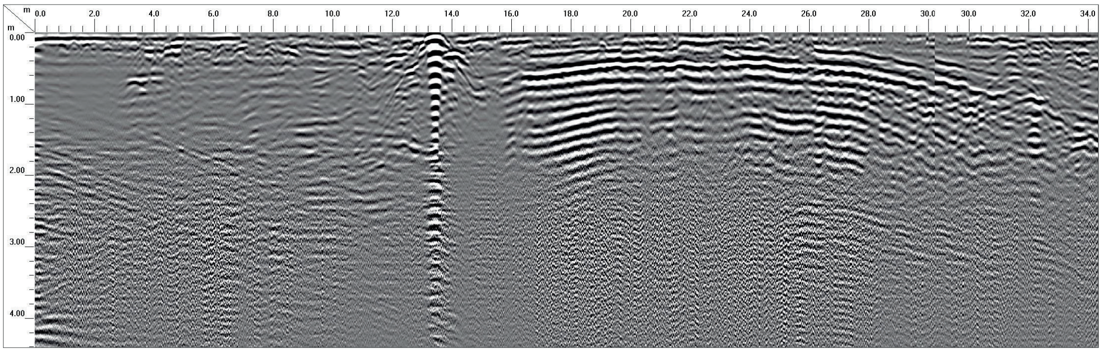
Block G3: the counterscarp tunnel - underground
(light green)

Block G4: the moat
(dark green)

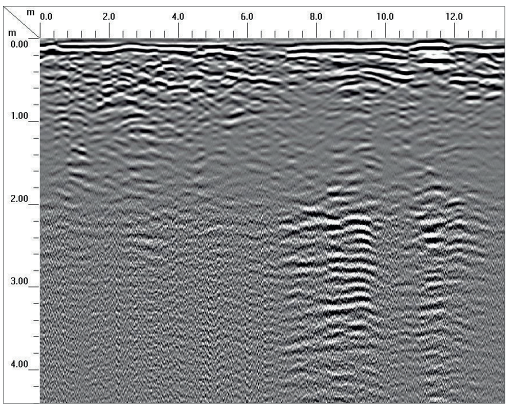
Block G5: Galleria dei Cavalieri
(purple)

Block G6: Galleria verso il Parco - underground
(orange)

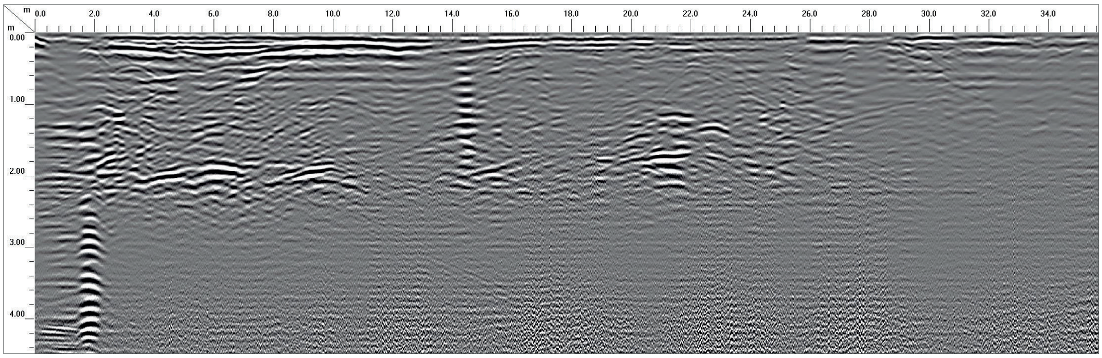
Block G7: Torre della Vittoria - underground
(violet)



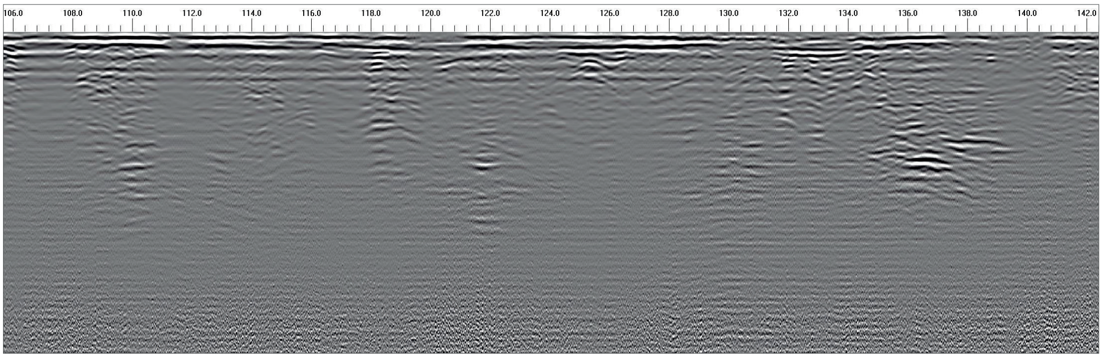
Block G1: Rivellino di Santo Spirito - part 1



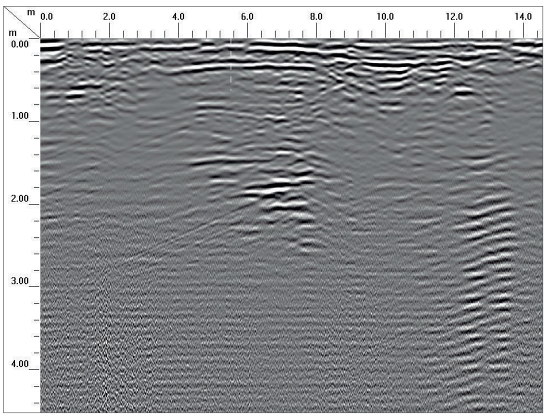
Block G2: Rivellino di Santo Spirito - part 2



G3.a



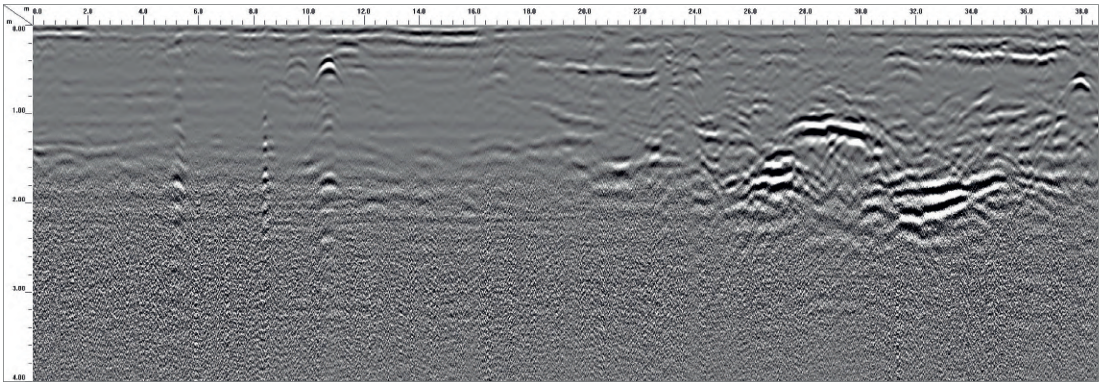
G3.b



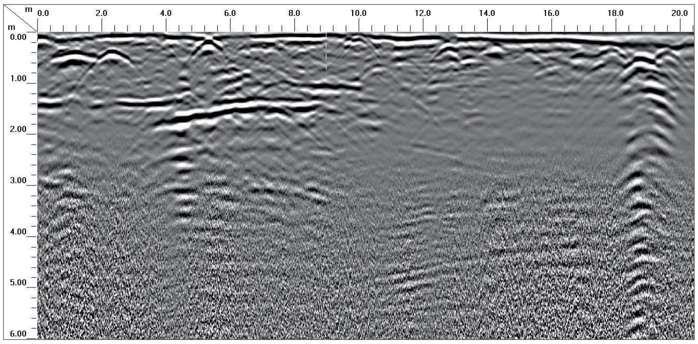
G3.c

Block G3: the counterscarp tunnel - underground

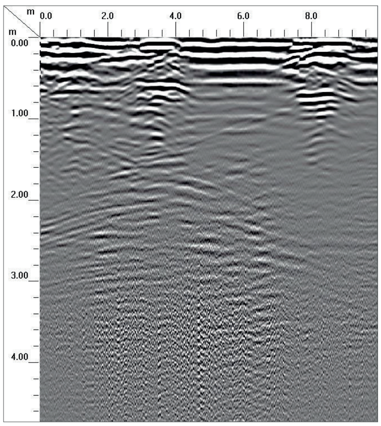
The radargrams shown are presented separately (with different names) as they describe specific portions of the counterscarp tunnel and, therefore, present distinct underground elements.

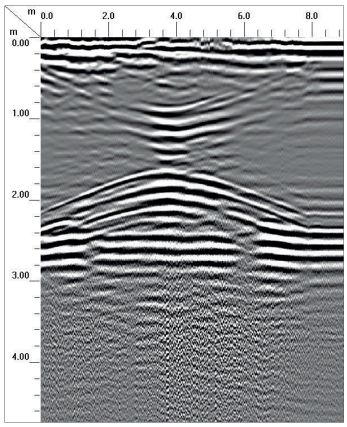


Block G4: the moat



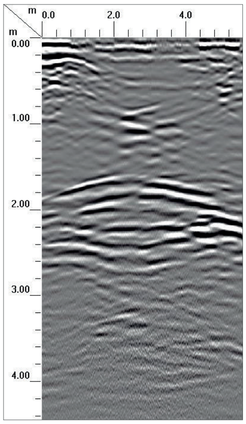
Block G5: Galleria dei Cavalieri





Block G6: Galleria verso il Parco - underground

The radargrams are treated as a single piece of data as they are two scans of the same underground element carried out in parallel within the room called “Galleria verso il Parco”.



Block G7: Torre della Vittoria - underground