INTEGRATION OF DIFFERENT TYPES OF SURVEY OUTPUT AND THE INFORMATION ASSET IN A 3D MODEL OF THE CASTELLO SFORZESCO IN MILAN

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KEY WORDS: Levels of Geometric Information, Digital twin, 3D data, Digitization, Castello Sforzesco, Architectural Heritage.

ABSTRACT:

In recent years, the architecture domain, driven by today's digital transition, has been actively exploring the world of digital twins, also thanks to the technological advancement that supports the progress on the issue. Within this context, the present work deals with the wide world of Architectural Cultural Heritage digitization. It aims to obtain a tool to support knowledge, investigation, and management of the built heritage. The research proposes an approach for digital twin development that comprehensively describes the architectural asset, including elements that are no longer present or visible. For this purpose, the three-dimensional model collects the available heterogeneous geometric datum, inevitably characterized by different levels of accuracy. The digitization model designed involves the coexistence of objects belonging to different Levels of Geometric Information (LOGI). All types of data then cooperate in defining the overall geometric information. Therefore, this framework allows for exploiting geometric information from both geomatics digital surveys and historical sources. This system allows obtaining a digital model that includes the different evolutionary phases of architectural assets by providing an overall view of these structures, an essential notion for operating properly on this kind of architecture. The digitization system was tested on a particular case study, the Ghirlanda of the Castello Sforzesco in Milan. The complexity of the property and the richness of the information heritage guided this choice, providing the basis for an appropriate and effective experimental activity.

1. INTRODUCTION

In the last decades, the world has dealt with an increasingly preponderant Digital Revolution. This exponential phenomenon, which has taken on unparalleled relevance in recent years, has led objects, services, and processes to change their form, thus taking on a digital character. In this climate of transformation, the field of architecture, and specifically of architectural heritage, is also experiencing the effects of the Digital Era. It finds great support at the governmental and legislative levels, with important incentives and guidelines affecting this area, both nationally and internationally (Direzione Generale Musei, 2016; Council of Europe, 2017; MiBACT, 2017; IPER, 2018). A primary case is the 2030 Agenda (United Nations, 2015). The text promotes the strengthening of efforts to safeguard the built heritage, emphasizing at the same time the centrality of the advancement of ICT for overall development. Similar directions come also internally to the single nations, which focus greatly on the enhancement of the architectural assets. An example is the recent PNRR (Italian Government, 2021), the National Recovery and Resilience Plan approved in 2021 by the Italian Government.

Today's technological impetus seems to have infused new energy to revive the enhancement of Architectural Heritage, which is becoming increasingly important within the identity of territories and their communities. All this results in a conspicuous amount of research and trials on the digitization theme, with multiple declinations and purposes. Indeed, it is dealt with in several areas: survey, monitoring (Lerario and Varesano, 2020; Tarani et al., 2020), facility management (Beak et al., 2019), information fruition (Carrion-Ruiz et al., 2019; Dhanda et al., 2019), etc.

This renewed attention to the preservation of built heritage assets, supported by today's tools and technologies, has also addressed new studies on the issue of digital twins. It is possible to trace many examples of digital reconstruction of lost buildings. Such activities aim to transmit knowledge and experience the no more existing assets (Campi et al., 2019), also exploiting ICT solutions such as Virtual Reality (Barone and Nuccio, 2017; Bolognesi and Aiello, 2020) and Augmented Reality (Canciani et al., 2016). The topic of digital twins is finding also great responses primarily for assets still existing on the territory. Researchers are always testing new approaches and solutions for their enhancement (Banfi and Mandelli, 2021; Pulcrano, 2022), knowledge (Santagati et al., 2018; Bolognesi and Aiello, 2019; Palma et al., 2019; Aiello et al., 2020), management (Osello et al., 2018; Banfi et al., 2019), preservation (Chiabrando et al., 2017), etc. This multiplicity implies that the internal system of the various models and their development process can vary depending on the final goal (Lopez et al., 2019).

This research work, however, starts from precise assumptions that lead it to detach itself from the cases named in the previous lines. There is no doubt that knowledge of an architectural asset inevitably passes through the study of its history and the processes that affected it. For this reason, a digital twin must consider not only the restitution of the state of affairs but must also describe the previous phases, the elements that no longer exist, or those for which, although not visible, it is possible to assume a partial presence. Therefore, for this purpose, the

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https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-219-2023

digitization system must allow the collection of geometric information from sources of a varied nature and with different levels of accuracy: from point clouds to historical iconography, passing through ancient texts and cartographic documentation.
The state of the art on this precise digitization approach shows some works dealing with the specific topic of architectural palimpsest analysis. Although some of the work is limited to mapping the structure still existing (Micoli et al., 2013; Barazzetti et al., 2015; Barazzetti and Banfi, 2017; Campi et al., 2017; Stanga et al., 2017), it is possible to identify some of them that deal with both the digitization of the current state of architectural heritage and previous historical phases. These digital twins (Guidi and 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 what is still visible, complete with the reconstructions of the elements no longer existing but deduced from the study of the documentation. Since they are sparse cases, it is challenging to identify a consolidated and common procedure. What emerges from these experiences is the centrality of managing the coexistence of geometric information with different levels of accuracy, obtained from heterogeneous reference sources (Rodriguez-Gonzalev et al., 2017). The topic is not new, and some works have dealt with it, proposing different solutions (Guidi et al., 2009). Some studies (Banfi, 2019; Banfi, 2020) propose classification systems to organize reference information and model components, based on their accuracy. Systems of this type provide structure and rigor to the digitization process and start from the observation of the sources themselves and their characteristics.
It is immediate to perceive that studies and activities on the topic of digital twins are countless. On the other hand, it is also possible to notice that there is still no clear and established way regarding the digitization approach pursued with the research work described in the text.

The present work is set in this contest, working with a peculiar case study, the Castello Sforzesco in Milan. Its historical and architectural complexity and particular wealth of heterogeneous information and sources make it an ideal case study to test the effectiveness of the proposed system.

2. METHODOLOGY

In this experimental climate, the present study introduces a digitalization methodology designed to comprehensively represent, in a digital environment, the complex architectures inherent to our built heritage. The implementation of this method culminates in a three-dimensional model that encompasses extant structures, those no longer visible, and ultimately, elements that were formerly constituents of the building but have since been lost. A digital model of such nature is the sole means of elucidating ongoing processes, as well as specific phenomena or junctures identifiable within the architectural system. To thoroughly comprehend an architectural piece deeply entrenched in history, it is deemed essential to incorporate within the digital twin, past historical-architectural strata that are no longer visible or existing.
Consequently, such a digital twin must be equipped to gather data from disparate information sources. Indeed, architectures of this nature are typically associated with an extensive corpus of documents, textual works, and information collected over their lifespan. Contemporary sources, including photographic materials, and conventional and modern survey outputs, among others, complete this ensemble. This results in geometric information with varying levels of accuracy. Furthermore, such data may encompass the entire structure or only a part of it, thereby functioning in a complementary manner.
The proposed system aims to methodically aggregate all available geometric information about an architectural asset, in addition to data generated or traced in subsequent phases. The ultimate objective is to provide a tool that supports and facilitates the comprehension and analysis of intricate structures and their architectural-spatial configurations. The core idea is that this system, supported by contemporary three-dimensional representation techniques and information technology, can make the narrative of these buildings, complex due to their historical and documentary stratification, more straightforward and accessible. Additionally, it serves as a holistic model for future research and insights concerning assets.
In summary, the proposed approach, structured to efficiently manage the incoming novel information and subsequent updates to the digital twin, stems from the desire to achieve a suitable information tool that underpins the management of built heritage.

2.1 The digitization model and the LOGI system

The approach was based on the issues that emerged from the analysis of the cultural heritage world. Considering architectural assets in general, what arose first, was the fragmentary nature of the available geometric documentation. 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 to develop a system that allows easy updating when new detailed surveys or unpublished resources of geometric knowledge become available. The basic idea is to produce a 3D model with multiple levels of accuracy, derived from the material at disposal, often heterogeneous in terms of accuracy. The structure stems from the idea of LOGI: Level of Geometric Information. The digitization method envisaged provides for three, into which the available material is divided and according to which the various elements of the building are then modeled. The differentiation is made according to whether they are spaces and structures investigated by the modern geomatics survey, whether they present only a document collection, or whether they are only present as a hypothesis as they are no more existing. The definition of these modeling 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 modeling (Banfi, 2017; Brumana et al., 2018).
The approach to digitization of geometric knowledge has been graphed in Figure 1 and it is structured as follows:

- LOGI 1. The first level collects the objects modeled on the hypotheses derived from historical documentation. The latter consists of graphics, cartography, iconography, and photographic material. Therefore, this level leads to simple three-dimensional elements that materialize structures that are no longer visible but probably present. This information, although often approximate, is essential for the planning of interventions.
- LOGI 2. This level includes documents produced using traditional surveying methods, such as classic geometric surveying and trilateration. It is common that such documentation, as in the case of the Castello Sforzesco (in the experimental stage), is partial or does not describe completely the surveyed elements.
- LOGI 3. It represents the highest level in terms of details and accuracy. Information and material from modern geomatics

surveys fall within this group. They are for example point clouds and surveys with a level of accuracy of a few millimeters. Bearing in mind that the approach aims to generate a support tool for managing the built environment, in the modelling phase, the elements of LOGI 3 require a simplification factor.

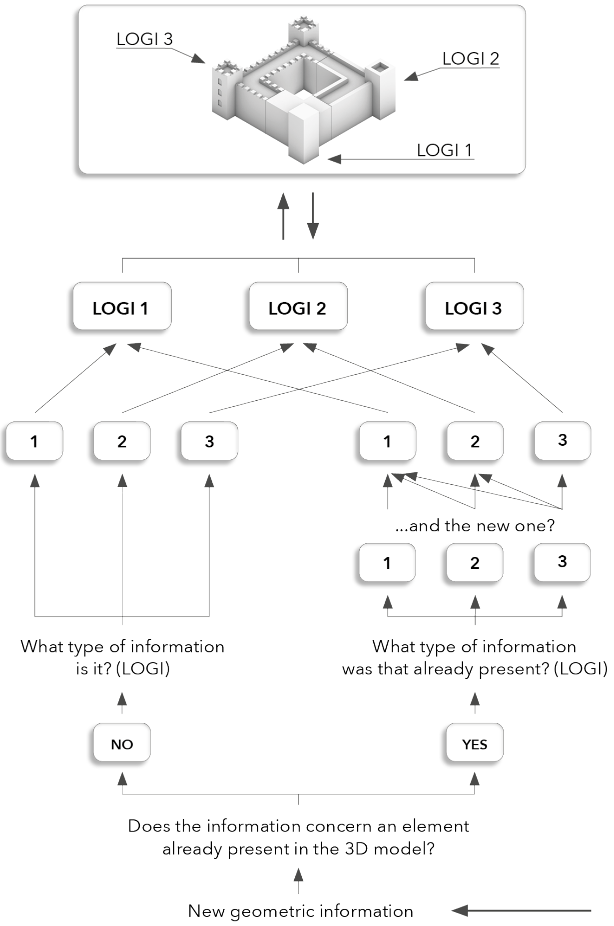

Figure 1. The approach for developing and updating the geometric digital twin

These levels have been defined based on the possible types of sources commonly found when studying and analyzing this type of architecture. As the technology progresses, this organization may be extended by inserting new levels with even greater accuracy.
It is necessary to specify that the association of a source, and its geometric information, to a specific LOGI cannot be based solely on the nature of the source and on the technology used for its determination. The discriminating factor, in the case of uncertainty, 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 hypothesized 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 proposed digitization method does not give any indication of the 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 modeling tools. It is important to add, although it is not the subject of this text, that this approach works in parallel with an information system for the management of sources and related geometric information. This second part of the framework manages the reference material of the model, relating it to the 3D itself and creating a kind of specific database to support the digital twin and as a basis for its legitimization.

3. THE DIGITAL MODEL OF THE CASTELLO SFORZESCO IN MILAN

The work included an experimental phase on the chosen case study, the Ghirlanda of the Castello Sforzesco in Milan (Figure 2).

Figure 2. View of the Castello Sforzesco in Milan

The Castello Sforzesco, a prominent historical architecture in Milan, Italy, boasts a rich and intricate history (Beltrami, 1894; Padovan, 2019). Initially constructed in the 14th century by the Visconti family, the castle underwent multiple reconstructions and expansions. The house of Sforza, the new lords of Milan, initiated a significant transformation of the fortress, converting it into a stately residence. This era saw its embellished with the works of renowned artists such as Bramante and Leonardo da Vinci.
Following the Spanish conquest in the 16th century, the castle's function shifted to that of a military garrison, resulting in massive structural modifications to accommodate the new purpose. In this period, with the Royal Fortress, the castle reached its maximum expansion. The subsequent Austrian and Napoleonic dominations in the 18th and 19th centuries further altered the edifice, as it was utilized for military and administrative purposes, but destroyed the Spanish work. In 1893, architect Luca Beltrami embarked on a comprehensive restoration project, endeavoring to return the castle to its former Sforza-era layout. At this stage, the Ghirlanda was topped. The surviving elements, a few above-ground ruins and the underground infrastructure have survived to the present day.

The present work considers only one part of the Ghirlanda complex, the northwest portion (Figure 3). This area goes from Torre della Colubrina, located in the corner, to the Porta del Soccorso system, including the above-ground elements, the moat and the ground itself. The case study was chosen based on its characteristics, which make it a perfect subject on which to test the digitization system. Given its importance in the area and its deep historical character, the available reference sources are innumerable and varied. Moreover, the numerous modifications over the centuries have made this building very stratified and complex, providing ideal conditions to experiment with the designed approach.

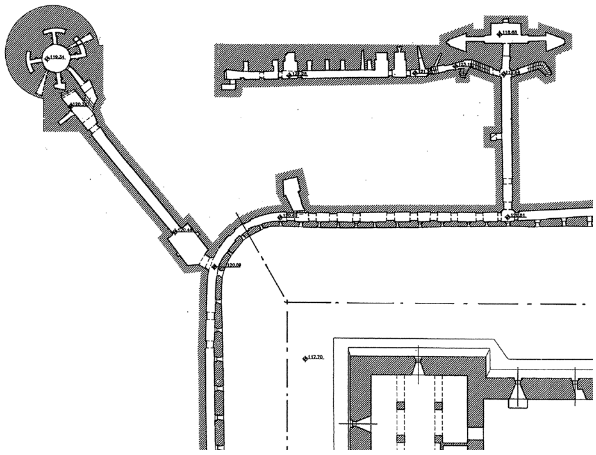

Figure 3. First basement floor plan of the studied area. Some rooms of the Torre della Colubrina (left) and part of the Porta del Soccorso (right) are visible

3.1 Development of the geometric digital twin

The experimentation on the Castello Sforzesco started with its detailed study and the consequent identification of the sources of geometric information for subsequent 3D modeling. 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. All these sources, plus the surveys' outputs, represent the references for the digital transposition of the built complex. Also and above all, they legitimize the result obtained and endorse the choices made for developing the three-dimensional object. Searching and collecting was not a linear process, but reiterative and cyclical. It started by considering the reference figures who have studied the Milanese fortress and then moved on to Italian and foreign archives (due to the various dominations), collections, and online databases. The result is a cluster of texts, iconographic material, historical and modern cartography, graphs of recent surveys, and much more. This analysis involved the entire structure of the asset, to understand the general dynamics that affected it. From it were then chosen the proper references for modeling the case study, the northwest corner of the Ghirlanda. The identified data, although abundant, were not sufficient for developing a model that describes the case study in all parts. In addition, no modern digital surveys were present, thus leaving LOGI 3 devoid of sources and making it impossible to fully test the system.
It was necessary to carry out a survey campaign to complete the geometric information dataset. The topographic, photogrammetric and laser scanner survey involved some of the underground spaces and the elements present at street level, which are the exteriors of Torre della Colubrina and Porta del Soccorso. The survey output is visible in Figure 4 and consists of a set of point clouds of different types (photogrammetric and laser scanner) scaled and georeferenced correctly thanks to the topographic and GPS data obtained.

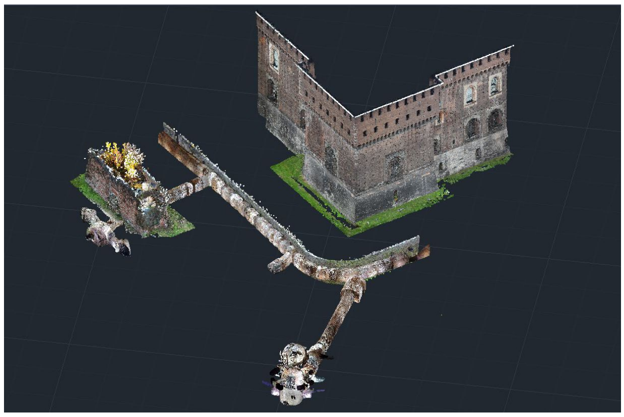

Figure 4. View of the point clouds obtained with the survey

Once the required dataset was completed, the modeling phase began, exploited in Rhinoceros software. The proposed system does not consider a precise tool as it is an approach and not an operational protocol. The decision derives from the possibilities offered by this software, in terms of modeling and interaction with external material.

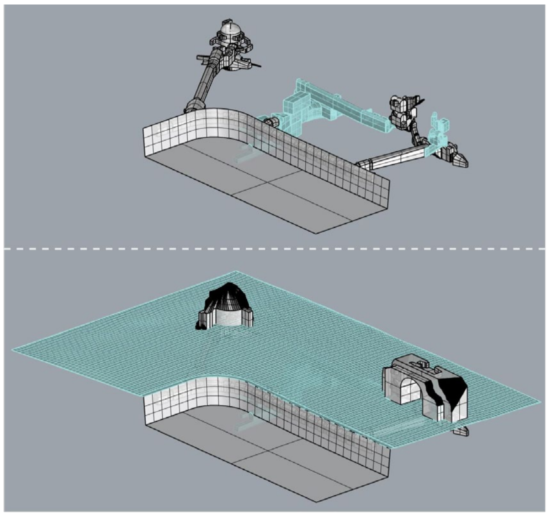

Figure 5. Two views of the digital model with the elements of LOGI 2 and 3

The first elements developed are those related to LOGI 3, namely the spaces surveyed for the experimental activity. These are the structure of Torre della Colubrina, the counterscarp tunnel, the complex of Porta del Soccorso, the counterscarp wall, and the moat ground surface. All these blocks were modelled in Rhinoceros based on the point clouds, and they are visible in Figure 5 with a grey color. The digital twin was completed with the principal sources, which legitimize the 3D model itself. These sources support, at the same time, an understanding of the shapes.
The second phase involved the blocks of LOGI 2 visible in Figure 5 in light blue. These accessible spaces only present information derived from traditional surveys. In this specific case, the sources are mainly paper graphics derived from a geometric survey by trilateration carried out in the 1990s and a CAD plan drawn in 1:200/1:500 scale detail. This group also includes the terrain shape, obtained from the Digital Terrain Model (DTM) data made available by the Italian Ministero dell'Ambiente e della Tutela del Territorio e del Mare. The one-

meter grid of the LIDAR survey can’t properly return the land model, due to the insufficient number of points collected in the area. 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 elements assumed from the historical documentation complete the 3D model. Therefore, these latter are the structures assimilated with LOGI 1, as the original volume of the Ghirlanda or the former level of the moat, in yellow in Figure 6. The dimensions of these components have been extrapolated from the various historical documents. The planimetric geometry of the Spanish Bastions, for example, derives from the Teresian Cadastre of 1751, and their vertical development instead from some iconographic documents. The result, therefore, consists of elementary and approximate geometries that nonetheless allow for stimulating considerations on the relations with the context and the still visible structures of the asset.

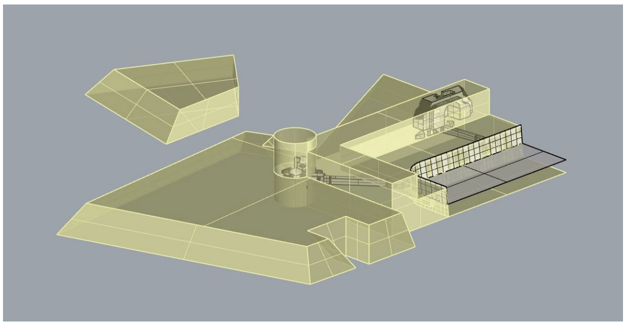

Figure 6. Model with elements of LOGI 1 (in yellow)

It is evident, observing the images, the great strength of today's three-dimensional representations in the domain of complex and strongly stratified architectures. They greatly facilitate understanding of these buildings, and the spatial dynamics present. Furthermore, downstream of this description, it is possible to observe how this approach allows information, that usually would not be approached and evaluated in the same environment, to communicate with each other. It facilitates this process by equalizing the language of all sources. It makes the information three-dimensional but keeps it separate in the different levels. This organization also makes it easy for the digital twin to evolve as new information comes in. The components change levels, and the model modifies itself in an attempt to represent the current and past state of affairs more accurately.

3.2 The digital model as a place for knowledge

Below are some of the results obtained from the analysis of the 3D model. It not only facilitated understanding of this asset but also introduced stimulating issues and insights for further study and research. The aim is to show how a digital object, such as this one, also allows its self-improvement and enrichment. It is possible since it highlights topics of possible deepening, generating the opportunity to update and enrich the model with new information. But this is also achieved thanks to the characteristics of this type of model, due to the interaction between geometric information derived from heterogeneous sources.

The first observation 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 today's Topographic Database and the volumes in the model it is immediate to wonder how much of these structures are still present below the ground level of Parco Sempione or the neighboring streets. The image (Figure 7) gives an idea of this and suggests possible areas of investigation or surfaces to be careful of in case of intervention. It gives rise, for example, to the idea of developing, from this type of digital object, building-scale constraint maps capable of working three-dimensionally, exploiting the information even of hidden structures such as ramparts.

Figure 7. Zenith view of the Spanish Bastion (in green), superimposed on the Teresian Cadastre and the DBT of the area

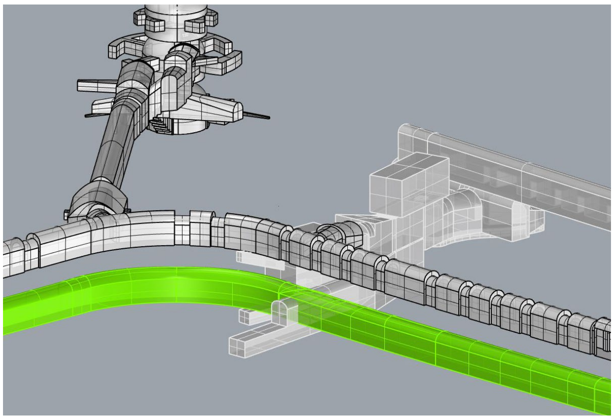

Figure 8. The intersection between the Casamatta Celestino and the lower counterscarp tunnel (in green)

Another issue deals with the hypothesis of the second counterscarp tunnel, modeled in the 3D. Considering the original depth of the moat and the position of the available walkway, its keystone was placed at 119.10 m a.s.l., two meters below its current walking level. Nevertheless, the model reveals situations that contradict, or at least revise, the hypothesis itself. At this elevation, it would intercept other known and currently walkable structures, such as the Casamatta Celestino (Figure 8). 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. The entanglement prompted further investigations that refuted the original hypothesis and

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thus denied the presence of such a pathway. Following this, the model took on a new configuration, updating its components.
A third point concerns the complex of Porta del Soccorso. Observing the plan, it was also possible to identify a large volume of the structure not yet surveyed. Stairs occupy, in fact, approximately 60% of the total cubature, the innermost and adjacent to the vaulted passage. This simple observation 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 9), where the vertical block surveyed and the 5,30 meters wide, whose massive character and possible articulation are still in doubt.

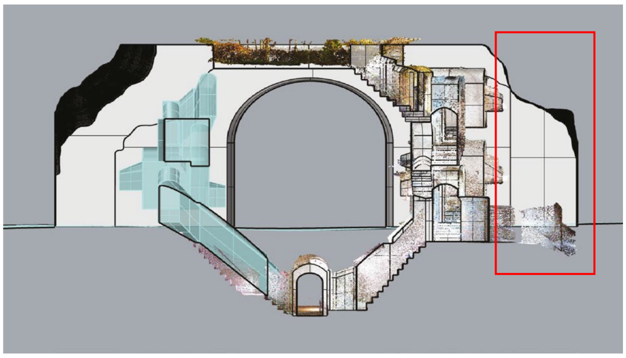

Figure 9. Cross section of Porta del Soccorso. The red line indicated the not surveyed volume mentioned in the analysis

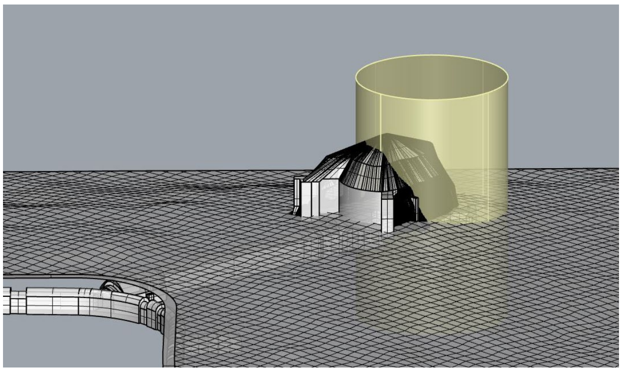

Figure 10. Comparison of the ruin of Torre della Colubrina (with corner caponier) and the original volume

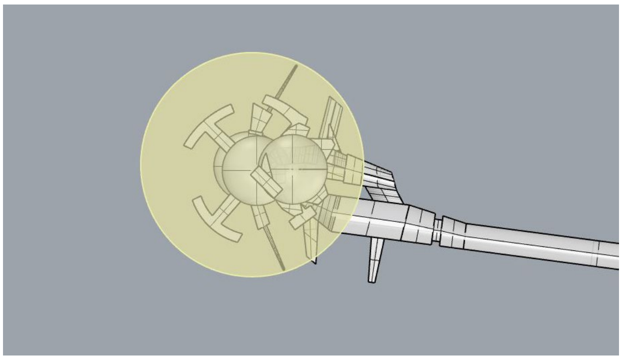

Figure 11. Top view of casemates of Torre della Colubrina with its original volume

A similar situation emerges by observing the relationship between the current configuration of Torre della Colubrina and the hypothetical original volume (Figures 10-11). In addition to raising questions about what may still be present under the grassy surface of Parco Sempione, the model makes wondering about the original massive volume of this structure and how it was organized internally (apart from the still practicable casemates). One hypothesis envisages the presence of secret snail scales, designed by Leonardo da Vinci, which could have been inserted analogously also in the uninvestigated masonry of the Porta del Soccorso. This may only be conjecture, but there is no doubt that this kind of analysis opens up countless questions and insights, aimed at discovery and knowledge.

These are just some of the many situations and issues encountered with the development and study of the digital model. Modeling software, as seen in this section, allows the three-dimensional object to be analyzed, manipulated, and entered into the dynamics of the building. This process identifies how much can be studied and deepened, to support and validate the various hypotheses formulated. One result of this cyclic system is, therefore, the continuous updating of the three-dimensional model, which is self-feeding. This process leads to a gradually completer and more verified 3D, through the accumulation of new sources and investigation data.

4. CONCLUSIONS

The work explored the digitization of architectural heritage, proposing an approach to describe the built heritage from a geometric point of view. At the same time, it is designed to collect sources and information of different natures and accuracy in the same object, making it possible to exploit the heterogeneous documentary and information heritage of these buildings.

The system has proven its effectiveness. The tool made it possible to successfully bring together sources and information which are not normally considered jointly and managed in the same manner. The work process thus equalized the source information and its language. This transformation was essential to create a model capable of collecting all the existing data, although not homogeneous.
The experimental activity conducted on the Milan case study revealed some themes for possible future directions. Although the model originates as a support for geometric-spatial knowledge, the previous section has shown that this tool can also be a knowledge promoter, highlighting issues and situations to be investigated. Going deeper into this kind of fruition, it would be interesting to test it as a holistic model, on which to base detailed studies. The idea is to consider it a neutral model, loaded with geometric information, on which to carry out specific insights by inserting additional data for analysis based on the underlying 3D. Another line of work concerns the extraction of supporting material from the digital twin itself, aimed, for example, at territorial planning. This area has already been partly explored, experimenting with the extraction of detailed 3D constraint maps, for the Castello Sforzesco area, as a supplement to the spatial scale tools already available.

These possible developments complement the work outlined, sharing its ultimate goal: to support heritage knowledge and facilitate its transmission. Only knowledge, indeed, which in turn allows for a critical understanding of states and phenomena, makes it possible to manage, conserve and enhance the architectural heritage.

ACKNOWLEDGEMENTS

This research was supported by Soprintendenza Castello, Musei Archeologici e Musei Storici. We thank Prof. Claudio Salsi for this collaboration, Dott. Giovanna Mori for the coordination of the Castle resources and both technical and administrative staff.

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