FROM THE DIGITAL TWIN OF ARCHITECTURAL HERITAGE TO THE DEFINITION OF THE CONSTRAINT MAPS. THE CASE STUDY OF THE CASTELLO SFORZESCO IN MILAN

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ABSTRACT:

The work presented here is part of the widespread digitisation process that is affecting the world of architecture and cultural heritage. The text reports part of the activities carried out on the Castello Sforzesco in Milan, in collaboration with its Superintendence bodies. This work proposes an innovative way to draft, in a digital environment, 3D constraint maps, capable of describing and protecting the complex system of structures in that area, especially in the subsoil. The activity began with the creation of a georeferenced 3D model of all the existing architectural elements in the analyzed area of the Castle. The work was carried out on the northwest corner of the fortress, the area between the Torre della Colubrina and the Porta del Soccorso. The modeling activity was based both on data obtained from surveys and historical documentation describing structures that are no longer visible. From the 3D model, it was then possible to obtain all useful data to draw up constraint maps in GIS (Geographic Information System) environment. This latter allows multiple interactions both with the normal surface cartographic information (Topographic Database and others) and with the multitude of datasets available for managing the territory and its subsystems. The constraints consider a 'safety' offset, applied in all three directions. These maps describe the various three-dimensional areas, referring to the different structures present in the subsoil, within which it is recommended to operate with extreme caution, in relation to the position and conformation of the same identified assets.

1. INTRODUCTION

Over the past decades, habits, processes, and tools are increasingly subject to a rapid digital transformation, which is also consistently affecting the field of architecture, which is experiencing the effects of the Digital Era. In recent years, international guidelines (Council of Europe, 2017; IPER, 2018) have proved to be an important driver, defining the objectives and cornerstones of this phenomenon. Some examples are the 2030 Agenda (ONU, 2015) and its guidelines, and the great incentive of the PNRR in the Italian context. This climate has set the stage for countless studies, insights, and trials about digitalization in the AEC sector. This phenomenon is addressing research through different themes, from BIM for facility management in new buildings (Riexinger et al., 2018) to the tourist fruition of architectural cultural heritage (Barone and Nuccio, 2017; Partarakis et al., 2017; Agnello et al., 2019; Bolognesi and Aiello, 2019; Carrión-Ruiz et al., 2019). This transition to the digital world is now a prerequisite to continue protecting our Cultural Heritage (Battini and Landi, 2015; Gribaudo et al., 2017; Tommasi et al., 2019). For the assets of the Underground Built Heritage (UBH), however, the current procedures are not so well structured to enable congruent management and protection. Although there is no shortage of experiments and studies on the subsoil elements safeguarding topic (Smaniotto Costa et al., 2021; Varriale, 2021; Gorgoglione et al., 2023; Smaniotto Costa et al., 2023), it is not yet possible to identify a consolidated approach.

The work described in the following paper deals with these issues through the case study of the Castello Sforzesco in Milan. This experimentation has developed from a wider activity, conducted within an agreement with the Superintendence Body of the castle.

The potential of the three-dimensional object, in terms of describing a complex architectural system (Stanga et al., 2017; Banfi et al., 2019; Bolognesi and Aiello, 2020) such as the one observed, combined with the need for greater protection of the existing heritage, have laid the foundations for this research. The aim of this in-depth study involved the elaboration of constraint maps, extrapolated from the 3D model and drawn up for each individual structure (and infrastructure) that constitutes the Milanese Castle. It was possible to obtain several maps that consider different and complementary architectural elements from time to time, also managing the constraint in terms of vertical development.

These tools aim to support the conscious management of the built environment, the soil, and the subsoil. They complete the contents of those on a territorial scale, which already exists for municipalities.

As far as the Lombard administrations are concerned, LR 12/2005 establishes that the Piano delle Regole (PdR) of the Piano del Governo del Territorio (PGT) identifies the system of constraints and the buildings and areas subject to protection (or caution for areas at archaeological risk). As can be seen in Figure 1, the Castello Sforzesco area and its surroundings are characterized, simply and indistinctly, by two constraints. The first concerns elements with architectural and/or archaeological prescription of direct protection (Legislative Decree 22-01-2004 n. 42, Part II - Title I, Articles 10-11), and the second aimed at safeguarding areas with conspicuous characteristics of natural beauty or geological singularity (Legislative Decree 22-01-2004 n. 42, Part III - Title I, Art. 136.1.a, .b). For the entire area, there is also the indication of archaeological risk. Type A risk is for

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the innermost portion of the city up to the limit defined by the north side of the moat and type B is for the area towards Parco Sempione.

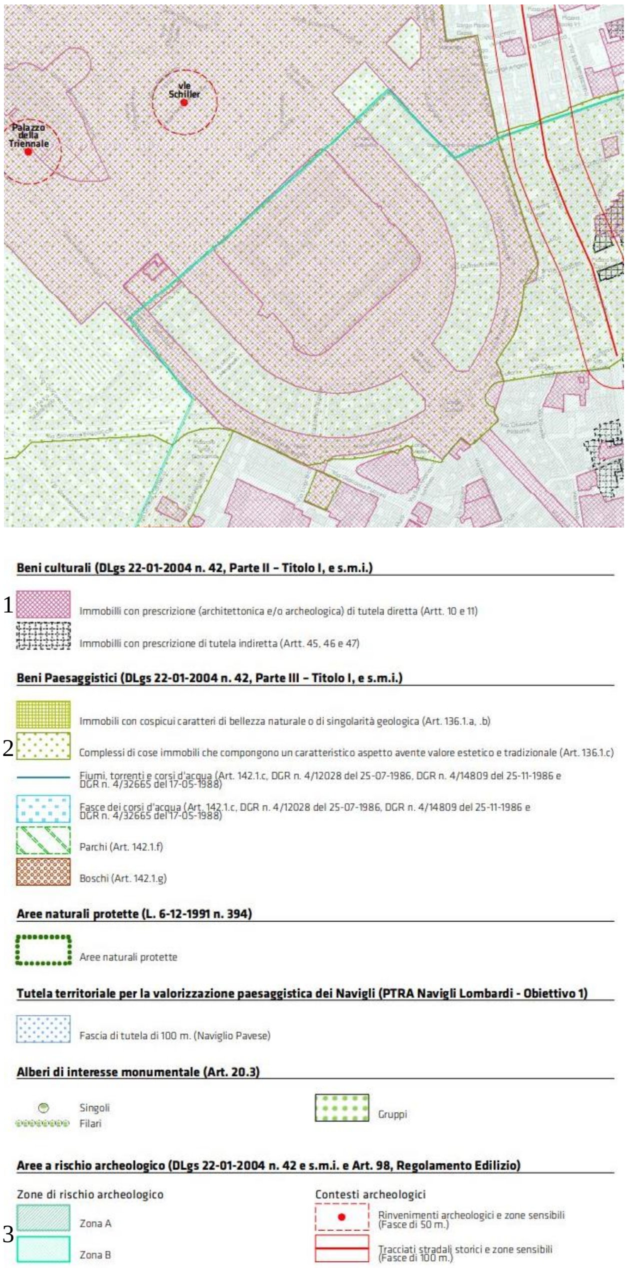

Figure 1. Extract from Table R.06/2D ("Vincoli di Tutela e Salvaguardia"), Piano del Governo del Territorio (PGT) of the Municipality of Milan. The area is under architectural/archaeological prescription (1) and has archaeological risk (3). In addition, buildings inside the area, including the Castello Sforzesco, are classified as elements with aesthetic and traditional value (2).

This discrimination does not seem to consider the whole apparatus of the Ghirlanda and the Spanish Bastions. Those structures occupy a considerable portion of the park's subsoil (Figure 2), making even this northernmost area assimilable to a type A archaeological risk zone.

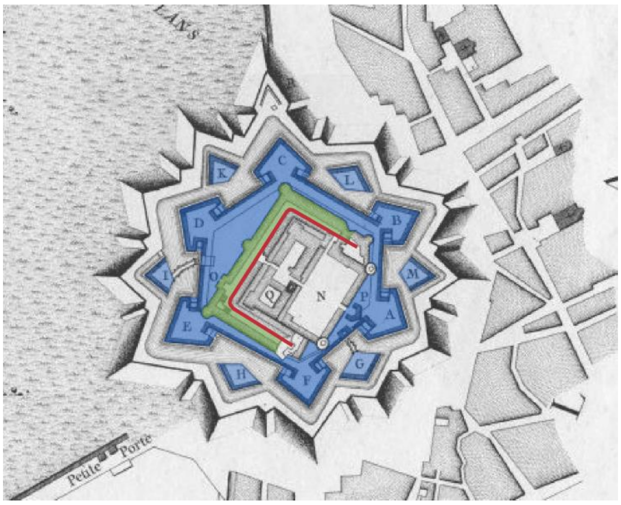

Figure 2. Position of the Ghirlanda and the Spanish Bastions with respect to the current limit of Parco Sempione (red line). Scheme obtained on the map "Plan du chateau de Milan pris par l'Armée de S.A.R. Don Philippe. 1745", Delahaye, Guillaume-Nicolas, 1775.

This information, which may be sufficient for indications on a territorial scale, does not allow for thoughtful and conscious work on delicate areas such as the Castello Sforzesco (or other architectural heritage), where the reasoning requires smaller design scales. Guideline instruments should set the conditions for at least plausible preliminary speculations, thus providing indications of the consistency of the visible and non-visible state of affairs.
This has become evident from recent problems that emerged during the pedestrianization works in and around Piazza Castello. During the excavations, the great ruins of the Spanish Bastions surfaced, lying less than half a meter under the green mantle of the flowerbeds. The work product aims to help in overcoming the difficulties that are still encountered when intervening in these kinds of areas, which are characterized by historical and architectural stratifications, and thus to manage and protect the built heritage.

1.1 The case study

The research work employed as its case study the Castello Sforzesco in Milan (Figure 3), an iconic Cultural Heritage of the city with articulated architecture and rich history.

Figure 3. Bird's-eye-view of the Castello Sforzesco in Milan (Google Earth).

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This tale begins in 1300 with the Visconti and then passes under the control of the Sforza family and other foreign dominations, which have changed its appearance and character (Padovan, 1996; Beltrami and Bellini, 2009; Padovan, 2019). Its history and the many changes over the centuries make it an interesting case study for the activities carried out. The analyzed area, however, is limited to a portion of the Milanese fortress and this consists of the Northwest corner. The moat bordered this portion on one side. On the opposite side, the section studied continues towards Parco Sempione. On the other two sides, the Torre della Colubrina and the Porta del Soccorso define the limits. The volume studied consists of several elements. The first is the moat, whose ground is at a higher quote than the original one. The infrastructure of the Ghirlanda undoubtedly characterizes the area and its spaces are the only ones currently accessible. All these rooms are part of a more imposing structure. It was trimmed at the end of 1800 (Paoli, 2014), during the interventions conducted by Luca Beltrami (Istituto Italiano dei Castelli, 1997). Above ground, there are some ruins, those of the Torre della Colubrina and those of the Porta del Soccorso, whose geometries are still recognizable. Further outside, today’s presence of base part of the Spanish Bastions is almost a certainty. Beyond their border, there was a second moat, which was lost in the same period as the Ghirlanda. It was transformed into a disposal site for the rubble of the Ghirlanda itself.
As a first attempt, the work focused only on this area of the asset, although the aim is to operate on entire architectures, testing this approach as a knowledge and preservation tool for the built heritage in general.

2. METHODOLOGY

The work process involved four phases (Figure 4).

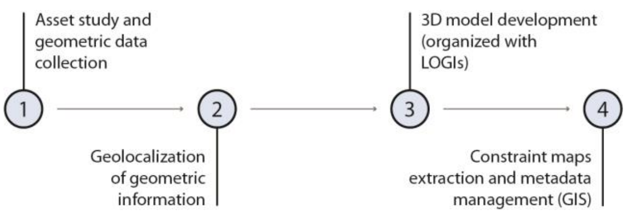

Figure 4. Scheme of process steps.

The first moment was dedicated to the study of the architecture under analysis, addressing both the issue of its current conformation and its historical and architectural evolution. This first phase involved the collection of sources of a different nature: point clouds and other outputs from survey campaigns carried out at the juncture of this study, graphic works from previous works, historical documentation, iconographic material, cartography, etc. This in-depth study made it possible to identify some separate elements within the fortress, deriving from distinct phases of its history, which could then be dealt with separately in subsequent phases.
After placing and georeferencing what was retrieved, the third phase led to the development of the georeferenced 3D model. This stage aimed to provide a three-dimensional object capable of fully describing a complex architecture as the result of interventions and elements from different periods. This representation must also meet the need to convey information about the possible presence of structures that are no longer visible, as they were destroyed or hidden during different historical periods. It was also necessary to describe the areas surrounding the case study, where once stood the imposing defensive structures of which there are still some traces. The model, therefore, gathers information of heterogeneous origin and transforms it into volumes, with an accuracy that varies according to the nature of the resource itself. The level of accuracy of geometric information varies depending on whether the information was traced by reading an ancient text, looking at modern cartography, or in a point cloud obtained through a digital geomatics survey.
For the last step of the work, the 3D representation, which simplifies the understanding of the complex architecture of Cultural Heritage, permitted an agile extraction of geometric information, otherwise difficult to determine. Once the necessary data had been obtained, operations involved moving into a GIS (Geographic Information System) environment. Consequently, constraint maps were produced, which exploit GIS metadata tools to also associate altimetry information with the constraint itself. The choice to move into this environment derives from the various possibilities that such software provides when it comes to handling information on the territory and relating different data and systems. In complex environments, such as the case study, it is essential to create tools, which can be developed in GIS, to support design and implementation. These must examine interactions with the built environment, both above ground and below ground, in the logic of the smart city. (Garcia-Ayllon and Miralles, 2015; Vishnivetskaya and Alexandrova, 2019).

3. 3D MODEL DEVELOPMENT

When working with architectural cultural heritage, it is often not easy to interpret information and historical documents, due to the complexity of the structures and the peculiar articulation of spaces. The use of a 3D object tries to overcome this hurdle, facilitating the understanding of spatial dynamics (Banfi and Oreni, 2020). Precisely for this reason, the formulation of constraint maps starts from three-dimensional modeling. A correct and thorough mastery of the geometric and historical information of these architectures is the prerequisite for developing tools for built environment thoughtful management.
Considering architectural heritage in general, what emerged first, was the fragmentary nature of the available geometric information. From this observation emerges the urgency of structuring an approach to develop a correct 3D model of a building, starting from different types of sources: historical texts, graphic designs based on trilateration, photographic material, point clouds, etc. The three-dimensional product should describe the history of the transformations of the building, thus also reporting the elements no longer visible but probably still present, especially if they relate to the urbanized fabric and the surrounding systems.
In addition to its intuitiveness, it offers great possibilities in terms of geometric modeling, as opposed to other software that struggles with irregular and unique structures such as those encountered when working with architectural heritage (Osello et al., 2018; Guzzetti et al., 2021). In addition, it suits well to the import of reference materials, such as point clouds and raster/CAD files.
To develop a product with the above characteristics, the modeling used an approach based on multiple levels of accuracy, derived from the material available, often heterogeneous and different in terms of precision. The structure has three Levels of Geometric Information (LOGI) into which the available sources are divided and according to which the various elements of the building are modeled. The definition of the three levels takes its cue from the LODs associated with BIM processes (BIMForum, 2018; Alshorafa and Ergen, 2021) and other research work that has developed a similar classification for digital models (Banfi, 2020). The design of

this type of 3D model involves the coexistence of objects at different LOGI. The distinction is made according to whether they are spaces investigated by the modern geomatics survey, they present only a documentary collection, or whether they are only present in the form of hypotheses, as they are no more available. Developing the 3D model in several blocks leads to the thoughtful consequence that each of them can be updated whenever new material is available, either from surveys or as the result of archival research. This approach allows to enrichment and modify the three-dimensional object simply and continuously. Accordingly, knowledge never starts from the beginning but accumulates and evolves. The increasingly comprehensive tool thus supports drafting always-up-to-date constraint maps.

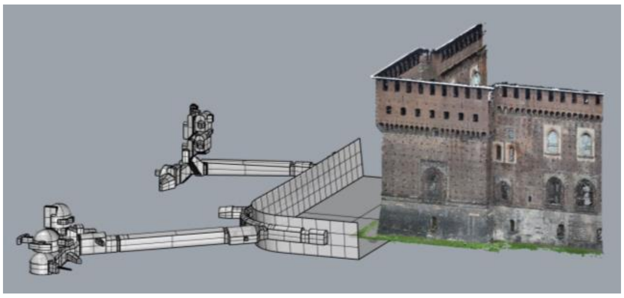

Figure 5. Image of the 3D model showing the underground spaces of the Ghirlanda, and the moat (LOGI 1).

Bearing in mind these criteria, the modeling of the Northwest corner of the Castello Sforzesco has begun. The first elements realized are those related to LOGI 3 (Figure 5). They are the structures associated with a high level of accuracy since they present a modern geomatics survey. These are all the accessible spaces of the Ghirlanda, except for the Casamatta Celestino and Galleria delle Radici. The exteriors of Colubrina Tower and Porta del Soccorso also belong to this group, as well as the ground surface.

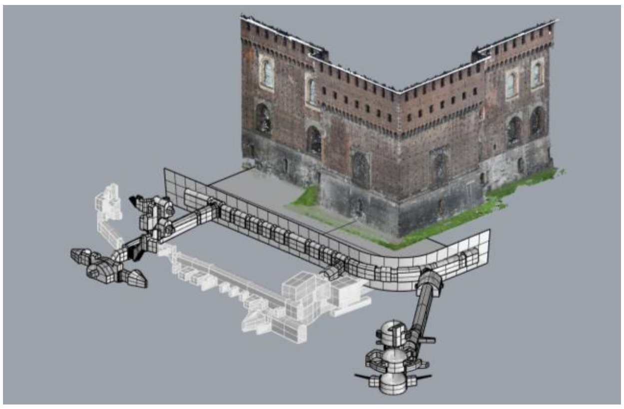

Figure 6. Image of the model with the volumes of the LOGI 2.

The second modeling phase concerned the accessible spaces that do not have geomatics and digital surveys. For these rooms paper graphics are available. They are the output of 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. It is, therefore, the modeling of the blocks of LOGI 2 (Figure 6). They coincide with the lift pump rooms, Casamatta Celestino, Galleria delle Radici, and the casemates and the lift system inside Porta del Soccorso (east side).

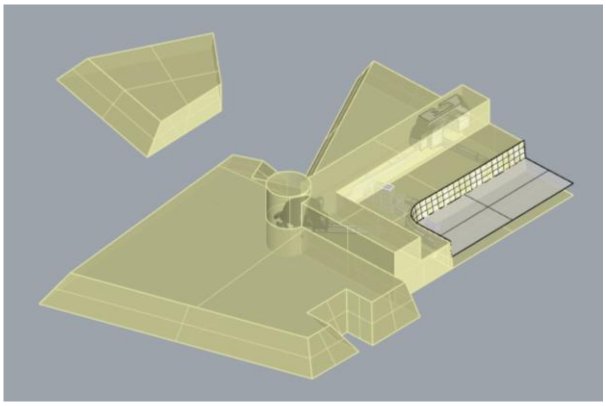

Figure 7. Image of the model with the volumes of the LOGI 1 (Torre della Colubrina, Ghirlanda, and Spanish Bastions).

The 3D model was completed with the elements assumed from the historical documentation, therefore, the structures assimilated with LOGI 1, the lower one (Figure 7). The modeled elements are as follows: the volume of Torre della Colubrina, the second counterscarp path, the original level of the moat, the original volume of the Ghirlanda, and the portion of the Spanish Bastions present in that area. The last two structures were deduced from the study respectively of the Lombardo-Veneto Cadastre of 1881 and the Teresian Cadastre of 1751. All these elements have simple and approximate geometry, they coincide with overall dimensions. However, they make it possible to consider the asset in its complete form, justifying greater protection in otherwise unregulated areas.
Even an initial comparison in the Rhinoceros environment between the 3D model, combined with the historical reference documentation, and the cartographic information of the Topographic Database (DBT), immediately reveals the complexity of the interactions between the Castle system and the city system (Figure 8).

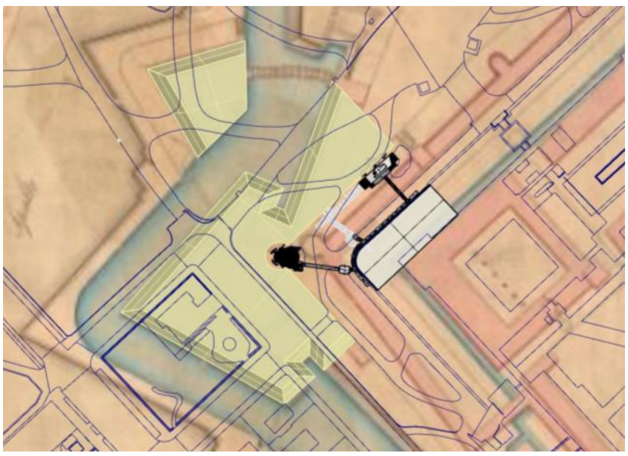

Figure 8. Comparison between the Spanish Bastions model, the Teresian Cadastre of 1751, and the DBT of the area.

It is easy even at a preliminary stage to delineate areas of vulnerability, also considering the superficiality of some underground structures to ground level. In agreement with the current trend of increasing attention and protection of the built heritage within the dynamics of territorial management, a mapping of constraints at the scale of the building may prove to be a valuable element in addition to the tools currently available.

4. THE CONSTRAINT MAPS

Once the 3D model was completed, it was possible to move on to the last phase of the work and thus to the realization of the constraint maps. The three-dimensional representation made it easy to extract the geometric-spatial information required for the mapping phase. The data obtained consists of the perimeter of the area of the structures and the height interval in which the constraint itself is valid. This information is essential where, as in this case, there are structures and fragile elements in the subsoil. Imposing a constraint along the z-axis allows an understanding of the real possibilities for action in such areas. It is evident that where there is an archaeological remnant a few centimeters below street level, in most cases, it will not be possible to present with an intervention. On the contrary, a consistent thickness may allow a project for an urban greening project or even a more impactful alternative.

Before this, the process involved identifying the elements for which maps would then be prepared. As mentioned above, the Castello Sforzesco, like other buildings, presents itself as an ensemble of interventions and structures added over the centuries, often relatively autonomous from one another. Each of these has its characteristics and features, for which separate considerations about protection, therefore, become necessary, also in relation to their position within the new urban system and their state of conservation.

Concerning the Milanese fortress analyzed, this process distinguished several systems, some present above ground, or at least for a considerable portion, to others only developed underground (or whose ruins are hidden beneath the external walking surface). Torre della Colubrina and Porta del Soccorso, point elements of the castle system, fall into the first group. Although their development does not end at the level of the park, a good portion is still visible outside. The protection constraint will operate both above and below the ground (as far as Torre della Colubrina, whose volume remains partially buried), thanks to the association of the altimetry data in the GIS environment. The remaining elements, which develop entirely underground, are the following: the complex of the Spanish Bastions, the external moat, the Ghirlanda, and the system of rooms and paths inside it. The reason for this last distinction derives from the current knowledge of the state of conservation of the two elements. While on the one hand, there is no certainty of the material consistency of the Ghirlanda volume, in the other case the situation is very clear. The intricate succession of spaces that characterizes the interiors of the defensive structure is well known, which requires a more stringent approach in terms of constraints and protection than in the previous case.

After this preliminary phase, the work began with the extraction of the perimeters of the elements (Figure 9), from which the constraint surfaces were then derived. Considering that the working method aims to obtain tools for the built environment management in three-dimensional terms, it was also necessary to analyze the vertical development of the structures. This activity took place in the Rhinoceros environment. As mentioned earlier, thanks to the description and representation potential of these tools, the management of geometric information becomes agile and efficient, even where the structures are very articulated.

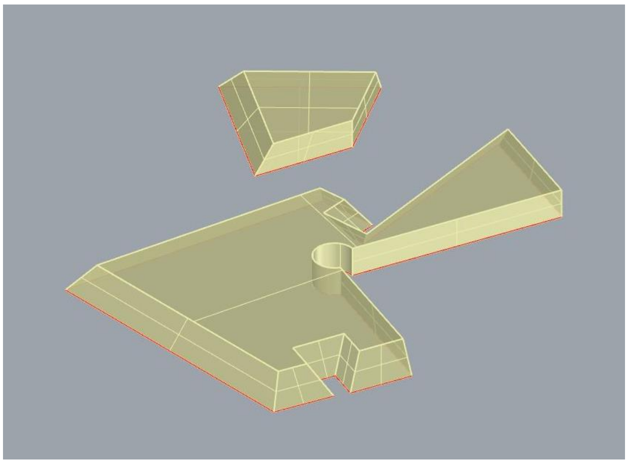

Figure 9. The perimeter of the Spanish Bastions in the studied area. It is with the reference volume.

As a matter of safety, and also because some geometries derived from historical documents whose accuracy may leave room for uncertainty, it was deemed appropriate to apply a security offset to the obtained perimeters. On a flat-rate basis, five meters have been applied for structures belonging to LOGI 2 and LOGI 3, and ten meters for those of LOGI 1. The latter value comes from the observation of discrepancies found between information from today's surveys and that of historical sources, which are, indeed, on the order of 5-10 meters. The offset, possibly confined to the ground elevation when the constraint exceeds that limit, has also been applied to altimetry values (Figure 10). Moreover, the perimeter was regularized, to simplify the constraint application.

The process involved exporting the geometric data in a .dxf file, aimed at subsequent transfer to the GIS environment, exploiting QGIS.

Structure	Border	Elevation	Offset	Final elevation
Spanish bastion	Above	124.50	No	**124.50**
	Bottom	113.10	Yes	**103.10**
		height above sea level		

Figure 10. Example of the manipulation of the height datum through the association of a safety offset where necessary. It has not been applied to the upper border because this latter corresponds to the level of Parco Sempione.

The first operation with QGIS software involved setting up the file in terms of the coordinate system. The 3D model, and part of the reference material, were developed in the official Italian national reference system: ETRS89 ETRF2000 (DM 10 November 2011). This reference system is mandatory for the entire public administration and in the EPSG documents it is referred to as RDN2008. The project, therefore, provided for this setting. 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 perimeters obtained in the previous step were then imported through the .dwf file (Figure 11). The elements became a single shapefile and were subsequently transformed from lines into polygons with the specific QGIS command (Figure 12).

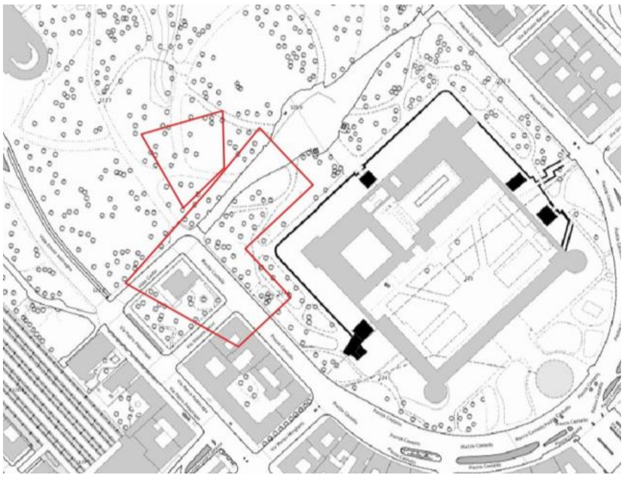

Figure 11. Perimeters of the Spanish Bastions imported in .dxf format into the GIS environment. The reference base is the Topographic Database of the area.

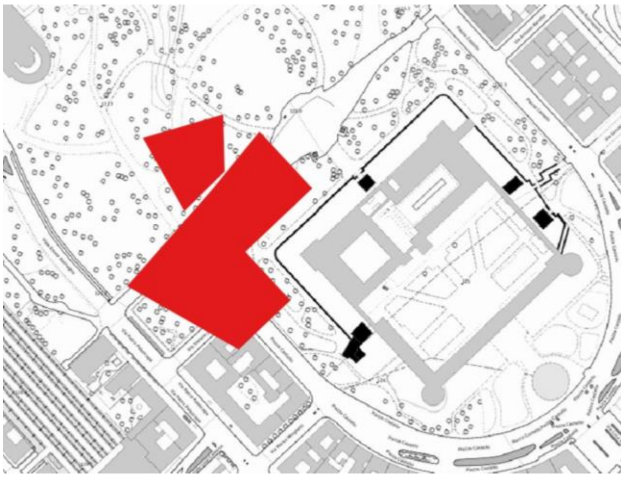

Figure 12. The perimeters imported from 3D, following transformation into polygons, produced surfaces (in red).

The .shp format allows taking advantage of the metadata management tools of that file type. The last part of the work, therefore, produced a structure for organizing the attributes of the surfaces obtained (Figure 13). The table was organized to fulfill specific functions, both IT and practical. The first column provides for the insertion of an ID, which allows the unique identification of each surface and serves as a reference term for the addition of further data. The second column is for the name of the structure to which the constraining surface refers (e.g., Spanish Bastions, Colubrina Tower, etc.). These first two columns are the initial section of the table, the one intended for feature recognition. The second part, on the other hand, serves as a link with the PGT and its material. Its system of classification and nomenclature of mapped areas has been reproduced. The next six columns show the following data: box, town hall, local identity nucleus, sheet, and map (*riquadro, Municipio, nucleo di identità locale, foglio, mappale*). The information entered must therefore follow the system proposed by the PGT and be compliant, to structure the possibility of overlapping contents. The third section of the attribute table describes the constraint. The first necessary data are those relating to the geometry of the protected area: surface, minimum and maximum altitude. In addition to this information, it was assumed that it would be possible to insert further columns describing the level of attention, the type of constraint (concerning the classification of the PGT), and further notes.

	ID_surface	STRUCTURE	RIQUADRO	MUNICIPIO	NUCLEO IL	FOGLIO	MAPPALE
1	_001	Bastioni Spagnoli	2	1	1_DUOMO	345	20
2	_002	Torre della Colu...	2	1	1_DUOMO	345	20
3	_003	Bastioni Spagnoli	2	1	1_DUOMO	345	20
4	_004	Ghirlanda	2	1	1_DUOMO	345	20

MAPPALE	SUP_MQ	H_MIN	H_MAX	LIV_ATT	VINCOLO	NOTE
20	4447	103,100	124,500	High	-	-
20	991	105,500	138,000	High	-	-
20	17640	103,100	124,500	High	-	-
20	6693	105,500	135,000	Medium	-	-

Figure 13. Image of the QGIS attribute table developed for the organization of information related to constraint surfaces.

This kind of structure, although possible for changes and improvements, is a performing solution. All surface features refer to a single .shp file and an attribute table collects data useful for recognizing and understanding the element itself. In addition, such a setup grants the possibility of filtering, selecting, and displaying elements based on common characteristics, simplifying processes of analysis and management of the data itself.
At the conclusion, a final data visualization test was conducted to understand the flexibility of the material produced. The ultimate goal is to provide a broader range of figures with the ability to know the consistency of the assets with which they are going to interact. For this reason, it is useful to understand whether it is possible to make use of such data through platforms and tools that are easy to read and use. As much as QGIS presents itself as intuitive and user-friendly software, it remains a sector tool. The last step of the paper investigates the visualization possibilities in Google Earth. The platform is available to everyone and is now such a well-known tool that it is the basis of our land observation activities. Providing the possibility of visualizing constraint maps in such an environment greatly expands the basin of use of the data, as well as facilitating the understanding of the interactions between the maps (and the structures from which they derive) and the built environment, thanks to the 3D visualization provided.

Figure 14. Image of the .kml file imported into Google Earth.
To do this, the .shp file of the constraint maps was exported in .kml format, making sure to include the associated metadata as well. Once Google Earth (Pro) was opened, the system allowed the .kml file to be inserted with the "import" function. Since all

the data were georeferenced, the placement was done correctly without any further steps. Despite several trials of exporting, data shows up as a perimeter and not a surface. Nevertheless, by querying each element, it is possible to view all the data previously organized in the attribute table (Figure 14). It is not possible to compare Google Earth and GIS software in terms of metadata management. Nevertheless, it proves to be a communication tool that allows easy data transmission.

5. CONCLUSIONS

The work presented here consists of the first experimentations with an innovative approach to defining 3D constraint maps. The historical and architectural complexity of the Castello Sforzesco and its location in a stratified and established fabric guided the choice of the case study. The objective was to select a territorial environment on which properly test the proposed framework. Despite this, it will be necessary to carry out further verifications, on other areas of the fortress or other case studies, to understand the shortcomings and possible improvements.

Given the possibilities of moving from 2D to 3D, another interesting development there could be.

As it is happening with BIM models, it would be interesting to test the inclusion of the entire 3D model in a GIS environment, without developing the 2D maps. In this scenario, the management of the elevation data would be imputed to the model itself and no longer to the attribute tables alone, as was decided in this first phase of the work. This would provide an opportunity, even at a later stage, to verify information related to constraint areas and test additional ways of drafting constraint maps.

In addition, exploiting the three-dimensional model in combination with today's communication technologies would lead to positive implications in terms of information fruition. For example, one proposal could be data visualization through mobile apps using augmented reality. Similar tools and solutions are now the basis for a more agile reading and application of information, allowing for an exponential expansion of the user basin.

The research aims to develop tools capable of supporting knowledge and management of the built Cultural heritage, exploiting the possibilities offered by the world of new technologies for data collection and management (geometric and otherwise). The usefulness of current tools for territorial governance, such as the PGT mentioned above, is beyond doubt. However, this work demonstrates the need to complement the large-scale information already available with detailed tools for the most delicate and complex spots of the urban fabric. The ultimate goal is to ensure that the specialists involved have the information they need to deal with the built heritage, both the visible one and, more importantly, the one hidden underground.

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