THE "DIAGNOSTIC SURVEY": A METHODOLOGY FOR THE KNOWLEDGE OF A COMPLEX ARCHITECTURAL PALIMPSEST

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ABSTRACT:

A multidisciplinary approach that availing of the use of different techniques, such as topography, three-dimensional laser scans, photogrammetry, archival studies and stratigraphical analysis, can permit to define a whole methodology of analysis useful for the knowledge of complex architectures and for the identification of potential problems related to the static structure of the buildings, as well as the deepening of their evolutionary framework.
This outline was so applied for the analysis of the northern portion of the Castello Sforzesco of Milan (Torre Falconiera and Ponticella), where Sala delle Asse is located, allowing the acquisition of a *corpus* of information. The diagnostic detection operations carried out were therefore conducted with the primary purpose in order to verify the geometries of the buildings and to define an exhaustive framework of the equilibrium and imbalance of the factory.
The comparison between the documentary sources and the direct sources has made it possible to correlate the information to identify the construction phases and the subsequent interventions of restoration, rearrangement and to define new possible functions. The *corpus* of diagnostic-cognitive investigations conducted on the Torre Falconiera and contiguous spaces also allowed us to delineate the state of art in which the structure has come up to date and to highlight its critical points interpreting the phenomenology with awareness

1. INTRODUCTION

As part of the broader project aimed at the cognitive activities for the conservation project of the Sala delle Asse of the Castello Sforzesco in Milan,[1], the purpose of acquiring geometric and photographic information was to produce a database of quantitative and qualitative information (three-dimensional geometric and photographic data) connected to the architectural volumes of the Castle's north corner tower (the Torre Falconiera), the Ponticella and the volumes of the contiguous spaces (Guidi et al., 2009).
The geometric documentation produced by laser scanner instrumentation and photogrammetric techniques has been cross-examined for diagnostic purposes through the creation of targeted sections and orthorectified images useful for verifying the most critical points of the structure such as imbalances, contiguity or continuity of crack networks, cause/effect relationships inherent to the nature and types of instabilities.
The survey made it possible to obtain internal and external façade elaborations and three-dimensional models useful for mapping and in-depth knowledge of the dynamics of the crack system in both two-dimension and three-dimension.
The produced works have also been used as knowledge bases necessary for understanding and unveiling, thanks to stratigraphic analysis, the semantic meaning of the matter of the ancient structure, a real text with "stone compositions".
Hence a particular attention to still new disciplinary perspectives with the deployment of non-invasive tools and methodologies of survey and interpretation, more incisive in bringing out things and objects.
The great multidisciplinary approach that such research has offered, the large amount of data and the numerous subjects participating have made clear the need to set up a system that allows dialogue between the different operators thus permitting to share information even during the activities (Bertocci and Bini, 2012).
Therefore, the knowledge process referred to surveys that were able to give geometrically correct bases of the plans, the elevations and the sections in order to tell a long-lasting history (synchronic and diachronic) regarding the objective three-dimensionality of the actual state of the surviving architecture as a summation of overlaps, juxtapositions, but also of demolitions or substitutions in space and time.
A metric survey increasingly improved in order to be able to read, in a diagnostic and semantic key, geometrical and constructive anomalies, but also discontinuities, similarities, reconsideration, dialectics of sequences and overlapping of the several stratigraphic activities that make these explicit through temporal and spatial relationships.
The accurate surveys, together with rigorous and autonomous documentary researches and the analysis of material and direct sources, were cognitive contributions aimed at understanding the architectural text through the complex of historical-constructive notions and the identification of the equilibrium/imbalance conditions of the structure itself. These investigations made it possible to identify the relative chronologies of the built elements by recording the technical knowledge, the use and processing of the materials, but also the deterioration and instability.
As a text, the artifact has thus become a source of analytical-interpretive exercises and the understanding of the *materia*

[1] Project coordinated by the Centro per i Beni Culturali (directed by prof. Lucia Toniolo) e directed by Comune di Milano (Settore Soprintendenza Castello – Musei Archeologici e Musei Storici del Comune di Milano e Civiche Raccolte Artistiche del Castello, Claudio Salsi).

signata, not concluded and finalized, must always be able to be renewed over time. Every material event (ecofact or artefact) of the building has been a vehicle of continuous understanding: knowing in order to preserve, but also conserving to know the matter of monuments, which are to be preserved in their historical stratification.

2. THE THREE-DIMENSIONAL DOCUMENTATION

The documentation activity of a multifaceted architectural framework like the Castello Sforzesco that is complex from the dimensional point of view and diverse in space and time, implies a high difficulty in planning the actions both on field both in data processing. So, the survey layout was elaborated taking into account the morphology and location of the spaces affected by the activities (the Sala delle Asse and all the adjacent spaces to it: the Sala dei Pilastri, the Sala 20, the space between the Sala delle Asse and the Sala 20 – called “intercamera”, the staircase connecting the Sala delle Asse to the Sala 20, the Sala del Gonfalone, the rooms in the Ponticella and the Sala dei Ducali) and, considering the architectural, dimensional and material characteristics of the structures, it has defined the organization of the work using two different approaches whose synergy has made it possible to obtain a result of greater accuracy without excessively delaying the implementation time schedule.
In fact, we opted for a topographic polygonal network using a prismless total station (Topcon GPT-3002) with the aim of providing a single reference system and acquiring the coordinates of 94 topographic reference points. These allowed to perform the alignment and recording procedures of laser scanner data with greater control compared to the one offered by traditional software that provide the automatic recognition of targets or homologous surfaces between close scans, without the geometric data addition into the calculation. The topographic network has been implemented by placing a fixed reference point in each space to be detected and adding, in case there was no free field for lining up the previous reference point with the next one, additional passage points in the areas bordering the various rooms.
Due to the Castle's particularly complex geometries and the need to bind data relating to spaces located at different levels (moat level, ground floor, intervault and upper room) the spatial definition of the network was rather complex. This also because we wanted to create closed polygons able to guarantee greater control over possible angular and linear errors of the network itself. So fifteen reference points (named from number 1000 to 15000) have been built which, thanks to the preparatory work carried out before the detection on site, allowed to create closed polygons for the entire network. This with the exception of the point located in the intervault (13000) which, due to the limited space and the presence of only one access point from the Sala 20, could not be reconnected to other polygonal arms. In the same way references 2000 and 15000 are also terminal points of two ranges, which are not problematic since the 15000 is a control point inside the Sala delle Asse where another reference point is already positioned, and one that is better integrated with the topographical network (1000), while 2000 is located in a secondary space with respect to the project’s focus area (figure 1). The first activities were focused in identification of the 15 reference points on the ground trough wooden stakes in the outdoor areas and adhesive targets in the internal areas, recorded jointly with the laser scanning operations in order to ensure coherence between the data collected with the two different acquisition systems.

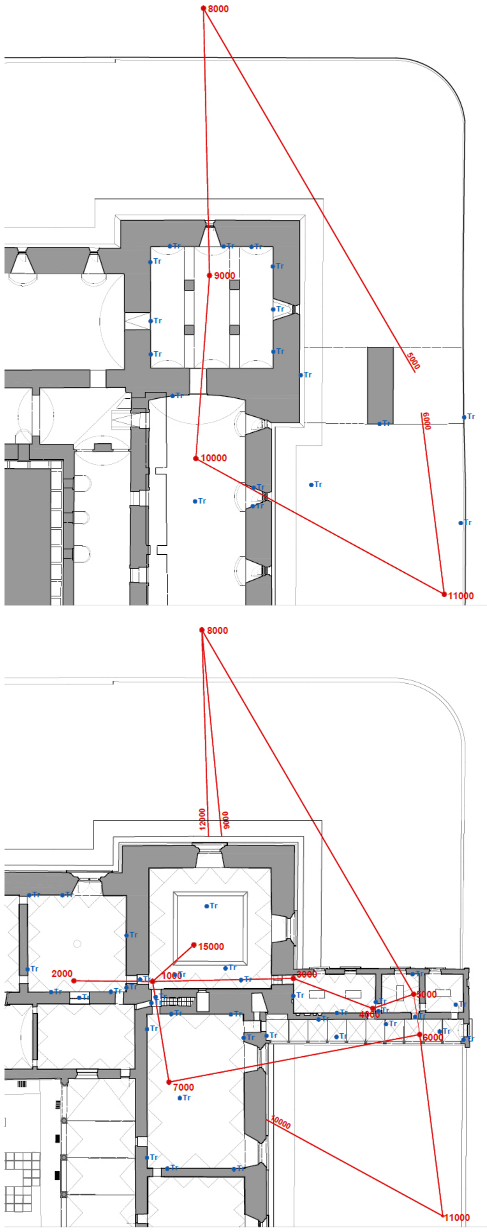

Figure 1. Topographic network of two different levels (ground and Sala delle Asse floor)

Before starting the three-dimensional acquisitions, the optimal resolution value was identified for the purpose of the documentation activities, namely the best compromise between a satisfactory level of detail and the number of registered points (Garzulino, 2016). This was planned taking into account the amount of data that these instruments can acquire in relation to the processing limits of the hardware available. It was therefore essential to accurately define the objective of the documentation phase and above all to determine the necessary detail in order to be able to carry out the subsequent data processing operations in the best possible way. In fact, we focused the activities on the survey of the structures and the architectural elements as a whole and in the acquisition of all useful information for the identification of the main phenomena of decay and imbalance such as internal and external cracks.
For three-dimensional survey a high-speed terrestrial laser scanner (FARO Focus 3D 120 Uni) was used, which uses phase shift technology and is equipped with an integrated digital camera with a 2 megapixel sensor. This instrument is suitable

for medium working distances (between 1 m and 50 m) and it is able to acquire almost 1 million points per second with an accuracy of about 2.5 mm at 50 m distance from it. The laser scanner used is a limited size and weight tool, very manageable and useful especially in complex situations.

The targets, used as specified to help throughout the point cloud's alignment phase verifying the geometric precision, have been positioned, where possible, on the perimeter walls of the various spaces, on the ground and on the information boards, so as not to have covered portions on the structures during laser and photographic acquisitions. The targets were also placed at different heights, at a distance not less than 1 m from the scanner and in such a way that the angle of incidence between the laser beam and the checkerboard reference was possibly not less than 35°. This in such a way as to minimize the inaccuracies in the operations of alignment and finalization of the point clouds, because the more inclined the checkerboards are with respect to the line of sight towards the scanner, the worse the checkerboard detection could be. All the scans were performed with a rotation of the instrument of 360° around the vertical axis and of 300° around the horizontal axis, at a height between 0.50 m and 1.50 m from the ground. To obtain homogeneous results, it was preferred to use the same resolution and quality parameter for most scanning points (one point every 6 mm at a distance of 10 m between instrument and portion to be detected; 122.000 points/sec; color registration) paying attention to the position and the dimensional differences of the spaces object of survey (figure 2).

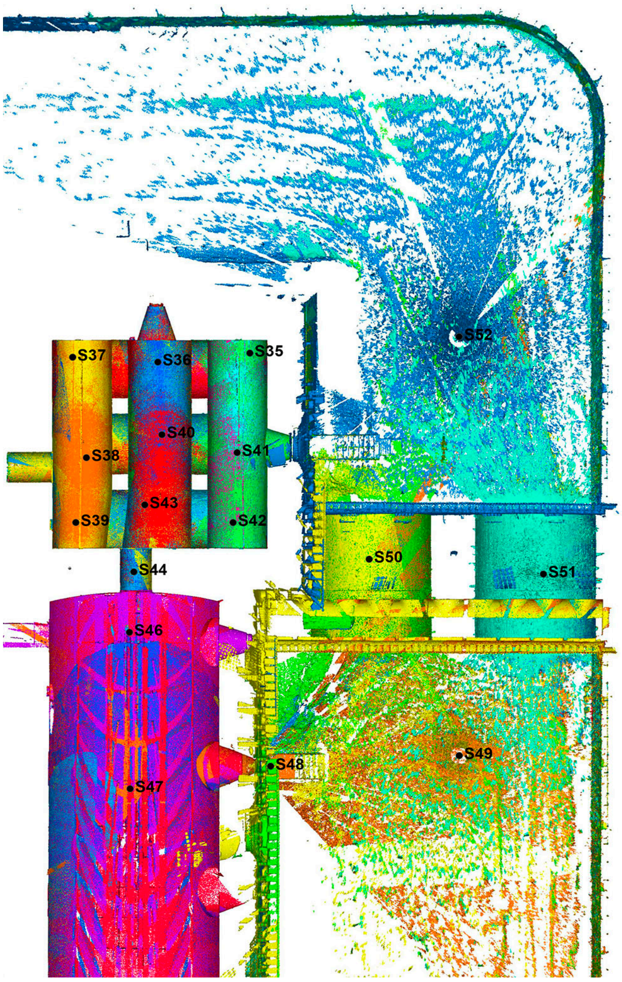

Figure 2. Position of the single point clouds on the ground floor.

In general, for the smaller and geometrically simpler spaces (for example the internal spaces of the Ponticella) two complete scans were carried out with color acquisition, while for larger rooms, much more complex from an architectural point of view and with problems related to hidden areas that were being formed due to display cases and information panels, more scans were chosen. In addition, some scans were carried out in order to build up a data network to connect various groups, especially the interior spaces with the outside ones and the rooms on different floors. The survey of the intervault between the Sala delle Asse and the Sala 20 was very complex, this because of its morphology, in the most lateral areas and near the walls, this space has a height of about 1.50 m, while approaching the center the height decreases more and more until zero. Moreover, the extrados of the underlying vault and the partitioning walls with small openings for the passage between one compartment to the other led to a noticeable increase in the number of scans compared to what was initially estimated (figure 3). Given the almost absent lighting in this space, the point clouds were made without the acquisition of images.

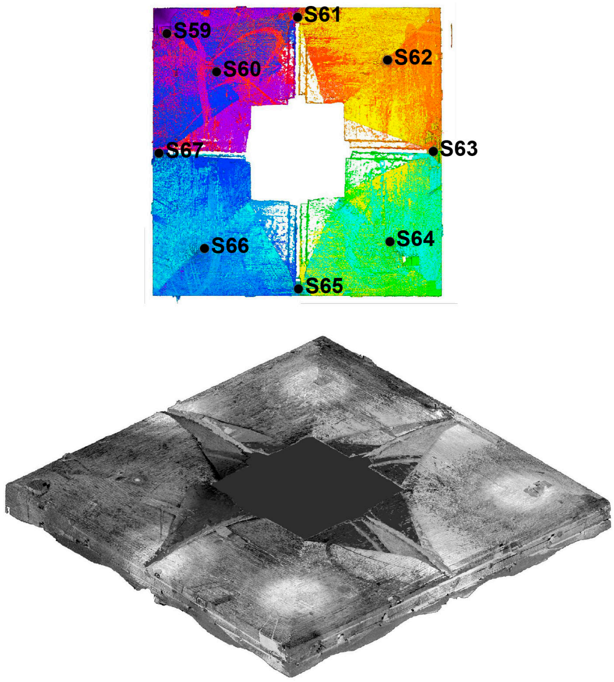

Figure 3. Position and view of the point cloud of the space between Sala delle Asse and Sala 20

In order to avoid heavy cleaning operations on all the single point clouds, given that the portion of the Castle involved in the documentation activities is part of the itinerary of the museum, it was decided to perform the data recording in the only day of closure to the public, dividing the operations into four separate days.

Once the acquisition of the geometrical and chromatic information was completed, a first data processing was carried out (using the FARO Scene v. 4.8 software), it was performed on the individual scans, or portions thereof, by applying some automatic pre-processing filters. The software has in fact identified and removed the scanning points resulting from the acquisition of two objects or parts of them with a single impulse, thus eliminating all the incorrect generated points. Subsequently, due to partial acquisition of an object the saved data were removed and the noise of the clearly altered surfaces was reduced from the point of view of the general geometric coherence. This operation has mainly focused on data relating to some particularly critical finishes, such as some bright black metallic surfaces, highly polished chrome or mirror surfaces, and portions of the glass cases, thus allowing the substitution of morphologically incoherent values with the average values of the surrounding area correctly acquired, in order to obtain a surface more adherent to reality. The acquisition of shiny surfaces, such as the above mentioned, often leads to reflections superposed on the true laser projections and, in addition, speckle noise makes it difficult to analyze the captured information (Amir and Thörnberg, 2017). To prevent this type of problem it would be possible to cover shiny surfaces with a thin layer of antireflective coating before measurement, but this solution was not suitable to our specific case because the surfaces on which to intervene would have been many and in any case not important for the subsequent analysis phases.

Once these operations were completed, the next phase allowed the identification of the targets in each scan, associating them with a progressive numbering. Through the common points between the different clouds, the reference points and their relative coordinates, it was possible to place the scans in the space and then align them reducing to a minimum the errors related to the angular closing, the distance and the propagation of the error in general. These operations allowed an accurate control of the error, result in all cases below the acceptable limits[2], thus giving back a highly reliable result from the metric point of view. Particularly problematic and time-consuming was the alignment of the scans carried out in the space between the Sala delle Asse and Sala 20. This is mainly due to two reasons: the first relating to the very small size of this space and the second relating to the presence of only one little connection with other spaces (the Sala 20).

Considering that the instrument is able to acquire data up to a distance of about 120 m, it has become necessary to remove all the non-essential points, those redundant and those relating to the spaces not included in the survey. So as to avoid an excessive weighting of the complete cloud, to improve the general visualization of the three-dimensional survey and also to facilitate the operations of projection of the points for the construction of the plants, sections and elevations.

In the final phase of processing, the spherical images were applied to the complete cloud (Russo et al., 2010), thus associating the chromatic data with the geometrical one of the single detected point (figure 4). The spherical images were also used to navigate into the spaces, moving and approaching the elements of interest, and being able to measure, for example, the distance between two points or extract the coordinate of a particular point of interest.

The work carried out thus far, in particular the survey produced using laser scanner technology, lays the bases for subsequent geometric and diagnostic research conducted directly studying the already-acquired point cloud without needing to carry out other on-site surveys. Thanks to the quality and quantity of the acquired information, it was in fact possible to extract, using specific softwares, a series of traditional documents, including plans, sections and elevations, useful as support bases for subsequent phases of analysis of the entire work group.

For this operation, a specific software was used; this is able to process the recorded points and to project them onto defined planes or on new section planes. The software also allowed to choose the area affected by the projection (from a few millimeters portion to the whole cloud of points), the level of detail and the color of the points with their intensity (black and white or real color).

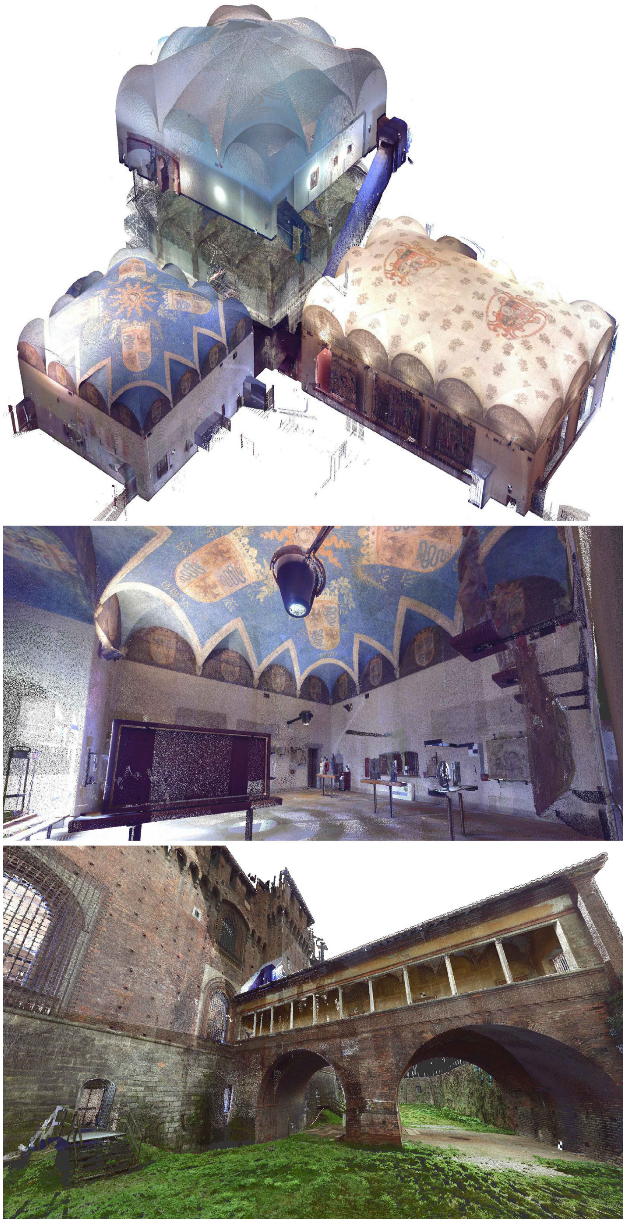

Figure 4. Different views of the colored final point cloud

From the qualitative point of view, the elaborations in plan, section and elevation of the interiors were more than satisfactory and with a level of detail such as to be able to use the only projection of the points on the various section planes as basis for the subsequent mappings. For the outside spaces, however, since the laser acquisitions were performed from the ground and the Torre Falconiera has a height of about 35 m, the final density of the cloud did not allow to identify all the characteristics necessary for subsequent stratigraphic analysis, but only to outline the geometries of architectural elements. It was therefore necessary to implement the laser scanner survey with a two-dimensional photogrammetric survey in 1:50 scale and 1:20 scale for some details.

For the rectification of each image that has composed the final works, the necessary coordinates, about 10, have been extrapolated from the cloud of points. All the adjacent photographs have been acquired in order to have a good overlap between them and thus to ensure, during the mosaic phase, a complete and satisfactory result as regards the richness of the

[2] The maximum errors were in the alignment of the group of scans C (from scan 35 to scan 52); average linear error 0.0025 m, maximum linear error 0.0086 m, maximum angular deviation 0.0030°.

details. The shoots were made with a digital SLR camera equipped with a full-frame sensor[3] and with different standard lenses[4], in relation to the distance from the fronts. For the photographs of the areas under the Ponticella, where the distance was very close, was instead used a wide-angle lens[5] that required, during the processing of the orthorectified images, a special procedure for the elimination of geometric deformations introduced by the optical configuration of this type of lens. Subsequently specific softwares were used which allowed to eliminate the radial deformation and the perspective deformation existing in the photographic shoot, taking advantage of the geometrical information and the exif data contained in the single images. The removal of the deformations and the simultaneous sizing of each image made it possible to obtain individual rectification portions which, correctly positioned through the mosaic process, gave rise to the final results (figure 5). These have been accurately verified by crossing the data coming from the laser scans thanks to the comparison with spatial coordinates not taken into account previously for the rectification phases (Zangheri, 2017).

Figure 5. Orthorectified image of the east façade.

It was therefore possible, starting from the final point cloud and these elaborations, to produce an accurate three-dimensional model of the current conformation of the area object of study and then to define three-dimensionally the volumetric and constructive variations, in historical series, deriving from the conducted stratigraphic analysis (Angheleddu et al., 2015).
The modeling phase was preceded by a careful selection of the elements that wanted to be represented three-dimensionally, allowing to obtain more manageable polygonal models that could be used as a reference base for the main architectural structures. The meditated choice of reconstructing the surfaces instead of using the cloud of points obtained is mainly due to facilitate the division of the spaces and portions constituting the Castle focusing more on the architectural elements of interest leaving out all the information not considered useful for the ultimate purpose of research (figures 7). In this way it was possible to transmit with greater simplicity the indispensable information concerning the complex architectural structure and related evolutionary information, modeling the elements according to their relevance with different levels of detail. These operations have thus made it possible to obtain three-dimensional models that were easily manageable and more suitable for hosting subsequent analyzes.

3. THE STRATIGRAPHIC AND DIAGNOSTIC ANALYSIS OF THE CASTLE ARCHITECTURE

The study of multi-layered architectural structures has become a consolidated experience that can potentially be applied to any building without preconceived distinctions of formal value or subdivisions in hierarchies that are now not evaluated. The non-destructive visual stratigraphic survey method is not aimed at directly applying interpretative schemes that identify pre-existing or conventional models for a given context, but it wants to know the artefact, the relationships between the parts, the structures and the functions that make up the system in the whole with its own specific identity. This is characterized by the “history of material culture”, a discipline that uses direct information from archaeology and its auxiliary and indirect sciences (historical-archival sources), for the purpose of a global reconstruction of material transformations (Bortolotto et al., 2011). These studies have been applied to the Castle, together with archival research (text documents and historic pictures) to identify the key phases of construction and more precise dating of some modifications. These took place between the first constitution of the *Castrum* and its life until the XX century, which were also confirmed by direct reading of the building. The identification of different stratigraphic units (S.U.) and architectural elements (A.E.), along with their exact number, allows us not only to identify every construction activity surveyed, but also to subsequently relate them, until we can draw up the reading by phase.
The elevation’s stratigraphic analysis of the Torre Falconiera and the Ponticella proceeded precisely in this way, identifying different constructive activities and eight macro phases of evolution (from 1386 to now).
The use of different colors, which refer to the identified historic phases, facilitate the reading of the stratigraphic palimpsest (figure 6). The subsequent realization of three-dimensional models allows the overall reading of the artefact by relating documentary sources and direct sources for the external elevations, the construction phases and interior interventions.
Castrum portae Jovis has been erected next to the city wall by Galeazzo II Visconti in 1368. The building, unlike the coeval Pavia Castle (around 1360), is designed exclusively with defensive functions.
After Gian Galeazzo Visconti succeeded to his father Galeazzo II (post 1386), the Castle was expanded with a “cittadella” towards the countryside in which it’s planned to locate the dwelling and the guardhouse.
The addition of Gian Galeazzo includes the Corte della Rocchetta, the angular square towers, the keep in the middle of the front and the rampart. Today, only the I phase base remains in place because, after Duke Filippo Maria Visconti death in 1447, it was decided the Castle demolition.
With the arrival in Milan of the new Duke Francesco I Sforza, the ducal finances are used for the reconstruction: these interventions (phase II) are visible on the Torre Falconiera façade.

[3] Nikon D600: CMOS sensor 35,9 x 24,0 mm (FX format), picture area 6016 x 4016 pixels, 12 or 14 bit NEF memorisation, 100 – 6400 ISO, 39 autofocus points.
[4] Nikkor AF-S 50 mm F/1.8 G and Nikkor AF-S 28-300 mm F/3.5-5.6 ED VR.
[5] Nikkor AF-S 18-35 mm F/3.5-4.5 G ED.

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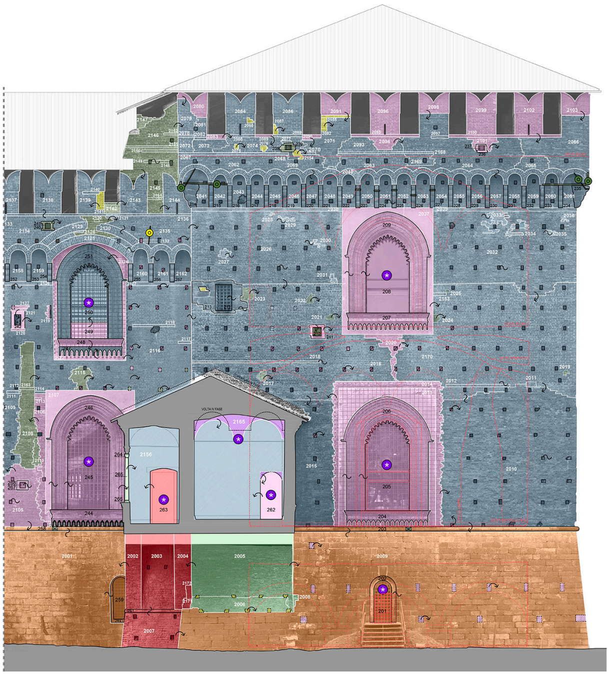

Figure 6. Stratigraphic palimpsest of the east façade.

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The III phase (post 1455) is characterized by the construction, next to the tower, of a two arched brick bridge for the connection of the Castle with the church of Santa Maria del Carmine. On this bridge starts the construction of the Ponticella (IV phase). Bridge arches are enlarged to support the new rooms called "camerini", built to expand the ducal residence.

With the fall of Ludovico il Moro the Castle is converted to military use (V phase) and therefore modified to be adapted to this new function; Sala delle Asse, Sala dei Ducali and Sala del Gonfalone are used as stables. In addition, a wastewater and animal sewage drainage system is created cutting ducts in the floor, then conveying liquids in long external downpipes, visible in the photographic images of the late XIX century.

In October 1893 the barracks-castle passes to the State and then to the City of Milan. This involves further interventions for the establishment of the School of Art. Luca Beltrami took care of this intervention (VI phase), heavily revising the external appearance of the Castle. Specifically, the Torre Falconiera recovers fifteenth-century styles and the Ponticella the previous decorative apparatus (figure 7).

From a planimetric point of view, new openings are realized between the Sala delle Asse and the Ponticella, originally accessible only from the external "loggia". At the same time, takes place the restoration of the Sala delle Asse, followed by the restoration of the "Saletta Negra" in 1912.

The current Torre Falconiera and Ponticella configuration is due to the reorganization carried out by BBPR in 1954 (Phase VII) and the Ponticella suffered further internal modifications starting from 1954 (VIII phase).

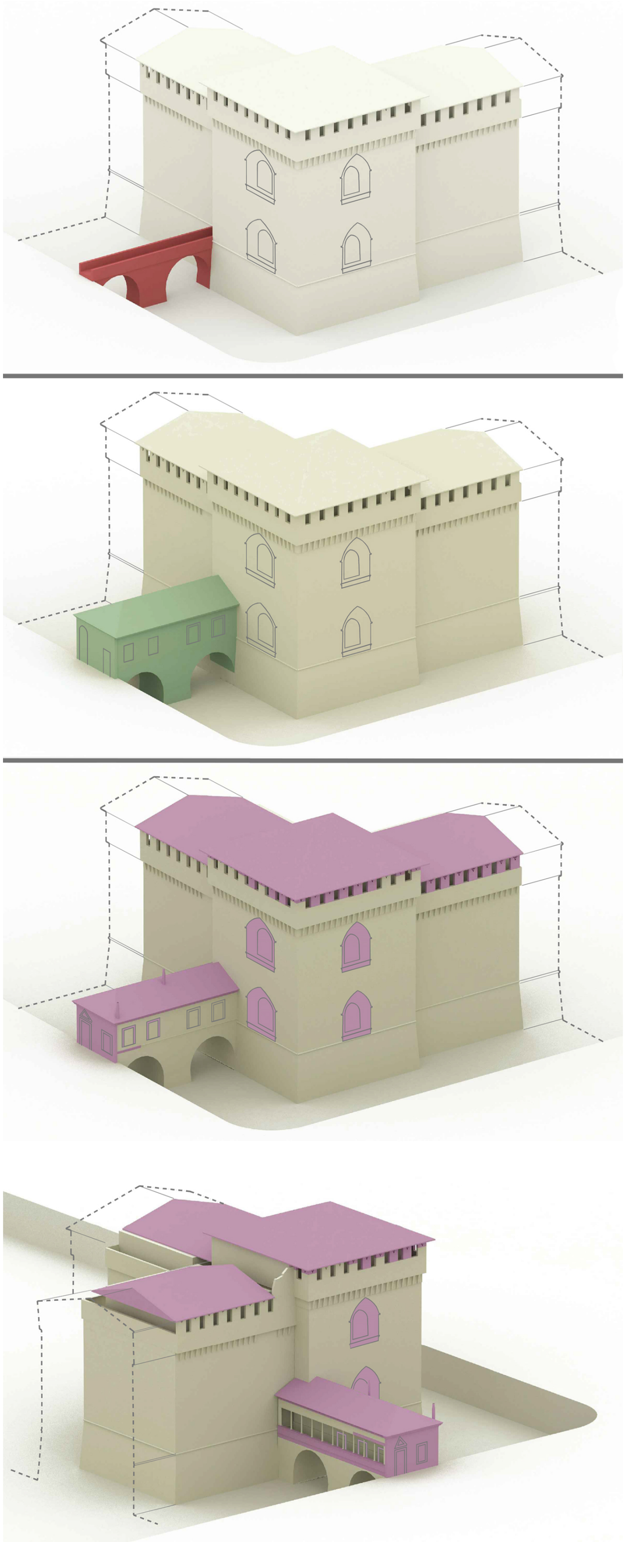

Figure 7. Three-dimensional schematic representations showing architectural structure transformations over time. From the top, model of the III phase (red), model of the IV phase (green) and model of the VI phase from both sides (pink).

4. CONCLUSIONS

The cross-referencing reading with the results ascribable to each survey conducted has allowed us to reconstruct the formation process of the Torre Falconiera, the Ponticella and their evolution during the time.
The cognitive diagnostic investigations carried out for the definition of a future conservation project of the structure of the Sala delle Asse and the Ponticella (survey activities, phase modelling, stratigraphic analysis, crack readings) have also highlighted a phenomenology of degradation/instability strongly correlated to its evolutionary phases. It is precisely by carefully reading the relationship of "cause-effect", between its phases of activities/interventions and the cracking systems (discontinuities and cracks), that we can extrapolate some important events.
The Torre Falconiera's historical/developmental aspect as well as its static/dimensional one, with research carried out by the TeCMArcH Laboratory, made it possible to understand the current state of conservation, identifying some of the causes of deterioration and imbalance in the Sala delle Asse as well as to define the correct interventions.

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