The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-M-9-2025
30th CIPA Symposium “Heritage Conservation from Bits:
From Digital Documentation to Data-driven Heritage Conservation”, 25–29 August 2025, Seoul, Republic of Korea

From Digital Documentation to Data-Driven Heritage Conservation of San Francesco della Vigna in Venice: A Methodology for Monitoring and Valorization

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Keywords: Cultural Heritage 3D Reproduction, Church of San Francesco della Vigna, Diagnostic Investigations, Drone and Laser Scanner Survey, Historical Digital Twin, Static and Seismic Vulnerability Assessment.

Abstract

This contribution illustrates the experimental research associated with the ongoing monitoring activities for conserving the façade and bell tower of San Francesco della Vigna church in Venice. The study investigates various technologies and tools for the terrestrial and aerial surveying, documentation, safeguarding, valorization and intervention on Venice's architectural heritage.

The result of the research is a data acquisition methodology for monitoring and vulnerability assessments, yielding to specific graphic deliverables and, crucially, a digital twin, enabling in-depth static and dynamic analyses through Finite Element Modeling (FEM). Notably, the digital model of the statues in the façade's niches was created also using artificial intelligence (AI) and subsequent organic modelling to generate a mesh suitable for structural calculations.

This methodology facilitates the implementation of continuous monitoring of material degradation and crack patterns through non-invasive methodologies. It ensures knowledge and digital documentation of the artifact's conservation status and safety, and, most importantly, allows for a data-driven heritage conservation.

The digital twin revealed several critical issues, including: the inclination of the upper facade, where verticality assessments indicated a deviation from plumb; chromatic alterations, likely due to differential weathering and leaking; and stress concentrations within the decorative statuary.

The collaboration between the Studio Forti architecture firm and University Iuav of Venice demonstrates to the deep synergy between multiple knowledge and skills, with the common goal of protecting and conserving monumental assets through targeted and informed monitoring and intervention.

1. Introduction

The monastic complex of San Francesco della Vigna in Venice, since its first design in the second half of the 13th century by Marino da Pisa, is the result of continuous stratifications and architectural adaptations that involved leading figures in Venetian architecture, art and politics (Foscari and Tafuri, 1983). In particular, the Church of San Francesco della Vigna was completely renovated starting in 1534. The project, entrusted to Jacopo Sansovino, owes its origin to architectural and cultural phenomena codified in a cultural program promoted by the friar Francesco Zorzi and the Doge Andrea Gritti. In fact, Sansovino introduced architectural models that did not conform to Venetian tradition in the mid-16th century, and for the construction of the church, Sansovino's design was strongly influenced by Zorzi himself (Onda, 2008).

The façade is instead a project by Andrea Palladio, dating back to 1564 and commissioned by Patriarch Giovanni Grimani, Figure 1. It presents a compositional language with references to models of buildings from Roman antiquity and is probably Palladio's first ecclesiastical project in Venice (Foscari and Tafuri, 1983), resolving the façade of a Christian building with pagan architectural elements. The compositional scheme consists of a pediment that closes the main nave, while the lateral naves are closed by a sector of a minor order tympanum: a clear compositional solution of superimposing two temple pediments, as demonstrated in Wittkower's interpretation (Wittkower, 1964). The median trabeation unites the two orders, while the thermal window attached to the trabeation emerges in the center. The portal is framed by columns and is marked above by an arch closed by a slab of carved stone; laterally and symmetrically to the portal, the composition of the façade is marked by two niches with two bronze statues inside depicting respectively Moses and Saint Paul, produced in 1592 by Tiziano Aspetti. These are two elements that strongly characterize the monument from a plastic and chromatic point of view, in contrast to the candor of the Istrian stone.

Positioned close to the apse area of the Church, the bell tower represents another characterizing element, not only of the complex of San Francesco della Vigna but also of Venice, being one of the bell towers that most stands out in the skyline of the city (Figure 2). Built by Bernardino Ongarin between 1571 and 1581, it was erected to replace the previous bell tower that was almost completely destroyed by lightning in the 12th century. The bell tower has a stone base, a brick shaft with fluting, and a conical spire.

Figure 1. Portion of Facade (Robinelli, 2025)

Figure 2. Bell tower (Robinelli, 2025)

It can therefore be deduced that the origin of the monastic complex and its development embody different artistic and architectural languages, influenced and dependent on events of both a political and artistic-cultural nature. Although this theme has been widely investigated from an historical point of view, as the rich bibliographic panorama testifies, on the contrary, the survey and monitoring works carried out over the centuries are few (Borgherini, Guerra and Modesti, 2010).

The religious Order of the Minor Franciscans, represented by the Lombard-Venetian Province of the same Order, owner and manager of this important site, has therefore deemed it appropriate to start a program aimed at increasing the state of conservative knowledge of the facade and bell tower of the Church in order to be able to plan appropriate interventions in time.

At the end of 2023, the Order commissioned Architecture Studio Forti, in active collaboration with the VIDE Laboratory of Università Iuav di Venezia, to carry out an architectural survey campaign with subsequent representation through solid modeling and cataloging of the most evident alteration, degradation and instability phenomena. This is not a program aimed solely at gaining knowledge of the monument, but rather a more complex system that uses monitoring techniques to make use of experimental methods and principles to prepare appropriate scheduled and controlled maintenance. The proposed method allows the monument's current state to be represented through a survey and then a 3D digital model, thus obtaining not only a traditional two-dimensional graphic representation and thus allowing reflections on the entire three-dimensional structure. It is therefore possible to also contemplate the temporal component in association with future conditions of degradation and static instability (Forti, Rocca, D’Acunto, Camaiti, 2021). The digital model thus constitutes itself as a system for archiving and recurrently monitoring the various data.

It is now widely known that modeling proves to be an essential tool capable of providing a solid knowledge base necessary to guide subsequent actions, including the required monitoring process. The campaign still in progress has as its objective the construction of a model that can be disseminated and implemented over time for a correct setting of any maintenance and/or monitoring actions, thus also allowing for timely intervention with respect to degradation phenomena that could worsen over time.

In the initial phase of this program, particular attention was paid to the iconographic material and a detailed archival research was undertaken, in particular carried out at the Historical and Current Archives of the Superintendence for the Architectural Heritage and Landscape of Venice and the archive of the Province of Sant’Antonio dei Frati Minori (Figure 3-4). It was in fact considered essential to verify and compare the information obtainable from the documents – in particular from the archival drawings– and from the data obtained from the survey campaign.

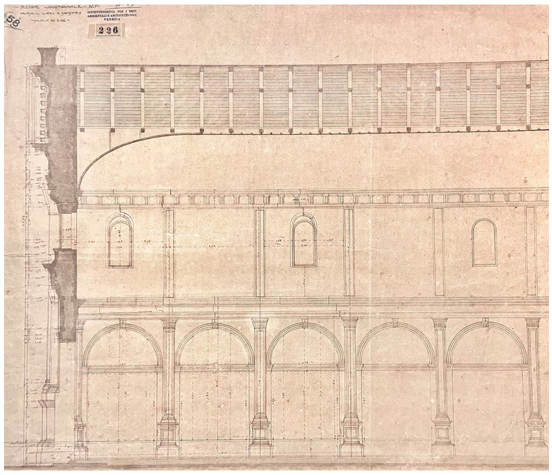


Figure 3. Section highlighting the façade’s out of plum, 1979 survey from Venice Superintendency Drawings Archive

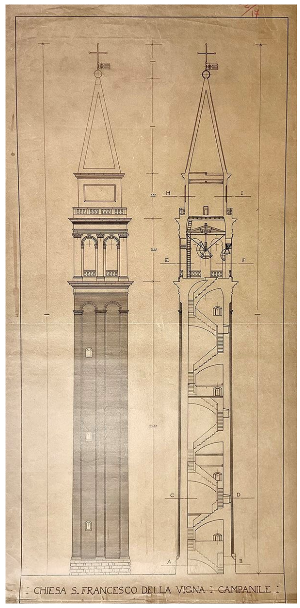


Figure 4. Belltower elevation and section, from Venice Superintendency Drawings Archive

The research has shown that over time the survey campaigns were developed in completely distinct phases, without a real interrelation between representation and diagnostics. The different phases of historical-archival analysis of the artifact, survey with application of different methodologies, digital graphic restitution, digital processing for the creation of virtual clones, interpretation and data management have thus returned a series of graphic works necessary for a complete understanding of the architecture in a critical-interpretative key, following a well-defined sequence of operations and always comparing the results with previous studies (Forti, Friso, Liva, Rocca, 2024). The result of the survey and historical-archival analysis operations has revealed a fundamental knowledge base and essential support for any cognitive and interpretative processing linked to subsequent investigations, which will be refined from time to time. Unlike the defined nature of the restoration project, which often finds its completion in the conclusion of the intervention, the conservation program is carried out continuously over time through a series of operations that are not always directed on the artifact. The study pursues the purpose of knowledge and monitoring of the state of conservation of the object examined, aiming to integrate and systematize the information produced in order to have the most objective knowledge possible of the façade and bell tower of San Francesco della Vigna.

2. Methodology

The workflow of the multidisciplinary methodology proposed by the authors for a data-driven heritage conservation is visually presented in Figure 4, focusing on the church analyzed in this study, specifically the façade and one of its two statues components of the decorative apparatus. This methodology is characterized primarily by its non-invasive nature, marking a significant advancement beyond traditional investigation protocols and it integrates cutting-edge technologies for surveying and 3D restitution, ending in the creation of a Historical Digital Twin, that serves as a crucial tool for vulnerability assessment and conservation strategies. The 3D model serves multiple objectives: it enables comprehensive control, precise measurements, identification of material and structural vulnerabilities, color alterations, cracks, and damage. Crucially, it facilitates the creation of a reliable digital clone for subsequent numerical analyses, making it ideal for monitoring the aforementioned material and static issues.
Indeed, by synergizing expertise from surveying, digital twinning, and structural and seismic engineering, this research explores the capacity of a detailed 3D model to bolster vulnerability assessment (also through accurate Finite Element models - FEM), monitoring and conservation of Cultural Heritage assets. A key strength of this methodology is its multiscale applicability, allowing for detailed analysis from individual artistic components to the complete façade system.

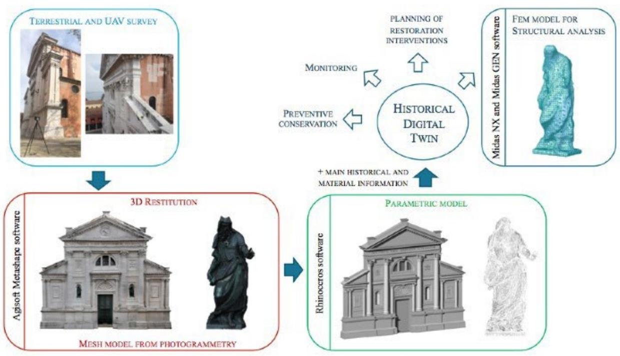


Figure 4. Workflow of the methodology adopted for heritage conservation

The methodology adopted for the 3D survey and subsequent reconstruction of the heritage artefact involved the application of indirect techniques, encompassing both terrestrial (via laser scanning and static photogrammetry) and aerial acquisition. For terrestrial data acquisition, a FARO CAM2 Focus S 150 laser scanner was utilized, operating in grayscale mode for both the interior and exterior environments of the church and bell tower. This was complemented by a Nikon D850 digital camera with a 50mm f/1.4 lens for photogrammetric acquisitions. Their specifications are given in Table 1:

FARO focus S 150		Nikon D850	
Reading speed	976000 points per s	Sensor size	35.9 x 23.9 mm
Accuracy (max)	1mm at 150m	Image size	8256 x 5504 pixels
Accuracy (used)	2.1/10m	Focal length	50mm
Field of vision	360° x 300°		

Table 1. Characteristics of terrestrial survey instruments

Scan positions were selected to ensure over 50% overlap between scans, thus guaranteeing accurate surface reconstruction. For point cloud registration, clearly visible architectural features were used as control points to facilitate alignment. Regarding the laser scans, five were performed at distances ranging from 10 to 20 meters from the facade.
Laser scanner surveying was integrated with direct measurements, which served as a crucial verification step. A series of total and partial measurements, obtained using a laser distance meter, enabled the precise scaling and orientation of the point cloud with respect to the software's internal reference system. Indeed, a preliminary topographic survey was conducted to establish a georeferenced framework, enabling the accurate collimation of data acquired from both laser scanning and photogrammetry.
The use of aerial photogrammetry was necessitated by the considerable height of the church and the presence of an opposing building merely 5 meters away. These factors would have precluded a detailed assessment of deterioration on protrusions and recesses using terrestrial techniques (photogrammetry or laser scanning), thereby generating unacceptable distortions and shadow zones for a reliable 3D model. Furthermore, drone-based surveying allowed for the evaluation of static risk factors (e.g., cracks, material detachments, kinematic movements) on the upper facade and its protruding elements, enabling data-driven planning for targeted interventions. Following sensor calibration and flight planning at a 2-meter distance from the surfaces, approximately 700 drone-acquired photos were captured along horizontal strips to ensure high overlap and detail. A drone DJI Mavic 2 Pro with HDR video 4K 10 bit was employed, with characteristics presented in Table 2:

Sensor size	2.54x2.54 cm
Image size	5472×3648 pixels
Focal length	28 mm
Flight time	31 min

Table 2. Characteristics of drone

Figure 5. Close- up image from drone survey (Zamengo, 2023)

For the survey restitution part, Agisoft Metashape software was utilized for the phases of point cloud management and photograph processing, and for the elaboration of dense point clouds and their associated meshes. This software is based on Structure-fromMotion (SfM) technique (Azzola et al., 2019), using computer vision algorithms to detect significant points in photos, obtain their parameters, and cross-reference these points across multiple images to identify their 3D spatial coordinates using mostly automated alignment (Lucignano, 2021). This topic has been extensively studied in literature (Barba et al, 2020). Therefore, a sparse point cloud is produced, which is then refined into a dense, geo-referenced, and scaled point cloud through manual adjustments to remove extraneous points. Finally, a mesh is built from this dense cloud, creating a 3D polygonal model that accurately represents reality in both texture and shape (Figure 6). The 3D construction, and the consequent digital documentation, of the cultural heritage artifacts is completed by creating a parametric model in Rhinoceros via reverse engineering (McNeel, 2024). This accurate, volume-representative model, termed the Historical Digital Twin, (Marra et al., 2021) effectively assumes the role of the primary database for digital documentation, serving as the foundational medium upon which controls, verifications, and vulnerability assessments are performed.

The whole procedure for survey and 3-D restitution for cultural heritage preservation is fully explained and detailed in Rocca et al. (2024).

The realization of the asset's three-dimensional virtual clone not only allows for a visualization of its geometric-spatial configuration and serves as a repository for the digital documentation of the cultural heritage asset, but also functions as a tool for data-driven heritage conservation. Indeed, this navigable instrument enables the identification of changes to the existing condition and the delineation of targeted interventions on the asset, addressing both material and structural aspects (e.g., those stemming from static/seismic vulnerability studies), all guided by scientific accuracy.

Figure 6. Textured 3D model of the church facade

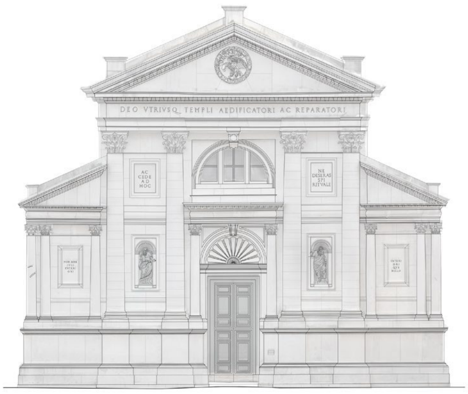
A further step in the proposed documentation and conservation methodology involves the generation from the 3D artifact model of a numerical-mathematical model (detailed 3D Finite Element Modeling – FEM) to understand the function of individual components and to conduct safety analyses. This model can be generated for the entire facade or for one of its constituent elements, such as the statues.

Indeed, FEM analysis is crucial for performing static and dynamic calculations essential to assess a structure's safety and seismic vulnerability. The highly accurate 3D model generated provides technicians/engineers with specialized expertise the ability to rapidly identify areas of concern and interpret structural behavior. For instance, the digital twin of the façade (Figure 7) revealed a significant verticality deviation in its upper section. This out-ofplumb condition was identified by analyzing thin point sections (derived from the dense mesh or 3D model) to reconstruct the tympanum's profile and compare it against the vertical axis.

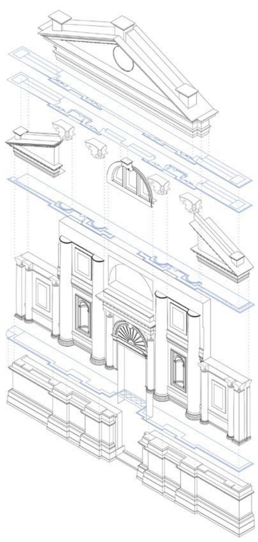
Subsequently, the methodology is applied also at a refined scale to a specific constituent element of the façade - the bronze statues by Aspetti. This work specifically deepens the methodology for these statues. As anticipated, the restitution phase leading to Digital Twin can be generated for cultural heritage assets of every scale, however, different challenges arose in accurately and reliably reconstructing these irregularly shaped elements.

Contemporary survey methodologies, digital modelling and the application of artificial intelligence (AI) have fostered the indepth study of statuary by promoting research, experimentation and conservation work on artistic and cultural heritage (De Luca 2011, Lo Turco et al. 2020). The transcription of data from physical models to the digital environment facilitates the acquisition of high-definition artefacts and facilitates the manipulation of geometric curves belonging to surfaces (mathematical models) or point clouds that return a more or less complex reticular structure (numerical models - Migliari, 2003). In particular, the well-known process of reverse modelling, originally developed in the engineering-mechanical sector and subsequently applied to Cultural Heritage (Liva, 2021), has undergone a rapid evolution, outlining a well-defined methodology of analysis and intervention that is based on the collection of data, their registration in a system of common coordinates, up to the production of the clone in a geometric and chromatic guise very faithful to reality. In the case of the two Aspetti statues, the management of incomplete mesh versions had been added to the aforementioned complexity of the survey operations carried out by drone. In order to proceed with structural analyses, it was necessary to have continuous and unbroken surfaces.

The initial handling of a hypothetical encumbrance was accomplished through the utilization of the Meshy AI generator, which processed potential completion postures derived from analogous cases. This model was then refined and customized using the sculpting tools of the Cinema 4D software, with individual anatomical and vestigial components being modelled to fill the physical void of the niche. A particular focus was placed on the connecting edge between the two meshes, one of which was derived from the survey and the other was approximated by artificial intelligence. This was done to accurately check a transition band connecting all polygon vertices. In order to proceed with the joining of the different portions of the models, any anomalies or gaps were corrected manually. In order to guarantee the efficacy of the finite element method calculation, the modelling phase was followed by a remeshing operation. The purpose of this operation was to reduce the geometric complexity of both the Mosè and San Paolo. Despite the simplification, the two models retained their physical identity and degree of detail thanks to an algorithmic procedure already integrated in most modelling software and necessary precisely for numerical models derived from photogrammetric surveys or laser scans.



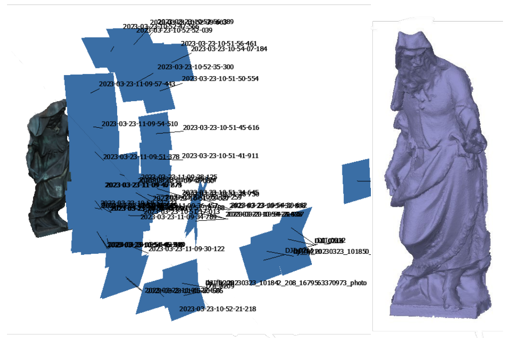
(a)



(b)

(c)

Figure 7. Workflow of Scalzi Façade digital twin modeling: (a) superimposition of elevation and point cloud, (b) reconstruction phase in Rhinoceros, (c) parametric model representative also of the correct volumes



(a) (b)

Figure 9. Mosè statue: (a) sparse cloud with shooting points, (c) dense cloud

Figure 10. Mosè statue digital model, highlighting both texture and simplified mesh

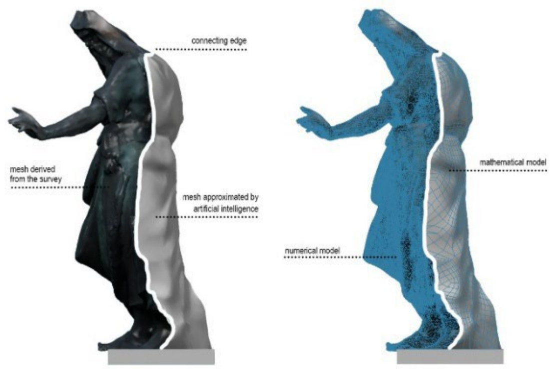


Figure 11. Mosè statue 3D digital model with indication of the double nature of the mesh

3. Vulnerability Assessment

As stated, utilizing the detailed 3D Finite Element Model (FEM) obtained through the non-invasive methodology, a powerful tool is provided. When integrated with engineering expertise, this instrument allows for the comprehensive assessment of an asset's static and seismic vulnerability. Furthermore, structural safety can be evaluated at various levels of detail against diverse mechanical actions. These include forces such as wind or impacts, seismic events, or the impacts of environmental variations specific to lagoon environments. Thelevel of detail required for the analysis dictates the application of the 3D model. It can either furnish the necessary parameters for expeditious methods or serve as the basis for computing FE models to conduct more in-depth static and dynamic analyses. Regarding one of the constitutive elements of San Francesco della Vigna complex, the bell tower, the accurate, volume-representative model (Historical Digital Twin) is suitable for providing the necessary data to apply the simplified seismic vulnerability assessment, specifically the LV1 method for towers and bell towers, as prescribed by the Cultural Heritage Guidelines (Direttiva, 2011).

For this structural typology indeed, which exhibits a predominantly vertical development and cantilever-like behavior, the LV1 method requires the calculation of a seismic safety index (Is). This index is based on simplified mechanical models of flexural-compression collapse and on characterization data of the structure. The model thus yielded an Is of 5.2 (for shear-sliding failure and a return period Tr of 2475 years), indicating that the bell tower's primary vulnerabilities are its tendency towards overturning (in relation to the observed out-of-plumb) and the presence of thrusting ramps/vaults.

However, following a prioritized intervention approach, the model revealed that the deterioration process primarily affects the statues, namely the prominent projecting elements. Consequently, the focus of the conservation program shifted to the imposing bronze statues situated in the façade's niches. Indeed, due to the percolation of rainwater in areas lacking proper drainage (nonrunoff planes), so within the cavities and folds of the drapery, hazardous levels of corrosion have been observed. Then, given the planned restoration of the statues, the models will enable the development of a data-driven conservation program for these sculptures.

A preliminary static stress analysis was performed to ascertain the current structural state, specifically focusing on the impact of the statue's self-weight. The insights derived from these numerical analyses, performed on the FE model through MIDAS Gen software (Midas, 2024) are crucial for identifying regions of elevated stress distribution, which inherently represent areas with a heightened susceptibility to damage under static loads.

For instance, Figure 12 illustrates the principal stress distribution within the Moses statue resulting from its self-weight, revealing a stress concentration in the ankle zone. Indeed, the highest principal stress values are observed in the bronze statue at a location where the support area is reduced. However, both the maximum tensile and compressive stresses remain safely below the bronze's material strength limits.

The safety analysis, a key component of this data-driven conservation program for the statues, utilizes the aforementioned models to investigate their propensity to overturn under dynamic actions such as wind and seismic events. This investigation is conducted either through FEM analyses or by employing simplified analyses of local mechanisms, having precise geometric data available from the 3D models.

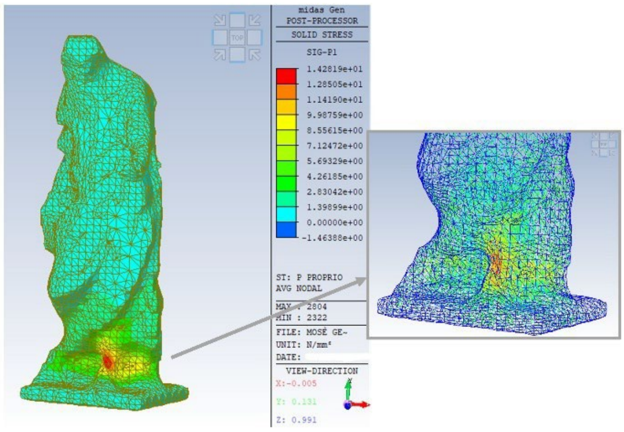


Figure 12. Mosè statue results: maximum principal stress distribution with the representation of the principal stress orientation for the most critical area.

4. MONITORING PROCESS

In the field of restoration, monitoring represents an essential aspect in terms of protection. The acquisition of adequate knowledge on the possible forms of degradation and vulnerability proves to be an opportunity for investigation and an activity of fundamental importance in the field of Monumental Heritage. It is in fact widely demonstrable how the increase in knowledge leads to a better calibration of the operational interventions on historical artefacts and very often to a reduction of the same: in fact, one of the key principles and goals of conservative restoration can be summarized in the concept of "minor intervention".

The three-dimensional digital models obtained following the indirect survey campaign and restitution phase allow to collect the relevant information with respect to the overall knowledge of the artifact and the possible evolution of the critical issues found. An adequate investigation of the material and structural modifications aims to become a methodological model for the correct restoration, between knowledge and action, prevention and restoration.

The façade has not been affected by recent interventions. In fact, the last restoration dates back to 1995 and presented, as regards the Istrian stone facing, states of material degradation that were not excessive or worrying. Instead, more static problems were detected at the time, due to the action following the lowering of the bottom of the left corner which caused an out of plumb line towards the exterior. Now this action seems to have stopped and the façade seems to be stable and not different from the previous situation.

As regards the two bronze statues present in the niches, the material conservation appears more compromised, probably as a consequence of the different conditions of exposure to the aggressive lagoon environment. In fact, for some parts affected by corrosive phenomena, the formation of superficial patinas and consequent drippings on the stone facing are more evident. It was therefore considered necessary to study in detail the geometries and plasticity of the statues, precisely because these factors influence the exposure to the environment and the consequent formation of the different patinas. In fact, even just visually, the mechanical and leaching action of the waters appears different on the exposed surfaces compared to the more protected ones, subjected to stagnant aqueous layers. The necessary exhaustive understanding of the formation mechanism of the geometries, still in progress, will then allow us to effectively define the possible conservation treatments (Scott,1994).

As for the bell tower, this has suffered some collapses with rotation of the shaft, according to what was found in the archival documentation and in a study on the structural stability of the bell towers of Venice dating back to 2011, undertaken by the Superintendency of Venice in collaboration with Università Iuav (Lionello, 2011). Through the construction of the model and further current analyses in the field, we aim to determine an evaluation based on the structural behavior over time and the degree of conservation.
The three-dimensional digital model, defined as digital twin, proved to be necessary not only for cataloging and disclosing the relevant information in relation to the artifact, but also as an aid in defining intervention plans. In fact, a systematic cataloging was carried out, verified by multidisciplinary scientific research, according to predefined fields and integrated with an illustrated abacus for the definition of forms of degradation or alteration (Figure 12-13). The records proved to be a support element for restorers and bodies responsible for conservation, both as a database of the current state and as a support for possible future interventions. First of all, it was considered appropriate to carry out a cataloging of the vegetal elements present in order to undertake maintenance interventions that began in the spring of 2024 (Figure 14). Interventions prepared via climbing mode, relying on the model itself which enables data-driven intervention and conservation, which are able to solve the problem of the presence of vegetal-biological colonization and the pulverization and/or detachment of stuccos. The organization of the cataloguing, supported by the digital twin, was an opportunity to deepen and reorganize the current state of knowledge in relation to the monument. This is a process that can never be defined as concluded and that over time, on the occasion of future interventions and studies, must be continuously enriched by updated information compared with the state of conservation of the materiality of the artifact.

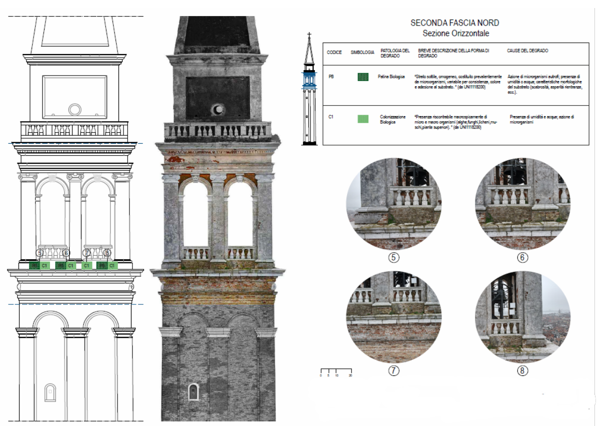


Figure 12. Degradation and biological colonization mapping summary sheet for the bell tower

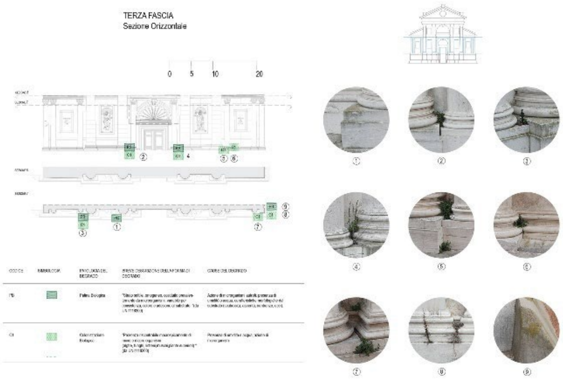


Figure 13. Degradation and biological colonization mapping summary sheet for a portion of the façade

Figure 14. View of the facade during climbing monitoring intervention (Sinigaglia, 2024)

5. Conclusions

The proposed methodology for monitoring and valorization of Cultural heritage, applied to San Francesco della Vigna complex in Venice has shown how the use of digital technologies has established constructive dialogue between different professional skills and academic institutions, facilitating cultural exchange and the dissemination of knowledge.
The analysis of the data documented in the obtained digital twin enabled the formulation of interpretative models for degradation and instability processes. Furthermore, the in-situ comparison with the proposed model allowed for the estimation of their reliability and effectiveness for diagnostic, conservation, and operational purposes
This methodology is useful because it enables progress to be made in protecting monumental heritage in accordance with Article 29(1) of the Cultural Heritage and Landscape Code. This article ensures that cultural heritage is conserved through coherent, coordinated and planned study, prevention, maintenance and restoration activities.
This means that instead of being always guided by immediate need or necessity, this methodology allows for data-driven decisions and interventions aimed at preventing and planning actions.

It is therefore possible to create a “digital identity card” for each monument that describes its characteristics and provides immediate and implementable knowledge of any critical issues.

Acknowledgements

The authors would like to thank Fr. G. Cavalli of O.F.M., Fr. G. Ravaglia of O.F.M., the *Comitati Privati Internazionali per la Salvaguardia di Venezia* in particular the President P. Marini, Venice in Peril Fund in particular Dr. S. Steer for supporting the research and the intervention. L. Canella, F. Castaldello Zamengo, L. Mattiazzi for their contribution in the drawings editing.

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