Preventive and Planned Conservation: A Knowledge-Based Tool to Manage Heritage at Risk. Strategies for the Pitti Palace in Florence

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This paper explores risk management in architectural heritage and advocates planned conservation as an effective alternative to unstructured emergency interventions. It presents the first results of a multidisciplinary research on the sandstone facades of the Pitti Palace in Florence (Italy), which are deteriorating and detaching mainly due to the intrinsic characteristics of the Pietraforte. The study was conducted as part of an institutional agreement between Università Politecnica delle Marche and the Uffizi Galleries, with support from the Laboratory for Stone Materials and Applied Geology, Environment, and Landscape of the University of Florence. The aim is to address Preventive and Planned Conservation strategies to manage material deterioration and ensure the physical integrity and safe use of the building, with a heritage- and people-centered approach. In this context, the paper presents the method and activities that led to a knowledge-based tool for assessing stone detachment hazard and prioritizing conservation efforts. The tool combines archival documents, research on previous restorations, analysis of the asset's state of conservation and instrumental diagnostic, the latter to validate the method. The results will help establish a methodological framework for future statistical analyses, supporting the development of a predictive model to govern complexity in heritage preservation, mitigate deterioration and ensure public safety.

Keywords: architectural heritage, stone detachment hazard, previous restorations, material conservation, public safety, predictive approach

1. INTRODUCTION

Risk assessment is the first fundamental step in identifying effective mechanisms to protect and preserve cultural heritage for future generations. For architectural heritage, these mechanisms are primarily aimed at balancing its nature as a unique and non-renewable resource and its potential as a powerful and dynamic asset with a remarkable resilience to changing conditions (CHCfE 2015).The increasing complexity of this situation arises from the variety of hazards that can threaten heritage and the individuals who experience it, considering by hazard any phenomenon, substance, or situation that has the potential to cause disruption or damage to infrastructure and services, people, their property, and their environment (Abarquez and Murshed 2004; UNESCO et al. 2010). The typology of hazards – including meteorological, hydrological, geological-geomorphological, biological, human-induced, and climate change-related hazards – encompasses sudden catastrophic events and gradual, cumulative processes, both of which can have a major impact on heritage (UNESCO et al. 2010). While the former generally tends to attract more attention, it is imperative to recognize the importance of properly managing the latter, in which specific technical and operational measures are crucial to mitigate the slow destruction and protracted degradation of built heritage. Such measures, including restoration work that strengthens architectural structures and surfaces, are meticulously designed and implemented to yield tangible benefits; however, their multifaceted outcomes can potentially compromise conservation efforts and the heritage materiality, thereby playing a pivotal role in shaping future risk management strategies.

Over the last three decades, the risk management methodology has been at the heart of the decision-making process in conservation matters (Konsta and Della Torre 2021). Among the various efforts to develop coherent and clear procedures for risk management in the field of historic architecture, Preventive and Planned Conservation (PPC) is of particular interest as a medium- to long-term strategy that integrates the conservation and enhancement of the asset for its effective management (Moioli 2023). In addition, an integrated (European Commission 2014), people-centered (Council of Europe 2005) and value-based (ICOMOS 2013; European Commission 2019) approach to heritage conservation and management has become increasingly prominent. Furthermore, knowledge-based actions foster knowledge-driven approaches, which serve as the basis for a good governance and high-quality projects (Dimitrova et al.

2020; Europa Nostra 2024). These principles have gained significant traction among the major international heritage institutions, who have recognised their relevance to the preservation of the Outstanding Universal Value of World Heritage sites and of built heritage as a whole (Magar, Thompson, and Wijesuriya 2022; UNESCO WHC 2002; UNESCO et al. 2013; Orioli, Ugolini, and Mariotti 2022).

Studies representing milestones in architectural heritage and risk management have been developed as well as widely used methodological manuals and operational toolkit (Stovel 1998; UNESCO et al. 2010; ICCROM 2016; European Commission 2018; Council of Europe 2020). These international policy documents have concretely supported a future-oriented vision to holistically address current challenges applied to heritage (Council of Europe 2022; ICSM CHC 2022).

Italy has played a significant role in shaping this vision, notably through the theoretical contributions of Cesare Brandi and Giovanni Urbani, whose work gave a decisive impulse to the debate on PPC and laid the foundations for both current Italian legislation and recent strategic guidelines (Della Torre 2021; Petraroia 2023; Legislative Decree 42/2004; Ministerial Decree 154/2017; Legislative Decree 36/2023; SIRA 2023). Their intuition supports a co-evolutionary conservation strategy, based on integrated and predictive care, as a sustainable alternative to deferred restoration, which is often costlier and less effective at addressing root causes of degradation (Vandesande et al. 2018; Vandesande and Van Balen 2018). This paradigm shift reflects the cultural evolution of the concept of restoration, which is moving towards PPC, and which does not intend to freeze the asset in a state of unchanging equilibrium but to manage its transformations (Moioli, Van Balen and Vandesande 2014; Buriti 2019; Della Torre 2023).

Moreover, digital technologies have become key enablers of PPC, enhancing every stage of the process – from initial data acquisition and diagnostics to monitoring and future planning (Daniotti, Gianinetto and Della Torre 2020; Muench et al. 2022). These technologies support the transition from conservation 'project' to 'process' but also from a 'curative' to 'preventive' approach, enabling the development of predictive models and facilitating planning through data-driven methodologies. However, reliable predictions require in-depth, well-structured knowledge grounded in historical data and interdisciplinary expertise.

In this perspective, a growing body of research has clearly recognized the pivotal role of knowledge acquisition in developing more efficient risk management strategies (HYPERION project 2019–22; PROCULTER project 2019–21; World Monuments Watch program 2025; HeritageWatch.AI 2025).

Other notable projects have contributed to new practices aimed at mitigating the effects of climate change (Heracles 2016–19; STORM project 2016–19), while several studies have explored the implementation of maintenance activities based on preventive approaches (CHANGES project 2015–19; HeritageCARE 2016–19; WARMEST project 2017–22). Within this framework, the HeritageCARE project developed standardized inspection procedures, documentation and classification criteria as well as a 'damage rating system' for condition and risk assessment, to enable a nearly objective recording of the data documenting the heritage state of conservation and facilitate the scheduling of future maintenance actions (Masciotta et al. 2019; Lourenço et al. 2022).

The systematic documentation and classification of damage provide a basis for modelling real-world deterioration processes and predicting future trends. This can be achieved through the development of forecasting algorithms using statistical and computational methods, including linear regression analysis and fuzzy logic processes

(Prieto et al. 2017; Cagigas-Muniz et al. 2019; Prieto, Verichev, and Carpio 2020; Moreno et al. 2022), machine and deep learning (Ali et al. 2022; Marín-García et al. 2023; D'Orazio, Bernardini, and Di Giuseppe 2023; D'Orazio et al. 2024; Masini et al. 2024;). Furthermore, advancements in digital environments such as HBIM, GIS and digital collaborative platforms enable the georeferencing and spatial analysis of conservation-related data (Myers, Dalgity, and Avramides 2016; Jouan and Hallot 2020; Fiorani et al.2021; Charlton et al. 2021; Mammoli, Mariotti, and Quattrini 2021; Moyano et al. 2022; Nieto-Julián et al. 2023; Langella et al. 2023; Néroulidis et al. 2024).

These tools, combined with a multidisciplinary and integrated approach, support the systemic management of complex heritage sites; this is exemplified by the Milan Cathedral, where the integration of digital technologies and predictive practices, alongside continuous monitoring activities, is ensuring a data-driven management system for its preservation (Fassi, Achille, and Teruggi 2011; Cigada et al. 2017; Della Torre and Cantini 2018; Cantini et al. 2020; Canali et al. 2021; Teruggi et al. 2021; Barazzetti et al. 2022; Barazzetti, Previtali, and Roncoroni 2022; Barazzetti 2024).

The fundamental characteristic that binds these studies together is the sustainable and future-oriented vision, the experimental and extensive use of digital technologies as well as the primary focus on heritage material deterioration. The state of conservation of our heritage results from a complex interaction of factors, including features and properties of building materials, orientation, climatic conditions, exposure to wind and sunlight, and dynamics involving the surrounding environment. On closer inspection, heritage also stems from layered restoration works, which document the conservation efforts undertaken over time. A systematic understanding of the location and timing of these interventions would enable the evaluation of their impact on heritage and the effectiveness for preservation; this, in turn, should inform future conservation strategies to be included in the PPC plan. Nevertheless, there is a paucity of studies that have comprehensively analysed the significant influence of previous restorations, with the majority of research concentrating on structural works. Notably, there is a lack of investigations that integrate knowledge of past surface and deep consolidation treatments into the planning of future interventions. In this sense, the development of knowledge-based tools is a fertile ground for experimentation and for which the quality of diagnostic technologies and the digitization of qualitative and quantitative information are essential (Italian Ministry of Culture 2022).

This paper contributes to addressing this critical research gap by exploring the role of heritage knowledge domains related to past restorations and current conservation conditions in the development of predictive tools for risk management. It highlights the need for circular knowledge development and proposes methodologies that support PPC through the integration of qualitative and quantitative data, enabled by advanced diagnostic and digital technologies.

2. OBJECT AND AIM

This paper presents the results of an ongoing multidisciplinary research, whose main aim is to support a paradigm shift in the management of the problem caused by the accelerated deterioration processes of the stone facades of the Pitti Palace in Florence. The intention is to promote a step change in the planning and management practices of architectural heritage conservation with strategies of PPC by adopting a predictive, heritage- and people-centered approach.

Managing the Pitti Palace today means responding adequately and rapidly to a twofold need: to guarantee the physical conservation of the facades, which are susceptible to damage because of intrinsic characteristics of the building stone, and to ensure the public safety of the more than 5 million tourists who visit it every year, also attracted by the UNESCO label, without interrupting visits (Uffizi Galleries 2023; UNESCO WHC 1982).

This research addresses the issue of risk management, focusing on the hazard of stone fragments falling, through PPC and innovative tools capable of ensuring, on the one hand, the conservation of the authentic material of the building and the safe use of the external spaces of the Palace, on the other hand. With this in mind, the paper presents the fundamental preliminary work of collecting, structuring and combining quali-quantitative data that led to an experimental knowledge-based tool to understand which stone elements are the most at risk and to define conservation priorities and techniques for the facades of the Pitti Palace.

3. THE PITTI PALACE IN FLORENCE: CONSTRUCTION HISTORY AND MANAGEMENT CHALLENGES

Located in the historical center of Florence – declared a World Heritage Site in 1982 – and in front of the Boboli Gardens, the Pitti Palace (Figure 1) is one of the architectures that has contributed most to the consolidation of the Florentine building tradition, which developed around the use of Pietraforte and Pietra Serena due to their durability, versatility and ease of extraction, a practice that dates back to the Middle Ages (Pecchioni et al. 2021; Fratini and Pecchioni 2024). One of the most important sources of Pietraforte in Florence was the Boboli quarry, in the Oltrarno district. It supplied Pietraforte for a wide range of construction, including palaces (e.g. Pitti Palace, Palazzo Medici Riccardi, Palazzo Vecchio, Palazzo Strozzi, Palazzo Rucellai), churches (e.g. the Church of Santa Maria Maggiore), bridges (e.g. Ponte Vecchio, Ponte Santa Trinita), to name but a few (Bastogi and Fratini 2004; Pecchioni et al. 2021).

This study focuses on the facades of the Pitti Palace's main courtyard, well-known as Cortile dell'Ammannati, where the Pietraforte quarried from Boboli was used as building, cladding and decorative stone (Landi et al. 2019).

Built in the mid-15th century by the Florentine merchant Luca Pitti, the Pitti Palace was a symbol of the political and economic power of the Medici and later the Habsburg-Lorraine and the Savoy dynasties. Today, it is one of the world's most important museums, part of the Uffizi Galleries Museum.

In terms of architectural configuration, the palace is the result of several enlargements over time. The original core, smaller than its current structure, was built in the mid-15th century for the Florentine merchant Luca Pitti (Figure 2a-b). Although no definitive documentation exists, the design is widely attributed to Filippo Brunelleschi (Fabriczy 1979). The first expansion was carried out by architect and sculptor Bartolomeo Ammannati, who from 1561 transformed the palace into the new Medici residence, first requested by Eleanor of Toledo and then by Duke Cosimo I (Fossi 1967). Bartolomeo Ammannati's extension tripled the size of the palace, by building a central body leaning against the back of the 15th century building and two wings perpendicular to it; thus, creating the Cortile, the courtyard that became the link between the naturalistic landscape of the Boboli Gardens and the architectural landscape of the city. The construction site made use of the Pietraforte quarry in Boboli, which was located next to the palace and had already been used to build the first part of the palace, so that the material was easy to obtain and transport was reduced to a minimum, since the quarry and the construction site were practically one and the same (Rodolico 1953; Facchinetti 2000). The use of Pietraforte gave material continuity and solidity to the palace's structures, while the rusticated ashlar technique gave plasticity to the facades, with three overlapping orders featuring variations in the treatment of the ashlars and columns. The work was completed after almost twenty years (Figure 2c-d) and represents one of the best examples of Italian Mannerism (Kiene 2002).

Subsequent alterations to the courtyard facades were minimal, while three additional expansions were undertaken on the central volume. Between 1620 and 1650, Giulio and Alfonso Parigi extended the main facade towards Piazza de' Pitti, maintaining Brunelleschi's architectural language (Figure 2e). In the 18th century, Giuseppe Ruggieri and Niccolò Gaspare Paoletti were responsible for the Rondò delle Carrozze (1764-65) and the Rondò di Bacco (1783-95) (Matracchi 2024). During the 19th century, Pasquale Poccianti and Luigi Del Moro primarily focused on enhancing the internal circulation systems, making minor adjustments to the palace's external appearance (Figure 2f).

From that point onward, the palace's facades, and particularly those designed by Bartolomeo Ammannati, have undergone a series of restoration campaigns, beginning in 1889 (Amministrazione della Casa di S.M. in Firenze 1889), in response to the critical condition of the Pietraforte stone. For these research, the main focus is on those facades designed by Bartolomeo Ammannati, where the interventions, carried out intermittently until the early 2000s, have primarily addressed issues such as the detachment of stone fragments and the surface degradation of the ashlar masonry.

The fragility of Pietraforte has emerged over the centuries, affecting numerous buildings and being closely linked to diagenetic processes (Scelza et al. 2022). The extensive use of this turbiditic sandstone and the related degradation due to intrinsic characteristics have significantly impacted on Florentine architectural heritage, requiring the urgent development of a comprehensive urban conservation strategy. Falls and detachments have become more frequent (Gurrieri 2009), with serious consequences also for the safety of people, culminating in the dramatic episode of the detachment of a corbel in the Basilica of Santa Croce, which killed a Spanish tourist in 2017. At present, the persistent occurrence of detachments remains a serious hazard, including at Pitti Palace (Figure 3). Such occurrences, especially if we consider the number of buildings made by Pietraforte across the city, are of great concern to the administrations responsible for managing this heritage, which – supported by the scientific community – are maximizing their efforts to slow down the degradation processes and prolong the life cycle of historic architectures. These actions aim to preserve the heritage social utility while guaranteeing public safety, but also to make sustainable use of the public fundings allocated to heritage preservation (Mariotti et al. 2023).

In particular, the Uffizi Galleries, as managers of the Pitti Palace, have promoted and participated in discussions with academic institutions, which are proving to be extremely useful in managing the problem, even though scientific research, especially if experimental, takes months or years to carry out while material deterioration progresses rapidly. In recent years, the Uffizi Galleries have adopted a multidisciplinary approach to conservation, trying to implement a step change in the care planning and management of its architectural heritage (Pozzi 2022; Mariotti et al. 2023).

Initially, monitoring activities were promoted to deal with emergencies, with targeted checks on individual stone blocks, the removal of detached fragments with a high risk of falling, and the installation of temporary safety measures to meet minimum preventive safety standards, such as nylon nets (Figure 4). In 2018, a close collaboration was established with the Department of Earth Sciences and the Laboratory for Stone Materials and Applied Geology, Environment and Landscape at the University of Florence (DST-LAM, Unifi). This partnership supported the monitoring activities mentioned above, but also contributed to define a new theoretical and methodological approach, based on the integration of data from a broader research project on the degradation of Pietraforte in several Florentine buildings, to estimate the hazard of deterioration and detachment of stone elements. Since 2021, this open issue has been the subject of research conducted by the Department of Construction, Civil Engineering and Architecture at the Università Politecnica delle Marche (DICEA, Univpm), focused on previous restorations and their impact on the state of conservation of the facades of the Pitti Palace, to optimize their future preservation.

4. MATERIALS AND METHODS

This paper discusses the method and the workflow that led to a knowledge-based tool for monitoring and predicting the most critical risks to heritage conservation and public safety concerning the Pietraforte facades of the Pitti Palace's courtyard, the Cortile dell'Ammannati. Pietraforte is a turbiditic sandstone that exhibits convoluted laminations and calcite veins, resulting from its geological history. This stone has a propensity to disintegrate into flakes, which can pose a significant hazard if they fall to the ground.

The tool is intended as a scientific basis for planning the continuous care of the building and as a knowledge infrastructure that can be shared and implemented over time. So far, DST-LAM of Unifi and DICEA of Univpm have contributed to its construction, combining different scientific competences in a strictly operational way. The knowledge infrastructure includes information on the history of the building, restoration and the diagnostics of materials, the latter being used to validate the method.

In terms of methodology, this research uses traditional processes and tools of architectural heritage restoration (archival research, historical-critical analysis, visual damage/degradation inspections) and diagnostics (instrumental geomechanical surveys). The work employs a heuristic approach and is based on a continuous flow of 'incoming' and 'outgoing' knowledge, both for the orientation of short-term conservation projects and for the stratification of information on the building, enabling medium- and long-term planning of conservation activities.

The workflow, divided into three main phases, is presented as follows:

- geomechanical characterization of the facade rusticated ashlars through instrumental tests and experimental investigations carried out by the DST-LAM of Unifi (section 5);
- parameterization of the knowledge, resulting in two indices – one for the previous restoration works and one for the state of conservation of the facade rusticated ashlars – conducted by the DICEA of Univpm (section 6);
- first implementation and validation of a knowledge-based tool for estimating the hazard of detachment by combining the DICEA indices, validated on the basis of the results of the instrumental tests carried out by DST-LAM (section 7).

The research was conducted on a test area of the facades of the Cortile dell'Ammannati. Operationally, the facades were divided into quadrants according to the architectural articulation, and each quadrant was assigned an identifying numerical code for each stone block. The analysis focused on the area considered to be the most significant and vulnerable, based on the current state of conservation of the facades, as confirmed by a recent monitoring campaign (Landi et al. 2019). The test area corresponds to the quadrants of the first and second levels of the outermost bay of the western facade, facing the Boboli Gardens, for which a representative sample of ashlars was selected for study (Figure 5).

5. PIETRAFORTE AS GEO-HERITAGE: A DIAGNOSTIC APPROACH TO ESTIMATE THE BEHAVIOR OF STONE ELEMENTS

Since 2018, DST-LAM has been carrying out the monitoring of the stone facades of the Cortile dell'Ammannati at the Pitti Palace using an aerial platform. These surveys are necessary to verify the deterioration of the material over time due to its physical properties and weak points. The analysis of the state of conservation of the Pietraforte facades was carried out in three stages:

(1) a simple and rapid method of observation from a distance, with on-site inspections supported by document analysis. The remote visual inspections made it possible to identify phenomena of deterioration and/or instability at a macroscopic level;
(2) a close-up inspection to obtain a more precise assessment of the state of conservation of individual masonry elements on the facade;
(3) finally, a morphological and morphometric study, followed by ultrasonic and sclerometric analysis of representative points on the stone surfaces.

The planned and necessary interventions for the monitoring work included the obtaining of precise photographic documentation, the mapping of safety measures implemented during the survey, the removal of unstable pieces of stone that were obviously fragile to prevent them from falling, and the collection of fragments while identifying their location in the facade for possible future repositioning.

The close-up examination with the probing manual trowel made it possible to classify the blocks on the basis of the sound they made, which generally helped define the resistance of the material and the presence of internal cavities, micro and macro fractures, and to identify those in poor condition. When the material showed signs of poor conservation, tests with the Schmidt hammer and ultrasound were carried out to confirm the state of relaxation detected and the presence of cracks masked by previous restoration fillings and surface patinas. In addition, all the elements studied with the instrumental tests were also described in terms of their morphometric and morphological characteristics. All the results are presented in thematic maps.

DST-LAM is actively involved in extensive research linking the mineralogical, petrographic, physical, and mechanical characteristics of the Florentine sandstones with their state of conservation (Figure 6) (Salvatici et al. 2020; Centauro et al. 2022; Salvatici et al. 2023). This research is especially concerned with events of detachment and fall. In particular, the Pietraforte rusticated ashlars are often protruding architectural elements, which makes them susceptible to decay phenomena induced by weathering. The latter, combined with the physical characteristics of the stone, can lead to the detachment and loss of stone blocks. The study of Pietraforte as a geo-heritage with its morphological, mechanical, physical, mineralogical, and petrographic characterization, is an important starting point for understanding the possible evolution of the decay processes.

A multi-analytical characterization of this stone has been carried out in several case studies of Florentine rusticated ashlars used in different architectural contexts (Centauro et al. 2022; Di Bilio et al. 2022; Bonora et al. 2023). This multi-analytical characterization has been developed, which involves the numerical correlation of data derived from specific non-destructive instrumental tests and morphometric analysis (Di Bilio et al. 2022). This tool quantifies and evaluates the blocks or parts of blocks most prone to detachment or fall. The method focuses on diagnosing the susceptibility of stone materials to decohesion and detachment, which pose a potential risk to both individuals and the integrity of the architectural heritage. Taking into account the historical significance of the building under investigation, this approach aims to improve our understanding of conservation practices. It plays a crucial role in preventing deterioration caused by weathering, pollution, and the specific lithological characteristics of the stone, thus contributing to the preservation of the monument. The processing methodology is based on a multi-criteria heuristic approach that combines the weights with the different instability factors, according to a knowledge-based approach. Based on discriminating parameters – such as Non-Destructive Testing (NDT) like ultrasound and sclerometer – and predictive factors, such as morphological and morphometric conditions, the most vulnerable elements are identified. This method represents a probabilistic approach that establishes a scale of increasing risk, although it does not provide deterministically sufficient conditions to predict the detachment of stone elements.

The purpose of NDT, including ultrasonic and Schmidt hammer testing, is to assess the mechanical properties of the material under test at the point of inspection. Ultrasonic pulse velocity testing, performed with the IMG 5200 CSD instrument, allows the measurement of the velocity of propagation (V_p) of mechanical waves. This technique is used to qualitatively assess the compactness and homogeneity of the stone and to detect cracks, discontinuities, and cavities in the material.

The Schmidt hammer test, performed with Original Schmidt live L, Proceq instrument, provides information on the strength of the surface area being tested. The test measures the rebound of a mass impacting on the stone surface (rebound index, R). By considering the rebound value (R) and the ultrasonic velocity (V_p), it is possible to assess the mechanical properties of the material: high V_p and R values indicate a stone in good condition, while low values indicate problems that may affect the surface and/or the stone matrix in depth (Falchi et al. 2015). More precisely, V_p values below 2000 m/s indicate a moderate to severe state of degradation due to the presence of open fractures, detached sections or even surface disintegration. Similarly, R values below 30 suggest that the surface is either exfoliated or fractured, or that the investigated element contains portions of loose material (Centauro et al. 2022). For both techniques, the measurements were always taken at identical points according to a regular grid, which allowed a comparative analysis of the distribution of values.

Furthermore, an analysis of morphological and morphometric parameters was conducted; the attributes investigated was those influencing the stability of the ashlars:

- Overhang. Each rusticated stone ashlars corresponds to different projections calculated from the plane of the facade. This morphometric behaviour is a key factor in assessing the vulnerability of the analyzed element; an increase in the overhang results in a heightened exposure to atmospheric agents. Furthermore, the greater volume increases the likelihood of discontinuities occurring at critical angles of instability.
- Discontinuities. They are a prominent feature of Pietraforte stones with calcite veins. The calcium carbonate that forms these veins is prone to dissolution when exposed to water. This phenomenon results in fractures that can cause entire sections of the stone to detach. Moreover, the veins are the most fragile areas of the Pietraforte, as the rock tends to fracture along one of these veins, even if they are not degraded. In the context of this study, the number of discontinuities and, if present, the number of open veins, are considered.
- Laminations. These features represent an additional factor contributing to the deterioration of Pietraforte, particularly those of a convoluted nature. Depending on the orientation of the rusticated ashlars, these laminations may occur in different places, and some may not be visible. Such instances are

considered when they are clearly visible and show clear signs of deterioration along the vein line.

The integration of the NDT results with morphological and morphometric analyses and laboratory tests enabled us to identify the most critical blocks (Figure 7). This is a pivotal stage in the conservation of stone facades, establishing actions and practices required to properly preserve heritage at risk. The result is a probabilistic index that closely approximates the behaviour of the sandstone elements. These elements are classified into three levels of alert (Low, Medium, High), providing a comprehensive understanding of the potential risks associated with each component. The proposed diagnostic approach allows the selective monitoring of critical stone elements, facilitating the conservation of architectural heritage and improving the safety of the numerous tourists who visit both the Cortile dell'Ammannati and the Pitti Palace every year.

6. THE PARAMETERIZATION OF KNOWLEDGE

The research developed by Unifi's DST-LAM represents the first fundamental step in planning structured monitoring and management actions for the facades of the Pitti Palace. The diagnostic approach to Pietraforte as a geo-heritage emphasizes the importance of instrumental knowledge in heritage preservation, primarily from a material- and structure-related perspective. The use of non-destructive methods and tools ensures the full preservation of the asset's ancient material but requires costly and time-consuming inspections, especially in relation to scaffolding.

Building on the virtuous process initiated by DST-LAM, the DICEA of Univpm launched a complementary analysis of the facades of the Cortile dell'Ammannati, integrating qualitative knowledge as pivotal as the instrumental data.

Operationally, DICEA proposes two knowledge-based indices to contribute to a new strategic approach for managing the risk of detachment and falling stone fragments, while exploring empirical methods closely aligned with the scientific ones. Based on the dual assumption that deterioration significantly contributes to the detachment of fragments and that restoration should aim to limit this phenomenon, the research focused on two knowledge domains: firstly, the 'previous restoration works', largely traced through archival documents; and secondly, the 'state of conservation' of the ashlars, closely observed and assessed on site, with the goal of interpreting for each of them their impact on the conservation of the ancient material and on the safe use of the asset.

To relate these qualitative insights to the DIST-LAM index, it was first necessary to parameterize them. The parameterization process consisted in assigning a numerical value according to the impact in terms of restoration works (superficial/deep), and severity of degradation (medium to high loss of stone material).

Two numerical indices were then calculated:

- the 'Previous Restorations Index' (PRI) briefly describes the 'clinical history' of restorations carried out on each rustication over time, understood as a stratification of interventions; it follows that the higher the index result, the more the rustication has been subjected to conservation efforts, and therefore, the more likely it is to be in a critical state;
- the 'Deterioration Index' (DI) refers to the current state of conservation of each rusticated ashlar; it follows that, in this case, the higher the index result, the more likely it is that the rustication is more prone to detachment.

6.1 The Previous Restoration Index (PRI)

As already mentioned, the Previous Restoration Index (PRI) is used to describe the ‘clinical history’ of each rustication, assessed in terms of the stratification of restoration works occurred in the past.

The calculation of the index was preceded by a recent and unpublished research carried out at six public archives in Florence, including the Uffizi Galleries Archives and the Historical Archives of the Superintendency for Archaeology, Fine Arts and Landscape Heritage of the city of Florence and the provinces of Pistoia and Prato. The study made it possible to trace the restoration work conducted on the facades of the Cortile dell’Ammannati from 1889 to the present day, which had never been fully systematized and of which there was no real knowledge. It has also been possible to document the evolution of the materials and techniques used in the restoration work, as well as the way in which the restauration sites were managed, highlighting the fact that in the past the work was carried out on an emergency basis (Figure 8).

The results showed that works mainly consisted of Surface Consolidation (SC) and Deep Consolidation (DC) interventions. The overall analysis indicates that, among surface consolidations, the most commonly employed in the past were fluosilicate-based treatments in the 1970s, followed by perfluoropolyether-based water-repellent treatments such as ‘Fomblin’ in the 1980s, and ethyl silicate-based consolidations performed on multiple occasions during the 2000s. With regard to deep consolidations, the most common solution involved the use of metal (specifically brass, iron, and copper) cramps, binding elements, and pins. This latter technique varied depending on the period in which the restoration work was carried out: brass, iron and copper rods were used from 1939 until the 1980s, after which they were replaced by stainless steel rods; since the 2000s fiberglass has been increasingly employed. The use of hydraulic mortars injections and epoxy resin was also widely documented (Quagliarini et al. 2025).

Finally, the restoration works were mapped according to their date and the specific portion of the facade they affected, and then arranged in chronological order (Figure 9a). In addition, typological mappings of the various consolidation techniques applied to the Cortile facades were carried out to illustrate the stratification, frequency, to assess their effectiveness and long-term durability (Figure 9b).

During the parameterization phase, each restoration intervention analyzed was given a numerical value representative of its impact, assessed on the basis of restoration experts' judgement. In general, the value is equal to 1 for surface consolidation interventions and 2 for deep consolidation interventions and, in both cases, increased by 0,5 if poorly compatible materials (cement mortars or metal elements that were not protected against oxidation) were used (Table 1). A double-entry summary table was created, with each row corresponding to a quadrant of the Cortile dell'Ammannati, and each column corresponding to the different types of intervention described above. This table serves as a fundamental tool for pivotal analysis: by isolating each column, it is possible to determine which portion of the facade each type of intervention was applied to; conversely, reading each row reveals which restoration interventions were carried out on each quadrant, ultimately leading to the PRI. The resulting calculation gives a value between 0 and 10, which can be assigned to 3 alert classes: Low (PRI<4,0); Medium (4,0≤PRI<6,0); High (PRI≥6,0). The higher the index score, the more the quadrant has been the subject to restoration efforts, and therefore, the more likely it has been in a critical state.

The calculation was done as follows:

(1)

$$PRI_i = 10 \cdot \sum_{j \in R_i} x_j \Big/ \sum_{j=1}^{n} x_j$$

Legend:

PRI_i: PRI index for i-th portion (quadrant or stone element);

x_j: numerical value for j-th intervention;

R_i: represents the set of interventions made on the i-th portion;

n: total number of interventions made.

The results of the PRI are summarized in Figure 10. At a macroscopic level, it is evident that the western facade has undergone the most restoration work over time, probably due to its orientation and exposure to weathering agents. Additionally, it currently experiences the highest tourist flow, since it is close to the Pitti Palace café and to the main entrance of the Boboli Gardens.

It is feasible to perform the calculation at a more detailed level: following the methodology outlined above, a thorough analysis was conducted on a sample of stone blocks extracted from the test quadrants. The archival data were subsequently verified through both visual inspections and instrumental assessments. The PRI was recalculated for each sampled stone element, as presented in Table 2 and illustrated in Figure 11. These results were then implemented in a GIS environment, from which the thematic map was generated.

6.2 The Deterioration Index (DI)

The second index developed is the Deterioration Index (DI) and it describes the conservation status of the ashlars. The work involved a first phase of on-site data collection and parametrization of the acquired knowledge, and a second phase of numerical processing to define the DI.

Figure 12 explains the workflow for the definition of the model. In the upper part there is an explanation of the first phase. In line with Italian prescriptions defining Normal 1/88 'Macroscopic alterations of stone materials lexicon' (CNR-ICR 1990), and subsequent UNI 11182:2006 amendments (UNI 2006) and using the 'ICOMOS-ISCS Illustrated glossary on stone deterioration patterns' (Vergès-Belmin 2008), a detailed stocktaking exercise of the conservation status of the stone ashlars in the test quadrants was conducted. The main forms of deterioration that affect the Pietraforte rusticated blocks of the Cortile's western facade can be classified as follows: (1) deposit, (2) efflorescence, (3) encrustation, (4) moist area, (5) delamination, (6) crumbling, (7) granular disintegration, (8) crack, (9) loss. The on-site surveying of each form of degradation was carried out using the above-mentioned categories (Figure 13). Following a review of the descriptions provided by international guidelines, the analysis focuses exclusively on physical-mechanical forms of deterioration that may result in the detachment or loss of stone fragments (delamination, crumbling, granular disintegration, crack and loss), and thematic maps of those were developed accordingly within a GIS environment. This enabled the measurement of the extent of each type of deterioration. The absolute surface (S_{di}, m^2) of each deterioration form and the area of each ashlar (S_{si}, m^2) was then measured. Based on their ratio (S_{di}/ S_{si}), four degradation intensity levels were defined: None (N), Low (L), Medium (M), High (H), with which a numerical value (W) of 0, 5, 7, and 9, respectively, was associated according to the experts' judgement (Table 3). These values were assigned based on a scale ranging from 0 to 10. Given that, a value of 0 is assigned exclusively in the absence of degradation. Higher values are assigned based on the previously established ratio. Specifically, deterioration affecting less than 20% of the stone surface is classified as low and is assigned a value of 5. Deterioration extending between 20% and 40% is categorized as medium, with a corresponding value of 7, whereas deterioration affecting more than 40% of the surface is considered high and is assigned a value of 9.

This yields the table of the conservation status of ashlars (Table 4), which provides a comprehensive overview of the types of deterioration identified and their extent for each stone ashlar in the test area.

Based on the information organised in Table 4, it is possible to proceed to the second phase and develop the DI, that provides a brief assessment of the overall condition of each stone ashlar; DI was calculated using a mathematical model, to obtain results as objective and repeatable as possible. The approach to the model is heuristic. The analysis model employed is Multiple Linear Regression (MLR), which represents a class of mathematical models for supervised learning, useful for studying the correlation between a numerical target variable (the dependent variable) and a set of explanatory variables (independent variables) describing the observations of a given dataset (Milanato 2008). Regression models are regarded as empirical models and, in many cases, can approximate complex real-world phenomena using a linear regression equation. However, regression equations are typically valid only within the range of regressor variables observed in the dataset (Montgomery, Peck, and Vining 2021). Given these considerations, MLR was selected as the most suitable model for this application. Generally, the correlation between the dependent variable and the independent variables is expressed as follows (2):

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \cdots + \beta_n x_{ni} + \varepsilon_i \qquad (2)$$

Where y_i is the dependent variable, x_{1i}, x_{2i}, …, x_{ni} are the independent variables, β_0, β_1, β_2, …, β_n are the regression coefficients, and ε_i represents the random error of the model (Prieto et al. 2017).

The parameterization phase is resumed in the lower part of Figure 12. In the definition of the MLR model, the DI is considered the dependent variable, while the five forms of deterioration are the independent variable. In the present case, the dataset, consisting of a sample of ashlars, was divided into two groups: a first, more substantial group was used for training the model, which, once verified, was employed to calculate the DI of the ashlar under investigation. For supervised training, the DI target variable was initially assigned manually to the random sample of stone ashlars according to considerations guided by experts' judgment. The independent variables are their numerical value (W).

The prediction model was developed both through Microsoft Power BI and Microsoft Power Query using R script, and through Microsoft's ML.NET's Model Builder, a graphical extension of Microsoft Visual Studio 2022. A total of four MLR models were defined to calculate the DI. The first model (M1) was developed using Microsoft Power BI, and Table 5 provides a summary of its statistical metrics. The other three models were developed using Microsoft ML.NET, and each of them was investigated to identify the best regression model for the dataset in terms of a specific statistical parameter. Specifically, model M2 yields the best coefficient of determination (R^2), M3 provides the lowest Root Mean Squared Error (RMSE), and M4 gives the lowest Mean Squared Error (MSE). A summary of these three models is presented in Table 6.

Subsequently, the DI was calculated for the stone ashlars under investigation using all four models, as reported in Table 7. As shown, the predicted DI values are quite consistent across all models. However, due to its better statistical metrics, M1 – developed using Microsoft Power BI – was adopted as the preferred solution.

This choice ultimately enabled the definition of Equation (3) for the calculation of the DI:

$$DI = 2{,}14 + 0{,}15x_{DL} + 0{,}16x_{CR} + 0{,}21x_{GD} + 0{,}13x_{CR} + 0{,}17x_{LS} \quad (3)$$

Legend:

x_{DL}: delamination weight;

x_{CR}: crumbling weight;

x_{GD}: granular disintegration weight;

x_{CR}: crack weight;

x_{LS}: loss weight.

An examination of Table 5 indicates that the five explanatory variables appear to possess predictive capability with regard to the dependent variable DI and are statistically relevant. The coefficient of determination R^2 is very close to 1 and according to the ANOVA statistics:

- $F > F_{(\alpha,k,k\text{-}n\text{-}1)}$, where F is equal to 176,6654, α is equal to 0,05, k is equal to 5, k-n-1 is equal to 30, and $F_{(0{,}05,5,30)}$ is equal to 2,5336, obtained by the Fisher–Snedecor tables;
- Significance F (p-value) < 0,05

The statistic metrics referred to each explanatory variable confirm their significance:

- Stat t > Stat $t_{(\alpha,k\text{-}n\text{-}1)}$, where Stat t represents the t-statistic for each variable, as reported in the table, α is equal to 0,025, k-n-1 is equal to 30, and Stat $t_{(0{,}025,30)}$ is equal to 2,042, obtained by the Student's t-table.
- p-value < 0,05, where the p-value represents the significance value for each variable, as reported in the table.

The selected model demonstrates general validity, featuring a slope coefficient

(2,14) that reflects the exclusion of certain deterioration phenomena which, although having a minor impact on detachment or fall of stone fragments, do in fact exist. While M1 is statistically significant, at this stage of the research it approximates the deterioration of the stone elements, albeit with some remaining uncertainty, and remains subject to further refinement in terms of representativeness.The results of applying the M1 model to the investigated stone ashlars – as in the corresponding column of Table 7 – were subsequently integrated into the GIS environment for further analysis and the extraction of thematic maps (Figure 14).

7. IMPLEMENTATION OF THE KNOWLEDGE-BASED TOOL

The knowledge acquired so far opens up new scenarios for the management of the facades of the Pitti Palace, in terms of the conservation of heritage materiality, and public safety. A multi-parametric analysis can be performed by comparing the two approaches employed: geomechanical analysis (section 5), and the analysis of previous restoration works alongside the heritage state of conservation (section 6).

The indices derived from the qualitative information parameterized in this study (PRI and DI), and developed by the DICEA, were combined to get the knowledge-based tool. The results were then validated by comparing them with those obtained through the multi-analytical instrumental model devised by DST-LAM.

The developed model can be applied on a large scale to assess the condition of the stone ashlars, since it does not require any specific equipment, and, if integrated with the precise diagnostic tests, it can provide valuable support in defining conservation strategies for the facades of the Pitti Palace.

Operationally, this knowledge-based tool is founded on a logical sequence of combinations among alert classes. These classes are defined by adapting international guidelines for the risk assessment and management of cultural heritage (ICCROM 2016,

p. 18; UNESCO et al. 2013, p. 30) to the specific context of Pitti Palace. The tool, outlined in Table 8, enables the integration of knowledge from the past (PRI) and present (DI) to inform future actions according on the final alert classification. Specifically, a low alert class indicates that no immediate action is necessary; a medium alert class suggests the need for regular visual monitoring, while a high alert class requires in-depth instrumental diagnostics conducted by qualified technical specialists.

The attribution of the alert class follows a twofold safety-oriented approach: since the DI is an index that synthetically describes the current state of conservation of the ashlars, developed by considering only those forms of degradation that significantly affect detachment and the falling of stone fragments, it is logical to assert that the higher its value, the higher the final alert class should be. The PRI provides a concise indication of the stratification of restoration works carried out on each stone ashlar over time. Each past intervention introduces an additional variable which, in general, increases the complexity of analyzing the individual stone element and its conservation state, requiring increased attention. Therefore, at this stage of the research, the higher its value, the higher the final alert class should be. According to this rationale, the remaining sections of the Table 8 are completed by prioritizing the highest class, thus ensuring that the final results consistently emphasize safety.

As shown in Figure 15, most of the ashlars on the second floor fall into the high alert class, while on the lower floor, the distribution is more homogeneous between the high and medium alert classes. The estimation results obtained by the DICEA's prediction model are in line with the estimates obtained by the DST-LAM group, and the resulting alert classes never underestimate the alert classes developed by the geology lab that are considered 'close to reality'. Thus, the predictions are all validated by the results of the instrumental tests of the Florence laboratory.

Further reflections can be made on the contribution of each parameter. Concerning the state of conservation, there is a proportionality between degradation and the probability of detachments/falls occurring. This finding confirms the initial assumption that, as the intensity of the five forms of degradation analyzed increases, so does the probability of reaching the potential level of damage.

Regarding previous restoration works, their contribution has been considered by assessing the proportional relation between the invasiveness of the interventions and the need for action for safety reasons. Although this approach tends to simplify the complexity of the real-world impact of restorations, it does not diminish the alertness to the areas most affected by conservation efforts. On closer inspection, often some restoration works are beneficial in preserving the ancient material, some have no benefit (zero contribution), while others accelerate degradation. In this regard, there are interventions that have contributed to the conservation of the stone elements; however, there are also cases where it has proved ineffective or has even increased or aggravated the deterioration, as proved by some particularly critical elements (Figure 16).

8. CONCLUSIONS AND FUTURE WORKS

The potential detachment and falling of stone fragments from the sandstone facades of the Pitti Palace pose a hazard to both its conservation and the safe experience of the heritage sites. The construction material, Pietraforte, tends to disintegrate, triggering dangerous degenerative processes caused primarily by endogenous factors inherent to the lithotype. This has led to the experimentation of new conservation and management strategies for the monitoring of each rusticated ashlar.

The aim is to support the strategic policies of heritage managing bodies and institutions through the design and implementation of a knowledge-based tool, that employs a heritage- and people-centered approach to address the specific challenges of palace facades.

The novelty of this research lies in the attempt to provide operational tools for defining priorities in conservation, based not only on the results of instrumental geomechanical tests on the stone (quantitative knowledge, numerical data), which here serves as a validation element for the proposed method, but also on historical-documentary, material and technological analysis (qualitative knowledge, non-numerical evidence). The study aligns the international and national recommendations that place knowledge at the heart of any quality intervention on cultural heritage, valuing above all the ‘history of restorations’ as an operative source for conservation purposes (Ministerial Decree 154/2017, art. 3).

The experimentation focused on the western facade of the Cortile dell’Ammannati of the Pitti Palace, which today exhibits the most critical conservation issues due to the combined effect of multiple layers of consolidation interventions carried out over the centuries and the high exposure to both atmospheric agents and the tourist flows visiting the museum.

To achieve the research objectives, the DICEA of Univpm defined two numerical indices by parameterizing the qualitative knowledge: the Previous Restoration Index (PRI), based on past restoration activities, and the Deterioration Index (DI), reflecting the current state of conservation of the rusticated ashlars in the test area of the facade. Their combination, through a correlation of alert classes, has resulted in a first knowledge-based tool that, validated using the instrumental diagnostic analyses of the DST-LAM of Unifi, enables a preliminary assessment of the hazard of detachment and fall of stone fragments by adequately assigning alert classes, without ever underestimating the results.

In conclusion, the proposed study has the potential to reduce reliance on emergency measures, which often leave little room for reflection and frequently tend to result in temporary solutions. The tool serves as a complement to geomechanical surveys, which, although essential for defining PPC strategies, are more costly and time-consuming. In this regard, the tool streamlines evaluation procedures and minimises the economic impact of the preliminary verification of the alert status of stone facades by guiding more targeted instrumental analyses with close-monitoring efforts based on a qualitative pre-assessment. This pre-assessment does not require scaffolding, yet provides a comprehensive overview of risk distribution across the facades.

For future developments, particular attention will be devoted to refining both the DI and PRI. The DI is currently based on a Multiple Linear Regression (M1), which, although identified as the most suitable among those tested, still demonstrates only partial representativeness and offers room for improvement. To enhance the reliability and effectiveness of the predictive tool, future research will focus on expanding the dataset of investigated ashlars and exploring alternative modelling strategies, including different mathematical approaches and logic-based combination systems. In this regard, it is important to note that the Uffizi Galleries are actively promoting these improvements. They have made the acquisition of data on the state of conservation – according to the criteria presented in this paper – a foundational requirement in upcoming conservation project tenders and monitoring activities, thereby contributing to the enrichment of the dataset. This also serves to demonstrate the value of the proposed knowledge-based tool within the operational practices of the managing institution.

Additionally, with regard to the PRI, further efforts will focus on optimizing its definition by testing innovative techniques to improve the identification of restoration materials, such as pins that are partially visible to the naked eye. The research will also aim to develop operational guidelines that integrate the timetable for periodic monitoring with both past good practices and new stone consolidation solutions, which will be tested on pilot construction sites.

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AUTHOR CONTRIBUTIONS

Conceptualization: CM, PR, TS, AC. Methodology: CM, AC. Validation: CM, TS, AC. Investigation: CM, TS, AC. Writing original draft preparation: CM, PR, TS, AC. Writing review and editing: CM. Visualization: AC.

In particular: 1. Introduction [CM], 2. Object and Aim [CM, PR, TS, AC]; 3. The Pitti Palace in Florence: Construction History and Management Challenges [PR, AC]; 4. Materials and Methods [AC]; 5. Pietraforte as geo-heritage: a diagnostic approach to estimate the behavior of stone elements [TS]; 6. The Parameterization of Knowledge [CM]; 6.1 The Previous Restorations Index (PRI) [CM]; 6.2 The Deterioration Index (DI) [AC]; 7. Implementation of the knowledge-based tool [CM, AC]; 8. Conclusions and Future Works [CM]. All authors have developed and agreed to the final version of the manuscript.

DISCLOSURE STATEMENT

The authors report there are no competing interests to declare.

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Table 1. Numerical value associated with each restoration work.

	CODE	Type of consolidation technique	Value
Superficial consolidation	**SC1**	Application of fluosilicate products	**1,00**
	SC2	Brush or spray application of ethyl silicate	**1,00**
	SC3	Ammonium carbonate packs dissolved in Japanese paper pulp	**1,00**
	SC4	Repairs with cement or hydraulic mortars (carried out in the 60s)	**1,50**
	SC5	Repairs with cement or hydraulic mortars (carried out in the 80s)	**1,50**
	SC6	Sealing of detached and recoverable fragments with hydraulic mortars	**1,00**
	SC7	Sealing of detached and recoverable fragments with epoxy resin	**1,00**
	SC8	Sealing of cracks with transparent silicone	**1,00**
	SC9	Grouting with mastic and Pietraforte powder mixture	**1,00**
	SC10	Grouting with fluoroelastomer mixture added with natural powders and pigments	**1,00**
	SC11	Spray application of water-repellent protective products (Fomblim) based on perfluoropolyether with hand sprayer	**1,00**
	SC12	Brush or spray application of hydrophobizing protective product based on hexafluoropropene	**1,00**
	SC13	Application of ethyl silicate-based consolidating agent (Primal at 10%) with hand sprayer	**1,00**
Deep consolidation	**DC1**	Reinforcements with metal pins (iron, brass, copper)	**2,50**
	DC2	Embedding with stainless steel bars and saturation filling with epoxy resin	**2,00**
	DC3	Pinning with stainless steel pins (max Ø2.3mm) coated with resin (thermosetting)	**2,00**
	DC4	Glass fiber rods and saturation filling with epoxy resin	**2,00**
	DC5	Installation of brass, iron, copper metal cramps or binding elements (now visible).	**1,50**
	DC6	Replacement or removal of old brass, iron, copper metal cramps or binding elements	**1,00**
	DC7	Injections of cement mortars or hydraulic mortars	**2,50**
	DC8	Injections of fluid epoxy resin	**2,00**

Table 2. Double-entry summary table and PRI results: stone ashlars are listed in the rows, while restoration work is detailed in the columns.

ID stone element	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	SC13	DC1	DC2	DC3	DC4	DC5	DC6	DC7	DC8	PRI
1185	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	YES	NO	YES	NO	YES	NO	YES	NO	**5,1**
1187	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	YES	NO	NO	YES	NO	**3,8**
1186	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
1199	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
1201	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
1238	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**3,1**
1247	YES	NO	NO	YES	YES	YES	NO	YES	YES	NO	YES	NO	NO	YES	NO	YES	NO	NO	NO	YES	NO	**5,5**
1272	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	YES	NO	YES	NO	NO	NO	YES	NO	**4,6**
1274	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
1281	YES	NO	NO	YES	YES	YES	NO	YES	YES	NO	YES	NO	NO	YES	NO	YES	NO	NO	NO	YES	NO	**4,9**
1283	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	YES	NO	YES	NO	NO	NO	YES	NO	**4,6**
1290	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
1292	YES	NO	NO	NO	NO	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**1,5**
1373	YES	NO	NO	YES	YES	YES	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,8**
3244	YES	NO	NO	YES	YES	YES	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,8**
3246	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
3249	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
41	YES	NO	NO	NO	NO	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**1,5**
42	YES	NO	NO	YES	YES	YES	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,8**
395	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**3,1**
397	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**3,1**
401	YES	NO	NO	YES	YES	YES	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**3,4**
403	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
405	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
407	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
412	YES	NO	NO	NO	NO	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**1,5**
418	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
420	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
1764	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
1767	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
3147	YES	NO	NO	YES	YES	YES	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,8**
3148	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
3150	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
3152	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,5**
3161	YES	NO	NO	YES	YES	YES	NO	YES	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	**2,8**

Alert classes: Low (PRI<4,0 in yellow); Medium (4,0≤PRI<6,0 in orange); High (PRI≥6,0 in red).

Table 3. Descriptive variables valuation for the deterioration forms.

Deterioration extension (quantitative valuation)	**Intensity level (qualitative valuation)**	**Numeric value (W) (parameterization)**
$\frac{S_{di}}{S_{si}} = 0$	None (N)	0
$0 < \frac{S_{di}}{S_{si}} < 0,2$	Low (L)	5
$0,2 < \frac{S_{di}}{S_{si}} < 0,4$	Medium (M)	7
$\frac{S_{di}}{S_{si}} > 0,4$	High (H)	9

S_{di}: absolute surface of each deterioration form (m^2)
S_{si}: size of each ashlar (m^2)

Table 4. Quali-quantitative summary of the conservation state of the investigated stone ashlars.

ID stone element	Delamination	Crumbling	Granular disintegration	Crack	Loss
1185	(H) 9	(H) 9	(H) 9	(H) 9	(M) 7
1186	(M) 7	(H) 9	(H) 9	(L) 5	(L) 5
1187	(M) 7	(H) 9	(H) 9	(N) 0	(H) 9
1199	(M) 7	(N) 0	(M) 7	(H) 9	(N) 0
1201	(M) 7	(L) 5	(H) 9	(H) 9	(N) 0
1238	(M) 7	(L) 5	(M) 7	(H) 9	(L) 5
1247	(L) 5	(L) 5	(M) 7	(H) 9	(N) 0
1272	(H) 9	(H) 9	(H) 9	(H) 9	(H) 9
1274	(H) 9	(H) 9	(H) 9	(H) 9	(H) 9
1281	(H) 9	(H) 9	(H) 9	(M) 7	(M) 7
1283	(H) 9	(H) 9	(H) 9	(H) 9	(L) 5
1290	(M) 7	(L) 5	(M) 7	(N) 0	(N) 0
1292	(M) 7	(L) 5	(M) 7	(N) 0	(M) 7
1373	(H) 9	(H) 9	(H) 9	(H) 9	(H) 9
3244	(H) 9	(H) 9	(H) 9	(N) 0	(H) 9
3246	(N) 0	(N) 0	(N) 0	(N) 0	(N) 0
3249	(N) 0	(N) 0	(N) 0	(N) 0	(N) 0
41	(L) 5	(N) 0	(M) 7	(H) 9	(L) 5
42	(L) 5	(N) 0	(L) 5	(H) 9	(L) 5
395	(M) 7	(N) 0	(L) 5	(N) 0	(L) 5
397	(M) 7	(N) 0	(L) 5	(M) 7	(L) 5
401	(M) 7	(L) 5	(M) 7	(H) 9	(M) 7
403	(M) 7	(L) 5	(M) 7	(N) 0	(L) 5
405	(L) 5	(N) 0	(M) 7	(N) 0	(N) 0
407	(M) 7	(N) 0	(M) 7	(N) 0	(L) 5
412	(H) 9	(L) 5	(H) 9	(N) 0	(M) 7
418	(M) 7	(N) 0	(M) 7	(N) 0	(L) 5
420	(M) 7	(N) 0	(M) 7	(N) 0	(L) 5
1764	(L) 5	(N) 0	(N) 0	(N) 0	(L) 5
1767	(N) 0	(N) 0	(N) 0	(N) 0	(N) 0
3147	(H) 9	(H) 9	(H) 9	(H) 9	(H) 9
3148	(H) 9	(L) 5	(N) 0	(H) 9	(N) 0
3150	(H) 9	(L) 5	(H) 9	(N) 0	(L) 5
3152	(H) 9	(L) 5	(M) 7	(M) 7	(M) 7
3161	(H) 9	(H) 9	(H) 9	(H) 9	(H) 9

5. Summary of the multiple linear regression model for the definition of the Deterioration Index made by Microsoft Power BI (M1).

Regression statistic	
Multiple R	0,983439404
R^2	0,967153061
Adj. R^2	0,961678572
Standard Error	0,348180319
Observations	36

Analysis of variance (ANOVA statistics)

	Degree of freedom	*SS*	*Mean Squared deviation*	*F*	*Significance F*
Regression	5	107,0853362	21,41706724	176,6654249	2,62763E-21
Residuals	30	3,636886037	0,121229535		
Total	35	110,7222222			

	Coefficients	*Standard Error*	*Stat t*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2,142155395	0,218493784	9,804193777	7,23679E-11	1,695931559	2,588379232
Variable x_1 (Delamination)	0,152243755	0,027642323	5,507632353	5,5577E-06	0,095790599	0,20869691
Variable x_2 (Scrumbling)	0,15856404	0,023905104	6,633062166	2,41204E-07	0,109743305	0,207384775
Variable x_3 (Granular disintegration)	0,205876731	0,038917183	5,290124215	1,02669E-05	0,12639724	0,285356221
Variable x_4 (Crack)	0,131675713	0,015143476	8,695210624	1,06791E-09	0,100748609	0,162602817
Variable x_5 (Loss)	0,167660891	0,017613523	9,518873107	1,4243E-10	0,131689278	0,203632504

Table 6. Summary of the Microsoft's ML.NET model for the definition of the Deterioration Index realised with Microsoft's Visual Studio 2022 (M2; M3; M4).

Statistic metric	Value	Best model	Training time imposed	Training time used by ML.NET	Explored models
M2 - Best Coefficient of determination (R^2)	0,9399	SdcaRegression	300 seconds	295 seconds	292
M3 - Best Root Mean Squared Error (RMSE)	0,3706	SdcaRegression	300 seconds	261 seconds	260
M4 - Best Mean Squared Error (MSE)	0,1466	SdcaRegression	300 seconds	288 seconds	519

Table 7. Summary table and DI results from the different models defined: stone ashlars are listed in the rows, while deterioration forms is detailed in the columns.

ID stone element	Delamination	Crumbling	Granular disintegration	Crack	Loss	M1	M2	M3	M4
1185	(H) 9	(H) 9	(H) 9	(H) 9	(M) 7	**9,2**	**9,0**	**9,0**	**9,0**
1186	(M) 7	(H) 9	(H) 9	(L) 5	(L) 5	**8,0**	**8,0**	**7,9**	**7,9**
1187	(M) 7	(H) 9	(H) 9	(N) 0	(H) 9	**8,0**	**8,0**	**8,0**	**8,0**
1199	(M) 7	(N) 0	(M) 7	(H) 9	(N) 0	**5,8**	**5,7**	**5,7**	**5,7**
1201	(M) 7	(L) 5	(H) 9	(H) 9	(N) 0	**7,0**	**6,9**	**6,9**	**6,9**
1238	(M) 7	(L) 5	(M) 7	(H) 9	(L) 5	**7,5**	**7,4**	**7,4**	**7,4**
1247	(L) 5	(L) 5	(M) 7	(H) 9	(N) 0	**6,3**	**6,3**	**6,3**	**6,3**
1272	(H) 9	(H) 9	(H) 9	(H) 9	(H) 9	**9,5**	**9,3**	**9,3**	**9,3**
1274	(H) 9	(H) 9	(H) 9	(H) 9	(H) 9	**9,5**	**9,3**	**9,3**	**9,3**
1281	(H) 9	(H) 9	(H) 9	(M) 7	(M) 7	**8,9**	**8,8**	**8,8**	**8,7**
1283	(H) 9	(H) 9	(H) 9	(H) 9	(L) 5	**8,8**	**8,7**	**8,7**	**8,7**
1290	(M) 7	(L) 5	(M) 7	(N) 0	(N) 0	**5,4**	**5,5**	**5,5**	**5,5**
1292	(M) 7	(L) 5	(M) 7	(N) 0	(M) 7	**6,6**	**6,6**	**6,6**	**6,7**
1373	(H) 9	(H) 9	(H) 9	(H) 9	(H) 9	**9,5**	**9,3**	**9,3**	**9,3**
3244	(H) 9	(H) 9	(H) 9	(N) 0	(H) 9	**8,3**	**8,3**	**8,3**	**8,3**
3246	(N) 0	(N) 0	(N) 0	(N) 0	(N) 0	**2,1**	**2,4**	**2,4**	**2,5**
3249	(N) 0	(N) 0	(N) 0	(N) 0	(N) 0	**2,1**	**2,4**	**2,4**	**2,5**
41	(L) 5	(N) 0	(M) 7	(H) 9	(L) 5	**6,4**	**6,3**	**6,3**	**6,3**
42	(L) 5	(N) 0	(L) 5	(H) 9	(L) 5	**6,0**	**5,9**	**5,9**	**5,9**
395	(M) 7	(N) 0	(L) 5	(N) 0	(L) 5	**5,1**	**5,1**	**5,1**	**5,1**
397	(M) 7	(N) 0	(L) 5	(M) 7	(L) 5	**6,0**	**5,9**	**5,9**	**6,0**
401	(M) 7	(L) 5	(M) 7	(H) 9	(M) 7	**7,8**	**7,7**	**7,7**	**7,7**
403	(M) 7	(L) 5	(M) 7	(N) 0	(L) 5	**6,3**	**6,3**	**6,3**	**6,3**
405	(L) 5	(N) 0	(M) 7	(N) 0	(N) 0	**4,3**	**4,4**	**4,4**	**4,4**
407	(M) 7	(N) 0	(M) 7	(N) 0	(L) 5	**5,5**	**5,5**	**5,5**	**5,5**
412	(H) 9	(L) 5	(H) 9	(N) 0	(M) 7	**7,3**	**7,3**	**7,3**	**7,3**
418	(M) 7	(N) 0	(M) 7	(N) 0	(L) 5	**5,5**	**5,5**	**5,5**	**5,5**
420	(M) 7	(N) 0	(M) 7	(N) 0	(L) 5	**5,5**	**5,5**	**5,5**	**5,5**
1764	(L) 5	(N) 0	(N) 0	(N) 0	(L) 5	**3,7**	**3,9**	**3,9**	**4,0**
1767	(N) 0	(N) 0	(N) 0	(N) 0	(N) 0	**2,1**	**2,4**	**2,4**	**2,5**
3147	(H) 9	(H) 9	(H) 9	(H) 9	(H) 9	**9,5**	**9,3**	**9,3**	**9,3**
3148	(H) 9	(L) 5	(N) 0	(H) 9	(N) 0	**5,5**	**5,5**	**5,5**	**5,5**
3150	(H) 9	(L) 5	(H) 9	(N) 0	(L) 5	**7,0**	**7,0**	**7,0**	**7,0**
3152	(H) 9	(L) 5	(M) 7	(M) 7	(M) 7	**7,8**	**7,7**	**7,7**	**7,7**
3161	(H) 9	(H) 9	(H) 9	(H) 9	(H) 9	**9,5**	**9,3**	**9,3**	**9,3**

M1 is the multiple linear regression model defined by Microsoft Power BI, M2 is the best Microsoft's ML.NET model made by searching the best R^2 parameter, M3 is the best Microsoft's ML.NET model made by searching the best MRSE parameter, M4 is the best Microsoft's ML.NET model made by searching the best MSE parameter.

Alert classes: Low (DI<4,0 in yellow); Medium (4,0≤DI<6,0 in orange); High (DI≥6,0 in red)

Table 8. DICEA logic correlation of PRI and DI for the assessment of the alert class of each stone ashlar.

	DI low	**DI medium**	**DI high**
PRI low	Low	Medium	High
PRI medium	Medium	Medium	High
PRI high	High	High	High

Figure 1. Florence, Pitti Palace and Boboli Garden. Aerial view highlighting the architectural configuration of the palace and its integration with the surrounding landscape of the Boboli Gardens (Photo by Uffizi Galleries 2024).

Figure 2. Florence, Pitti Palace, Cortile dell’Ammannati. Historical illustrations and contemporary photographs.

(a) *Veduta della Catena*, detail (Petrini, Petrini, 1887); (b) *Assedio della città di Firenze nel 1530* (Vasari. 1560-62); (c) *Naumachia in the Court of Palazzo Pitti* (Scarabelli. 1589-92); (d) *Veduta di Palazzo Pitti e del Forte di Belvedere a Firenze* (Utens, 1599); (e) *Zocchi, Giuseppe. XVIII Century. Veduta del Reale Palazzo de' Pitti* (Zocchi, XVIII century); (f) Fischer, Carl von. 1812. *Survey of Pitti Palace* (Fischer, 1812); (g-h) Current view of the Pitti Palace main facade and the Cortile dell’Ammannati (Photos by Alessandro Ceppetelli 2025).

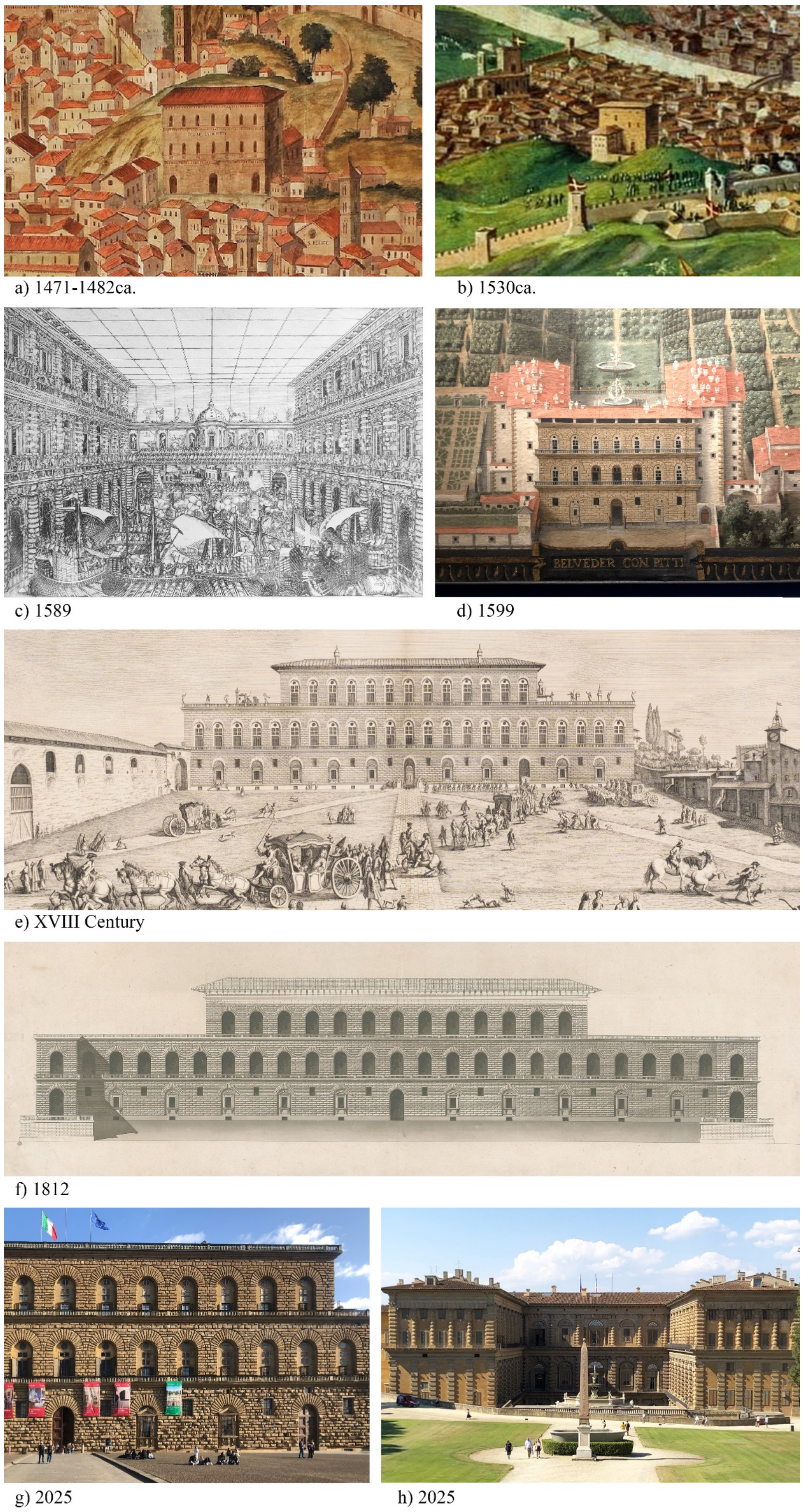

Figure 3. Florence, Pitti Palace, Cortile dell’Ammannati. Pietraforte rusticated ashlars from the second (a, b, c) and the first floor (d, e) of the western facade (Photos by Paola Ruggieri 2024).

Figure 4. Florence, Pitti Palace, Cortile dell'Ammannati. Temporary fall protection systems made of nylon nets, installed on the façades during the 2018-19 monitoring campaigns (Photos by Stefano Landi and Andrea Bonaccorso 2019).

Figure 5. Florence, Pitti Palace, Cortile dell’Ammannati. Identification of the test area (Graphic by Alessandro Ceppetelli).

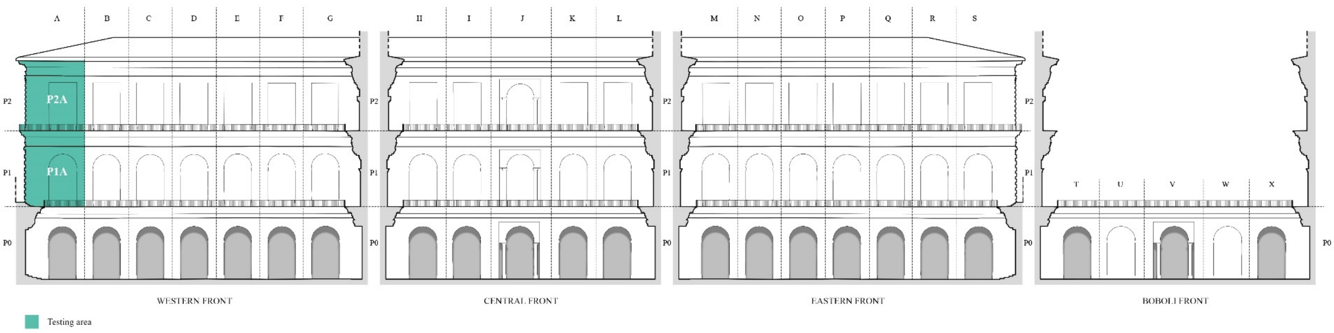

Figure 6. Florence, Pitti Palace, Cortile dell'Ammannati. Monitoring and diagnostic phases carried out by DST-LAM of Unifi: (a) Close-range visual inspection and instrumental analysis of stone surfaces conducted using an aerial platform; (b) Sclerometric testing performed with Original Schmidt live L, Proceq instrument; (c) Ultrasonic testing performed with the IMG 5200 CSD instrument; (d) Pachometric survey, which enables the detection of internal ferromagnetic metal dowels, performed with a DR3000JY, DRC Diagnostic Research Company instrument (Photos by Teresa Salvatici 2022).

Figure 7. Florence, Pitti Palace, Cortile dell'Ammannati. Average V_p values map (a), average R values map (b) and the classification of stone ashlars based on multi-analytical characterization (c) (Graphic by Teresa Salvatici).

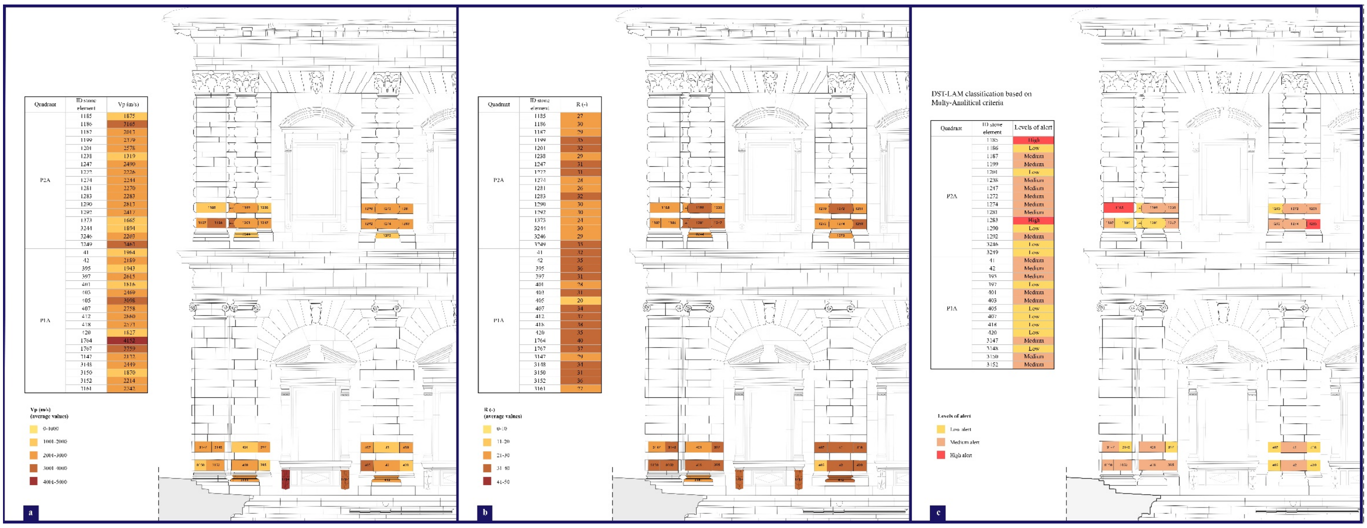

Figure 8. Florence, Pitti Palace, Cortile dell'Ammannati. A brief summary of stone ashlars in a critical state of conservation and consolidation interventions carried out during the XX-XXI century.

(a) Large rusticated ashlar fragments detached from a column on the second floor in 1965; (b) Restoration work on the west facade in 1966; (c) Critical condition of rusticated columns on the second floor in 1976; (d) Installation of metal cramps or binding elements during restoration in 1986; (e) Surface and deep detachment of a rusticated column in 2009; a trace of a previous mortar intervention is also visible. (f) Injections of fluid epoxy resin during restoration in 2011 (Photos a-d are from the Photographic Archive of the Superintendency for Archaeology, Fine Arts and Landscape Heritage of the city of Florence and the provinces of Pistoia and Prato, Palazzo Pitti - Cortile dell'Ammannati, nn. 28908, 32487, 81768, 142621, Photo courtesy of the Italian Ministry of Culture; Photos e-f are from the Uffizi Galleries Archive, Photos by Mauro Linari 2009-11).

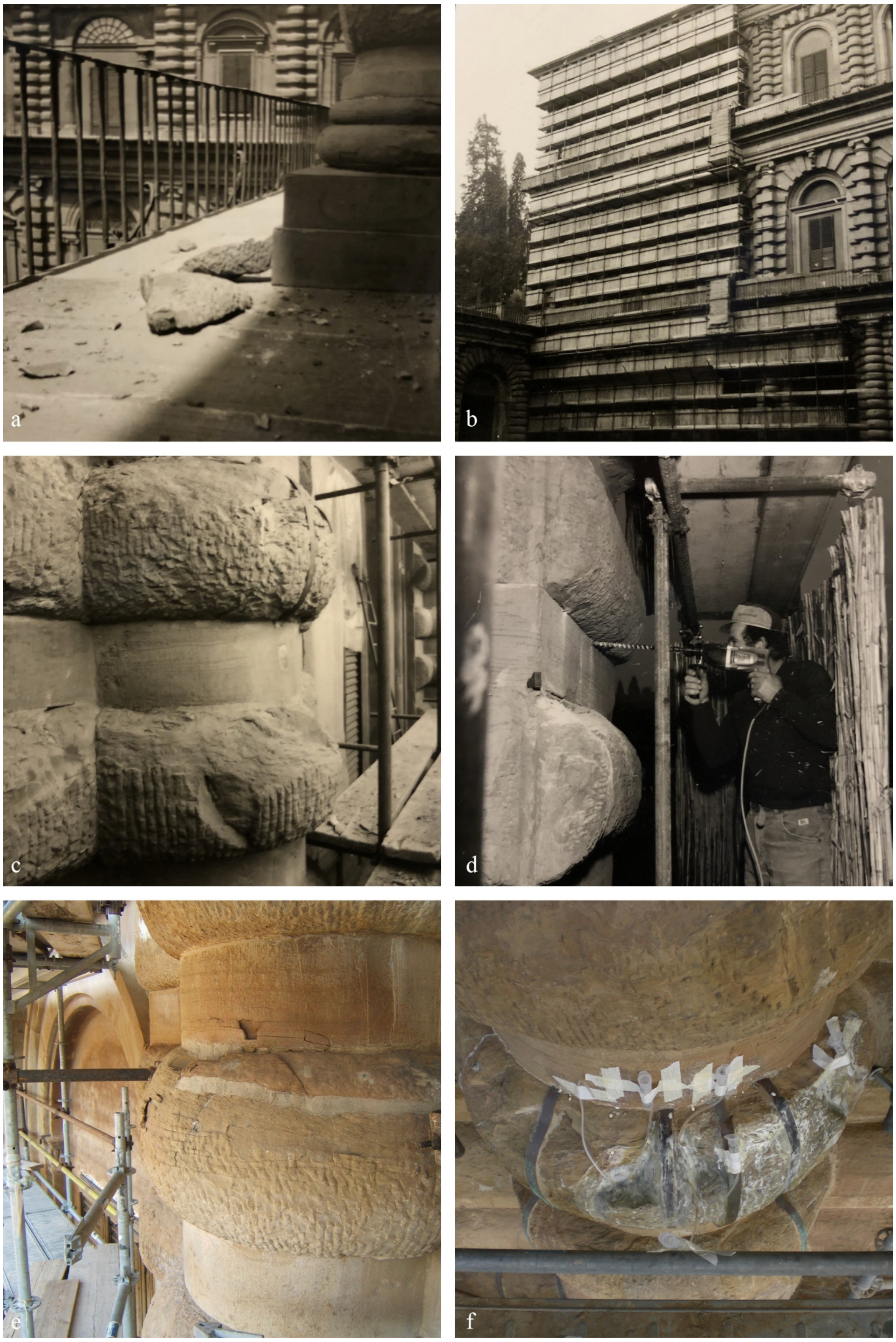

Figure 9a. Florence, Pitti Palace, Cortile dell’Ammannati. Spatial mapping of restoration site. The highlighted areas in the upper image indicate restoration works performed in 1966, while the lower image correspond to interventions carried out in in 1987 (Graphic by Alessandro Ceppetelli).

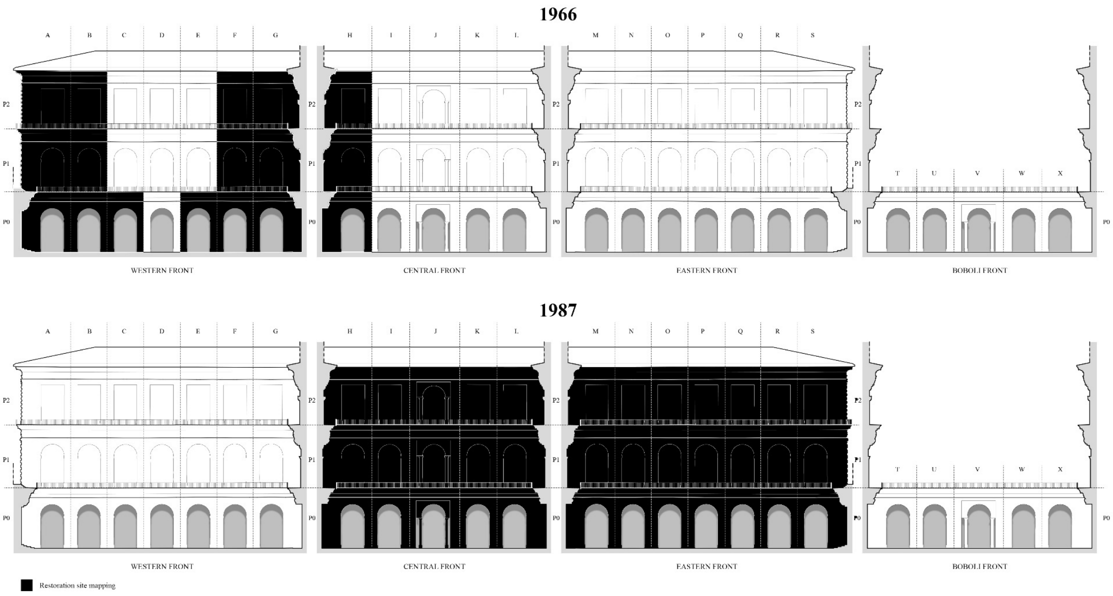

Figure 9b. Florence, Pitti Palace, Cortile dell’Ammannati. Examples of consolidation intervention mapping. The highlighted areas in the upper image indicate where deep consolidation was carried out through injections of cement or hydraulic mortars. In the lower image, highlighted areas show surface consolidations performed by brush or spray application of ethyl silicate (Graphic by Alessandro Ceppetelli).

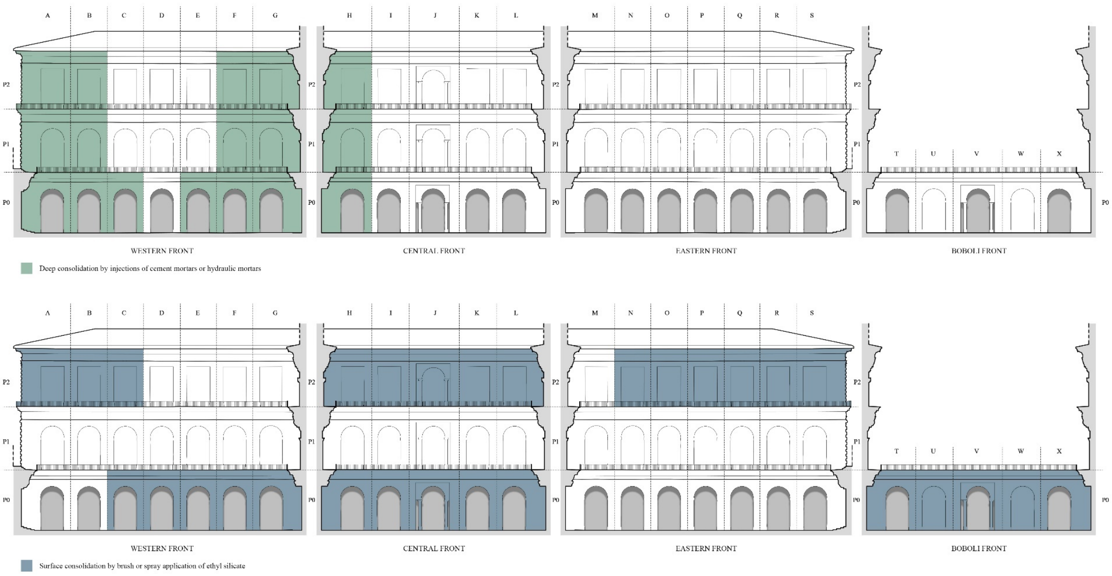

Figure 10. Florence, Pitti Palace, Cortile dell’Ammannati. Previous Restoration Index (PRI) results for all quadrants of the Cortile dell’Ammannati (Graphic by Alessandro Ceppetelli).

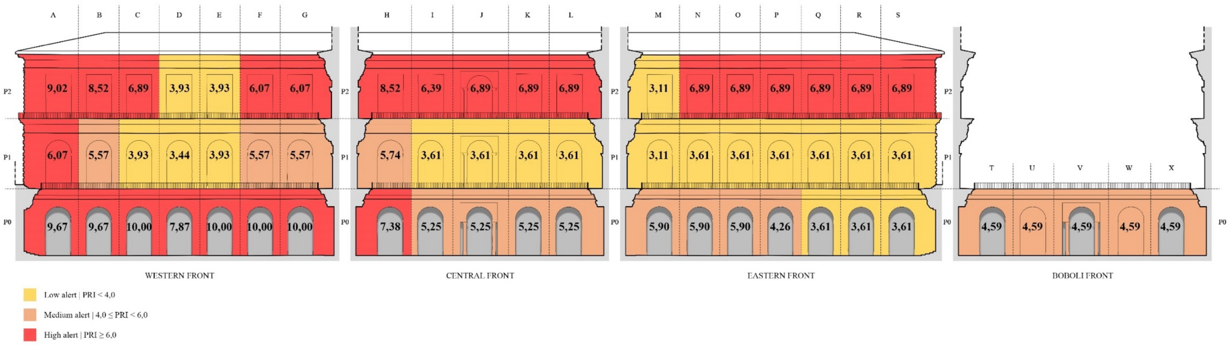

Figure 11. Florence, Pitti Palace, Cortile dell'Ammannati. Previous Restoration Index (PRI) results for sampled stone elements processed through GIS Software (Graphic by Alessandro Ceppetelli).

Quadrant	ID stone element	PRI
P2A	1185	5,1
	1187	3,8
	1186	2,5
	1199	2,5
	1201	2,5
	1238	3,1
	1247	5,5
	1272	4,6
	1274	2,5
	1281	4,9
	1283	4,6
	1290	2,5
	1292	1,5
	1373	2,8
	3244	2,8
	3246	2,5
	3249	2,5
P1A	41	1,5
	42	2,8
	395	3,1
	397	3,1
	401	3,4
	403	2,5
	405	2,5
	407	2,5
	412	1,5
	418	2,5
	420	2,5
	1764	2,5
	1767	2,5
	3147	2,8
	3148	2,5
	3150	2,5
	3152	2,5
	3161	2,8

Low alert | PRI < 4,0
Medium alert | 4,0 ≤ PRI < 6,0
High alert | PRI ≥ 6,0

Figure 12. Workflow for the definition of the DI (Graphic by Alessandro Ceppetelli).

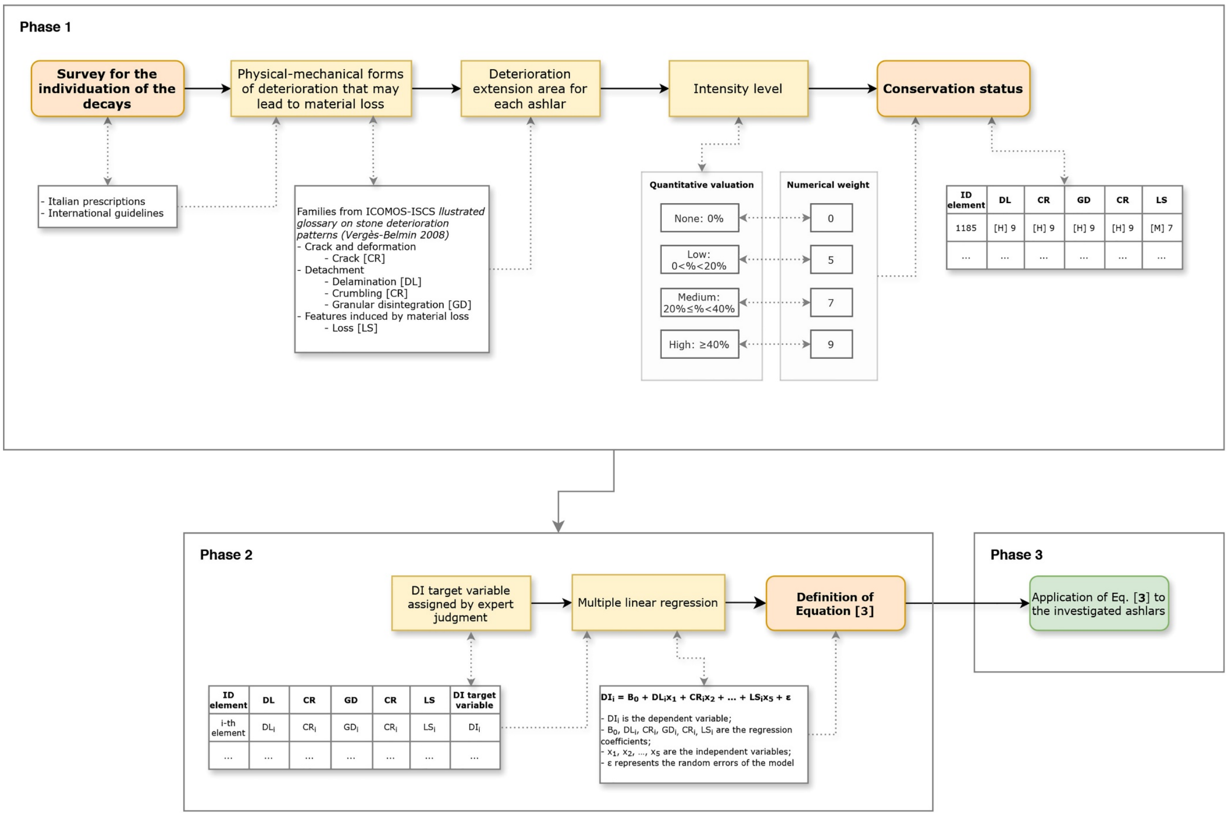

Figure 13. Florence, Pitti Palace, Cortile dell'Ammannati. Sample survey sheet and mapping of deterioration forms, according to international guidelines and processed through GIS Software (Graphic by Alessandro Ceppetelli).

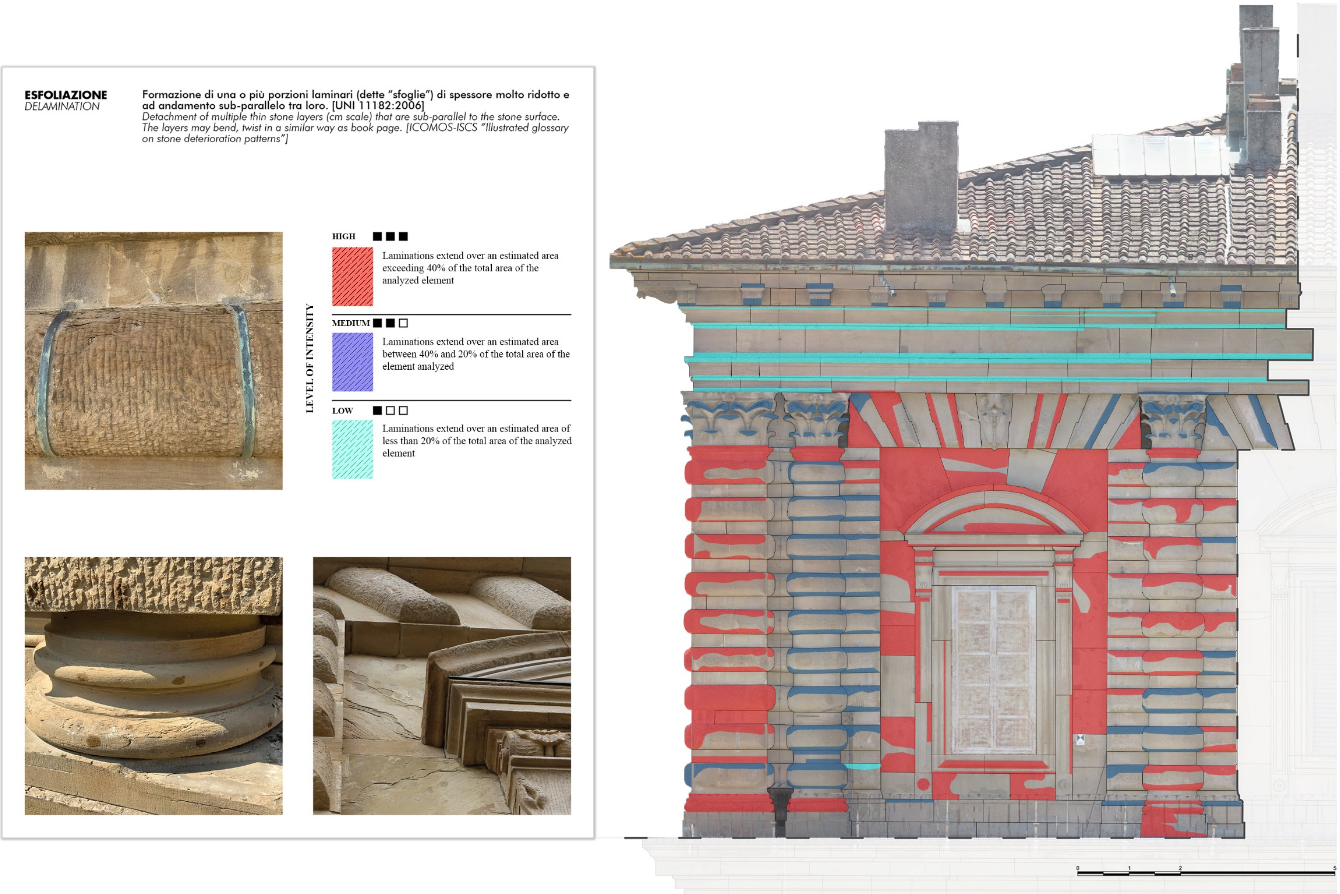

Figure 14. Florence, Pitti Palace, Cortile dell'Ammannati. Deterioration Index (DI) results for sampled stone elements processed through GIS Software (Graphic by Alessandro Ceppetelli).

Quadrant	ID stone element	DI
P2A	1185	9,2
	1186	9,2
	1187	8,1
	1199	5,8
	1201	7,0
	1238	7,5
	1247	6,3
	1272	9,5
	1274	9,5
	1281	9,0
	1283	8,9
	1290	5,6
	1292	6,7
	1373	9,5
	3244	8,5
	3246	2,3
	3249	2,3
P1A	41	6,3
	42	6,0
	395	5,2
	397	6,0
	401	7,8
	403	6,4
	405	4,4
	407	5,6
	412	7,4
	418	5,6
	420	5,6
	1764	3,9
	1767	2,3
	3147	9,5
	3148	5,6
	3150	7,1
	3152	7,9
	3161	9,5

Low alert | DI < 4,0

Medium alert | 4,0 ≤ DI < 6,0

High alert | DI ≥ 6,0

Figure 15. Florence, Pitti Palace, Cortile dell’Ammannati. Comparison of results obtained using the DICEA knowledge-based tool (a) and the DST-LAM multi-analytical model (b), both processed through GIS Software (Graphic by Chiara Mariotti, Alessandro Ceppetelli and Teresa Salvatici).

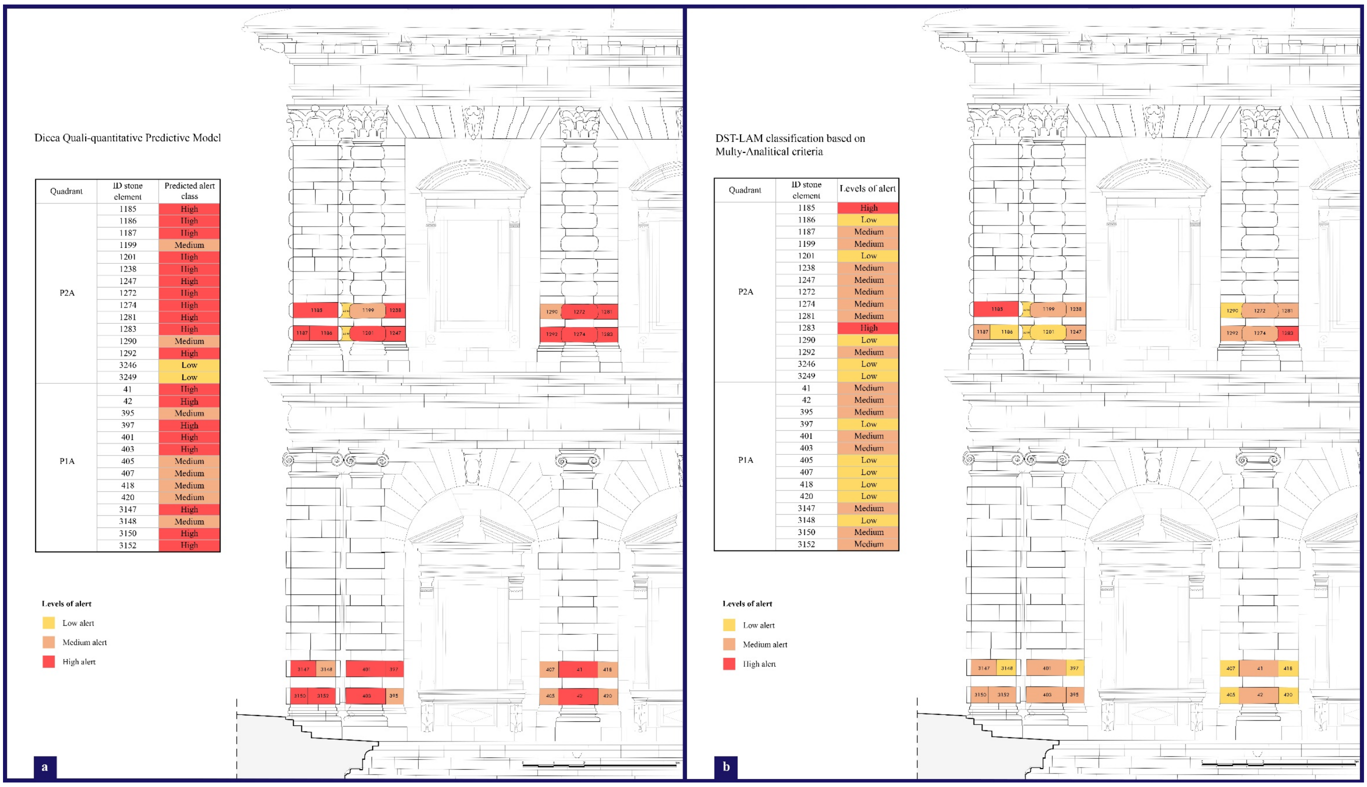

Figure 16. Florence, Pitti Palace, Cortile dell'Ammannati. Critical stone ashlars due to previous interventions and material discontinuities in the test area (Photos by Chiara Mariotti and Alessandro Ceppetelli 2022).