Fabiana Di Ciaccio
Lidia Fiorini
Grazia Tucci *Editors*

Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks

OPEN ACCESS

Springer

Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks

Fabiana Di Ciaccio • Lidia Fiorini • Grazia Tucci
Editors

Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks

Springer

Editors
Fabiana Di Ciaccio
Department of Civil and Environmental Engineering
University of Florence
Florence, Italy

Lidia Fiorini
Department of Civil and Environmental Engineering
University of Florence
Florence, Italy

Grazia Tucci
Department of Civil and Environmental Engineering
University of Florence
Florence, Italy

ISBN 978-3-032-12339-8 ISBN 978-3-032-12340-4 (eBook)
https://doi.org/10.1007/978-3-032-12340-4

This work was supported by Italian National Research Programme (NRP) - PE05 (CHANGES) (B53C22004010006).

© The Editor(s) (if applicable) and The Author(s) 2026. This book is an open access publication.

Open Access This book is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.
The images or other third party material in this book are included in the book's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the book's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

If disposing of this product, please recycle the paper.

Contents

Part I Tangible Heritage Knowledge and Cultural Context

Part II Digital Twins and Documentation for Cultural Heritage

Part III Monitoring, Assessment and Preventive Conservation of Heritage Against Climate Change

Part IV Restoration and Sustainable Strategies for Heritage Preservation Against Risks and Climate Change

Part V Green Materials and Methodologies for Conservation

Chapter 1
Introduction

Gianmarco De Felice, Fabiana Di Ciaccio, Speranza Falciano, Lidia Fiorini, Rodorico Giorgi, Cristiano Riminesi, and Grazia Tucci

Abstract Cultural Heritage, as a bridge between the past and future, represents the identity, values, and collective memory of societies. This volume, Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropogenic Risks, presents the Spoke 7 results within the CHANGES project, a pioneering initiative funded by the European Union's NextGenerationEU framework through the National Recovery and Resilience Plan (NRRP). The book explores innovative, interdisciplinary approaches to safeguarding Cultural Heritage in the face of climate change, natural disasters, and

---

G. De Felice
Roma Tre University, Department of Civil Engineering Computer Science and Aeronautical Technologies, Rome, Italy
e-mail: gianmarco.defelice@uniroma3.it

F. Di Ciaccio (✉) · G. Tucci
Department of Civil and Environmental Engineering, University of Florence, Florence, Italy
e-mail: fabiana.diciaccio@unifi.it; grazia.tucci@unifi.it

S. Falciano
Gran Sasso Science Institute (GSSI), L'Aquila, Italy
e-mail: speranza.falciano@gssi.it

L. Fiorini
Department of Civil and Environmental Engineering, University of Florence, Florence, Italy

La Sapienza University of Rome, Rome, Italy
e-mail: lidia.fiorini@unifi.it

R. Giorgi
Dipartimento di Chimica, Università di Firenze, Sesto Fiorentino, Italy
e-mail: rodorico.giorgi@unifi.it

C. Riminesi
Institute of Heritage Science, National Research Council, Florence, Italy
e-mail: cristiano.riminesi@cnr.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_1

anthropogenic threats, integrating expertise from engineering, material sciences, digital technology, and humanities to address the complexities of protecting both tangible and intangible cultural assets. The thematic sections of this book emphasize cutting-edge solutions, including digital twins, advanced monitoring systems, eco-sustainable materials, and preventive conservation methodologies. Moreover, case studies highlight real-world applications, spanning historic cities, landscapes, monuments, and individual artifacts. This collection underscores the importance of preparedness, resilience, and sustainability in Cultural Heritage preservation, advocating for collaboration across disciplines and scales.

Keywords Cultural Heritage · Climate change · Natural and anthropogenic risks · Interdisciplinary approach · Innovation · CHANGES project · NRRP—Next GenerationEU

1.1 The Spoke 7 Research Group: The Context and Its Mission

Cultural Heritage, in its most recent and internationally recognized definition, is described as "a group of resources inherited from the past which people identify, independently of ownership, as a reflection and expression of their constantly evolving values, beliefs, knowledge and traditions. It includes all aspects of the environment resulting from the interaction between people and places through time" (Consiglio d'Europa, 2005).

Cultural Heritage has always been exposed to both natural and man-made risks, but only in recent years it has become the focus of studies and projects aimed at developing shared strategies for risk management and reduction. As a result, new approaches and methods for safeguarding and conserving assets have been, and are still being, designed and enhanced (Commissione Europea, 2019). This book, Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks, presents the intermediate results of the Spoke 7 research group within the "Cultural Heritage Active Innovation for Sustainable Society"—CHANGES project (Fondazione Changes, 2023), funded by the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 funded by the European Union—NextGenerationEU (Agenzia per la Coesione Territoriale, 2023).

CHANGES is an extensive partnership funded under the Theme 5, "Humanistic Culture and Cultural Heritage as Laboratories of Innovation and Creativity." It aims to establish an international hub for training, research, and technological transfer in the fields of Culture and Cultural Heritage. The goal is to enhance the value of Italy's Cultural Heritage by promoting new sustainable approaches to its protection and enjoyment, creating stable partnerships between research and industry, and offering employment opportunities in the sector.

The project partners contribute to the six missions of the NRRP (i.e., Digitalization, innovation, competitiveness, and culture; Green revolution and ecological transition; Infrastructure for sustainable mobility; Education and research; Cohesion and inclusion; Health) by re-modeling CH as a foundational research domain and a key driver of innovation and competitiveness, able to advance education and strengthen social cohesion. The content of the WPs is fully aligned with the 'do no significant harm' (DNSH) principle guiding national and EU environmental regulations (Italia Domani, 2021).

The organizational structure of the CHANGES project draws inspiration from the concept of the "bicycle wheel," known in English as the "hub and spoke" model, where the "hub" is the central part of the wheel, and the "spokes" are the connecting rods. In this framework, the CHANGES Foundation acts as the hub, the central driving force of the project, while the thematic spokes represent the wheel's connecting components. Each of the nine spokes plays a fundamental role in the project and collectively forms complementary areas of expertise to build an extensive interdisciplinary ecosystem spanning the humanistic, technological, and cultural fields.

These spokes aim to support the protection, enhancement, and sustainable transformation of both tangible and intangible Cultural Heritage, addressing challenges such as digital conservation, the creation of creative ecosystems, the promotion of sustainable tourism, and the management of natural and anthropogenic risks affecting cultural assets.

The University of Florence coordinates the Spoke 7 in collaboration with the Gran Sasso Science Institute; the other partners include the Universities of Bologna, Naples (Federico II), Roma La Sapienza and Roma Tre, the National Research Council (CNR), the Opificio delle Pietre Dure (OPD), the Lazio Technological District for Cultural Heritage (DTC Lazio), the Italian Institute for Conservation and Restoration (ICR) and the Politecnico of Torino as associate partner.

Spoke 7 intends CH as an extensive and inclusive domain. The overall aim of the Spoke 7 is to advance the tools for protection and conservation of CH focusing on incumbent challenges caused by climate change and natural and anthropic risks (Aktürk & Hauser, 2024). The traditional distinction between natural and man-made hazards is in fact challenged by the combination and interaction of different hazards and causes, as natural disasters also cause migration and social conflicts, and human behavior accelerates natural processes (Blaikie et al., 2014). Phenomena related to climate change and natural/anthropic risks raise new research questions and open new challenges for modern societies, requiring a broad multidisciplinary approach towards problem solving, emphasizing the importance of preparedness and resilience (Genovese, 2021). A multi-scale approach is applied to encompass various scenarios and address both general and specific issues. Relevant case studies are identified in the following areas: environmental and historical landscapes, historic cities and minor historic centers, built heritage and monuments, and works of art.

The Spoke works to identify and strengthen the interrelations with the pillars of sustainability by designing and testing new heritage-based safety and energy efficiency systems, supporting digital and green transitions for enhancing the preparedness of cultural managers and local communities to natural and anthropic threats. In this context, efforts are being made towards an in-depth assessment of the tools for carbon leakage measures in CH, low energy consumption devices for monitoring, self-curing conservation products, digitization tools for preventive conservation of sites and collections, and integrated data management systems.

The development of diverse materials and products through circular mechanisms and low-carbon emission processes is considered a valuable indicator of innovation. Preventive conservation strategies and monitoring processes will help reduce the technological gap by testing more effective and efficient planned-maintenance tools (e.g. early hazard detection systems). To contribute to upgrade the accessibility standards, hazards repositories will be interoperable and compliant with FAIR principles (Wilkinson et al., 2016). Spoke 7 will set the foundations for a strong, energy-aware, multidisciplinary community within the broader heritage community.

The importance of this volume lies not only in the cutting-edge solutions it explores, but also in its function as a dynamic assessment of an evolving project. By sharing these results, the authors invite the wider research and practitioner community to engage with, and build upon, the methods and insights presented. This openness to collaboration and continuous improvement is essential for addressing the increasingly complex challenges that Cultural Heritage conservation now faces.

The book’s content reflects the multidisciplinary nature of the project, integrating knowledge from fields such as engineering, climate science, digital technology, and material sciences. The diverse case studies, ranging from the digital documentation of architectural sites to the sustainable restoration of historic buildings, illustrate how these methodologies can be applied to real-world scenarios. In particular, the focus on Italian cities (e.g., L’Aquila, Bologna, Firenze, etc.) demonstrates the local relevance of the research while also offering solutions with global resonance. As climate change continues to disrupt environments worldwide, the strategies developed here provide a valuable model for other nations facing similar threats to their cultural assets.

Moreover, this volume underscores the necessity of a comprehensive, multi-hazard approach. By integrating the latest advancements in digital twins, monitoring technologies, sustainable materials, and risk assessment protocols, the book outlines a clear path for how the Cultural Heritage sector can adapt to an increasingly uncertain future. At this critical halfway point, the research team has laid a solid foundation, yet the ongoing nature of the project ensures that these strategies will continue to be refined, tested, and further developed in the coming years.

Yet, the journey is far from over. The lessons learned at this stage will inform the next phases of the project, driving forward more resilient, sustainable, and forward-thinking conservation and protection approaches.

We extend our sincere appreciation to the authors and contributors for their dedication and forward-looking approach. By sharing their intermediate findings at this stage, they not only enrich the global discourse on Cultural Heritage, but also foster an environment of ongoing innovation and collaboration.

It is our hope that this book will inspire continued research, dialogue, and action, as we collectively work to safeguard the Cultural Heritage that defines and unites us all.

1.2 Structure of the Book

This volume is organized into five main parts, each addressing a specific thematic area within the CHANGES project. Each part comprises several chapters that examine different dimensions of Cultural Heritage preservation, offering multidisciplinary insights and practical approaches. Summary of the themes explored in each part and an overview of the chapters are presented below.

1.2.1 Part I: Tangible Heritage Knowledge and Cultural Context

This part of the Volume summarizes the work of three Universities that, with a common thread and complementary skills, try to address the issue of knowledge of tangible heritage and its cultural context, from a risk management perspective. The in-depth knowledge of the risk, gained through case studies, is an opportunity to identify strategies for its mitigation: know the risk to govern it, or at least to try—as much as possible—to mitigate it.

From the classificatory and methodical study of Sapienza, full of national and international regulatory references, indicators and data, knowledge and categories of risk, we pass through a broad spectrum of possible methodologies—proposed by the GSSI—to be applied to the study of risks and the consequent need for prevention, declined from time to time on a well-defined territory (whether national or urban), until we enter the dimension of the historic city. Concerning the historic city of L'Aquila the Network model between academic research, specialists, public administrations and communities fits perfectly. Finally, the case study of the historic city of Bologna analyses a melting pot of risks and opportunities of the contemporary city, but also a “counter-model of contemporary urban development”, suspended between natural risks and conservation, between history, memory and urban transformations, aesthetic values of the past, new citizenships and new forms of living, planning and entropy, public space and private space.

It is well understood that risk analysis does not stop only at indicators and quantitative analyses but must necessarily associate with the latter factors such as the well-being of communities, their relationship with Cultural Heritage, new forms of civilization and of inhabiting, perhaps even re-semanticizing, the places that bear Cultural Heritage.

Reading these pages, it is clear that an exquisitely humanistic approach does not prevent, indeed happily meets the most advanced frontiers of new technologies, IT tools (with advanced and complex platforms) and Artificial Intelligence, leading to a hybridization of knowledge that ends up generating and proposing composite models (IT, instrumental, intellectual, governmental) of risk management or support for decision-making processes.

This global approach aims not only to create specialized knowledge, but also to support political decision-makers, cultural operators and public administrations with adequate tools. The aim is to respond in effective and innovative ways to the new challenges of contemporaneity, where the effects of climate change are added, as a further variable, to the multi-risk equation of—already present—natural and anthropic risks on the territories. A proactive strategy to risk analysis is therefore proposed, promoting and encouraging greater resilience of territories, with an operational view applied to the different scales analyzed; without forgetting that historical sciences can place themselves at the service of communities and decision-making processes which can, more or less, have repercussions on communities themselves and their Cultural Heritage.

Chapter 2 establishes a methodological framework for analyzing multi-source data to assess and preserve outdoor tangible heritage. It consolidates hazard classifications, indicators, and protocols into a unified risk assessment framework, addressing gaps in current quantitative methods. Chapter 3 explores the case studies from the Spoke 7 project, emphasizing risk analysis, urban planning tools, and community-driven approaches for Cultural Heritage management, with a focus on the city of L'Aquila.

Chapter 4 highlights the historical city as a model for urban resilience and aesthetics, integrating nature-based solutions and urban heat island analysis through the Bologna case study.

1.2.2 Part II: Digital Twins and Documentation for Cultural Heritage

The contributions presented in this Part converge around a critical yet often overlooked aspect of Cultural Heritage preservation: the comprehensive documentation of the processes through which digital data are acquired and processed, forming the foundation on which preservation projects are built. This section proposes a preliminary protocol that aims to balance standardization with adaptability, offering an initial framework for addressing the multifaceted challenges faced by Cultural Heritage professionals. It emphasizes a holistic methodology that bridges traditional techniques with cutting-edge technologies, such as 3D digitization, photogrammetry, and Virtual/Augmented Reality (VR/AR), to support the creation of detailed and dynamic records of cultural assets. As Cultural Heritage sites confront threats ranging from natural disasters to urban encroachment, this section underscores the necessity of a robust, interdisciplinary approach that integrates technological, historical, and material science perspectives.

At the heart of this discourse lies the notion of the Digital Twin, a concept that moves beyond static documentation to offer a dynamic, real-time representation of heritage assets. These digital models serve not only as repositories of accurate data but also as tools for predictive analysis and informed decision-making. They facilitate risk-mitigation strategies that are both proactive and sustainable, ensuring that preservation efforts remain economically viable and ecologically sensitive.

By interweaving case studies with theoretical frameworks, the section also underscores the importance of metadata and paradata in contextualizing documentation processes. It emphasizes transparency and replicability, advocating for documentation protocols that record not only the data but also the narrative behind their creation. This approach aligns with broader European initiatives on Cultural Heritage digitalization, promoting cross-border collaboration and knowledge sharing.

In summary, this section positions thorough and comprehensive documentation as a fundamental responsability within heritage conservation, framing it as a dynamic and integrative practice essential to preserving the cultural and historical identity of the built environment.

Chapter 5 introduces a protocol for standardized documentation, aligning with European digitization strategies and focusing on sustainable methodologies. Chapter 6 discusses the integration of informative models with digital twins, addressing challenges in transferring data between structural analysis tools.

Several case studies are then presented and analyzed. Chapter 7 presents the Giovanni Pisano's pulpit, documented through scanning and photogrammetry systems and monitored with mechanical tests to assess the static behavior of the structure. Chapter 8 focuses on the Sanctuary of Vicoforte, where advanced monitoring systems and satellite data are used to create a digital twin for real-time diagnostics. In Chap. 9 the Ponari Nymphaeum is presented, highlighting its structural analysis and 3D virtual documentation in support to conservation. Chapter 10 evaluates the monitoring of artworks in Viterbo's Colle del Duomo Museum, combining microclimate sensors with UV-based 3D diagnostics techniques. Finally, Chap. 11. analyzes the Grotta degli Animali at Villa di Castello from a digital documentation perspective, emphasizing the importance of three-dimensional digital models for understanding artefacts and designing environmental monitoring systems.

1.2.3 Part III: Monitoring, Assessment and Preventive Conservation of Heritage Against Climate Change and Anthropic Risks

The preservation of outdoor heritage is increasingly challenged by various risks, including environmental factors, human activities, and climate change. Effective monitoring, risk assessment, and management strategies are essential for the preventive conservation of Cultural Heritage assets. This overview discusses recent developments in these areas, aiming at proactively addresses potential threats to heritage assets, ensuring their longevity and accessibility for future generations.

This Part focuses on new applications for monitoring impacts due to multi-hazard, natural and anthropic, and mitigating climate damage. Relevant case studies at different scales were considered to formulate multiscale procedures based on improved modeling approaches, in order to introduce the effects of environmental and mechanical damage and the development of digital sensing and monitoring technologies integrated with methods for seismic risk assessment. The integration of digital detection and monitoring technologies with multi-hazard risk methods is also proposed, and application protocols are also described. In the specific, Chap. 12 presents macromechanical models to analyze damage mechanisms in masonry structures due to mechanical and environmental actions. Chapter 13 proposes a framework for the dynamic conservation of wine cultural landscapes, integrating geospatial data to adapt to climate changes. In Chap. 14 strategies for preventive conservation in semi-confined environments are explored, with a focus on microclimatic changes in the Grotta degli Animali. Chapter 15 investigates vandalism as a threat to Cultural Heritage, offering historical analyses and prevention strategies; finally Chap. 16 studies the effects of climate change on maritime heritage, using the Island of Motya as a case study to propose integrated management strategies.

1.2.4 Part IV: Restoration and Sustainable Strategies for Heritage Preservation Against Risks and Climate Change

The preservation of Cultural Heritage against natural/anthropic risks and the effects of climate change raises new research questions and new challenges for modern societies, requiring a broad multidisciplinary approach that encompasses different scenarios and controls different scales, from landscape to built heritage and artefacts.

The community is required to find the right balance between the necessity of intervening to protect cultural assets from risks and the imperative to limit interventions to what is strictly necessary. A restoration strategy cannot be separated risk assessment and its impact on the cultural asset.

It is not possible to summarize the variety and complexity of this topic in a few contributions: in one case it is a matter of protecting the artwork in emergency conditions, in another case it is a matter of developing technologies to prevent the loss of the asset after a natural disaster or restoring the heritage to protect the landscape from natural hazards.

All these scenarios have a minimum common denominator: the use of advanced technologies to achieve an accurate assessment of the risk and the necessity to intervene, and the development of innovative solutions to minimise the impact of mitigation works on the cultural asset.

The glue between the different scales is represented by the development of sustainable intervention protocols and strategies that can be applied in different scenarios from the ordinary ones related to maintenance and preservation of the asset, to the emergency contexts aimed at avoiding its loss.

A further distinguishing character is represented by the strong multi- and interdisciplinary nature that allows the development of restoration strategies where innovative materials and technologies coexist, together with the recovery of ancient knowledge and techniques, as distinctive signs of a culture to be preserved.

This Part collects three contributions related to different emerging scenarios, either caused by natural hazard or climate change. Chapter 17 brings together transdisciplinary expertise focusing on terraced landscapes and their multidimensional values. Shared methodologies of risk assessment and mitigation strategies are outlined to mitigate hydrogeological risks while preserving cultural practices. Chapter 18 is devoted to the development of new technologies to ensure the safety of historic buildings against seismic risk while preserving not only their appearance with fair face stone masonry, but also their original construction rules. Chapter 19 illustrates the potential of using volatile binders in emergency contexts to secure works of art by means of temporary consolidation that allows transport in view of the subsequent restoration work, ensuring adequate consolidation and reversibility. The variety of the three contributions, the disciplinary experiences involved, and the different scales of intervention give rise to the complexity of developing shared methodologies and strategies for restoration and sustainable management of Cultural Heritage.

1.2.5 Part V: Green Materials and Methodologies for Conservation

The research and development of new materials and methodologies for the conservation of Cultural Heritage is a process that never ends, since the challenges we face are always new due to the great variety of new materials used in contemporary art for the creation of artistic works, for the environmental conditions of conservation which are changing significantly due to the continuous growth of urban areas with evident repercussions in terms of air pollution and the climate emergency, which is designing new and often dramatic scenarios.

At the same time, the great development of modern technologies and increasingly in-depth knowledge in the domain of nanoscience and biotech offers increasingly high-performance and long-lasting solutions.

In this project, complex conservation challenges are addressed from the perspective and the ever-growing need to adopt eco-sustainable materials and solutions, in compliance with the guidelines outlined by the Green Deal and the 2030 EU agenda. Technologically innovative approaches to systematization in a circuit of sustainable and environmentally friendly enhancement and fruition is an urgent need for the global community.

The contributions of this part embrace very different issues, moving from archaeological assets in outdoor environments, to contemporary mural paintings for which the term Street-Art is now universally recognized. The research here presented is united by the need to obtain materials from renewable sources through eco-sustainable processes, alternative to petrochemical-derived chemicals, thus representing some of the ambitious objectives of the project, of which the most significant results are reported in this part.

Chapter 20 investigates the use of dry-cleaning techniques that do not involve the use of solvents, for sensitive cultural artifacts, ensuring minimal damage during the cleaning process. Chapter 21 addresses biodeterioration in stone monuments, proposing eco-friendly biocides and integrated conservation strategies; in Chap. 22 the formulation of gels and composites from the extraction of ‘green’-classified oligomers and polymers from renewable sources is presented, while Chap. 23 explores formulations for the consolidation and protection of surfaces using composite systems of natural origin as novel green polymers, gels, and composites. Similarly, Chap. 24 focuses on nanocellulose compounds for reinforcing organic supports in cultural artifacts, promoting environmentally friendly consolidation methods and Chap. 25 deals with sustainable coatings for preserving street art, combining durability with aesthetic compatibility. Finally, Chap. 26 examines the use of materials obtained via 3D printing for the reintegration of missing structural and decorative restorations, emphasizing reversibility and lightweight materials.

Acknowledgement The work presented in this book is supported by the PE 0000020 CHANGES Project—CUP B53C22004010006, NRP Mission 4 Component 2 Investment 1.3, Funded by the European Union—NextGenerationEU.

References

Agenzia per la Coesione Territoriale. (2023). *Next Generation EU e il Piano Nazionale di Ripresa e Resilienza*. Accessed on November 2024, from https://www.agenziacoesione.gov.it/dossier_tematici/nextgenerationeu-e-pnrr/

Aktürk, G., & Hauser, S. J. (2024). Integrated understanding of climate change and disaster risk for building resilience of cultural heritage sites. *Natural Hazards*, 1–26.

Blaikie, P., Cannon, T., Davis, I., & Wisner, B. (2014). *At risk: Natural hazards, people’s vulnerability and disasters*. Routledge.

Commissione Europea. (2019). *Direzione generale dell’Istruzione, della gioventù, dello sport e della cultura, Quadro d’azione europeo sul patrimonio culturale*. Ufficio delle pubblicazioni. https://data.europa.eu/doi/10.2766/622226

Consiglio d'Europa. (2005). *Convenzione quadro del Consiglio d'Europa sul valore dell'eredità culturale per la società*. Consiglio d'Europa, Faro (Portogallo), 27, 2005.

Fondazione Changes. (2023). *Cultural heritage active innovation for next gen sustainable society*. Accessed on November 2024, from https://www.fondazionechanges.org/

Genovese, R. A. (2021). Cultural heritage, climate change, intercultural dialogue and strategies for integrated conservation. In *New metropolitan perspectives: Knowledge dynamics and innovation-driven policies towards urban and regional transition* (Vol. 2, pp. 1939–1951). Springer International Publishing.

Italia Domani. (2021). *The DNSH principle (Do No Significant Harm) in the NRRP*. Accessed on November 2024, from https://www.italiadomani.gov.it/en/Interventi/dnsh

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., & Mons, B. (2016). The FAIR guiding principles for scientific data management and stewardship. *Scientific Data, 3*(1), 1–9.

Part I
Tangible Heritage Knowledge and Cultural Context

Chapter 2
A Methodological Framework for Multi-source Data Analysis for the Assessment and Preservation of Cultural Heritage

Alessandra Battisti, Angelo Figliola, Maria Valese, and Herbert Natta

Abstract The wide range of risks posed by climate change that could potentially affect Cultural Heritage necessitates a multidisciplinary approach, as well as an initial examination of existing methods for risk assessment across various fields. Thus, the initial focus of the research conducted by the Sapienza PNRR work group was on a multidisciplinary framework to support the risk assessment process relating to the multivariate effect of climate change and the interaction of different risks on the tangible outdoor heritage. The research sets out to create a multidisciplinary framework aimed at supporting the risk assessment process, grounded in the classification of cultural heritage and aligned with European definitions and protocols. To gather the necessary information, such as hazard classifications, indicators, indices and thresholds, various methodologies were employed, including the analysis of major international protocols and EU research projects related to risk assessment involving cultural heritage, expert-based knowledge and a systematic review of the literature. The research seeks to address a gap in the field of quantitative, indicator-based risk assessment, in which a unified, comprehensive framework capable of consolidating in a single repository the main natural and anthropogenic risks, along with the associated taxonomy, does not yet exist. The framework is designed to be consulted by researchers, professionals, and public administrations, facilitating the

---

This contribution contains paragraphs of the article "Battisti, A.; Figliola, A.; Santarelli, M.L. A Framework for a Hazard Taxonomy to Support Risk Assessment of Tangible Outdoor Heritage. Heritage 2024, 7, 2984–3012, https://doi.org/10.3390/heritage7060140." It is published in Open Access under Creative Commons-CC by 4.0—authors' permission.

A. Battisti (✉) · A. Figliola · M. Valese · H. Natta
Sapienza University of Rome, Department of Planning, Design, Technology of Architecture, Rome, Italy
e-mail: alessandra.battisti@uniroma1.it; angelo.figliola@uniroma1.it; maria.valese@uniroma1.it; herbert.natta@ge.imati.cnr.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_2

evaluation of potential risks to the outdoor tangible heritage while allowing users to incrementally add exposure and vulnerability data for each specific risk.

Keywords Cultural heritage · Historic built environment · Risk analysis · Data-driven processes · Multi-risk assessment

2.1 Introduction

The evolution of the concept of Cultural Heritage (CH) from an isolated monument to a complex object, a synthesis of tangible and intangible components (Vecco, 2010) and a vector of sustainable economic and social development processes (Janssen et al., 2017), has profoundly changed the objectives of practices of conservation, protection and enhancement, emphasising the need to work on cultural heritage by including the transformation scenarios (Seekamp & Jo, 2020) required to preserve its Outstanding Universal Value (OUV) (UNESCO, 2021). In particular, the acceleration in recent years of the effects of climate change (CC), the increasingly frequent occurrence of extreme natural phenomena, and the dramatic destruction caused by recent war events have triggered a shared, global drive in the direction of defining strategies for the inclusion of risk assessment plans and prevention, as well as measures of mitigation and contrast, all aimed at avoiding or reducing the potential impact of specific damage conditions (Sabbioni et al., 2006; Shaw, 2022). The variety of risks capable of having an impact on Cultural Heritage—CH—requires a multidisciplinary approach and a preliminary overview of the existing methods for risk analysis and assessment in different fields. CH is permanently exposed to natural and anthropic hazards, due to the impact of climate change, which accelerates the effects of natural hazards, as well as those caused by human actions. The traditional distinction between natural and anthropic hazards is blurred by the combination and interaction of different hazards and causes, as natural disasters also cause migration and social conflicts, and human behaviour accelerates natural processes. The overall objective of the PNRR Research Project[1] is to deliver innovative solutions to mitigate the effects of climate change, as well as natural and anthropic risks to cultural heritage, all based on a comprehensive risk analysis of the multivariate effect of climate change and the interaction of different risks through an indicator-based approach. This semi-quantitative method involves using indicators associated with each risk determinant or component (such as hazard, exposure and vulnerability). These indicators are then normalized, weighted and aggregated to generate a comprehensive risk score. Thus, the starting point of the research

---

[1] Research Project PE05-CHANGES-SPOKE Protection and Conservation of Cultural Heritage against Climate Changes, Natural and Anthropic Risks, Thematic line: n. 3 "Multi-source digital data and metadata related to environment and historic landscape", P.I. Prof. Alessandra Battisti.

conducted by the Sapienza PNRR work group consists of a systematic review of the literature on risk-assessment approaches, methods and indicators, based on the classification of Cultural Heritage. The risk assessment framework establishes the methodological core of a future multi-criteria matrix and digital platform for defining specific operational guidelines connected to each risk, in order to draw up scenarios describing/predicting transformations in the Architectural Heritage, so as to support the development of mitigation and adaptation strategies (Battisti et al., 2022).

2.2 Risk Assessment Process

In the process of risk assessment, it is crucial to explore the interconnected dimensions of risk, focusing on the interplay between hazard, vulnerability and exposure (Burton et al., 1993). Hazards, as defined by the Intergovernmental Panel of Climate Change (IPCC), are potential sources of harm, encompassing both natural phenomena and anthropogenic events "that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources" (IPCC, 2012). The dynamic interaction among hazards, vulnerability and exposure underscores the complexity of risk, necessitating a holistic approach to mitigate its impacts. Hazards are inherently diverse and dynamic, spanning geological, meteorological and anthropogenic domains. Understanding the frequency, intensity and spatial distribution of hazards is crucial for effective risk assessment (Smith et al., 2023). Vulnerability, as defined by Adger (Adger, 2006), is the susceptibility of a system to harm, influenced by physical, social, economic and environmental factors. Social vulnerability often arises from disparities in wealth, education and healthcare access, as stated by IPCC, while physical vulnerability may result from inadequate infrastructure or inappropriate land use planning. A comprehensive vulnerability assessment is pivotal for identifying risk-prone areas and populations. Exposure refers to the degree to which elements at risk, such as populations, assets or ecosystems, are subject to a hazard (Cutter et al., 2000), and spatial and temporal dimensions of exposure play a crucial role in determining risk levels. Mapping exposure helps to identify high-risk areas, enabling targeted interventions and resource allocation. Thus, risk assessment integrates hazard analysis, vulnerability assessment and exposure mapping to quantify the likelihood and consequences of adverse events (UNEP, 2013).

2.3 Methodology Employed for Risk Assessment

Various methodologies and strategies are employed in risk assessment processes (Van Westen, 2023):

- *Quantitative risk assessment.* This method takes a numerical approach, utilizing hazard scenarios and the valuation of at-risk elements.
- *Event tree analysis.* Employing a quantitative perspective, this method involves defining trees to establish relationships between diverse hazards and events.
- *Risk matrix approach.* This approach tackles risk qualitatively, allowing for the categorization of risks based on expert knowledge, particularly in situations where quantitative data are either lacking or limited.
- *Indicator-based approach.* This semi-quantitative method involves the use of indicators associated with each risk determinant or component (such as hazard, exposure and vulnerability). These indicators are then normalized, weighted and aggregated to derive a comprehensive risk score.

Most of the methodologies introduced above take a quantitative approach that requires a clear overview of hazard taxonomy, such as indicators, indices and thresholds.

2.4 A Methodological Framework for Risk Assessment

Therefore, the initial point of the research involves conducting a systematic review of the literature on risk-assessment approaches, methods, and indicators. This process serves as the foundation for a multidisciplinary framework that includes the definition of risk, its categorization and its metrics, in the form of a measurable index, as well as its main target, all according to a CH classification harmonized with the definitions and protocols of the EU vocabulary. The framework has also been developed through a co-creation process based on collaboration between professionals and academics. This approach, integrating different indicators into a synthetic evaluation model, highlights the multidisciplinary, multi-objective nature of CH preservation. Managing this diversity while overcoming the barriers between disciplines has been a research priority, necessitating the sharing of expertise and data.

The methodological framework is defined as follows (Fig. 2.1):

- Analysis of the main international and national risk-assessment protocols;
- Definition of the initial risk classification, based on the two main categories: natural and anthropogenic risks;
- Identification of the main hazard components for quantitative or semiquantitative risk assessments.
- The second stage of the research is dedicated to the development of a risk taxonomy through the following strategies:
- Analysis of completed or ongoing EU research projects;
- Use of AI chatbots;
- Systematic review of the literature, plus a co-creation process.

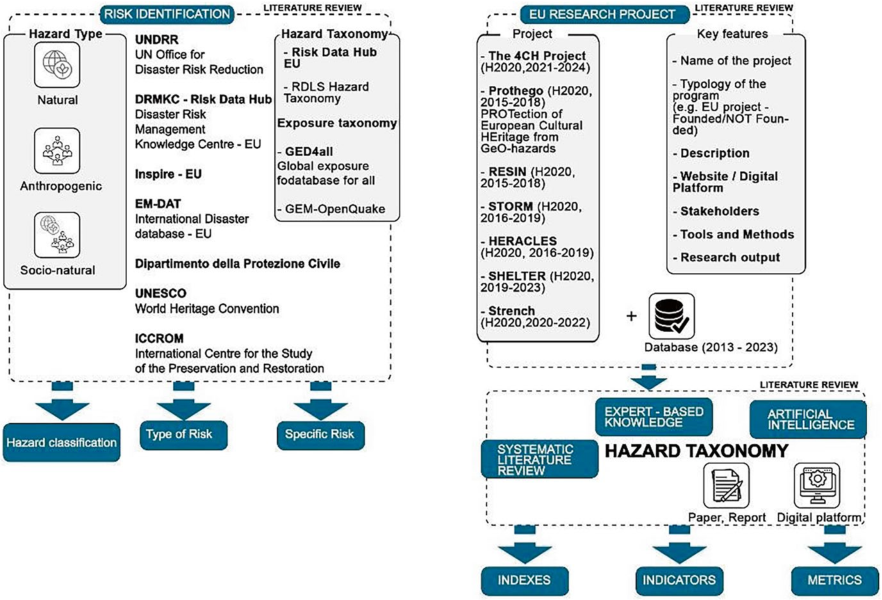


Fig. 2.1 Methodological framework

2.5 Classification of Risks in International Protocols

The analysis of the main national and international protocols on risk identification was conducted at a general and CH-specific level, in order to identify risk clusters (natural, anthropogenic, anthropogenic-natural) that could be considered invariant. Presented below are the primary selections that contribute to the task's perspective.

Three international references with specific focus on CH and risk assessment (Table 2.1):

Two international references on risk assessment (Table 2.2):

Three national references on risk assessment (Table 2.3):

Six protocols were selected, with one of the most important being the UNESCO World Heritage Convention, which ranks in detail the primary and secondary risk factors that can damage the OUV of the world CH. The primary factors, diversified and applicable to natural, anthropogenic and cultural-historical contexts, are summarized in 13 categories; the secondary ones, although not categorized as specific risks, make possible an accurate classification. The International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM), on the other hand, focuses on a detailed classification of potential risk factors for CH. The analysis of the context in which the CH is located precedes the identification of risks, which include: 10 agents of deterioration, six 'enclosure' layers that relate the heritage to the surrounding ecosystem, and three risk categories. The further

Table 2.1 Three international references with specific focus on CH and risk assessment

UNESCO World Heritage Convention	https://whc.unesco.org/en/factors/, accessed on 2 November 2023
International Center for the Study of the preservation and restoration of Cultural property ICCROM	https://www.iccrom.org/publication/guide-risk-management (accessed on 2 November 2023)
ICOMOS—ICORPInternational scientific committee on risk preparedness	https://icorp.icomos.org/ (accessed on 2 November 2023)

Table 2.2 Two international references on risk assessment

DRMKC—Disaster Risk Management Knowledge Center	https://drmkc.jrc.ec.europa.eu/riskdata-hub/#/ (accessed on 2 November 2023)
UN Office for disaster risk reduction	https://www.undrr.org/implementing-sendai-framework (accessed on 2 November 2023)

Table 2.3 Three national references on risk assessment

Department of Civil Protection Presidency of the Council of Ministers	https://www.protezionecivile.gov.it/it/ (accessed on 6 November 2023)
ISPRA—Istituto Superiore per la Protezione e la Ricerca Ambientale	https://www.isprambiente.gov.it/it (accessed on 6 November 2023)
INGV—Istituto Nazionale Geo-Vulcanologia	https://www.ingv.it/ (accessed on 6 November 2023)

protocols analysed in the research were those of the Disaster Risk Management Knowledge Centre (DRMKC) and the UN Office for Disaster Risk Reduction, both of which take a general, trans-scalar view of risks. The DRMKC identifies eight classes, distinguishing between natural hazards (Geophysical, Hydrological, Meteorological, Climatological), anthropogenic hazards (Technological and Transportation) and biological events resulting from interactions between natural phenomena and anthropogenic actions. The UN Office for Disaster Risk Reduction orders the risks into seven classes (Meteorological and Hydrological, Geohazard, Environmental, Chemical, Biological, Technological and Societal), each of which presents different types of risks, together with specific associated hazards. Secondly, the research addressed national protocols. One of the most valid is that drawn up by the Civil Defence Department of the Italian Prime Minister's Office, with identification of nine types of risk: Seismic, Meteo-Hydro, Volcanic, Tidal, Forest Fire, Sanitary, Environmental, Nuclear, and Industrial. The description of the typologies is purely qualitative, with references to national risk prevention plans and strategies. For a more in-depth discussion, the research looked at national agencies, such as the Italian Institute for Environmental Protection and Research (ISPRA) and the National Institute of Geo-Vulcanology (INGV), which focus on specific risks by detailing indices, indicators and metrics. The analysis of the classification proposed by the main protocols was preparatory to the definition of the two main classes of risks, natural and anthropic, and to the selection of the different types of risk to be associated with the respective classes within the research framework.

First, an initial partial clusterization of the risks was performed by analyzing the results of the progress of the European 4CH Project (2021–2024).[2] The 4CH provides a general classification of the risks based on the two main macro areas of natural and anthropic risks. As concerns natural phenomena, an additional classification was made for risks derived from cumulative processes, which is to say all the forms of deterioration that gradually accumulate over time or any process or intermittent and fluctuating event that takes place more than once a year, as well as risks due to catastrophic events that are often beyond human control. The risks belonging to the first sub-category (cumulative processes) are classified as natural and biological. The former comprise the following types of risk: sea level rise, glaciation, erosion, silting, desertification, groundwater, deposition and vibration. The biological risks comprise animal migration, vegetation, pests, decay and degradation. For the second sub-category, the classification proposed in the context of the 4CH Project is as follows: invasive species and extreme climate and geological events. The risk types underlying the invasive species category include fauna and flora, while the extreme climate events are fire, downpours, squalls, floods and hail. To conclude, extreme geological events are tsunamis, earthquakes, landslides and volcanoes. For the anthropic class, a subdivision is proposed based on intentionality: intentional and indirect risks of causing damage to the cultural heritage. The intentional risks are in turn classified between management and crimes against cultural heritage. As concerns the former, we find the following risk types: modern re-use, corruption, quarrying and political; and for the latter, vandalism, arson, theft, illegal excavations, illicit trafficking and collectors. The family of indirect anthropic risks comprises building/infrastructure/industry, land conversion, heritage management, socio-cultural risks and other. The building/infrastructure/industry category comprises industrial activity, constructions, transportation, pollution and mining. In land conversion, agriculture and forestation are included; in heritage management, negligence, neglect, restoration, tourism industry, visitors and handling are included; and in the socio-cultural category are changes in values, veneration, loss of traditional knowledge and performance.

Through the analysis of the deliverables dedicated to the mapping of risks and the development of case studies, the types of risks belonging to the natural and anthropic risk categories could be identified, and we thus completed the taxonomy by providing the missing information relating to indices, indicators and metrics of use for the purpose of the quantitative assessment of the risks. The classification proposed by the 4CH project was implemented with respect to the one proposed by the main international protocols that are the object of our study, as well as in relation to the specific research purposes. In particular, the final classification was configured as the result of the following operations:

---

[2] The 4CH project deals with the study of methods, procedures, and tools of use for creating a center of expertise capable of dialoguing with national cultural institutions, providing support and consulting as concerns the protection of the cultural heritage in relation to natural and anthropic risks.

- Homologation to the taxonomy used in the 4CH project with reference to the main international classes;
- Implementation of the natural risk types closely related to CC (e.g., heat waves and cold waves);
- Introduction of risk types resulting from interaction between natural and anthropic phenomena that can impact the conservation protection of CH;
- Specific classification of certain risk types that make reference to generic phenomena (e.g., pollution, floods);
- Selection of anthropic risks in relation to the specific purposes of the research.

The following is the classification that was developed (Table 2.4):

Having completed the classification and identified the risk types, the second phase of the research was related to the definition, if possible, of the associated specific risks, the probability classes, the indicators, the indices and the metrics of use for the purpose of quantitative or semi-quantitative assessment of the risk in relation to cultural heritage. The database's structure was articulated as follows:

- Risk class
- Risk type
- Specific risk
- Probability classes (in the event of qualitative assessment)
- Indicators
- Indices
- Metrics (in the event of quantitative assessment)
- Bibliographical references and sources
- Glossary

In order to complete the taxonomy and provide a framework that was as comprehensive as possible, the work proceeded as follows:

- Assessment of the projects financed by the EU framework programs that are concluded or in the completion phase, considering the timeframe of the past 10 years, 2013–2023.
- Use of artificial intelligence (AI) chatbots.
- Literature review and co-creation of the database with the support of specialists in the sector.
- Analysis of reports of national and international agencies specialized in managing and assessing specific risks (e.g., The World Meteorological Organization).
- Consultation of specific databases on the taxonomy of risks.

2.6 Selection of EU Projects on CH Risk Assessment

In this phase, five projects from the last 10 years were selected on the topic of multi-risk assessment of CH, providing elements potentially of use in identifying risk classes related to CC, so as to further refine the risk taxonomy. The first project

Table 2.4 Natural and anthropic risks for which to define the taxonomy

Natural Risk	
Severe weather	**Precipitation-related**
Heat wave	Desertification
Cold wave	Drought
Fire	**Geological events**
Downpour / heavy rainfall events	Earthquakes
Squalls / windstorms	Volcanos
Hail	Landslides
Environmental	Avalanches (indirect)
Sea-level rise	Tsunamis (indirect)
Storm surge	**Biological**
Silting	Decay
Ground frost	Vegetation
Erosion	Plant pests
Coastal erosion	Animal migration
Soil erosion	**Invasive species**
Flooding	Flora / Fauna
Flooding	Biodiversity loss
Coastal flooding	
Flash flooding	
Fluvial-riverine flooding	

Anthropic Risk	
Pollution	**Heritage crime**
Air pollution	Vandalism
Water pollution	Illicit trafficking
Soil pollution	**Management**
Building/infrastructure/ industry	Corruption
Carbonation and CO_2 uptake from concrete	Modern retooling
Salt crystallization	Political
Corrosion	**Socio-cultural**
Mining	Loss of traditional knowledge
Over-tourism	**Other**
Land conversion	War
Agriculture/forestation	

analysed is STRENCH (Interreg, 2020–2022), which presents a web GIS platform for the multi-risk analysis of phenomena caused by CC (such as heavy rain, flood, drought, extreme heat) in support of the determination of intervention priorities and strategies. An innovative element of the project, transferred to the research framework, is the possibility of analyzing the data in relation to past or future time scenarios, in order to understand the evolution of the phenomena and prepare appropriate strategies. One of the projects financed under the EU Framework Programmes was

PROTHEGO (H2020, 2015–2018), which proposes a methodology for the assessment of geomorphological risks, landslides, earthquakes and volcanic phenomena, complete with related indicators based on data from remote sensing activities, combined with national and international databases, in order to identify the European CH potentially at risk. Proven indicators and units were borrowed from the project and compared with a risk prevention and assessment tool designed to facilitate the planning of mitigation strategies. The analysis of the STORM Project (H2020, 2016–2019) supported the selection of implementation aspects of decision-making tools dedicated to the protection of historic centres and archaeological sites affected by CC-derived natural hazards, with respect to which the research clearly identifies indices and indicators. Furthermore, one of the outputs of the STORM research is a collaborative platform that enables the development of a set of new forecasting models aimed at the immediate identification of threats with a multi-scalar dimension. The RESIN Project (H2020, 2015–2018) was examined for its aspects of standardized vulnerability assessment methodologies and performance assessment of adaptation measures as a decision-support tool for the development of sound urban strategies. For the purpose of risk assessment, the project identifies 31 natural hazards for which quantitative assessment indices are reported, proving extremely useful for the completion of the framework. A holistic view, based on a data-driven process regarding the impact on CH of natural hazards associated with CC, was provided by the SHELTER project (H2020, 2019–2023). The research is based on evidence of the direct and indirect impacts of CC on CH, and on the need to provide useful methods and tools to identify, assess and consequently mitigate risks. From this research, it was possible to extrapolate a clear classification of natural hazards, developed through specific analysis sheets containing information essential to delineating the damage component associated with the following risk types: Geophysical, Meteorological, Climatological, Hydrological and Biological.

2.7 AI, Co-creation and Systematic Review of the Literature

In order to complete the framework's taxonomy, Artificial Intelligence (AI) tools—in particular trained models—were used, employing a large dataset updated to 2022, with specific queries submitted to the chatbot on indicators, indices and metrics related to specific risks. Although the operation is agile in terms of methods and timing, the results are not always reliable, meaning that their scientific consistency must necessarily be verified. In this sense, the use of AI tools is to be undertaken with great caution, requiring, from time to time, a reduction in the number of specific risks considered, so as to make the methodological process more targeted. In general, the use of this tool is especially recommended in the preliminary research phase, in order to narrow down the field of investigation, in particular with regard to anthropogenic risks. A further key step in compiling the framework was to search for parameters describing specific risks in reports from national and international agencies. Furthermore, having set up a multi-disciplinary and open-source framework, some risks were defined thanks to a co-creation process that drew on the expert-based knowledge of the "Sapienza" research team and of the entire multidisciplinary group of researchers of Spoke 7. Finally, the Systematic Literature Review (SLR) process made possible identification of the components missing from the framework, with respect to natural and anthropic risks, and potentially of use in semi-quantitative and quantitative assessments, or, in the event of their absence, identification of the methodologies and criteria used in the assessment processes.

2.8 Open-Source Framework for Data-Driven Reasoning in Risk Assessment

The research was developed to fill a gap present in the field of quantitative and semi-quantitative risk assessment. The state of the art on the topic does not present a unique and all-encompassing framework capable of collecting information on the indicators, indices and metrics that need to be consulted in order to evaluate potential risks to cultural heritage through remote-sensing analysis and monitoring. To carry out a synthesis of multi-source data, a series of strategies was adopted, including an analysis of the main international protocols, a study of EU projects for multi-risk assessments regarding CH, consultation of expert-based knowledge, and the performance of an SLR. The methodology described above made it possible to develop an open-source framework based on a reasoned classification of risks and presenting data regarding indicators, indices and metrics whose consultation facilitates the quantitative or semi-quantitative assessment of the natural and anthropic risks that may have repercussions on CH, from the architectural heritage to the natural landscape, in a multi-scale dimension (Battisti et al., 2024). Publicly available datasets were created in this study.

These data can be found here: [https://docs.google.com/spreadsheets/d/1bg9UyY8tctCj3eFlao3GGAzHk31tiLhTpfVFSl_3EFs/edit?usp=sharing].

The framework collects, in a single repository, the main natural and anthropic risks, together with the related taxonomy, constituting, right from the start, an open document implemented over the course of time through knowledge-based expertise that can be consulted by researchers, professionals, and public administrations readying assessments of risks in the CH sector. The proposed model will be implemented with the Exposure and Vulnerability risk components, which characterize the various risks in relation to the context of application (site-based evaluation process), in order to provide a complete assessment framework.

2.9 Conclusions

It should be emphasized that an in-depth understanding of risk assessment is crucial to defining a methodology, together with the tools and strategies employed, potentially useful to enhancing resilience, and which can be applied in different European contexts and on various components of CH. The adoption of specific selection and data-collection methods, the definition of semantic models (ontologies and vocabularies), and the design of a scalable and interoperable logical infrastructure are key strategies for the development of an information system that supports the entire knowledge process related to cultural heritage. These models consider and represent, in a format that can be shared and computed, the distinctive traits, as well as the visible and invisible uses, both past and present, and the risks to which the cultural heritage is subject, complete with the related impact assessments and forecasting scenarios, taking into account both tangible and intangible values, as such risks are made relevant to the territory by the presence of the CH. The current state of the ongoing PNRR Research, which has identified, quantified and evaluated some of the major risks related to CH on account of CC, extrapolating indices and measurement indicators in the process, is making possible the development of innovative methodological-knowledge models aimed at the definition of the Exposure and Vulnerability of the Built Environment and the establishment of Key Enabling Technologies (KETs), which represent, within technological-design culture, a priority research aim in terms of intervening in processes for the adaptation and control of phenomena brought about by CC. In particular, the framework is preparatory to the elaboration of a multi-criteria matrix (MCMA) that, combined with the use of modelling, and implemented through Geographical Information Systems (GIS), makes possible not only rapid modelling and simulation of intervention scenarios, but also predictions of their progressive validity in the short, medium and long term with respect to concrete case studies.

References

Adger, W. N. (2006). Vulnerability. *Global Environmental Change, 16*, 268–281.

Battisti, A., Figliola, A., & Santarelli, M. L. (2024). A framework for a Hazard taxonomy to support risk assessment of tangible outdoor heritage. *Heritage, 7*, 2984–3012. https://doi.org/10.3390/heritage7060140

Battisti, A., Valese, M., & Natta, H. (2022). Indicators as mediators for environmental decision making: The case study of Alessandria. *Land, 11*(607).

Burton, I., Kates, R. W., & White, G. F. (1993). *The environment as Hazard* (2nd ed.). Guilford Press.

Cutter, S. L., Mitchell, J. T., & Scott, M. S. (2000). Revealing the vulnerability of people and places: A case study of Georgetown county, South Carolina. *Annals of the Association of American Geographers, 90*, 713–737.

IPCC. (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation*. Cambridge University Press.

Janssen, J., Luiten, E., Renes, H., & Stegmeijer, E. (2017). Heritage as sector, factor and vector: Conceptualizing the shifting relationship between heritage management and spatial planning. *European Planning Studies, 25*(9), 1654–1672.

Sabbioni, C., Cassar, M., Brimblecombe, P., Tidblad, J., Kozlowski, R., & Drdácký, M. (2006). Global climate change impact on built heritage and cultural landscapes. In *Heritage, Weathering and Conservation* (Vol. 1). Taylor & Francis Ltd..

Seekamp, E., & Jo, E. (2020). Resilience and transformation of heritage sites to accommodate for loss and learning in a changing climate. *Climatic Change, 162*, 41–55.

Shaw, R. (2022). *Handbook on climate change and disasters*. Edward Elgar Publishing.

Smith, K., Ward, R., & Day, S. (2023). *Environmental hazards: Assessing risk and reducing disaster* (7th ed.). Routledge.

UNEP. (2013). *Global environment outlook (GEO-5): Environment for the future we want*. United Nations Environment Programme.

UNESCO. (2021). Updating of the policy document on climate action for world heritage. *23rd session of the general assembly of states parties*, November 24–26, 2021, Paris.

Van Westen, C. J. (2023). Risk assessment methods. Accessed on October 21, 2023, from https://www.cdema.org/virtuallibrary/index.php/charim-hbook/methodology/5-risk-assessment/5-5-risk-assessment-methods

Vecco, M. (2010). A definition of cultural heritage: From the tangible to the intangible. *Journal of Cultural Heritage, 11*, 321–324.

Chapter 3
The Case Studies: Data Acquisition, Natural and Anthropic Risks Analysis, Network of Competences as a Tool for Preservation of the Culture Heritage

Roberto Aloisio, Ilia Antenucci, Maria Giovanna Brandano, Elena De Panfilis, Speranza Falciano, Arianna Fedeli, Ludovico Iovino, Marco Modica, Ugo Rossi, and Enrico Stagnini

Abstract The chapter embraces a variety of approaches to risk analysis and identification of the best ways to safeguard cultural heritage. None of the proposed methods is exhaustive but each contributes to formulating a multidisciplinary method which, as this volume repeatedly shows, the topic itself requires. The academic study that underlies each contribution does not forget applicative and operational implications, particularly in the area studied by the group: the city of L'Aquila. First of all, the case studies of the entire Spoke 7 are distinguished by types, identified according to different scales of reference. The AirTable platform, used by all Spoke Partners, becomes an opportunity for exchange and collaboration between those who, for example, operate on the same type of risk. The scale of territories and landscape is the object of analysis of aerial photogrammetry, an aid to the protection and documentation of cultural heritage, but also an important tool for urban planning and management. On a national scale, the impact of natural events on cultural heritage has been studied, resulting from the interaction between specific hazards and the intrinsic characteristics of individual artefacts, but also the communities' capacity to absorb the impact of the event. Subsequently, we delve into the communities in a proactive approach to risk management, where we propose to collaborate with local communities in order to generate an endogenous capacity to face the risk, anticipating it, then working with awareness on prevention. The *fil rouge* is a constant eye on providing tools for managers of the *res publica* and decision makers, who can use georeferenced maps for planning, allocate resources for vulnerable communities, and use methodological frameworks to develop virtuous policies and forward-looking strategies for cultural heritage: the proposal that closes the chapter

---

R. Aloisio · I. Antenucci · M. G. Brandano · E. De Panfilis · S. Falciano (✉) · A. Fedeli ·
L. Iovino · M. Modica · U. Rossi · E. Stagnini
Gran Sasso Science Institute (GSSI), L'Aquila, Italy
e-mail: roberto.aloisio@gssi.it; ilia.antenucci@gssi.it; mariagiovanna.brandano@gssi.it; elena.depanfilis@gssi.it; speranza.falciano@gssi.it; arianna.fedeli@gssi.it; ludovico.iovino@gssi.it; marco.modica@gssi.it; ugo.rossi@gssi.it; enrico.stagnini@gssi.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_3

refers to the scale of the historic city, consisting of the planning and creation (in progress) of a network of expertise, cultural specialists and public administrations in the historic city of L'Aquila, to make possible shared and transversal policies—from decision makers to communities—for the care of cultural heritage, which is the identity and history of the communities that live it.

Keywords Cultural heritage · Risk assessment · Sustainable tourism · 3D scanning and modeling · Environmental monitoring · Multidisciplinary approach · Urban planning

3.1 The Case Studies and the Software Platform: Landscapes, Historical Cities, Built Heritage, Collections

3.1.1 The Case Studies

This section reports a large collection of case studies that are selected and analyzed to achieve the objectives of Spoke 7. The selected case studies have been identified among different categories of assets, including Territory and landscape, Historic city, Archaeology, Architecture and Collections. Each category presents unique challenges and opportunities in terms of vulnerability, conservation, adaptation to climate change and anthropogenic and natural risks. The selected sites also serve as practical examples to test innovative and multidisciplinary technological approaches developed by the project as a whole. A detailed study of the vulnerability of the sites also leads to an assessment of aspects related to the involvement of civil society such as the awareness of the importance of cultural heritage, the need to preserve it in an optimal way, for example by promoting sustainable tourism practices and improving the level of institutional coordination.

In order to effectively carry out the study of the various cases, a database has been created to store the collected data. By centralising data in a structured and organised way, it is possible to analyse and compare sites, eliminate data redundancy, improve data consistency and accuracy, and facilitate data sharing and collaboration between different users and systems, as well as make the data available for future research.

A detailed list of fields has therefore been defined to best describe the case studies, keeping in mind what has just been described and therefore the objectives that we want to achieve by analysing the data. The designated fields are:

- name, images, scale and description of the site;
- project objective;
- contact person and working group;
- risks, organised in categories;

- recent results and related projects
- areas of opportunity or risk (e.g. climate change policies in relation to cultural heritage, EU/local policies for the use of heritage as a tool for social inclusion and well-being, EU/local policies for technological innovation in relation to cultural heritage);
- specific achievable objectives;
- internal expertise and technical skills to be acquired by the site proponents;
- internal tools, materials and new tools to be acquired by the site proponents;
- good practices and stakeholders;
- accessibility to data and on-site;
- keywords and any notes.

Three main categories of risks have been defined and different risks have been listed for each of them as follows:

- *effects of climate change*, which include increased erosion, acceleration of erosion processes, increased precipitation, floods, temperature changes, increased humidity
- *natural risks,* which include seismic activity, floods, volcanic eruptions, fires, animals (insects, rodents, birds, bats, etc.), wind, landslides, drought, groundwater, microbiological attack;, invasive vegetation;
- *anthropogenic risks*, including: new populations (migrants/students), overtourism, pollution, improper site management, negligent rehabilitation/maintenance, looting and conflict, abandonment and lack of maintenance, construction and renovation works, vehicle risks, inadequate air conditioning, microclimate effects, lack of inventory, poor documentation or identification, vandalism and/or socio-political events, demographic decline and ageing, loss of local and traditional knowledge, reforestation and loss of agricultural land, urban sprawl and overbuilding, diffuse mobility;

In addition, three areas of opportunities or risks have been identified:

- climate change policies in relation to cultural heritage;
- EU/local policies for the use of heritage as a tool for social inclusion and well-being;
- EU/local policies for technological innovation in relation to cultural heritage;

Based on the above fields, the GSSI has developed a preliminary version of the database, which can be progressively improved according to the needs of the study groups. This will allow a more complete understanding of the specific challenges and opportunities related to each of the case studies towards the development of innovative solutions tailored to their needs. Overall, the database will be a valuable tool for the Spoke 7 team to monitor the progress of the project and ensure that the objectives are achieved effectively.

The case studies belong to one of the following five scale-based categories:

- *Territory and Landscapes*. This category includes case studies related to natural and cultural landscapes, such as parks, gardens, and rural areas, with historical and environmental significance. The focus of these case studies is on the preservation and management of these areas in the face of environmental and anthropic risks, such as climate change and natural disasters

- *Historic Cities*. This category includes case studies related to historic city centers and their architectural, artistic, and cultural heritage. The focus is on the preservation, management, and sustainable development of these areas, including the identification of risks and vulnerabilities and the development of mitigation and adaptation strategies.
- *Archaeology*. This category includes case studies related to archaeological sites, monuments, and artifacts. The focus is on the preservation, documentation, and interpretation of these cultural heritage resources, including the use of digital technologies, such as 3D scanning and modelling, to support conservation and management activities.
- *Architecture*. This category includes case studies related to architectural heritage, such as buildings, structures, and engineering works. The focus is on the preservation, restoration, and reuse of these resources, including the development of innovative materials and technologies to support conservation activities.
- *Collections*. This category includes case studies related to cultural heritage collections, such as libraries, archives, and museums. The focus is on the preservation, management, and use of these resources, including the development of digital technologies to support access and dissemination, as well as the identification and management of risks related to environmental conditions and human activities.

3.1.2 The Software Platform

The choice of the software platform to implement what was described above was based on criteria of simplicity, immediate availability and easy interfacing with other platforms that allow data concatenations and also visual data analysis. An optimal choice was therefore that of a Low-code platform.

The Low code (LC) movement states that Low code development platforms (LCDPs) accelerate software delivery by reducing the amount of hand-coding and time to market (Cabot, 2020). In this project, a platform for specifying case studies was crucial. For this reason, developing a data-intensive system may require too much time and could slow down the information collection needed for the project's progress. Subsequently, various candidate technologies have been evaluated to create a data-entry system for case studies that could expose data for integration with other systems. LCDPs are suitable for rapid prototyping and development technologies, especially for data-driven applications (Ihirwe et al., 2020).

AirTable is a cloud-based, data-driven LCDP that creates and shares relational databases with graphical user interfaces. The main advantage of this platform is that it can speed up the design and development of a system such as the one released for this project. Indeed, the data schema used for this data-entry system was simple but quite articulated.

Given the data schema reported in Fig. 3.1, we conceived Data tables in AirTable that are conceptually used by this tool to define the data structure. The main advantage of using a low-code platform is that the schema can be graphically or textually specified and refined without facing evolution problems related to consistency or corruption of data. For this reason, starting from the schema conceived with the working group, we refined it to reach a stable data structure defined as tables in the LCDP. Given the consensus of the initial schema, we released the first user interface used to insert the initial case studies. Also, the user interface can be graphically designed with the selected platform and offers a set of predefined styles for User Interface (UI).

One of the generated views is the *showcase* (see Fig. 3.2), where all the inserted case studies are listed, including all the filtering and sorting functionalities and the button to start a new specification.

Each case study and the data structure that underwent multiple refinements can be edited and refined. The current data structure offers a consistent selection of the risks, and the list is refined by each partner that can contribute to the data structure (Fig. 3.3). This mechanism allows for a "*human-in-the-loop*" consistent data and structure evolution that is particularly relevant when the project is still not stable in the definition.

The specification of the user interfaces also permits the generation of visual dashboards, as in Fig. 3.4. Every working group dealing with the case study can

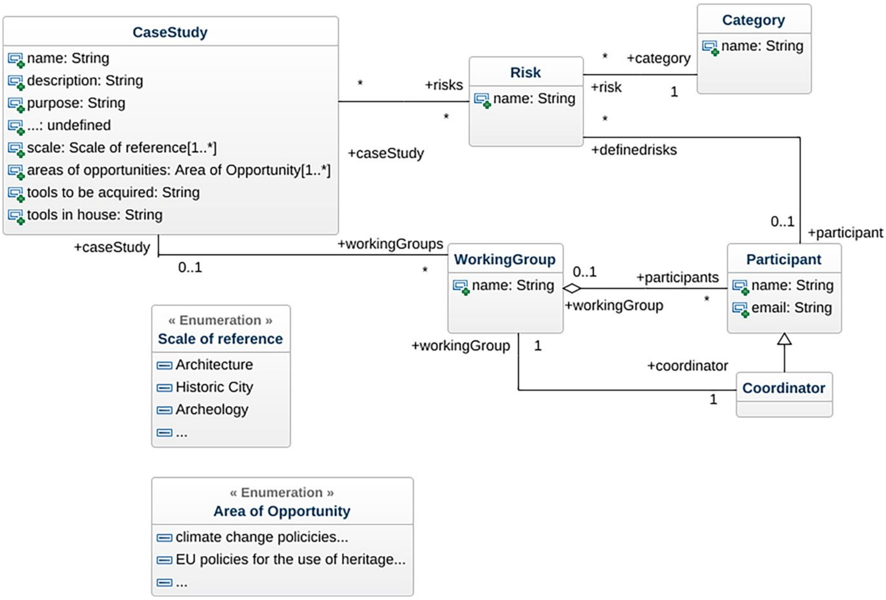
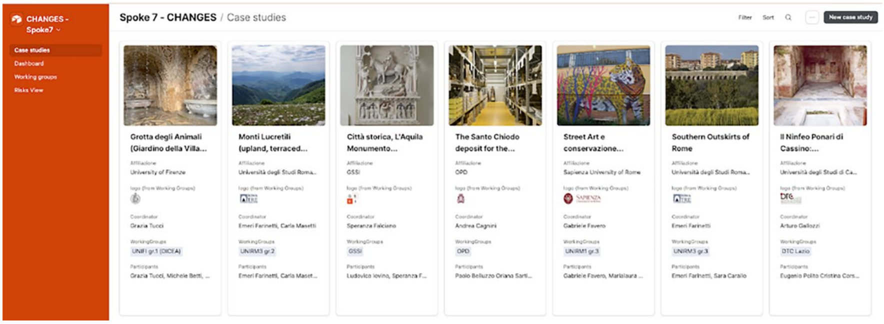


Fig. 3.1 Data schema



Spoke 7 - CHANGES / Case studies

Grotta degli Animali (Giardino della Villa...
Affiliazione
University of Firenze
logo (from Working Groups)
Coordinator
Grazia Tucci
WorkingGroups
UNIFI gr.1 (DICEA)
Participants
Grazia Tucci, Michele Betti, ...

Monti Lucretili (upland, terraced...
Affiliazione
Università degli Studi Roma...
logo (from Working Groups)
Coordinator
Emeri Farinetti, Carla Masetti
WorkingGroups
UNIRM3 gr.2
Participants
Emeri Farinetti, Carla Maset...

Città storica, L'Aquila Monumento...
Affiliazione
GSSI
logo (from Working Groups)
Coordinator
Speranza Falciano
WorkingGroups
GSSI
Participants
Ludovico Iovino, Speranza F...

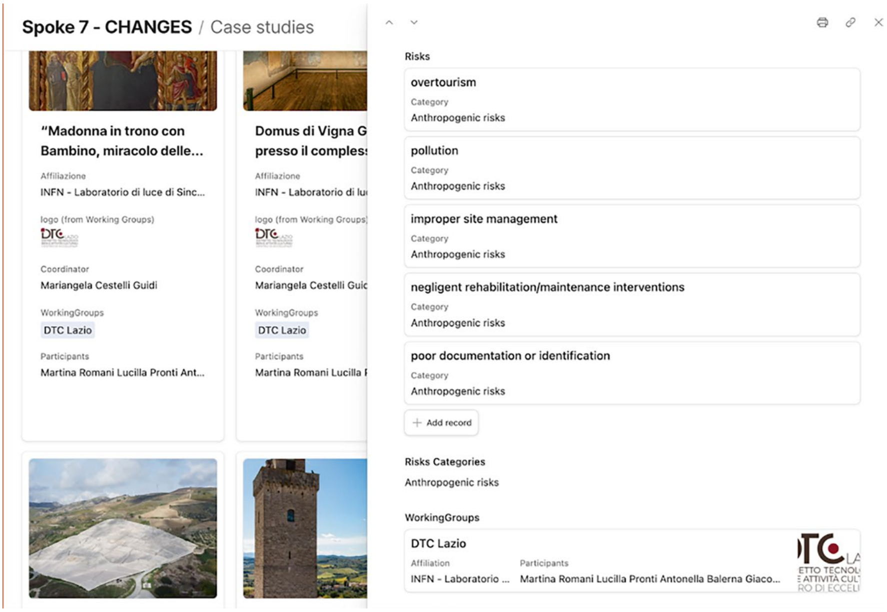
The Santo Chiodo deposit for the...
Affiliazione
OPD
logo (from Working Groups)
Coordinator
Andrea Cagnini
WorkingGroups
OPD
Participants
Paolo Belluzzo Oriana Sarti...

Street Art e conservazione...
Affiliazione
Sapienza University of Rome
logo (from Working Groups)
Coordinator
Gabriele Favero
WorkingGroups
UNIRM1 gr.3
Participants
Gabriele Favero, Marialaura ...

Southern Outskirts of Rome
Affiliazione
Università degli Studi Roma...
logo (from Working Groups)
Coordinator
Emeri Farinetti
WorkingGroups
UNIRM3 gr.3
Participants
Emeri Farinetti, Sara Caralio

Il Ninfeo Ponari di Cassino:...
Affiliazione
Università degli Studi di Ca...
logo (from Working Groups)
Coordinator
Arturo Gallozzi
WorkingGroups
DTC Lazio
Participants
Eugenio Polito Cristina Cors...

Fig. 3.2 AirTable showcase



Spoke 7 - CHANGES / Case studies

"Madonna in trono con Bambino, miracolo delle...
Affiliazione
INFN - Laboratorio di luce di Sinc...
logo (from Working Groups)
Coordinator
Mariangela Cestelli Guidi
WorkingGroups
DTC Lazio
Participants
Martina Romani Lucilla Pronti Ant...

Domus di Vigna G
presso il comples
Affiliazione
INFN - Laboratorio di lu
logo (from Working Groups)
Coordinator
Mariangela Cestelli Guic
WorkingGroups
DTC Lazio
Participants
Martina Romani Lucilla P

Risks

overtourism
Category
Anthropogenic risks

pollution
Category
Anthropogenic risks

improper site management
Category
Anthropogenic risks

negligent rehabilitation/maintenance interventions
Category
Anthropogenic risks

poor documentation or identification
Category
Anthropogenic risks

Risks Categories
Anthropogenic risks

WorkingGroups
DTC Lazio
Affiliation
INFN - Laboratorio ...
Participants
Martina Romani Lucilla Pronti Antonella Balerna Giaco...

Fig. 3.3 Data entry per a case study: selection of the risks

include members from other groups, assuring the diversity and coverage of the skills and backgrounds of the participants. In the generated dashboard, we can see not only the scale of reference for the case studies (see schema) but also how the risk categories are distributed, with an aggregated and detailed view. For instance, the last case study of the plot shows that one is exposed to only one type of risk, whereas the others are exposed to at least three types each.

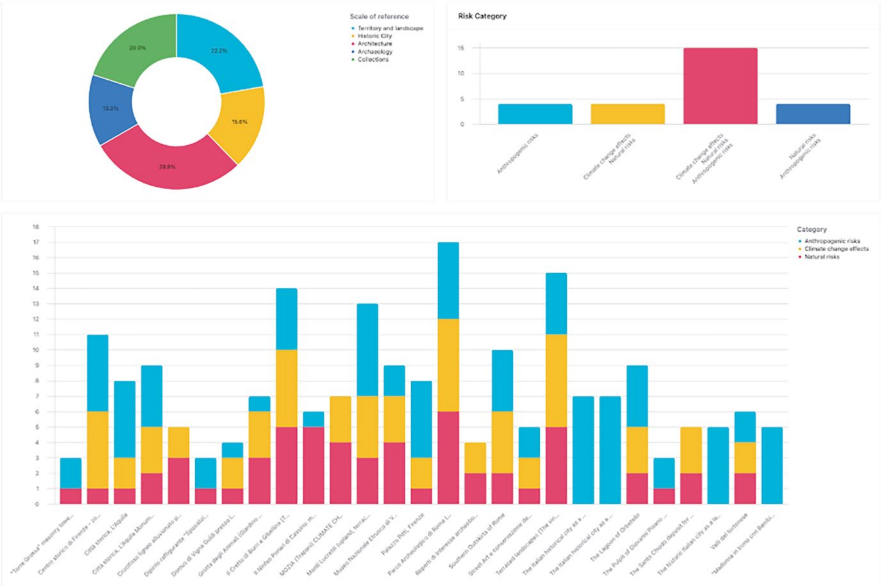
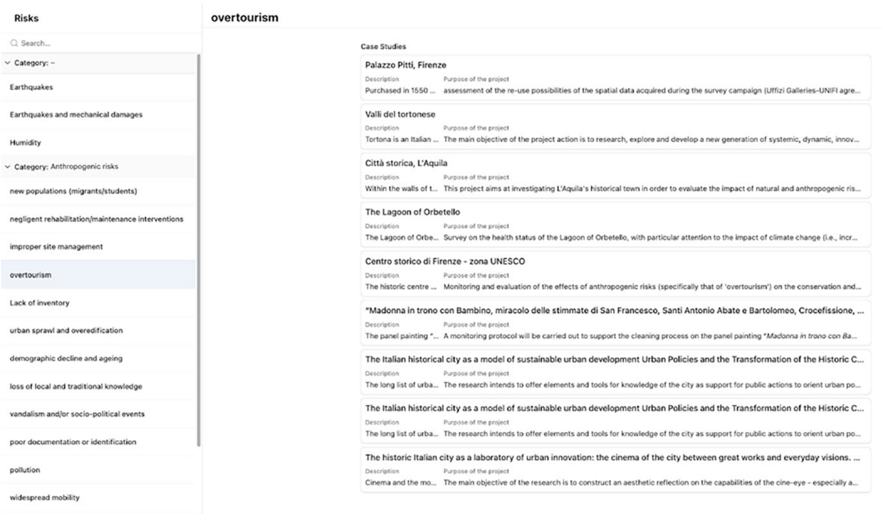


Fig. 3.4 Distribution of risk categories for the selected case studies



Risks

- Category: –
  - Earthquakes
  - Earthquakes and mechanical damages
  - Humidity
- Category: Anthropogenic risks
  - new populations (migrants/students)
  - negligent rehabilitation/maintenance interventions
  - improper site management
  - overtourism
  - Lack of inventory
  - urban sprawl and overedification
  - demographic decline and ageing
  - loss of local and traditional knowledge
  - vandalism and/or socio-political events
  - poor documentation or identification
  - pollution
  - widespread mobility

overtourism

Case Studies

	Description	Purpose of the project
Palazzo Pitti, Firenze	Purchased in 1550 ...	assessment of the re-use possibilities of the spatial data acquired during the survey campaign (Uffizi Galleries-UNIFI agre...
Valli del tortonese	Tortona is an Italian ...	The main objective of the project action is to research, explore and develop a new generation of systemic, dynamic, innov...
Città storica, L'Aquila	Within the walls of t...	This project aims at investigating L'Aquila's historical town in order to evaluate the impact of natural and anthropogenic ris...
The Lagoon of Orbetello	The Lagoon of Orbe...	Survey on the health status of the Lagoon of Orbetello, with particular attention to the impact of climate change (i.e., incr...
Centro storico di Firenze - zona UNESCO	The historic centre ...	Monitoring and evaluation of the effects of anthropogenic risks (specifically that of 'overtourism') on the conservation and...
"Madonna in trono con Bambino, miracolo delle stimmate di San Francesco, Santi Antonio Abate e Bartolomeo, Crocefissione, ...	The panel painting "...	A monitoring protocol will be carried out to support the cleaning process on the panel painting *"Madonna in trono con Ba...*
The Italian historical city as a model of sustainable urban development Urban Policies and the Transformation of the Historic C...	The long list of urba...	The research intends to offer elements and tools for knowledge of the city as support for public actions to orient urban po...
The Italian historical city as a model of sustainable urban development Urban Policies and the Transformation of the Historic C...	The long list of urba...	The research intends to offer elements and tools for knowledge of the city as support for public actions to orient urban po...
The historic Italian city as a laboratory of urban innovation: the cinema of the city between great works and everyday visions. ...	Cinema and the mo...	The main objective of the research is to construct an aesthetic reflection on the capabilities of the cine-eye - especially a...

Fig. 3.5 Case studies sharing the same category of risk

Another view (Fig. 3.5) shows all the case studies sharing the same risk so that participants can organise additional working groups to discuss cohesions and possible collaborations.

In the first stage of the project, we reached the complete specification of 27 case studies by 22 working groups in a few months. Moreover, since these platforms are open for integration, automatism was conceived to generate documents reporting the data inserted into the platform. Indeed, the specification of the case studies was helpful to the partners and decision-makers in understanding the composition of the case studies better, deriving the risk distribution, and working with data entry easily. The developed system allows data export but not in a formatted document that can be used as a deliverable or documentation of the single case study. For this reason, using the API—Application Programming Interface—exposed by the platform, we have automatically generated.docx documents, including part of the data inserted in the platform. This task would have required months, and thanks to this automatism, we generated all the documents in minutes. This mechanism was possible because of the API working as a contract of service between two applications. Indeed, a workflow specification platform was used to retrieve data from the case studies, traverse them to filter the needed information, and transfer formatted data into a Google document. Workflow automation tools—WAT—(Tuyishime et al., 2023) are low-code tools for the specification of pipelines and orchestration of services. Using visual languages, the developer can compose a pipeline of services executing tasks, e.g., retrieve data from the Airtable database, format it, transfer it into a Google document, store it in Google Drive, or even send it via email. The workflow can be even more complex, including a wide range of services and can be executed based on events or triggered by the user. The WAT used for this purpose was N8N, and the documents for all the case studies were generated.

After revising the generated documents, the partners revised data on the platform, and we noticed that one drawback of an incomplete data structure at the beginning was that it drove the specification of textual fields that could have been specified as pre-defined. For instance, we pre-specified the enumeration of "scale of reference" because this concept was clear from the requirement specification. This was not possible, for instance, for an initial categorization of the "*tools to acquire*" since we did not have a clear idea of "which tools" from the initial specification and which case studies the working groups would have specified. This aspect limits the possibility of having an aggregated view of the categories of tools to acquire, and we are stuck with free-form text. For instance, two case studies reported these tools to acquire: (1) OUTDOOR monitoring systems for CO_2 levels and (2) air quality monitoring sensors. These two tools can probably be grouped under the category of *IoT sensors,* and the two partners may collaborate to acquire the tools and devices or develop a single software system to collect data from these sensors.

In Fig. 3.6 we report an experimental extension of the data-entry platform where we propose using Large Language Models (Cheng et al., 2024)—LLMs—to transform free text fields into pre-defined selections automatically. The proposed architecture is again an orchestration of tools via APIs. The extension can use the free text fields of the case studies to interact with OpenAI (Alto, 2023) APIs to

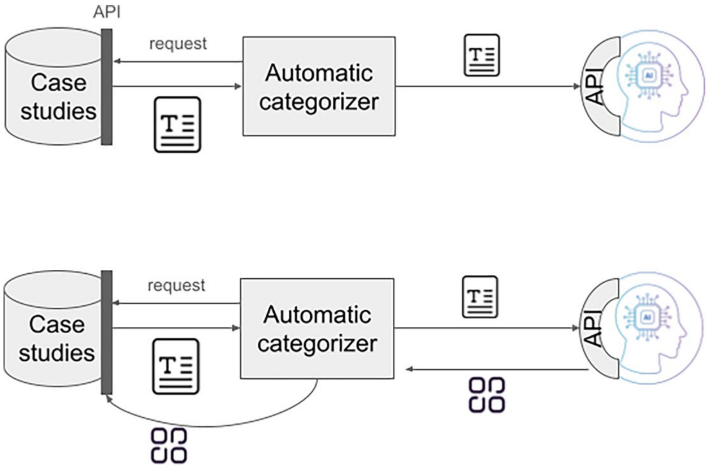


Fig. 3.6 Extension of the data-entry platform using Large Language Models

categorise the text automatically. Prompt-based text classification is a zero-shot text classification method (Kojima et al., 2022) that converts the classification problem into a language generation problem. An example of a prompt (simplified) may be, "Given this description of tools to acquire in the context of cultural heritage, what is the category of tools covering the specification?". This task can be repeated incrementally, and the first experimentations gave exciting results in transforming free text into predefined categories, e.g., Remote Sensing Tools, Data Collection and Analysis Tools, and Environmental Monitoring Instruments are some of the categories extracted from the text inserted in the free text fields collecting information on the "tools to acquire" field.

This picture shows how the proposed extension can increase the list of categories by enabling aggregated views based on free text fields, which was impossible with the data structure used to begin the specification of the case studies. In the data schema defined for the case studies, at least four fields can be progressively transformed into automated classification to enhance further the precision in the data entry of the working groups.

This methodology requires user feedback to be included officially in the next release of the platform. For this matter, we planned a validation based on focus groups (Wilkinson, 1998), where experts can express feedback on the transformed fields to classify the precision of the new functionality.

3.1.3 Data Analysis

Once some areas of opportunity/risk have been defined (innovation, technological networks, citizenships, climate change policies, etc.), the data collected in the previous phase may be grouped into the appropriate areas. Each case study will contribute to one or more areas with its specificities. The aim is to produce, as project results, dossiers of virtuous practices, technological solutions, operational guidelines, development of tools for the conservation of cultural heritage and a potential atlas of the historic city with a cartographic base where to insert knowledge from different disciplines, policies and operational indications. For instance, from the policies adopted to mitigate climate change, it is possible to evaluate the generated impact and suggest to decision makers either to modify them or to adopt them permanently (Fig. 3.7).

3.2 Data Acquisition Through Aerophotogrammetry Technique with Drones and Geolocalization of the Historical City's Landscape

The integration of drones with aerial photogrammetry techniques has transformed the way historic landscapes are studied, mapped and preserved. This method allows for extremely accurate and detailed mapping while having a low cost when compared to classic field survey methods. Aero photogrammetric techniques applied to drones allow researchers to acquire detailed aerial images and generate geospatial data that support urban analysis, planning and heritage conservation. This essay explores the principles, applications, and benefits of using drones and geolocation in acquiring data about historical cityscapes, with a specific focus on aerophotogrammetry.

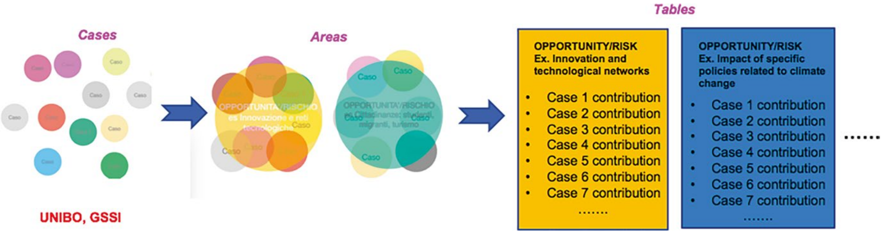


Fig. 3.7 Mapping of opportunity/risk extracted from the case studies in various areas of analysis such as innovation, climate changes policies, etc.

3.2.1 Aerophotogrammetry and Drones in Historical Landscapes

Aerial photogrammetry involves capturing images from aerial perspectives and processing these images to generate 3D models, Digital Elevations, Surface and Terrain Models (DEM, DTM and DSM), and georeferenced digital maps (Fig. 3.8). Traditionally, manned aerial survey campaigns were conducted for this purpose, but in the last decade, the use of UAVs (Unmanned Aerial Vehicles) or drones, has significantly reduced risks, costs and increased the flexibility of data collection.

Drones offer a number of advantages in the survey of historic cities:

Accessibility: drones can reach sites that might be difficult to access with traditional methods, such as inaccessible roofs, imposing façade, particularly fragile or dangerous sites following disasters.

High-resolution data: drones are equipped with cameras that capture high-resolution images, necessary for the detailed analysis of structures, landscape patterns and urban morphology.

Rapid deployment: drones enable rapid data collection over large areas, making it easier to monitor changes in the landscape over time or after restoration efforts.

The aerophotogrammetric process involves the georeferenced generation of both point clouds, meshes and 3D models and 2.5D e 2D rasters such as DEM and orthomosaics; these multi-dimensional models can be used to study urban forms, to analyze architectural characteristics and to support archaeological research and investigations, mitigating the impact of traditional survey techniques and reducing the surveying time (Fig. 3.8).

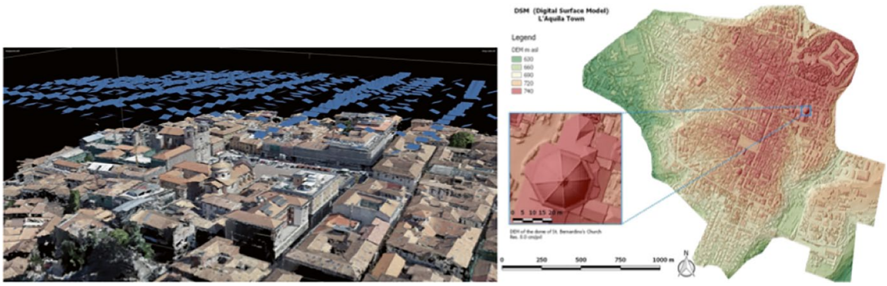


Fig. 3.8 On the left images captured by drone (blue sheets) and point cloud of a portion of the historical center of the city of L'Aquila; on the right the georeferenced Digital Elevation Model (DEM) of the historical center obtained from the point cloud

3.2.2 Geolocation and Its Role in Aerophotogrammetry

A fundamental characteristic of the photogrammetric aerial survey process lies in the possibility of obtaining georeferenced images. All unmanned aerial vehicles are equipped with a global geolocalisation system, useful both for carrying out flights on pre-established routes and for assigning a specific Latitude and Longitude value to each image acquired. The precision and accuracy of the GNSS (Global Navigation Satellites System) can be improved using a real-time (RTK Real Time Kinematics) or post-processing (PPK Post Processed Kinematics) correction system, which allows achieving high precision centimeter in positioning the detected object on the globe. The geolocated images are then processed using photogrammetric techniques to create detailed orthomosaics—highly accurate composite images that represent the historical city in its true geographical context. The advantage in producing geolocalized maps is being able to use data in Geographic Information Systems (GIS) to layer and overlay historical maps, images of the present and spatial data to conduct comparative or evolutionary analyses. Researchers and city planners can then examine the evolution of urban spaces, study the impact of modern infrastructure on historical sites, or assess the vulnerabilities of heritage buildings in the context of climate change, urban expansion or in a post-extreme event (Di Michele et al., 2023).

3.2.3 Applications in Historical City Mapping

The use of UAVs and aerophotogrammetric techniques in defining the urban landscape of historic cities finds application in various fields:

Cultural Heritage Documentation and Preservation
In cities with a high density of cultural heritage, drones are often used for study and documentation aimed at the conservation of structures with high cultural value. Detailed three-dimensional models contribute to the work of archaeologists and conservationists, providing information on the conditions of the structures, useful for drawing up restoration projects and creating digital archives for future generations. As part of the reconstruction process of the city of L'Aquila, for example, there were several discoveries of archaeological interest following the demolition of buildings compromised by the 2009 earthquake. These discoveries were first carefully documented also with the use of drones and then covered again by the reconstructed buildings (Figs. 3.9 and 3.10).

Urban Planning and Management
Drones can provide a powerful tool for understanding spatial relationships within a historic city and assessing how new developments can integrate without compromising heritage sites. The high resolution of orthomosaics and 3D models enable careful planning of infrastructure and help ensure that modern interventions respect the historical and cultural context of the city. In a study by Zhang et al. (2018),

Fig. 3.9 Discovery of structures dating back to the fourteenth–fifteenth century following the demolition of a modern building

drones were used to model urban areas, providing crucial information for planners tasked with managing urban development while preserving cultural landmarks.

Tourism and Virtual Reconstruction

As the global tourism industry continues to evolve, driven in part by the growing demand for virtual experiences, aerophotogrammetry is becoming increasingly vital in the creation of immersive, interactive environments. Drones capture highly detailed aerial and ground-level imagery, which is then used to generate 3D reconstructions of historical cities and landmarks. These reconstructions enable tourists, researchers, and history enthusiasts to explore cultural heritage sites remotely, preserving the experience for those unable to visit in person.

For instance, in Pompeii, drones equipped with photogrammetric technology have been used to create digital models of ancient ruins and urban layouts. Brumana et al. (2019) demonstrated how UAV-based photogrammetry could be employed to develop high-resolution 3D maps of the Pompeii site, offering a virtual walkthrough experience. This approach is particularly beneficial for preserving fragile sites, which can be subject to damage due to over-tourism or environmental degradation.

Beyond enhancing virtual tourism, these digital models can serve as valuable educational tools. Virtual reconstructions allow users to visualize historical sites in their original forms, providing a deeper understanding of the cultural and architectural significance of ancient cities. Museums and educational platforms have begun

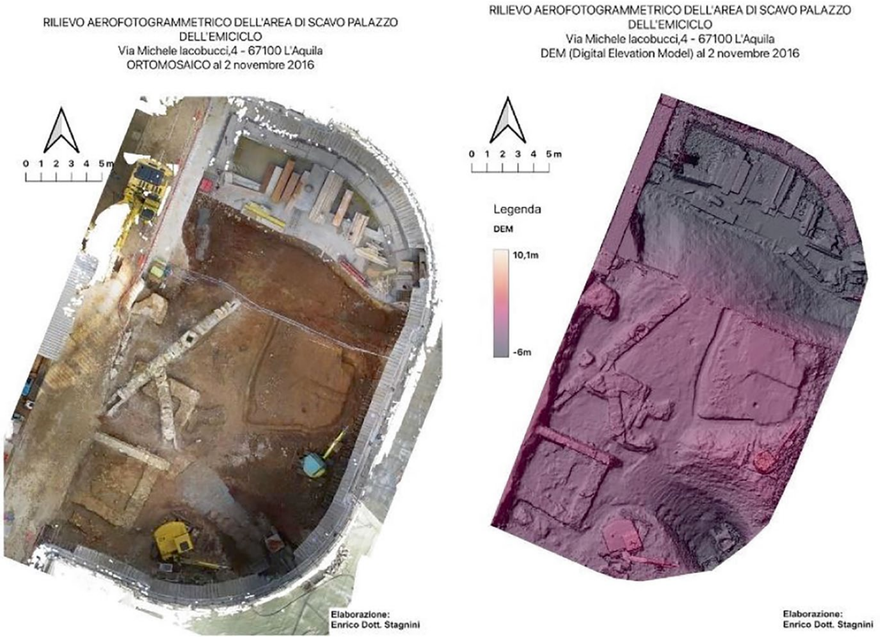


Fig. 3.10 Discovery of structures dating back to the thirteenth century following the seismic adaptation works of the Palazzo dell'Emiciclo in L'Aquila. Orthomosaic on the left and DEM on the right; resolution 5.0 cm/pixel

to incorporate these models into their exhibits, offering interactive and engaging ways for the public to learn about the history and structure of these locations.

Moreover, aerophotogrammetry also supports efforts to reconstruct or restore damaged heritage sites. After natural disasters or other destructive events, historical cities can be digitally reconstructed using drone-collected data. This process is invaluable for both documenting pre-disaster conditions and guiding restoration efforts. For example, following the devastating earthquake in Kathmandu in 2015, drones were used to capture and reconstruct the damaged historical structures, providing a basis for restoration projects aimed at preserving Nepal's cultural heritage (Nex & Remondino, 2014).

In conclusion, the integration of drones, aerophotogrammetry, and geolocation technology has revolutionized the way historical city landscapes are documented, studied, and preserved. By allowing for non-invasive data acquisition, highly accurate georeferenced models, and detailed reconstructions, this approach has become indispensable in urban planning, cultural heritage conservation, and tourism. Drones offer unparalleled flexibility and accessibility, allowing researchers to capture data from challenging environments while preserving the integrity of fragile historical sites. Furthermore, the combination of virtual reconstruction and 3D modeling not only serves practical applications for conservation but also opens new avenues for public engagement and education, ensuring that the legacy of historical cities endures for future generations.

3.3 Natural Risk Analysis for Cultural Heritage Using Statistical Tools: Earthquake and Hydrogeological Risks

Preserving cultural heritage, both in its tangible and intangible components, is vital for maintaining a community's identity, history, and values. This statement is increasingly true due to the tension worldwide that comes from a series of natural and man-made threats. It is, in fact, very evident that in the last decade, human beings have experimented in severe ways with many challenges, from COVID-19 to the pernicious effects of climate change, passing through the political conflicts in many parts of the world.

Therefore, in these complex times, preserving as much as possible the cultural heritage of many places might foster a sense of belonging and continuity that connects generations through shared traditions and narratives and can also reduce the loss that individuals might currently suffer. Indeed, it is very well known that cultural heritage can enhance social cohesion, promoting, among other things, understanding among individuals and encouraging respect for other diverse cultures (Giglitto et al., 2022).

Without claiming to be exhaustive, we could say that both man-made and natural hazards can produce significant threats to cultural heritage by directly affecting the physical objects exposed to precise events but also indirectly through a loss of the cultural identities and historical narratives that these objects inherently embody. In this chapter, we are mainly interested in natural hazards, specifically climate and seismic hazards.

Earthquakes are events that, due to current knowledge, are impossible to predict. They are characterized by a sudden ground shaking that, depending on the magnitude, can lead to more or less severe damage to historic buildings, monuments, and archaeological sites, often also compromising the structural integrity of those buildings. For instance, on September 26th, 1997, an earthquake destroyed the vault of the Basilica of San Francesco in Assisi. After this event, extensive restoration efforts were implemented to restore the Basilica of San Francesco's vault, preserving its historical and artistic significance.

Hydrogeological risks, instead, might be more deceitful because they have a lower impact on physical buildings. Still, they can alter landscapes dramatically, inundating archaeological or historic structures and buildings, leading to deterioration and eventual loss of different arrays of artifacts. For instance, extreme weather events can exacerbate flooding in low-lying areas, inundate archaeological sites, or even erosion caused by heavy rainfall, which can physically destroy centuries of history because of their impacts on the monuments. An example of this process is the city of Venice in Italy, where the combined effects of climate change (e.g., sea level rise and increased rainfall) have led to a more frequent and severe phenomenon known as "acqua alta". For instance, the famous Basilica of San Marco in Venice was highly damaged in 2019 because of this event.

It is important to note that when we deal with the impact of natural events, the impact on cultural heritage results from the interaction between specific hazards and the inherent characteristics and exposure of the artifacts. Therefore, the structural integrity of these fragile sites might often be compromised due to their age and construction methods, which may not withstand intense natural events. Furthermore, without dedicated preservation and safety management, the cultural heritage might be in danger because of the lack of adequate preparedness. Increasing in this way, the chance to suffer irreparable physical loss, which in the end turns into a profound loss of heritage and communal identity.

In this context, according to a review of the deliberations of the Italian 'Corte dei Conti' made by Villani (2023) it seems evident that the Italian government insufficiently and inefficiently spends on the preservation of cultural heritage, in detail even if the Corte dei Conti highlights various aspects, the most relevant for this work is that "*the management of interventions has predominantly appeared characterized by an emergency logic, rather than being tied to a virtuous cycle of three-year planning*" (Villani, 2023).

This evidence highlights the urgent need for a more structured and proactive approach to guarantee a necessary safeguard of the Italian cultural heritage against several different threats, natural ones *in primis*. Therefore, in this context, a preliminary step for preserving and conserving cultural heritage starts with understanding the potential impacts of these natural hazards. This can be done by applying an effective risk analysis encompassing the main components: hazards, exposure, vulnerability, and resilience. By doing so, it is possible to develop targeted strategies for preservation or underline places that are more at risk of suffering damage.

3.3.1 Risk Assessment Framework for Cultural Heritage

This section describes the steps for an effective risk assessment framework for cultural heritage. By modifying knowledge of the risk science (Modica & Zoboli, 2016), we provide a framework that encompasses all the components of the risk. By summarizing, we have the components of the risk consisting of three (plus 1) concepts: the hazard, the exposure, and the vulnerability (plus the resilience). Hazard refers to the potentially damaging event; exposure refers to objects that are under the threat of the hazards (e.g., population, properties); vulnerability refers to the intrinsic characteristics of the exposed objects that can create or reduce the potential for harm. Furthermore, resilience is the capacity to absorb a given amount of shock.

When looking at a risk framework assessment then, we can specify the following four steps: (i) first, we assess the exposure, namely the presence of the cultural heritage sites; (ii) second, we look at the identification of hazards specifically to the cultural sites; (iii) we assess the socio-economic vulnerability (and resilience) of the area under analysis; (iv) we assess the risk as a function of the previous three aspects. Together, these elements create a holistic understanding of the risks, which allows us to develop effective management strategies.

The exposure is based on the location of cultural heritage sites. A first proxy of the exposure can be based on the number of sites present in each territory, even if we might acknowledge the quality of these sites. However, a qualitative analysis of the exposure cannot be done at a granular scale, and this would require further analysis that might be dedicated to the analysis of their significance to the surrounding community. This analysis might also consider further factors such as population density, well-being, and presence of social capital, all of which can influence how a community responds to damage to its cultural heritage. It is important to note that exposure is relevant to understanding the community significance of these sites; in fact, some of these may serve as focal points for cultural practices, festivals, educational activities and tourism attractors, making their preservation vital for community cohesion and identity nonetheless, to have a quick tool only a quantitative preliminary analysis can be provided as a first step.

Hazard assessment instead relies on identifying the various natural hazards that could impact cultural heritage sites. These hazards can be very different in terms of characteristics and type of impact on the culture. Of course, each cultural site's peculiarities make it prone to a specific hazard. For instance, cultural heritage in coastal areas (e.g., Venice) may be particularly vulnerable to sea-level rise, while historical sites in mountainous areas, such as the Appenine, might be prone to seismic activity. Similarly, areas close to volcanoes can be potentially prone to volcanic activities (e.g., Ercolano and Pompei in Campania). Identifying these hazards requires interdisciplinary collaboration, but in general, it is possible to find hazard maps provided by hazard experts at different levels of accuracy. Geographic Information Systems (GIS) are vital in mapping hazards at different scales.

Once hazards are identified, we need to assess the final component of risk, vulnerability, from a socioeconomic point of view. The link here is not immediate, but we can infer that socioeconomic vulnerability significantly impacts cultural heritage, especially about the impact of extreme natural events, because communities with limited socio-economic resources often face great issues in preparing and responding to extreme events (as underlined in the previous section). However, in these areas, there is also the possibility that 'indirect' forces enter into operation to increase the impact of damages after disasters. Socio-economically disadvantaged areas may lack infrastructures, technical expertise, and emergency plans for effective risk management, resulting in inadequate protection for cultural heritage sites. Finally, underdeveloped areas might be unable to mobilize resources for restoration and conservation projects. For this purpose, Marin et al. (2021) provides a vulnerability composite indicator for Italian municipalities; the indicator of vulnerability in their work is based on 17 normalized and weighted variables and provides, in this way, a measure for the evaluation of socioeconomic vulnerability.

By combining these elements, we can build a holistic and context-specific risk management that addresses the complexity of natural events, and the socio-economic characteristics of the communities and places affected.

Fig. 3.11 Risks of cultural heritage (Source: authors' elaboration)

3.3.2 Results and Discussion

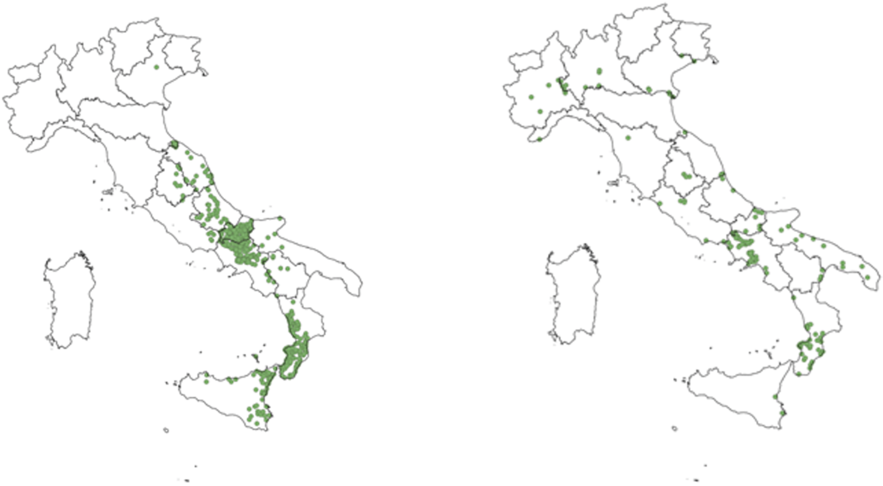
We apply the abovementioned framework to the Italian case (see Fig. 3.11). Our analysis includes all the Italian municipalities with the exclusion of the Sardinian ones, and we proceed in two steps. First, we define indicators for all the concepts mentioned above (and by including resilience), and second, we look for municipalities that show a high risk of suffering damage from a series of natural hazards (namely earthquakes, floods, and landslides).

We start building three indicators for each concept mentioned above. Exposure is a quantitative measure of the number of cultural sites in each municipality. Data are ("beni vincolati—ISCR—Istituto Superiore per la Conservazione e Restauro") from the ISPRA (the National Agency for Environmental Research and Protection) web portal. The indicator of vulnerability, as mentioned above, is composed of 17 different socio-economic variables. Finally, the hazard is connected to the natural system, and the data come from the hazard maps provided by INGV for earthquakes and ISPRA for landslides and floods.

By means of a cluster analysis then, we define the municipalities that show the highest exposure and vulnerability, and we intersect with the municipalities that are in the highest hazardous decile according to the different threats. Results are provided in Fig. 3.12.

In conclusion, our analysis highlights the critical role of socio-economic characteristics in this type of process. As shown on the maps, cultural heritage sites at risk are mainly localized in the southern regions. This is because these areas often face a combination of high exposure to natural hazards, but that endow limited socio-economic resources for effective risk management, resulting in an increased likelihood of damage. Therefore, we once again underline that the socio-economic variables of a territory can hinder preparedness and recovery efforts.

In this work, we developed a comprehensive risk assessment framework for cultural heritage. This framework includes all the risk components: exposure, hazard, vulnerability (and resilience). Each component is pivotal in understanding the multifaceted risk faced by peculiar objects such as cultural sites. Ultimately, this work aims to promote a method that might support the creation of resilient cultural heritage that can face a different series of natural threats, continuing to work as a vital part of community identity and history. Furthermore, this work aims to promote a method that might support the creation of resilient cultural heritage that can face a different series of natural threats, continuing to work as a vital part of community identity and history. By looking at municipalities with the highest risk profiles, we



a. municipalities at high seismic risk

b. municipalities at high flood risk

c. municipalities at high landslide risk

Fig. 3.12 Municipalities that show high risk for selected hazard

believe we can suggest with this work a suited process to face more critical situations to suggest policymakers better-tailored interventions and allow them to allocate resources to protect cultural heritage efficiently. This support thus might ensure that communities retain their identity and history even when facing increasing environmental challenges as nowadays fostered by climate change.

3.4 From a Reactive to a Proactive Approach to Risk Management in Cultural Heritage Preservation

Our contribution aims to provide an innovative approach to the governance of cultural heritage and its preservation, particularly from the perspective of risk management. We start with a critical analysis of what we define as heritage essentialism and the related reactive approach to risk management that is currently predominant in cultural heritage preservation. We here point to the limitations in the conventional approach, arguing that the common understanding of cultural heritage presupposes reactive responses to both natural and human-caused risks looming over the preservation of cultural heritage. A reactive approach to risk management customarily calls on government bodies to respond to existing threats after these have happened or have started to take form with emergency-like characteristics. A proactive, commons-based approach to risk management, for its part, demands cooperating with local communities with the aim of generating endogenous capacity to deal with a potentially dangerous situation in an anticipatory manner. A proactive approach, from our perspective, requires the involvement of local communities through participatory mechanisms aiming at instilling a sense of preparedness in risk management and prevention, particularly at a local community level.

The discussion of the proactive approach to risk management in cultural heritage preservation is intended here as the innovative contribution of the proposed analysis. The proactive approach to risk management and prevention paves the way, in our view, to a more dynamic understanding of cultural heritage, compared with the conventionally essentialist understanding of cultural heritage that we discuss in the next section of this contribution. In our view, cultural heritage should be viewed as a process, particularly as a socially validated process, rather than as a thing, as an object of legitimation by the state or inter-state international organizations, such as UNESCO as we will show, a key actor in cultural heritage preservation over the last five decades.

In the final instance, we hope that our text can provide a conceptually and methodologically innovative framework for risk management in cultural heritage preservation, to the benefit of cultural heritage practitioners and scholarly debates alike.

3.4.1 The Limits of Conventional Heritage Preservation Approaches

The conventional approach to cultural heritage preservation relies on the identification of outstanding cultural heritage that is predicated on the assumption of its universal value for humankind, as for instance in the preservation of globally renowned archeological sites, monuments and groups of buildings in the form of historical city centers.

In these contexts, state authorities as well as private actors mobilize exceptional resources on the preservation of heritage sites. Globally renowned heritage sites have traditionally played an important part in national identity building and its continuously reasserted value. However, an active state-led policy started to take shape only after World War II. The founding of UNESCO (the United Nations Educational, Scientific and Cultural Organization) in 1945 has been key in the institutionalization of cultural heritage preservation. UNESCO's role has risen to prominence at an international level with the initiative that has led to the creation of the 'World Heritage List' and the related 'World Heritage in Danger' list. Since its launch, this initiative has been conceived as a concerted effort involving national states and other relevant actors and stakeholders in the cultural sector, aimed at identifying cultural and national heritage sites of universal value. UNESCO's world heritage policy was formalized in 1972 with the adoption of the "Convention Concerning the Protection of the World Cultural and Natural Heritage" (see https://whc.unesco.org/en/conventiontext). The vast majority of officially recognized national states ratified the convention in the ensuing years. There are two main critical implications in UNESCO's approach to cultural heritage preservation: firstly, the competitive approach to cultural heritage designation of 'universal value' that its designation system implies, which risks downplaying the recognized value of un-designated heritage sites; secondly, the exceptional exposure of UNESCO's designated heritage sites to phenomena of over-consumption and over-tourism, which have intensified in the last two decades with the advent of low-cost airlines in the early 2000s and of online rental platforms one decade later.

On the first point, at the time of the Convention of 1972 UNESCO was already aware of the potential implications in hierarchically distinguishing between major and minor sites that its initiative could entail. Indeed, the Article 12 of the UNESCO Convention warns about "the fact that a property belonging to the cultural or natural heritage has not been included in either of the two lists mentioned in paragraphs 2 and 4 of Article 11 [the World Heritage List and the World Heritage in Danger] shall in no way be construed to mean that it does not have an outstanding universal value for purposes other than those resulting from inclusion in these lists". However, this caveat has not eliminated the hierarchization of cultural heritage implicated in the recognition of outstanding heritage sites, as well as its unintended consequences. Understandably, UNESCO has a rigorous approach to the recognition of heritage sites that can be included in its world heritage list. For instance, a group of buildings that, despite its recognized value for local and national identity, lacks perfect homogeneity in terms of age and style (for instance a modern building has been subsequently added to this built environment seeking a designation) will not be accepted in the list. This rejection of UNESCO designation runs the risk of further opening the way to the modification of a historical heritage site lacking characteristics of perfect homogeneity. More in general, the UNESCO world heritage list does not have an explicit strategy for 'minor' heritage sites. As a result, a small number of exceptional heritage sites tend to polarize the attention of state authorities and private donors, whilst the large majority of 'minor' heritage sites can remain overlooked or weakly protected. The second main risk in UNESCO's world heritage list approach is that it exposes the designated heritage sites to exceptional waves of over-consumption and over tourism, as a consequence of the worldwide marketing of these places that their designation as world heritage sites brings about. As said above, in recent decades this phenomenon has been exacerbated by the intensification of over-tourism resulting from the advent of low-cost airlines and digital platforms for short-term accommodation. Many authors and commentators, within and outside academia, have warned against the existential threat of over-tourism looming over places with UNESCO-designated world heritage sites (see for instance D'Eramo, 2014, who has coined the term 'UNESCOcide' to indicate the annihilating effects of over-tourism on local societies). Southern Europe is a special laboratory where we can observe these phenomena and related risks. In recent years, with the intensification of over.

tourism, these processes have become no longer exclusive to a limited number of small and mid-size cities, such as those with UNESCO-designated old towns dating back to the mediaeval age (such as Venice, Dubrovnik, Rhodes, Plovdiv, Granada), but have extended to a wide range of iconic places and heritage sites that are especially attractive for international and domestic tourism (Rossi, 2022). For instance, in the city of Naples, in Italy, an unplanned commemorative site for football star Diego Maradona has come to attract large crowds of visitors, threatening the livability of the surrounding neighborhood, a densely populated historical district known as Quartieri Spagnoli. This commemorative site now attracts more visitors than renowned cultural heritage sites or museums in the city. In this sense, it can be argued that UNESCO has opened the way to the aestheticization of heritage consumption that we observe today in a larger number of iconic places and historical urban areas.

As we have seen, the common approach to culture heritage recognition and preservation has significant problems and pitfalls. In this approach, cultural heritage is seen as a thing and particularly as an exceptional endowment that deserves to be recognized and celebrated by the established authorities (national governments as well as state-supported international organizations such as UNESCO) for the sake of national identity building as well as for place marketing purposes. The customary response to the risk of over-consumption that looms over officially designated heritage sites is of reactive nature. In recent years, authorities have started acknowledging over-consumption as an existential threat when this phenomenon takes the ultimate form of an emergency, a dangerous situation requiring immediate action. For instance, in Venice—a city where the number of visitors now exceeds that of residents in the historical town—the local government has resorted to a highly controversial 'access fee' as a way to reduce over-tourism. Venice's old town and its lagoon were designated by UNESCO as a world heritage site in 1987. However, in April 2023 UNESCO announced its intention to include Venice on its heritage danger list, calling on the Italian government to "ensure the utmost dedication" to ad dress the city's "long-standing problems", notably over-tourism and the effects of climate change on the lagoon's sea level. However, a few months later, the Italian government with the support of Venice's mayor publicly rejected UNESCO's recommendation, declaring Venice 'not at risk'. At the same time, Venice's city government announced the introduction of the access fee, a measure contested by environmentalist organizations and citizen groups, including anti-overtourism activists.

The controversies that arise around the different measures being proposed to deal with existing threats endangering the preservation of Venice as a world heritage site are illustrative of the limitations in conventional approaches to risk management in cultural heritage preservation that resort to merely reactive responses when a natural or human-caused risk has already manifested itself with emergency-like characteristics. In the next section of this text, we will put forward a commons-based, proactive approach to risk management centred on the idea of community preparedness.

3.4.2 Heritage as Commons and Community Preparedness

Scholars, heritage practitioners and activists alike are increasingly advocating for the treatment of heritage as a common, emphasizing community involvement as a crucial factor in preserving and managing cultural heritage. Approaching heritage as a common transforms it from a static given into a dynamic construct, fundamentally reimagining the relationship between society, cultural endowments, and risk. In this framework, risk reduction is not simply a technical or reactive endeavor; it becomes an anticipatory process that integrates the community as an active agent in identifying, managing, and mitigating threats to heritage. This shift prioritizes local knowledge, participatory governance, and collaborative stewardship, all of which are essential in creating sustainable, inclusive, and durable heritage management systems. By examining the core concepts of heritage as a commons, we aim to highlight the importance of community involvement in risk anticipation and the broader implications for heritage preservation.

The transition from understanding heritage as a given a static entity that is passively inherited and preserved by succeeding generations—to a construct—an assemblage of social practices and shared values—(Alonso González, 2014) is central to the idea of the commons, where heritage is no longer an object to be owned but a shared resource that is collectively managed and preserved. In this context, heritage is not just a physical or cultural entity but an incessant process of social engagement, inherently tied to the values, identities, and experiences of the community. The commons-based approach to heritage preservation requires a radical rethinking of governance structures, where the community becomes a co-manager and co-creator of heritage rather than a passive beneficiary. This participatory model of governance aligns with broader theories of the commons, which prioritize collective action, inclusivity, and sustainability over extractivist or exclusionary practices.

Importantly, the commons framework also allows for a more democratic and equitable management of cultural resources, especially in cases where state intervention is limited or ineffective (Lekakis, 2020). Community-driven initiatives have the potential to not only preserve heritage but also to foster social cohesion, enhance local identities, and promote sustainable development. By positioning heritage within the commons, communities can exercise greater agency in determining how their cultural assets are managed, protected, and utilized, thus reducing dependency on external actors and mitigating the risks associated with privatized governance models and state neglect.

One of the key benefits of treating heritage as a commons is its potential to anticipate and mitigate risks through community involvement. As explained before, conventional heritage preservation strategies often focus on reactive measures—intervening after damage has already occurred, whether from natural disasters, neglect, or human activity. However, such an approach is inherently limited, as it fails to address the underlying vulnerabilities that make heritage sites and practices susceptible to harm in the first place. By contrast, a commons-based approach emphasizes proactive and anticipatory risk management, where the community plays a central role in identifying potential threats and developing strategies to mitigate them before they materialize.

Understanding heritage as a commons has also implications for practices of classification, design, and management. Rocco and Clarke (2022) argue that community involvement in heritage management is essential for creating resilient systems that can adapt to changing conditions, whether environmental, social, or economic.

Communities possess valuable local knowledge and insights that are often overlooked by external experts or state authorities yet are crucial for effective risk identification and mitigation. By involving communities in the decision-making process, heritage management becomes more responsive to local needs and conditions, allowing for more tailored and sustainable solutions. Furthermore, Rocco and Clarke (2022) suggest that participatory governance models can help reduce the risks associated with top-down, bureaucratic approaches that may be disconnected from the realities on the ground. For example, as seen in the UNESCO examples in the previous section, state-led heritage preservation efforts may prioritize certain sites or practices over others, often based on criteria that do not align with local values or needs. This can lead to the marginalization of certain communities or the neglect of lesser known but equally important heritage endowments. In contrast, a commons-based approach encourages the inclusion of diverse voices and perspectives, ensuring that heritage preservation efforts are more equitable and representative of the community as a whole. Moreover, collaborative governance practices can help build the ability to cooperate within communities, which are essential for effective risk reduction. When communities are actively involved in the management of their heritage, they are more likely to take responsibility for the preservation process and contribute to the long-term sustainability of heritage sites and practices. This sense of responsibility is crucial for fostering active participation, as it encourages communities to take care of their own cultural endowments and to develop strategies for protecting them in the face of future challenges.

The shift toward treating heritage as a commons has profound implications for the way in which heritage is classified, managed, and preserved. One of the key challenges in this regard is the need to develop new frameworks for heritage classification that reflect the dynamic, participatory nature of the commons. Traditional classification systems, which often rely on subjective expert-based methods for evaluation such as historical significance or architectural value, may not be sufficient to capture the diverse range of cultural practices, sites, and endowments that are valued by communities. A commons-based approach requires more flexible and inclusive classification systems that prioritize community values and local knowledge over expert-based methods for evaluation. This may involve recognizing intangible heritage practices, such as traditional crafts or rituals, as equally important as tangible heritage sites, and ensuring that preservation efforts are tailored to the specific needs and priorities of the community. In terms of management, the commons-based approach also calls for a rethinking of the role of heritage practitioners and state authorities. Rather than acting as sole decision-makers, heritage practitioners must adopt a more facilitative role, working alongside communities to co-create management strategies and provide technical support where needed. Similarly, state authorities must recognize the limitations of top-down approaches and embrace more collaborative governance models that prioritize community involvement and local knowledge.

In conclusion, approaching heritage as a commons offers a compelling alternative to the extractivist tendencies of privatized governance models and the failures of state-led preservation efforts. This framework emphasizes community involvement, not only as a tool for preserving heritage but as a strategy for anticipating and reducing risk. By recognizing the community as an active agent in heritage management, the commons-based approach fosters more inclusive, democratic, and sustainable practices that are better equipped to deal with existing environmental or human-caused threats. Through participatory governance, collaborative decision-making, and the inclusion of local knowledge, cultural heritage can be preserved as a living, dynamic resource that reflects the values, identities, and experiences of the communities that steward it. Ultimately, this shift toward heritage as a commons holds great promise for creating durable heritage management systems that prioritize long-term sustainability over short-term economic value extraction.

3.5 A New Tool for Preservation of the Cultural Heritage: A Network of Local Competences

The city of L'Aquila, a case study of this project, preserves a significant historical and artistic heritage that goes from the eighth to the twentieth century, including the contemporary arts that have always found fertile ground there, by virtue of a combination of history, culture and territory that, intrinsically linked and interconnected, have characterized and still transform its urban and natural landscape. The city has its roots in the Middle Ages when, starting from the year of its foundation, in 1254, its urban layout was divided into quarters and "head-quarter" churches; from there it increased its wealth thanks to the mercantile and artisanal flourishing of the fourteenth–sixteenth centuries and later, despite having a constant sense of decadence, it practically lived “off its income”—like “a Venice of the mountains” (Clementi, 1997)—until the Unification of Italy.

The recent earthquake of 2009 has profoundly affected the city, determining an urban, socio-cultural and, in some ways, even identity (Brumana et al., 2019; Carbonara et al., 2010) transformation: on the other hand, from the state of emergency (MIBAC, 2009; Vanore, 2010) to the reconstruction—still in progress—L’Aquila has been the largest construction site in Europe, which has condensed knowledge, skills and interinstitutional collaborations on the territory, also allowing for experimentation that elsewhere could not even have been thought of. The result is an entire city in full fervor in the context of the recovery and revitalization of the citizenship and its Cultural Heritage, through an extraordinary Know-how on the themes of recovery and conservation, inter-institutional collaboration, prevention for the safety of citizens and their movable and immovable assets.

Since many and still open questions and unknowns remain about the reconstruction process of the historic city of L’Aquila (Fantini, 2015; Videtta, 2012), it is now worth experimenting with a new operational strategy: a local-scale Network that operates not only in conservative and integrative intervention strictu sensu, but also in good practices of prevention and preventive maintenance, planned in a concerted manner. This Nework does not distort the specificity and individual autonomies but systematizes the technical-scientific and operational potential. The historical and artistic heritage of the city of L’Aquila—wounded and, in some ways, still in need of revitalization—could be one of the linchpins on which to base this “weaving” work where the warp and woof are the skills of protection, conservation and enhancement (in the broad spectrum of functions outlined by the Code of Cultural Heritage and Landscape). This is possible by networking competences and infrastructures, tools and protocols of Institutions, Bodies, Universities and Research Centers, Companies and Associations (European Commission, 2010) operating in the sector and committed to the protection and transmission of cultural heritage. This is why we propose the development of a Network of Competence for the cultural heritage of the historic city of L’Aquila and the surrounding area, with the possibility of extending this experiment on a regional scale (European Union, 2021; Regione Abruzzo, 2020). This proposal emerges from an analysis of the territory aimed at identifying its gaps and from a constant dialogue with involved institutions, first and foremost with those of the Ministry of Culture, about the potential of the sector’s expertise.

The Mission of this network of know-how, formalized through a Framework Agreement, therefore intends to preserve the knowledge and transfer the skills inherent to the cultural heritage, both material and immaterial, of the city through continuous work of sharing and implementing these: on the one hand, this facilitates the activation of forms of collaborative research (through Implementation Agreements, which designate and develop specific and targeted projects) thanks to a happy dialectic between the world of research and the technical-scientific skills of the “insiders”; on the other, it favors an innovative approach—naturally respecting the respective competence—of interoperability and co-responsibility between Institutions of different nature, making the available human and economic resources

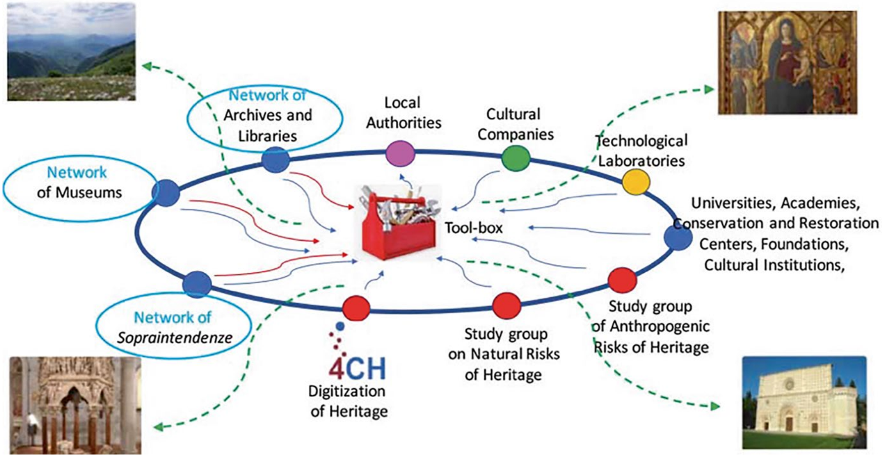


Fig. 3.13 Flow of (diagnostic and conservation) **tools** and **protocols**: from the nodes to the Tool-box and from the Tool-box to the Heritage

(often lacking in the sector) more efficient and effective. Such co-participation would determine a process of continuous and reciprocal training between the nodes of the network (Fig. 3.13), from technical staff to researchers, from political decision makers to citizens, from institutions to communities, for a process of local development (Bocci, 2020; De Varine, 2005), which also involves the progressive recognition of the value of cultural heritage, at once a place of subjectivity and collectivity and a source of well-being for all citizens. The objective is to create a research network and a service infrastructure, distributed across the urban and peri urban territory and then also regional, which favors inter-institutional and inter-professional action and exchange. Establishing a network of resources could therefore activate real best practices and multidisciplinary methods, which are now established in the discipline of protection and management of cultural heritage on the national territory. The proposed Network structure is a formula in embryo, therefore susceptible to changes and adjustments, but it is hoped that the novelty of perspective can benefit the purposes described. Here is an initial list of the Subjects, identified as possible partners of this network, described in terms of skills, professionalism and according to the possible role/function of each in the Network:

- *Universities*: Academy of Fine Arts of L'Aquila; Gran Sasso Science Institute; University of L'Aquila.
- *Research bodies*: Gran Sasso Tech Foundation (GST); Laboratory of Nuclear Techniques for the Environment and Cultural Heritage (LABEC) with 4CH (Competence Centre for the Conservation of Cultural Heritage), the first European Competence Centre for the conservation of cultural heritage, which has chosen Abruzzo as its first experimental hub.
- *Restoration Centers*: New Museum of the Paludi di Celano, Restoration Centre (MUSE'), which houses—in addition to exhibition spaces and anti-seismic stor-

age—a restoration laboratory, belonging to the Regional Directorate of Museums of Abruzzo, under the General Directorate of Museums of the MIC.
- Museums: National Museum of Abruzzo (MUNDA); National Museum of 21st Century Arts, a branch of the MAXXI Foundation of Rome and managed by the latter.
- Archives and Libraries: Archival and Bibliographic Superintendence of Abruzzo and Molise; State Archives of L'Aquila; Salvatore Tommasi Library (Provincial Library).
- Superintendence of Archaeology, Fine arts and Landscape: Superintendence of Archaeology, Fine Arts and Landscape for the provinces of L'Aquila and Teramo (SABAP L'Aquila—Teramo); Superintendence of Archaeology, Fine Arts and Landscape for the provinces of Chieti and Pescara (SABAP Chieti—Pescara).
- Territorial and local public bodies: Municipality of L'Aquila; Province of L'Aquila; Abruzzo Region; Civil Protection Agency of the Abruzzo Region; Comando dei Carabinieri for the Protection of Cultural Heritage (TPC).
- Private individuals: Metropolitan Archdiocese of L'Aquila (Vatican), the largest owner of cultural assets; Local companies and restoration firms; Foundations and associations for cultural activities; CARISPAQ Foundation.

References

Alonso González, P. (2014). From a given to a construct: Heritage as a commons. *Cultural Studies, 28*(3), 359–390.

Alto, V. (2023). *Modern generative AI with ChatGPT and OpenAI Models: Leverage the capabilities of OpenAI's LLM for productivity and innovation with GPT3 and GPT4*. Packt Publishing Ltd.

Bocci, C. (2020). Cultura e sviluppo locale. *Il capitale culturale, 11*(2020), 81–89.

Brumana, R., Oreni, D., Raimondi, A., Georgopoulos, A., & Bregianni, A. (2019). From survey to HBIM for documentation, dissemination and management of built heritage: Theoretical pathways and applications. *Journal of Cultural Heritage, 2*(3), 433–434.

Cabot, J. (2020). Positioning of the low-code movement within the field of model-driven engineering. *Proceedings of the 23rd ACM/IEEE international conference on model driven engineering languages and systems: Companion proceedings, MODELS '20*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3417990.3420210.

Carbonara, G., Della Torre, S., & Petraroia, P. (2010). Riflessioni sul restauro e la ricostruzione dei centri storici dell'Aquila e del suo territorio. *Bollettino Italia Nostra, 451*(2010), 13–15.

Cheng, Y. H., Zhang, C. Y., et al. (2024.) *Exploring large language model based intelligent agents: definitions, methods, and prospects*. arXiv:2401.03428.

Clementi, A. (1997). *Storia dell'Aquila*. Dalle origini alla prima guerra mondiale.

D'Eramo, M. (2014). Unescocide. *New Left Review, 88*, 47–53.

De Varine, H. (2005). Le radici del futuro. Il patrimonio culturale al servizio dello sviluppo locale*,* a cura di D. Jalla, Bologna.

Di Michele F, Giannopoulou O, Stagnini E, Pera D, Rubino B, Aloisio R, Askan A, Marcati P (2023) Machine Learning for Damage Classification, Risk Mitigation and Post-earthquake Management. *International conference on energy and environmental science*, pp. 181–190.

European Commission. (2010). Green paper. *Unlocking the potential of cultural and creative industries*, Brussels.

European Union. (2021). European cluster panorama 2021. *Leveraging clusters for resilient, green and digital regional economies*.

Fantini, S. (2015). Il centro storico come bene paesaggistico a valenza culturale, in Aedon, 2.

Giglitto, D., Ciolfi, L., & Bosswick, W. (2022). Building a bridge: Opportunities and challenges for intangible cultural heritage at the intersection of institutions, civic society, and migrant communities. *International Journal of Heritage Studies, 28*(1), 74–91.

Ihirwe, F., Di Ruscio, D., Mazzini, S., Pierini, P., & Pierantonio, A. (2020). Low-code engineering for internet of things: A state of research. *Proceedings of the 23rd ACM/IEEE international conference on model driven engineering languages and systems: Companion proceedings, MODELS '20*. Association for Computing Machinery, New York, NY, USA, pp. 1–8. https://doi.org/10.1145/3417990.3420208.

Kojima, T., Gu, S. S., Reid, M., Matsuo, Y., & Iwasawa, Y. (2022). Large language models are zero-shot reasoners. In S. Koyejo, S. Mohamed, A. Agarwal, D. Belgrave, K. Cho, & A. Oh (Eds.), *Advances in neural information processing systems* (pp. 22199–22213). Curran Associates Inc.

Lekakis, S. (2020). *Cultural heritage in the realm of the commons*. Ubiquity Press.

Marin, G., Modica, M., Paleari, S., & Zoboli, R. (2021). Assessing disaster risk by integrating natural and socio-economic dimensions: A decision-support tool. *Socio-Economic Planning Sciences, 77*, 101032.

MIBAC. (2009). Sisma in Abruzzo: il recupero dei monumenti, XIII Salone dei Beni e delle Attività Culturali. Restaura – V Salone del Restauro e dei Beni Culturali (Venezia, 3–5 dicembre 2009), Roma.

Modica, M., & Zoboli, R. (2016). Vulnerability, resilience, hazard, risk, damage, and loss: A socio-ecological framework for natural disaster analysis. *Web Ecology, 16*(1), 59–62.

Nex, F., & Remondino, F. (2014). UAV for 3D mapping applications: A review. *Applied Geomatics, 6*(1), 1–15.

Regione Abruzzo. (2020). Abruzzo Prossimo. Linee di indirizzo strategico per lo sviluppo sostenibile e l'integrazione dei fondi 2021–30.

Rocco, R., & Clarke, N. (2022). Heritage as commons: Implications for classification, design, and management. In M. Hoekstra, L. Lousberg, R. Rooij, W. Wilms Floet, & S. Zijlstra (Eds.), *Inzicht: Academische vaardigheden voor bouwkundigen* (2021-2022 ed., pp. 359–376). Delft University of Technology.

Rossi, U. (2022). The existential threat of urban social extractivism: Urban revival and the extinction crisis in the European south. *Antipode, 54*(3), 892–913.

Tuyishime, A., Basciani, F., Iovino, L., Izquierdo, J. L. C., Cabot, J., & Pierantonio, A. (2023). Bridging workflow automation tools and EMF modeling ecosystems. *2023 ACM/IEEE international conference on model driven engineering languages and systems companion (MODELS-C)*. pp. 893–897. Available at: https://doi.org/10.1109/MODELS-C59198.2023.00140.

Vanore, M. (2010). Due città a distanza: fratture di spazi, tempi e identità de L'Aquila, in SISMYCITY. L'Aquila 2010, Venezia, pp. 10–13.

Videtta, C. (2012). I centri storici al crocevia tra disciplina dei beni culturali, disciplina del paesaggio e urbanistica: profili critici, in Aedon, 2 (2012).

Villani, M. (2023). I Controlli della Corte dei Conti a Tutela delle Bellezze Italiane*,* PARTE I—DOTTRINA, 3: 2023. Available at: https://www.corteconti.it/Download?id=d9d599b0-1fcc-4814-b9a0-9fb4f907c529

Wilkinson, S. (1998). Focus group methodology: A review. *International Journal of Social Research Methodology, 1*, 181–203.

Zhang, X., Rajan, S., Ji, S., & Lin, Y. (2018). Application of drones in urban management: The case of urban planning and environmental monitoring. *Cities, 81*, 63–73.

Chapter 4
The Historical City as a Critical Reference for Urban Aesthetics, History, and Climate Resilience

Andrea Borsari, Giovanni Leoni, Giovanni Bellucci, Ilaria Cattabriga, Francesco Di Maio, Elena Girelli, Federica Lecci, Ramona Loffredo, Danila Longo, Claudia Nigrelli, and Serena Orlandi

Abstract The research delineates the significance of the historical city as a pivotal counter-model of urban development, particularly in the context of Italy post-World War II. It emphasizes the need for interdisciplinary approaches that intertwine architecture and urban history with public engagement, aiming to enhance decision-making in urban policy while preserving scientific integrity. The historical city is examined not just as an academic subject but as an active entity contributing to contemporary urban dynamics, navigating the transformations that have established it as a historic center amid modern urban sprawl. The chapter posits that the historical city can counteract detrimental urban policies and advocate for sustainable practices by bridging the gap between enduring historical values and the rapidly evolving identity of "modern" cities. It calls for active political engagement from historical research, promoting a collaborative framework that can enhance community socio-cultural conditions and support informed political discussions regarding urban evolution. Furthermore, the study introduces the concept of "new urban aesthetics", highlighting the sensory and imaginative aspects of urban experiences and the shift toward aesthetic evaluations in the relationship between cities and their identities. It draws from early twentieth-century theorists and contemporary thinkers to explore how aesthetic dimensions shape urban environments and collective perceptions. The research identifies case studies to examine the intersection of new urban aesthetics with historic contexts. This comprehensive approach aims not only to create specialized knowledge but also to ensure that historical insights inform future urban development initiatives, thereby fostering community engagement and awareness

---

A. Borsari · G. Leoni (✉) · G. Bellucci · I. Cattabriga · F. Di Maio · E. Girelli · F. Lecci · R. Loffredo · D. Longo · C. Nigrelli · S. Orlandi
Università degli Studi di Bologna, Bologna, Italy
e-mail: a.borsari@unibo.it; giovanni.leoni@unibo.it; giovanni.bellucci2@unibo.it; ilaria.cattabriga3@unibo.it; francesco.dimaio6@unibo.it; elena.girelli3@unibo.it; federica.lecci2@unibo.it; ramona.loffredo2@unibo.it; danila.longo@unibo.it; claudia.nigrelli2@unibo.it; serena.orlandi4@unibo.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_4

of urban heritage. Building on this foundation, the Bologna case study demonstrates how historical insights can directly inform climate adaptation strategies. The study develops a multilayered analysis methodology to map and address Urban Heat Islands (UHIs) in the historical city's public spaces, integrating Nature-Based Solutions (NBSs) within a green infrastructure plan. By identifying vulnerable zones and simulating interventions with specific modeling, the methodology assesses improvements in microclimatic conditions. This approach provides a cross-disciplinary knowledge base that guides data-driven and long-term strategies for climate resilience, highlighting the historical city's role as both a cultural and ecological asset in the just transition toward sustainability.

Main research outputs:

- 1923 2023 Fernando Tàvora at 100, A. Esposito, G. Leoni, J.A. Bandeirinha, with G. Bellucci, eds., "HPA Histories of Postwar Architecture", vol. V, n. 11 (hpa.unibo.it, Open Access, Classe A-ANVUR, SCOPUS); printed ed. Siracusa: Lettera Ventidue, 2024, HPA Series;
- Envisioning Tomorrow's Cities O.M.Ungers Urban Reflections, A. Trentin, J.H. Gleiter, eds., "HPA Histories of Postwar Architecture", vol. VI, n. 12 (hpa.unibo.it, Open Access, Classe A-ANVUR, SCOPUS);
- The Churches and the City: European experiences between the 1950s and the 1960s, J. Alves da Cunha, A. Longhi, J. L. Marques, S. Singler with G. Bellucci, R. Maddaluno, eds., "HPA Histories of Postwar Architecture", vol. VI, n. 14 (hpa.unibo.it, Open Access, Classe A-ANVUR, SCOPUS);
- I. Cattabriga, E. Chinellato, A. Eghbali, R. Loffredo, Z. Mutton, eds.,. The Historical City. A Critical Reference and Role Model, Cham: Springer, 2024;
- E. Girelli, R. Loffredo, eds., Historical City and Visual Representation, Cham: Springer, 2026;
- Public Art, Urban Arts: Aesthetics, Practices and Languages in the City, A. Borchi, F. Fimiani, E. Chinellato, F. Sabatini, eds., "CPCL European Journal of Cre-ative Practices in Cities and Landscape", vol. 6, n. 2 (cpcl.unibo.it, Open Access, SCOPUS);
- Historical City and Urban Aesthetics, F. Di Maio, C. Nigrelli, eds., "CPCL Europe-an Journal of Creative Practices in Cities and Landscape", vol. 7, n. 2 (cpcl.unibo.it, Open Access, SCOPUS);
- A. Borsari, ed. Urban Aesthetics, "Iride. Rivista di filosofia e discussione pubblica", 2, 2025 (Classe A, Anvur);
- M. Cassani Simonetti, G. Leoni, Il Piano per il Centro Storico di Bologna 1969. L'archivio, Siracusa: Lettera Ventidue, 2026;
- M. Cassani Simonetti, I. Cattabriga, G. Leoni, The Reinvention of the "Historic Centre" in Postwar Europe, Siracusa: 2026 (to be published);
- D. Longo, R. Roversi, M. Massari, K. Fabbri, R. Mercuri, The Green Connections: Adaptive, Integrated, and Nature-Based Solutions for Urban Historic Centres, "TECHNE—Journal of Technology for Architecture and Environment", n. 28, 2024, pp. 181–190 (Classe A, Anvur) https://doi.org/10.36253/techne-15868.

Keywords Historical city · Urban development · Urban aesthetics · Community engagement · Cultural heritage · Urban Heat Islands (UHI) · Sustainability

4.1 New Urban Aesthetics and Historic City

This research aims to integrate historical perspectives on urban phenomena in historic cities with an aesthetic approach that emphasizes the sensory and imaginative impacts of new urban experiences. It briefly outlines key themes for an aesthetic reading of urban culture and references contributions that intertwine aesthetic frameworks with urban understanding.

A "new urban aesthetic" has emerged, particularly in English discourse, highlighting the relationship between cities and aesthetic evaluations. Recent studies on "rule by aesthetics" and the "aesthetic perception of urban environments" indicate that urban transformations are increasingly tied to visual identity and emotional resonance. In a competitive global economy, cities are crafted as "brandscapes," prioritizing their appeal through aesthetic identity aimed at specific social groups. This aesthetic dimension extends beyond individual perception to encompass the sensory interactions between people and their environments.

An attempt is made in the research to progressively compare this framework with historic cities, drawing insights from early twentieth-century philosophers like Georg Simmel, Sigfried Kracauer and Walter Benjamin, who explored concepts like "city as theater", "urban landscape" and "porosity." A subset of the research focuses on the intersection of new urban aesthetics and historical cities, establishing a philosophical base for interpreting urban phenomena. Some contemporary research trends of particular interest were then focused on for this purpose. Notably, Joe Blakey's (Barron & Blakey, 2024) perspectives on urban dimension emphasized aesthetics as a key to understanding cities, advocating for a participatory approach that considers the collective perception of urban spaces. Richard Shusterman's (2024) concept of somaesthetics further examined the relationship between the body and public/private spaces, highlighting the importance of democratic access and active participation in urban design. Sanna Lehtinen (2020) has investigated how contemporary urban aesthetics, particularly in historic contexts, inform the identity of cities while revealing the power dynamics at play.

Research interest is also shifting toward examining certain case studies that are particularly useful to compare also with the case of Bologna and its historical dimension. Such as the case of Venice, where tourism threatens local identity (Salerno, 2020), public art's role in challenging sexual and gender norms in Amsterdam (Zebraki, 2017), community museology, emphasizing participatory narratives around urban challenges in the case of Bogotá (Góngora, 2024), pandemic-induced urban experiences and student life, illustrating how aesthetic practices can foster memory and reinterpretation in historic cities, particularly in the

Bologna case. Collectively, these case studies propose a nuanced understanding of urban aesthetics that engages with historical contexts and contemporary challenges.

4.2 Conceptual Frameworks for the Transformation of the Historic City

The research project is dedicated to the study of the conceptual frameworks for the transformation of the historic city, with a particular focus on the case of Bologna. Specifically, the research starts from the position that philosophical aesthetics is a particular tool for analysing the city, not only in terms of the temporal stratification that passes through it, but specifically for the condition of the contemporary city, namely the metropolis (*Großstadt*). Therefore, although philosophical reflection has always explored the urban reality—especially the reflection of the Greeks on the *polis*—the attention will be directed specifically to the last two centuries. For this reason, we find the main conceptual frameworks of urban aesthetics in some classical authors, who were among the first to witness and reflect on the new phenomenon of the metropolis that they observed. These include the reflections of Georg Simmel (Antonioli & Borsari, 2020), Sigfried Kracauer (Reeh, 1991; Gorzanelli, 2025) and Walter Benjamin (Gilloch, 1996; Simay, 2005). Urban sensorium, hyper- and anaesthesia, curiosity, indifference, abstraction: these authors' concepts are still relevant today. A second part of the research will be devoted to the relationship between city and form, specifically through media studies and French post-structuralism. While the reflections of Gilles Deleuze, Félix Guattari (Vilaseca, 2014; Antonioli, 2017; Boundas & Tentokali, 2017) and Michel Foucault (Amato, 2009; Catucci, 2018) on the city have already been extensively explored in critical studies—starting with the attention given by geographers to a concept like heterotopia—their German reception, especially in the work of Friedrich Kittler (1988; McQuire, 2008), has not yet been sufficiently explored. For the German media theorist, the city functions as an impersonal device whose purpose is the transmission of information, including human information. Finally, a third part of the research will be devoted specifically to the problem of temporal stratification in the city, both synchronic and diachronic. With regard to the former, our attention will be drawn to philosophical disciplines such as dromology, founded by Paul Virilio (2023) and recently revived by the sociology of Hartmut Rosa (2005), which sees society as the result of differentiations of speed. Specifically, the urban dimension is where the process of acceleration reaches its climax. With regard to the second, the reflection on the stratification of times and worlds, as found in Ernst Bloch (1923, 1954–1959) or Hans Blumenberg (1986, 1989), allows us to consider the city as a space in which several simultaneous dimensions of history become complicated, including both visions of the future and instances of the past (Ascari & Borsari, 2023). The research is also currently being developed in terms of making the framework thus drawn profitable for understanding the case of Bologna as a historic city.

4.3 Public Space and Urban Transformation in the Historic City

In the constellation of concepts and questions that traverse the realm of the historic city, the distinction between public and private space has occupied a significant place. Since the late nineteenth century, the theoretical debate has variously linked the concept of the public to notions of "space", "sphere", or "publicity". This reveals a fundamental ambiguity and intertwining between the material dimensions of space and its political and symbolic ones. Public space is a space of physical and architectural structures and infrastructures, a space of practices and relationships, and a space regulated by certain institutionalized or informal norms. The idea of spatial organization as a product of power dynamics remains crucial for understanding some of the ongoing dynamics within inhabited spaces. One might consider how the aesthetic paradigm of decorum influences contemporary urban policies, fostering spatial segregation based on economic criteria. Yet, alongside the critique of these inequalities, there is also an increasing focus on the political significance of embodied subjectivities within public spaces, moving beyond institutional power to emphasize lived experiences and claims. The research aims to reconstruct the field of reflections taking shape in the concept of public space from its genealogies, definitions and interdisciplinary aspects, identifying its historical paradigms and discussing its contemporary terms and tensions. The relevance of this theoretical survey is being tested through a comparison with the analysis of the current state of public spaces in the city of Bologna, starting with municipal regulations governing urban policies and identifying key stakeholders. The study examines both the direct and indirect management of these public spaces, along with the various actors involved, including the public administration, investors, associations, and residents—whether loosely or formally organized into collectives. It also explores different architectural typologies of public spaces, analyzing specific examples within Bologna to better understand their functionality and the tensions at play. Lastly, attention is being given to practices that intentionally challenge institutional policies on the use of Bologna's public spaces, aiming to assess their room for manoeuvre and to dissect the conflictual dynamics involved.

4.4 Cinema and the City: Everyday Metropolitan Life in Amateur Cinema

Cinema and city have always had a privileged and, at the same time, multifaceted relationship. As has often been noted, cinema is historically born as an urban phenomenon since city constitutes the first subject of its images and it is within cities that cinema spreads in a sort of mise en abime that sees a new type of urban space, the movie theatre, filled by inhabitants intent on watching images of the city and its inhabitants (Bruno, 2008). On the one hand, many authors—Walter Benjamin and

Sigfried Kracauer in primis—have noted in cinema the privileged art of modernity capable of both showing and implementing—and perhaps even reversing (Bratu-Hansen, 2011)—those aesthetic-perceptual, social, political and economic changes that occurred during the nineteenth and twentieth centuries (Casetti, 2005) and inscribed in city and its life. On the other hand, there is an increasing urgency to think about cinema and city in their productive imbrication considering cinema as one of the actors within the processes of construction, perception, conception and change of cities (Shiel & Fitzmaurice, 2001, 2003). If there is no city without its (mental and filmic) imaginaries, it is important to consider how retrospectively these imaginaries contribute to the redefinition of the city itself by focusing on the role of cinema in the physical, social, cultural, and economic development of cities, considering visual mediation as a non-secondary part of urban processes.

In this context, my research proposes to reconsider this complex relationship between city and cinema by relocating it within a particular and little-studied film genre: home movies. Images of these films are the result of a primarily social practice that sees the entry, after photography, of cinematic devices into ordinary people everyday life. Once these films have left the primary circuit of domestic fruition becoming - in many ways - public, they allow us to reflect as much on the memorial role that cinema (in its non-professional side) played in everyday urban life as on some properly aesthetic aspects regarding the role of technical intermediation in the perception of places. Through these images it becomes possible to reflect on the affective relationship between dwellers and city—mediated and implemented through film images—as on the urban imaginaries that these images both show and generate. The research is conducted from archive material from various family collections of the city of Bologna and it is on this city that it primarily focuses. The aim is to retrace the many theoretical positions that have dealt with the delicate interconnections between city and images—especially cinematographical ones—by involving a new object of study capable of broadening the reflection beyond the cinema realised and experienced in a professional contexts.

4.5 'Historical City' as a Counter-Model of Urban Development

The research focuses on the role of the History of Architecture and Urban History in public engagement rather than on specialized methodological aspects. The intention is to explore how these disciplines can enhance decision-making processes in urban policy without compromising their scientific integrity.

The research advocates for a defined research-action field centered on the "historical city" from the post-World War II era to the present, particularly in Italy, while also considering broader geographic contexts. This approach aims to scrutinize the historical city not only as a subject of study but as an active participant in contemporary urban dynamics.

The historical city has undergone significant transformations, particularly after the war, where it evolved into a ‘historic center’ amidst a rapidly changing urban landscape. This development creates a dichotomy between the enduring values of the historical city and the sprawling identity of the ‘second city’, which often neglects its heritage. By analyzing these dynamics, the volume posits that the historical city can serve as a model for resisting detrimental urban policies and promoting sustainable practices.

The volume emphasizes the need for historical architectural research to engage with the political dimension of urban development actively. It suggests a collaborative, multidisciplinary approach that can transcend traditional disciplinary boundaries. The aim is to foster a shared vision that enhances the socio-cultural conditions of communities, moving beyond mere academic discourse to impactful, community-oriented research.

Moreover, it argues for a shift towards ‘community history’, where historical research becomes accessible and relevant to citizens involved in urban transformation. By leveraging digital tools and participatory practices, historians can maintain rigorous scholarly standards while contributing to public understanding of urban heritage.

In conclusion, establishing a defined field of research-action focused on the historical city is presented as a strategic response to contemporary urban challenges. This field not only aspires to produce specialized knowledge but also aims to facilitate informed political dialogue about the city’s evolution, ensuring that the historical context informs future urban development initiatives.

4.6 Urban Policies and the Transformation of the Historic City in Bologna

The research aims at analyzing the work of architect Pier Luigi Cervellati and his activity as a councillor of the municipal administration of Bologna, which led, under his guidance, to the elaboration of the “Plan for the Historic Centre” of Bologna in 1969, later implemented through the PEEP/Centro Storico of 1973.

The process that led to the elaboration of the 1969 Plan is part of the theoretical and design research, carried out in the academic and professional spheres, that actually oriented the administrative activity of the Municipality of Bologna and that had as its main instance that of constituting itself as a cultural act.

The research examines Cervellati’s involvement in the elaboration of the plan for his hometown from the very beginning, that is, from his convocation in the research group gathered around Leonardo Benevolo at the Faculty of Architecture in Florence from 1962 to 1965. The group carried out a fundamental study for the historic centre of Bologna, commissioned by the Bolognese administration, a little-known chapter of Bolognese town planning, especially if one compares it with the subsequent PEEP Centro Storico, which highlights the greatest experience carried out on the city's historic centre in the second half of the twentieth century. The subsequent use by the municipal administration of Bologna of that study for the elaboration of the mentioned plans shows how these studies were necessary for the subsequent urban and social policies promoted by the municipality. The narratives of the creators and promoters of the plans and the following historiography have placed the Bolognese experience on an international level, qualifying it as a political act, but, thanks to actors as Benevolo and Cervellati, it should be considered more than a mere technical act aimed at conservative restoration: a cultural, social, anthropological, and critical operation.

The research also delves into the report on the main vectors and themes that the plan addressed, as well as on the upstream objectives of the plan, aimed at drawing up a variant to the General Regulatory Plan signed by Giuseppe Campos Venuti, another important figure for the proposed theme. This is necessary to clarify to what extent Cervellati was able to take action and what areas he was most interested in, which tools he used, such as the typological and structural study of pre-existing architectural artefacts.

A significant part of Cervellati's work was centred on the communication of the plan to citizens. It mainly aimed at tracing and re-proposing the identity value of the historic centre to its residents and to all the citizens of Bologna. Indeed, thanks to the cultural impulse that Cervellati was able to give to the communication of the plan, it was recognised on the international scene and taken as a model by many foreign delegations, who visited Bologna to study and 'export' the plan, especially after the UNESCO Symposium held in Bologna in 1975. Therefore, the research illustrates which aspects of the plan in particular were considered 'exportable' cornerstones abroad as well as the reasons for this.

4.7 A Diachronic Analysis of the Political and Social Role of Large Containers Starting with the 'Plan for the Historic Centre' of Bologna (1969–2022)

The research project aims to reconstruct and analyse the processes of identification, acquisition, recovery, and adaptation to new social and cultural functions of the disused or little-used public monumental heritage of the city of Bologna. The rehabilitation of the so-called "large containers" (monumental complexes, large palaces, convents, etc.), starting from the first studies conducted during the drafting phase of the 1969 Plan for the Historic Centre (Major variant to the 1958 PRG), became the instrument for the reorganization, restructuring, and new distribution of collective services for the neighbourhoods during a phase of great social, cultural and economic changes in the city. The adoption of a public policy of services to support the housing policy thus became one of the most relevant aspects of the 1973–75 municipal programme plan.

The research project follows two main directions: the first is aimed at analysing the criteria and methods adopted during the analytical—survey phase and the realization one of the interventions on the large containers; the second is focused, on the one hand, on the study of the methods of communication and participation in the project and its realization and, on the other hand, on a diachronic analysis of the transformations that occurred over time following the intervention. For the first direction, based on the historical method, the research is founded on the identification of the archival sources kept in the archives of public institutions (Archivio storico del Comune di Bologna; Archivio della Regione Emilia-Romagna; Comitato per Bologna Storica Artistica etc.) and in the archival of the architects and town planners who played a central role in this path. At the same time, a study of the bibliographic sources produced by the public administration and by chroniclers and scholars is conducted.

While the first part focuses more on the study of bibliographic and archival sources, the second part is aimed at analyzing the data collected and at identifying experiences and criteria that can still be used in today's debate. The reconstruction and analysis of the close links between architecture, town planning, and the cultural, social, and political history of Bologna in the second half of the twentieth century provide the basis for defining operational models of intervention useful for the recovery of disused buildings and areas to host collective services.

4.8 The Churches and the City 1955–1968. Cardinal Giacomo Lercaro's Contribution to the Urban and Cultural History of Bologna

The cultural, political and social life that saw the city of Bologna as a protagonist between the 1950s and 1960s involved public figures from both the world of politics, which in those years was experiencing the bitter confrontation between the centre and the left, and the world of planners and technicians engaged in defining the lines of intervention and management of the city and the territory. Cardinal Giacomo Lercaro (1891–1976) was added to this extremely complex and varied context from April 19, 1952, who was to lead the archdiocese of Bologna until 12 February 1968. From the time of his arrival in the city, Lercaro saw a marked difference between the historical part, which was within the antique walls until the early twentieth century, and the new suburbs that, particularly after the Second World War, had experienced rapid and almost uncontrolled development. The cardinal promoted and guided a planning and cultural research on the relationship between the city and sacred space that led to the identification of new parishes and the construction of churches and parish centres intended as nodal points for the future social and cultural activities of the new neighbourhoods. Fundamental in this sense was the creation of the "Ufficio Nuove Chiese di Periferia" (New Suburban Churches Office), a body formed for the most part by young architects who had recently graduated mainly in Florence (among them were Giorgio Trebbi, Glauco and Giuliano Gresleri, Luciano Lullini, etc.) called upon in the first instance to read the critical issues and then to promote, in concert with the population concerned and the authorities, suitable design solutions.

In the summer of 1955, two key episodes took place that kick-started this operational process of "reconstruction" of the new suburbs. On June 26, from Porta Saragozza, Lercaro led the symbolic procession of the "peaceful conquest of the suburbs", an itinerary that would touch in the following hours the areas where the 44 new parish centres would be built. In the following September 23–25, Lercaro presided over the work of the first National Congress of Sacred Architecture, an event that included both moments of confrontation and the organisation of several exhibitions and, above all, supported an international confrontation with personalities from the ecclesiastical world and planners from many European countries. Lercaro had already initiated an important comfort with many counterparts, including Cardinal Josef Frings (1887–1978) in Cologne and Manuel Gonçalves Cerejeira (1888–1977) in Lisbon, which would lead to the establishment of fundamental relationships especially among young designers of new churches.

The premises, the critical and methodological analyses, the results obtained, sometimes contradictory and not always fully satisfactory according to Lercaro's high expectations, are for the most part contained in the review "Chiesa e quartiere" edited by the same operators of the Ufficio Nuove Chiese between November 1955 and September 1968, and where one can read all the salient moments included in the 13 years under study and in which Giacomo Lercaro's activity in Bologna was most incisive.

4.9 Urban Heat Island Mitigation in Historic Cities: Multi-layer Analysis, Software Simulations and Modelling as Supportive Planning Tools

Historic cities, due to their cultural and architectural value, represent not only a tangible heritage, but also a symbolic repository of the memory and identity of the communities that inhabit them. These urban areas are increasingly vulnerable to threats related to climate change, including rising temperatures, coastal erosion, extreme weather events, and sea level rise. These challenges pose significant risks, not only to the preservation of built heritage but also to the overall quality of life within these cities (IPCC, 2023; Nicolini, 2024).

Historic city centers, because of their unique characteristics and morphology, are particularly vulnerable to the urban heat island (UHI) effect, which leads to significantly elevated surface temperatures in urban areas compared to surrounding rural regions. Contributing factors include high building density, extensive use of impervious materials (e.g., stone, brick, and asphalt), and narrow streets that restrict airflow, thereby limiting the dissipation of accumulated heat. Furthermore, the scarcity of green spaces exacerbates the severity of the UHI phenomenon (Zhao et al., 2014; Pappalardo et al., 2023). In addition to compromising outdoor comfort in public spaces—directly impacting their usability—the UHI effect significantly affects the daily lives of residents. It increases health risks (e.g., metabolic disorders, dehydration, cardiovascular disease), raises energy consumption, worsens air quality, and diminishes biodiversity (Oudin Åström et al., 2011).

In response to this condition, UNESCO has developed a series of policies and strategies to mitigate the impacts of climate change on world heritage, focusing specifically on historic cities. The 2011 landmark document, Recommendation on the Historic Urban Landscape, including a Glossary of Definitions Preamble (UNESCO, 2011), provides guidelines for the conservation and management of historic cities, emphasising the importance of heritage knowledge, the protection and preservation of historic sites, and the need to involve local communities in the preservation process. This document highlights the urgent need for policies that consider the specific requirements of historic cities in the context of climate change and adaptation following an integrated approach. Recently, the 2023 Climate Action for World Heritage paper further reinforced these indications, drawing attention to specific risks that threaten cultural heritage and historic urban fabric (including infrastructure and local communities), such as sea-level rise and extreme heat waves (IPCC, 2022).

Addressing the challenges posed by climate change in historic cities, as outlined in UNESCO recommendations, necessitates a comprehensive, knowledge-driven methodology that takes into account the multifaceted environmental, social, and regulatory complexities inherent to these urban areas. Within this framework, multilayer mapping serves as an essential tool, enabling a systematic analysis of various thematic layers, uncovering their interconnections, and supporting the planning of targeted mitigation strategies.

In this context, Nature-Based Solutions (NBSs)—defined by the European Commission (2017) as strategies inspired and sustained by natural processes that enhance the resilience of territories—offer an effective and adaptable approach to mitigating the UHI phenomenon. Owing to their characteristics, typologies, and potential applications, NBSs can enhance the comfort and accessibility of public spaces, particularly during periods of elevated temperatures (Alves et al., 2024).

This section presents the integrated approach developed within the PNRR CHANGES—Cultural Heritage Active Innovation for Sustainable Society research project, applied to the historic city of Bologna for analyzing and planning potential interventions in public spaces aimed at mitigating the impacts of the urban heat island (UHI) effect. The methodology integrates multilevel mapping with ENVI-met software modelling and simulation. The mapped data categories—environmental, social, and built-environmental—provided a comprehensive information framework that guided the identification of sample areas for targeted interventions, primarily through the application of Nature-Based Solutions (NBSs).

4.9.1 The Bologna Case Study: Strategies for Climate Adaptation

Bologna has consistently demonstrated a systematic commitment to addressing the challenges posed by climate change, implementing numerous policies and projects aimed at reducing environmental impacts and enhancing urban resilience. These efforts align with global sustainability goals and international climate agreements. One of the city's key initiatives, the Urban Climate Green Strategy (Municipality of Bologna, 2022a), emphasizes urban greening as a central measure to mitigate the effects of heatwaves, enhance CO_2 absorption, and improve biodiversity. Additionally, the Urban Local Environmental Adaptation Plan, developed within the framework of the LIFE BlueAp project (Municipality of Bologna, 2015), outlines concrete actions to protect the city from the impacts of extreme climate events, such as sustainable water resource management, the promotion of green infrastructure, and innovative urban mobility solutions. Another key pillar of Bologna's climate strategy is the Sustainable Energy and Climate Action Plan—PAESC (Municipality of Bologna, 2021a), which sets ambitious goals for reducing greenhouse gas emissions and improving the energy efficiency of buildings. The plan promotes the adoption of renewable energy sources and the development of sustainable public transport systems. Complementing these strategies, the *Impronta Verde* (Green Footprint) project (Municipality of Bologna, 2021–2027) focuses on urban resilience and environmental protection through urban agriculture, the regeneration of green spaces, and the creation of ecological corridors. Furthermore, the city's General Urban Plan (Municipality of Bologna, 2021b) incorporates sustainability and climate adaptation goals into spatial planning, with a focus on creating resilient neighborhoods, redeveloping degraded urban areas, and adopting eco-friendly architectural solutions.

In addition to public planning initiatives, it is noteworthy that in 2022 Bologna was selected by the European Commission as one of the 100 cities committed to achieving climate neutrality by 2030. The city's goal is to reduce CO_2 emissions to zero, following a roadmap that includes actions on mobility, waste reduction, urban greening, and education. This ambition is further supported by the Climate Contract approved in 2024, (Municipality of Bologna, 2024) which outlines a program of commitments and investments, involving businesses, economic operators, institutional partners, the third sector, and citizens. Bologna's commitment to climate action also involves significant citizen engagement. In 2023 the city established the Citizens' Climate Assembly (Municipality of Bologna, 2023), a deliberative body composed of 100 randomly selected citizens who collaborated on drafting a document of recommendations for the municipality. Additionally, the city's collaborative approach to tackling climate challenges is reflected in its role as coordinator of the LET'SGOV project (2023–2025), funded by the European Union under the NetZeroCities program. This project focuses on reducing energy consumption and developing a model for enhanced multi-level governance.

4.9.2 Multi-layer Analysis to Support UHI Mitigation Planning

The risks and impacts of climate change are reflected in urban contexts in complex ways, compounding other crises, such as social challenges, that affect contemporary cities globally. Adopting a comprehensive approach capable of observing and analyzing urban environments—particularly historic ones—across multiple scales and levels of complexity is crucial for understanding how various factors and thematic domains interact.

The multilevel mapping methodology developed within the CHANGES project has proven to be an essential tool for planning interventions in Bologna's urban context. By leveraging available databases and thematic maps, and through the overlaying of multiple data layers—including climatic, social, and architectural information—it was possible to identify spaces most vulnerable to the urban heat island (UHI) effect.

The collected data focused on three main categories of inputs: the distribution of green spaces, the density of historic buildings, and demographic vulnerabilities. Specifically, the data included: new urban ecological corridors, green areas and public spaces envisioned in ongoing projects; proposals for the redevelopment of public spaces as part of the Participatory Budget (Municipality of Bologna, 2024b); public greenery, trees, and street furniture; the potential fragility index (Municipality of Bologna, 2022b); micro-climatic vulnerability data; proximity services and spaces (e.g., gardens, public parks, squares, socio-cultural, healthcare, and neighborhood services); sustainable mobility infrastructure (e.g., pedestrian zones, cycling paths, public transport); and historical-architectural constraints on buildings or portions of the urban fabric (Fig. 4.1).

The analysis of this data enabled the identification of priority areas for climate adaptation measures, such as the redevelopment of public spaces and the introduction of new green infrastructure. This integrated approach supported the development of targeted strategies to improve the urban microclimate while ensuring the preservation of historical heritage and the promotion of social well-being, in alignment with the Impronta Verde project, which served as the overarching framework (Fig. 4.2). The maps generated through this methodology facilitated the visualization and evaluation of the relationships between various factors, aiding in the identification of potential areas for sample interventions, which were further explored through detailed analyses (Fig. 4.3).

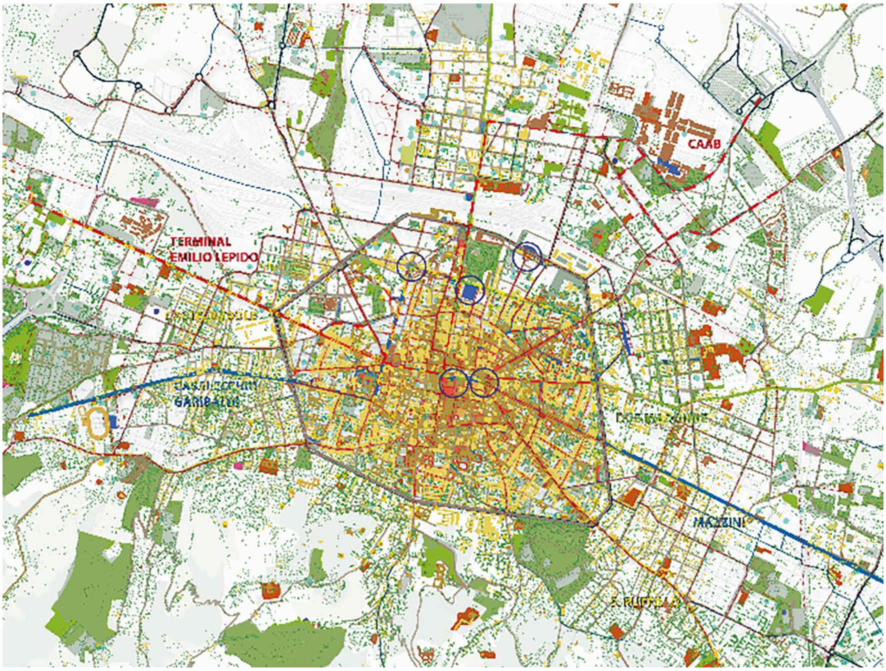


Fig. 4.1 Historic Centre of Bologna, multi-layer analysis. (Elaboration by Federica Lecci)

4.9.3 Software Modelling and Simulation to Test the Use of NBS

The multi-level analysis described in the previous section provided a comprehensive overview of Bologna’s historic center, which was instrumental in identifying a series of sample areas. These areas represent typical urban open spaces—including public and private courtyards, urban parks, streets, parking lots, squares, and residual spaces—where the application of Nature-Based Solutions (NBSs) was virtually tested through software simulations.

The software ENVI-met v.5.6.1 (www.envi-met.com) has been used to obtain a series of maps—Outdoor Microclimate Maps (OMM) (Gaspari & Fabbri, 2017)—of the pre- and post-intervention state of the study areas, through which to observe the transformations, paying particular attention to the possible enhancement of the UHI effect, parameterised through three classes of environmental data.

The microclimatic conditions generated by the simulations were based on a specific set of variables: the location (Bologna), the date (27th July 2021), chosen as representative of typical summer climatic conditions, and the time (11:00 AM), selected to reflect peak usage of public open spaces. The reference subject was modeled using a pre-set software profile: a 35-year-old man, 1.75 m in height, weighing 75 kg, standing, with a metabolic rate of 141.32 W. Additionally, the software

Fig. 4.2 The areas identified (green dots) for the sample interventions in the framework of the *Impronta Verde* project. (Elaboration by Federica Lecci)

Fig. 4.3 Detailed map of analysis, aerial photo of the current status and ENVI-met modelling of the application of NBSs (i.e., raingarderns, street trees and permable paving systems) on one of the sample areas. (Elaboration by Federica Lecci)

required the definition of cell dimensions, which establish the grid for constructing the model. Each cell represents a portion of the simulated area, to which specific attributes are assigned: materials for surfaces or height for building portions.

The simulation output includes detailed maps that provide microclimatic data, such as air temperature (Ta), surface temperature (Ts), physiological equivalent temperature (PET)—an indicator used to assess thermal stress on individuals, measured hourly—and the Universal Thermal Climate Index (UTCI), which quantifies the physiological response of humans to weather conditions.

For research purposes, and to assess the mitigation effectiveness of Nature-Based Solutions (NBSs), a catalog of solutions tailored for application in historic urban contexts was developed. This catalog includes the following categories: rain gardens, street trees, community gardens, permeable paving systems, eco-friendly urban furniture (e.g., integrated planter and seating systems), urban fruit trees, noise barriers in the form of freestanding green walls, and islands of coolness (e.g., greenery and shading elements).These categories have been selected basing on literature and main available catalogues review (DG RTD, 2021; UNaLab, 2019), the analysis of some case studies, and based on the scale and characteristics of the areas identified for experimentation. The types of NBSs have been then modelled—simplifying their characteristics—and imported into the ENVI-met software (Fig. 4.3) to proceed with simulations, and to obtain a series of maps of the different types of temperatures which allowed the impact evaluation of the adopted solutions on the UHI effect for comparison between the pre- and post-intervention state (Fig. 4.4).

4.9.4 Results

The development of effective strategies and tools that support concrete actions to mitigate the urban heat island (UHI) effect in historic city centers has been a primary goal of the integrated methodology applied to the Bologna case study. By building a robust knowledge base that integrates multiple thematic layers—environmental, social, and built environment—the methodology offers a comprehensive framework for identifying pilot areas. These areas, representative of diverse urban open spaces typical of historic centers and consolidated urban environments, were used to assess the effectiveness of Nature-Based Solutions (NBSs) in reducing UHI

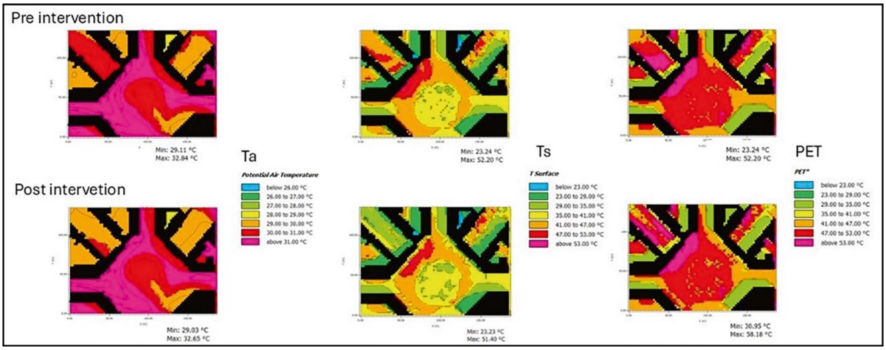


Fig. 4.4 Outdoor microclimate maps (*Ta* air temperature, *Ts* surface temperature, *PET* physiological equivalent temperature) of the pre and post-intervention state developed for one of the sample areas. (Elaboration by Federica Lecci)

impacts through pre- and post-intervention simulations of outdoor microclimatic conditions. Beyond the specific outcomes of the Bologna case study, the methodology demonstrated its strengths and potential for replication.

Multi-layer mapping proved to be a crucial tool for planning interventions. The integrated approach in Bologna facilitated the identification of complex interactions between environmental, social, and cultural variables, providing a solid foundation for informed decision-making. The analysis revealed how temperature distribution, land use, green space availability, and reflective surfaces help pinpoint areas most vulnerable to the UHI phenomenon. Assessing the climatic impacts on vulnerable populations—especially the elderly and children—underscored the direct link between thermal comfort and the accessibility of public spaces. Moreover, the synergy between ongoing or planned redevelopment projects and citizen proposals in the Participatory Budget process highlighted how urban adaptation efforts can align with both political priorities and community involvement. The methodology also successfully navigated the regulatory constraints associated with preserving historical and architectural heritage, ensuring that adaptation measures enhance, rather than compromise, the integrity and cultural value of these assets.

The integration of climate data, along with social and cultural characteristics, proved vital for the development of effective adaptation strategies. The ability to overlay these thematic layers allowed for the precise identification of priority intervention areas, guiding local policies toward sustainable and inclusive solutions.

Regarding the NBS application in pilot areas, the methodology enabled the detailed analysis of the benefits brought by various interventions, such as greening, depaving, and shading elements. The microclimatic simulations, created through ENVI-met software, offered a representative scenario for different types of urban open spaces, complementing traditional satellite data used for measuring climate change impacts in cities. By subdividing open spaces into smaller cells, the case study obtained more precise data, revealing a nuanced mosaic of micro-scale temperatures that vary even within closely located areas. This modeling, along with the NBS catalog tailored for historical contexts, facilitated both the planning and evaluation of transformations aimed at enhancing microclimatic comfort while improving public space quality and accessibility.

The use of ENVI-met, a 3D microscale modeling software for simulating complex urban environments, proved to be a highly valuable tool for urban planning efforts related to climate adaptation, outdoor comfort, and public health improvement. Its open-source nature and user-friendly interface make it accessible for broader use, offering significant potential for future applications. Additionally, the visual representation of results in map form made it easier to communicate the comparison between current conditions and projected outcomes, enhancing understanding for both experts and non-experts. This also opens the door for participatory co-design processes involving local communities, further reinforcing the relevance of NBS interventions in urban planning.

In conclusion, the integrated methodology tested in Bologna's historic city center—combining multilayer analysis with NBS simulation—holds significant potential for replication in other urban contexts. It can serve as a valuable resource for administrators, policymakers, and urban planners to develop data-driven strategies that promote a fair transition while preserving the unique identity of historic centers. Future research could explore the further application of this methodology in other cities, expanding the knowledge base for more resilient, inclusive, and sustainable urban environments. This approach not only addresses immediate climatic challenges but also supports long-term urban sustainability, ensuring that historic cities can thrive in a changing climate.

References

Alves, A., van Opstal, C., Keijzer, N., Sutton, N., & Chen Wei, S. (2024). Planning the multifunctionality of nature-based solutions in urban spaces. *Cities, 146*(104751), 1–16.

Amato, P. (2009). La genealogia e lo spazio. Michel Foucault e il problema della città. In M. Vegetti (Ed.), *Filosofie della metropoli. Spazio, potere, architettura nel pensiero del Novecento* (pp. 49–78). Carocci.

Antonioli, M. (2017). Urban war machines. In P. de Assis & P. Giudici (Eds.), *The dark precursor. Deleuze and artistic research, vol. II. The dark precursor in image, space, and politics* (pp. 431–436). Leuven UP.

Antonioli, M., & Borsari, A. (Eds.). (2020). *Georg Simmel et le champ architectural. Sociabilité urbaine, paysage et esthétisation du monde*. Mimesis.

Ascari, P., & Borsari, A. (Eds.). (2023). *Continuità e discontinuità nelle forme della cultura*. BUP.

Barron, A., & Blakey, J. (Eds.). (2024). *Aesthetics and the city*. Routledge.

Bloch, E. (1923). *The spirit of Utopia*. Standford UP (2000).

Bloch, E. (1954–1959). *The principle of hope*, MIT (1986).

Blumenberg, H. (1986). *Lebenszeit und Weltzeit*. Frankfurt a.M.

Blumenberg, H. (1989). *Höhlenausgänge*. Frankfurt a.M.

Boundas, C. V., & Tentokali, V. (Eds.). (2017). *Architectural and urban reflections after Deleuze and Guattari*. Rowman & Littlefield.

Bratu-Hansen, M. (2011). *Cinema and experience. Siegfried Kracauer, Walter Benjamin, and Theodor W. Adorno*. California UP.

Bruno, G. (2008). Motion and emotion. Film and the urban fabric. In A. Webber & E. Wilson (Eds.), *Cities in transition. The moving image and the modern metropolis*. Wallflower.

Casetti, F. (2005). *L'Occhio del Novecento. Cinema, esperienza, modernità*. Bompiani.

Catucci, S. (2018). *Potere e visibilità. Studi su Michel Foucault* (pp. 59–77). Quodlibet.

Directorate-General for Research and Innovation—European Commission. (2021). *Evaluating the impact of nature-based solutions. Appendix of methods*. Retrieved September 2024, from https://op.europa.eu/en/publication-detail/-/publication/6da29d54-ad4e-11eb-9767-01aa75ed71a1

European Commission. (2017). *Nature-based solutions*. Retrieved September 2024, from https://research-and-innovation.ec.europa.eu/research-area/environment/nature-based-solutions_en

Gaspari, J., & Fabbri, K. (2017). A study on the use of outdoor microclimate map to address design solutions for urban regeneration. *Energy Procedia, 111*, 500–509.

Gilloch, G. (1996). *Myth and metropolis. Walter Benjamin and the city*. Polity.

Góngora, A. (2024). The round corner: Community museology in the Bronx street. In I. Cattabriga et al. (Eds.), *The historical city. A critical reference and role model* (Vol. 8, pp. 127–137). Springer.

Gorzanelli, I. (2025). *Sigfried Kracauer. Per una decifrazione estetica della città (1925–1937)*. Ventura.

Intergovernmental Panel on Climate Change. (2022). Annex I: Glossary. In *Global warming of 1.5°C* (pp. 541–562). Cambridge University Press.

Intergovernmental Panel on Climate Change. (2023). Climate change 2023: Synthesis report. In *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC.

Kittler, F. (1988). The city is a medium. *New Literary History, 27*(4), 717–729. (1996).

Lehtinen, S. (2020). Editorial introduction to the special volume on urban aesthetics. *Contemporary Aesthetics, 8*. Retrieved December 2024, from https://contempaesthetics.org/2020/07/16/editorial-introduction-to-the-special-volume-on-urban-aesthetics/

Let's GOv project. (2023–2025). Retrieved September 2024, from span class=ExternalRefspanclass=RefSourcehttps://www.comune.bologna.it/myportal/C_A944/api/content/download?id=65eac19301e00400990e4c2d/span/span.

McQuire, S. (2008). *The media city. Media, architecture and urban space*. SAGE.

Municipality of Bologna. (2015). *Piano Urbano di Adattamento Ambientale Locale (LIFE BlueAP)*. Retrieved September 2024, from https://climate-adapt.eea.europa.eu/it/metadata/projects/bologna-local-urban-environment-adaptation-plan/

Municipality of Bologna. (2021–2027). *BO2.2.7.2.a. Impronta verde e neutralità*.

Municipality of Bologna. (2021a). *Piano d'Azione per l'Energia Sostenibile e il Clima—PAESC*. Retrieved September 2024, from https://www.comune.bologna.it/servizi-informazioni/piano-azione-energia-sostenibile-clima-paesc

Municipality of Bologna. (2021b). *Piano Urbanistico Generale (PUG)*. Retrieved September 2024, from http://dru.iperbole.bologna.it/pianificazione?filter=Piano%20Urbanistico%20Generale%20

Municipality of Bologna. (2022a). *Strategia Del Verde per Il Clima Urbano*. Retrieved September 2024, from https://www.comune.bologna.it/notizie/strategia-verde-clima-urbano

Municipality of Bologna. (2022b). *iLa fragilità demografica, sociale ed economica nelle diverse aree del comune di Bologna/i*. Retrieved September 2024, from span class=ExternalRefspanclass=RefSourcehttps://inumeridibolognametropolitana.it/studi-e-ricerche/la-fragilita-demografica-sociale-ed-economica-nelle-diverse-aree-del-comune-di/span/span

Municipality of Bologna. (2023). *Assemble cittadina per il Clima*. Retrieved September 2024, from https://www.comune.bologna.it/partecipa/percorsi/assemblea-cittadina-per-il-clima

Municipality of Bologna. (2024a). *Bologna tra le 100 città carbon neutral entro il 2030*. Retrieved September 2024., from https://www.comune.bologna.it/notizie/bologna-100-citta-carbon-neutral-entro-2030

Municipality of Bologna. (2024b). *Bilancio Partecipativo*. Retrieved September 2024., from https://www.comune.bologna.it/partecipa/percorsi/bilancio-partecipativo-23

Nicolini, E. (2024). Climate change adaptation and mitigation and historic centers preservation. Underway and repeatable technological design solutions. *Cities, 152*(105174), 1–16.

Oudin Åström, D., Bertil, F., & Joacim, R. (2011). Heat wave impact on morbidity and mortality in the elderly population: A review of recent studies. *Maturitas, 69*(2), 99–105.

Pappalardo, S. E., Zanetti, C., & Todeschi, V. (2023). Mapping urban heat islands and heat-related risk during heat waves from a climate justice perspective: A case study in the municipality of Padua (Italy) for inclusive adaptation policies. *Landscape and Urban Planning, 238*(104831), 1–27.

Reeh, H. (1991). *Ornaments of the metropolis. Siegfried Kracauer and modern urban culture*. MIT.

Rosa, H. (2005). *Social acceleration. A new theory of modernity*. Columbia UP. (2015).

Salerno, G. M. (2020). *Per una critica dell'economia turistica. Venezia tra museificazione e mercificazione*. Quodlibet.

Shiel, M., & Fitzmaurice, T. (Eds.). (2001). *Cinema and the city. Film and urban societies in a global context*. Blackwell.

Shiel, M., & Fitzmaurice, T. (Eds.). (2003). *Screening the city*. Verso.

Shusterman, R. (2024). City, architecture and somaesthetics. *Iride, 37*(2).

Simay, P. (Ed.). (2005). *Capitales de la modernité. Walter Benjamin et la ville*. L'éclat.

UNaLab. (2019). *Nature based solutions—Technical handbook. Part II*. Retrieved September 2024, from https://unalab.eu/system/files/2020-02/unalab-technical-handbook-nature-based-solutions2020-02-17.pdf

UNESCO. (2011). *Recommendation on the historic urban landscape*. UNESCO.

Vilaseca, S. L. (2014). Félix Guattari and urban cultural studies. *Journal of Urban Cultural Studies, 1*(1), 137–144.

Virilio, P. (2023). *La Fin du monde est un concept sans avenir,* Œ*uvres (1957–2010)*. Seuil.

Zebraki, M. (2017). Homomonument as queer micropublic: An emotional geography of sexual citizenship. *Tijdschrift voor economische en sociale geografie (Journal of Economic and Social Geography), 108*(3), 345–355.

Zhao, L., Lee, X., Smith, R. B., & Oleson, K. (2014). Strong contributions of local background climate to urban heat islands. *Nature, 511*(7508), 216–219.

Part II
Digital Twins and Documentation for Cultural Heritage

Chapter 5
The Role of Documentation in Risk Assessment

Lidia Fiorini, Valentina Bonora, Alessandro Conti, Fabiana Di Ciaccio, and Grazia Tucci

Abstract This chapter aims at providing a protocol for the comprehensive documentation of cultural heritage: it addresses the need for standardized procedures by targeting cultural heritage operators broadly, emphasizing generalizable methodologies over technical specifics. The outcome of this study aligns with the European approaches to digitalization, and focuses on the clarity, quality requirements, result evaluation, and data management plans. Aligned with a vision of digitalization for cultural heritage preservation, the protocol complements risk management efforts by integrating ongoing monitoring, restoration, and structural integrity assessments. This approach underscores sustainability and economic viability, encapsulated in the guidelines for Documentation Techniques and illustrated through Case Studies.

Keywords 3D digitization · Built environment · Conservation · Data management · Guidelines · Digital models · Documentation · Metadata · Paradata · Risk impact

---

L. Fiorini · V. Bonora · A. Conti · F. Di Ciaccio (✉) · G. Tucci
Department of Civil and Environmental Engineering, University of Florence, Florence, Italy
e-mail: lidia.fiorini@unifi.it; valentina.bonora@unifi.it; alessandro.conti@unifi.it; fabiana.diciaccio@unifi.it; grazia.tucci@unifi.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_5

5.1 Introduction

In the field of cultural heritage preservation and conservation, documentation stands as a crucial foundation for comprehending, protecting, and transmitting our shared heritage to future generations. Comprehensive and accurate documentation not only provides a detailed record of cultural heritage sites, but also plays a key role in identifying and mitigating risks that may compromise their integrity and survival (Kioussi et al., 2013). Historically, cultural heritage sites have been exposed to a wide range of threats, including natural disasters such as earthquakes, floods, and wildfires, as well as human-induced challenges like urbanization, pollution, and armed conflict. The development of effective risk management strategies requires a deep understanding of the vulnerabilities of cultural heritage sites, which can be attained through careful and systematic documentation (Ramalhinho & Macedo, 2019).

In the field of 3D documentation, methodologies have continuously evolved to address the shifting needs of heritage preservation and the new risks it faces (Alessandri et al., 2019). Traditionally, cultural heritage documentation relied on conventional surveying and mapping methods, which, while effective for their time, offered limited accuracy and scope. With the advent of advanced digital technologies, the field has undergone a transformative shift, providing unprecedented accuracy and detail even in challenging environments (Martínez-Espejo Zaragoza et al., 2017). Laser scanning, for instance, has become an indispensable tool for capturing detailed three-dimensional data of heritage sites, enabling not only accuracy measurements but also the creation of highly accurate digital reconstructions (Alessandri et al., 2020; Del Pizzo et al., 2024).

Photogrammetry, which converts overlapping images into detailed 3D models, offers a scalable and cost-effective approach to documentation (Bitelli et al., 2019). These digital models have revolutionized the way cultural heritage sites are visualized and analyzed, allowing researchers and conservators to explore and interact with heritage assets within virtual environments. This capability facilitates more thorough analysis, deeper interpretation, and more informed conservation planning. Moreover, in recent years, Virtual Reality (VR) and Augmented Reality (AR) have emerged as powerful tools that offer immersive and interactive experiences of cultural heritage. VR enables users to virtually explore heritage sites in fully immersive, digital environments, fostering engaging and educational experiences. Meanwhile, AR enriches physical site visits by overlaying contextual information, digital reconstructions, and interactive elements onto the real-world environment, thereby deepening the visitor's understanding and engagement (Barrado-Timón & Hidalgo-Giralt, 2019). The integration of these technologies not only enhances documentation and analysis but also creates new opportunities for public engagement, education, and the promotion of cultural heritage in innovative, accessible ways. By merging the physical and digital branches, these tools represent a new frontier in cultural heritage preservation, ensuring that the understanding and appreciation of heritage assets can reach broader audiences and be preserved for future generations.

The importance of documentation in cultural heritage preservation extends far beyond mere visualization and immersive experiences. It plays a critical and multifaceted role in enabling effective risk assessment and disaster preparedness. By capturing detailed records of physical characteristics, structural details, historical data, and other pertinent information, documentation equips stakeholders with the tools necessary to perform comprehensive risk assessments. This enables the identification of potential threats and an evaluation of their likely impacts, contributing to more informed and proactive conservation efforts (Khodeir et al., 2016).

Over the past two decades, there has been significant progress in research related to risk assessment and its implications for cultural heritage. However, these advancements have not yet been fully translated into practical applications, nor sufficiently integrated into policy and decision-making processes. One possible explanation for this gap lies in the incomplete transfer of quantitative data, which is essential for developing effective strategies for risk mitigation and impact reduction (Bonazza & Sardella, 2023). Without robust data, the formulation of preventative measures and long-term planning remains hindered, preventing the full realization of these research advancements in protecting cultural heritage.

The integration of this data with 3D documentation is expected to significantly enhance the ability to develop proactive conservation strategies, thereby improving the resilience and long-term protection of cultural heritage assets. By facilitating this integration, stakeholders will be better equipped to anticipate, mitigate, and respond to emerging threats in a timely and effective manner. Moreover, robust documentation will play a critical role in disaster preparedness and response by supporting the development of conservation strategies and contingency plans tailored to the specific needs of each site (Wilson et al., 2018).

Within this type of documentation, a discipline that undoubtedly plays a pivotal role is geomatics. Specifically, when dealing with small to medium-scale geospatial data, cartography emerges as a crucial component. In contemporary contexts, this form of documentation should be understood as a dynamic digital tool that facilitates the creation of layered, multi-dimensional representations of the territory. These representations are not limited to morphological data but also incorporate a wide array of information from different fields, such as temperature variations, atmospheric precipitation, traffic patterns, and much more. The primary advantages of this type of digital mapping are manifold. First, it allows for the rapid and frequent updating of data, ensuring that the information remains current and relevant. Second, it transcends the traditional concept of fixed map scales, enabling seamless transitions between highly detailed maps and broader, more generalised representations. This flexibility makes it an invaluable resource for a range of applications.

The thematic elements to be represented in such maps are numerous, especially when aiming for a comprehensive territorial analysis in relation to the risks it may encounter. These thematic layers are often interconnected, providing a multi-faceted understanding of the environment. Many of the thematic maps developed for these purposes—such as altitude maps, slope maps, land use maps, and hydrographic network maps—can be applied across a variety of contexts and adapted to address different types of risks. These versatile maps can be useful for general risk mitigation, regardless of the specific hazard being analyzed. Conversely, other maps may be highly specialized, focusing on particular risks such as wildfires, landslides, or seismic events, which are relevant only within the context of specific vulnerabilities. In this context, the dimension of time plays a crucial role. The ability to compile historical data that tracks the evolution of certain phenomena allows for the creation of temporal maps that illustrate how risks have developed over time within a given area. This temporal perspective is essential for understanding patterns and forecasting future risks, especially for those hazards that have a clear cyclical or historical precedent.

It is also important to emphasize that such documentation does not necessarily need to be created exclusively for the purposes of risk mitigation or territorial analysis. Often, these data sets already exist within administrative or institutional records, having been generated for various other uses. These pre-existing resources can be updated and repurposed for risk assessment, thereby reducing both time and costs associated with generating new data sets from scratch. Moreover, the integration of existing data allows for more efficient and comprehensive analyses, contributing to more effective planning and intervention strategies.

5.2 The European and National Landscape on Digitising Cultural Heritage at Risk from Climate Change

As previously mentioned, the digitisation of built heritage poses particular challenges. Architectures are functional assets. They are susceptible to the effects of wear and tear, rehabilitation, maintenance and conservation over time, so the digitisation process (which is inherently more complex than for museum assets) must also provide stakeholders with tools for management and informed decision-making.

“Managing a changing historic environment” (Wijesuriya et al., 2013) requires a high density of information content, including both geometric and non-geometric data, broader than that required for conservation alone.

The high cost and rapid obsolescence of plans for 3D digitisation of architectural heritage means that producing information to support decision making and management may be a more sustainable approach, as the data can be reused in other contexts, such as for valorisation and communication. The European Community has significantly promoted innovation in the cultural heritage sector, focusing on documentation, preservation, and sharing of Europe’s legacy. This has been achieved through directives, studies, and guidelines, alongside supporting major research projects like Europeana, the key digital infrastructure for European cultural heritage. The roots of this effort trace back to the Lisbon Strategy of 2000 (Hervás Soriano & Mulatero, 2010), which emphasized the role of digitalization in promoting European culture while also driving economic growth, employment, and social cohesion. In 2020, the Creative Europe programme should continue to support cultural sectors, including cultural heritage, in seizing the opportunities of the digital transition. Cultural institutions were encouraged to embrace digital tools and technologies to preserve and promote European heritage in an evolving digital landscape. The 2019 Green Deal, aimed at achieving climate neutrality by 2050, did not initially target cultural heritage but in 2022 (Directorate-General for Education, Youth, Sport and Culture (European Commission), 2022) identified the threats posed by climate change to cultural heritage and emphasized the role that heritage can play in the broader environmental goals of the Green Deal. The document called for interdisciplinary research into the impact of climate change on cultural heritage materials and the mitigation of risks. To monitor and protect heritage assets, it recommended studies on the behaviour of materials under environmental stress, using advanced technologies such as modelling, AI and 3D documentation. Additionally, the European Commission introduced a recommendation for a common European data space, which encourages member states to digitize their cultural heritage between 2025 and 2030. This aims to improve the preservation of at-risk heritage using technologies like 3D scanning, AI, virtual and augmented reality, and cloud computing. Such tools allow for non-invasive analysis and visualization of heritage damages, facilitating restoration and conservation efforts while also gathering knowledge on climate-related impacts and resilience strategies. In response to the COVID-19 pandemic, the European Council approved the Next Generation EU fund in 2020, amounting to EUR 750 billion to support the recovery of member states. In Italy, the National Recovery and Resilience Plan (PNRR) was introduced in 2021 to also use these funds to address some structural deficiencies in the Italian economy, particularly through the digital and environmental transitions. The plan has 16 components, including 'Digitalisation, Innovation, Competitiveness and Culture' and 'Education and Research', which specifically address the digital and environmental challenges for cultural heritage. This approach ties cultural preservation to wider economic and environmental reforms, ensuring that Europe's heritage continues to thrive in a digitally driven and climate-conscious future.

The National Digitisation Plan[1] has been created by the Central Institute for the Digitisation of Cultural Heritage—Digital Library to promote the digital transformation between 2022 and 2026. It aims to preserve the cultural heritage, to make it more accessible and to promote new professional actors and services, contributing to the achievement of the United Nations' 2030 Sustainable Development Goals,[2] namely quality education, decent work, economic growth, business innovation and infrastructure, and sustainable cities and communities.

The target groups are public and private GLAMs and cultural institutions, as well as professionals, academics, artists and other stakeholders.

PND has three sections: vision, strategy and guidelines.

---

[1] https://digitallibrary.cultura.gov.it/il-piano/

[2] https://sdgs.un.org/2030agenda

The goal is to move from digital conversion to digital transformation. This shift is a challenge for technology and culture. It involves creating a digital ecosystem (Sotirova-Valkova, 2024) based on the relationships between objects and between objects and people (Rovelli, 2018).

Cultural institutions should not consider digitalisation as a stand-alone initiative, but as an integral activity closely linked to all the decisions and actions. According to the Istituto Centrale per la Digitalizzazione del Patrimonio Culturale,[3] a digital copy correctly acquired for documentation purposes has an informative and cognitive value comparable to that of the object itself, since it represents its material characteristics and state of preservation. It can be used for simulations and monitoring if replicated over time. After the 2013 European Adaptation Strategy,[4] Italy adopted the "National Climate Change Adaptation Plan",[5] which include a section on heritage and landscape. Strategies for protection, control and prevention are based on vulnerability and risk assessment, as well as the study of heritage building materials and environmental degradation. Intense and increasingly frequent rainfall is damaging buildings and accelerating deterioration. In the Firenze area, rainwater leaches the calcium carbonate in the calcite veins of the typical 'pietraforte' stone, increasing the risk of blocks falling, potentially causing injury and loss of decorative elements. Prediction models suggest that in the near future, rainfall and increased atmospheric CO2 concentrations will increase the dissolution of carbonate rock materials (Bonazza et al., 2009). Research on the impact of climate change on cultural heritage is still limited, particularly on the correlation between material degradation and climatic variables and to deepen research from the territory and the city to individual objects.

The Extraordinary National Plan for Monitoring and Preservation of Immovable Cultural Heritage[6] defines the criteria for selecting artefacts to be monitored and the conservation interventions and control priorities. The level of risk is defined on territorial danger and buildings vulnerability indices and on monitoring and protection implementation systems. In order to assess the risks to a heritage property, a thorough knowledge of its condition and location is essential. A holistic approach is required, from the global to the particular, and from the context to the artefact. High-resolution diagnostics need to assess the structure or element, integrating technologies such as remote sensing, drones, photogrammetry and sensors to monitor the evolution of deterioration.

At present, the Cultural Heritage Risk Map[7] is the only available (and sometimes not updated) tool for planning interventions according to the concept of "level of risk".

---

[3] https://docs.italia.it/italia/icdp/icdp-pnd-digitalizzazione-docs/it/v1.0-giugno-2022/index.html

[4] https://climate.ec.europa.eu/eu-action/adaptation-climate-change/eu-adaptation-strategy_en

[5] https://www.mase.gov.it/pagina/piano-nazionale-di-adattamento-ai-cambiamenti-climatici-pnacc

[6] https://dgspatrimonioculturale.beniculturali.it/attivita-direzione-generale-sicurezza-del--patrimonio-culturale/bozza-automaticapiano-straordinario-di-monitoraggio-e-conservazione-dei-beni-culturali-immobili/

[7] https://dgspatrimonioculturale.beniculturali.it/attivita-direzione-generale-sicurezza-del--patrimonio-culturale/il-sistema-informativo-della-carta-del-rischio/

All the Italian documents cited introduce these themes without any operational reference.

However, it is important to remember that raw data must be interpreted and evaluated. Processing is what turns data into information, and this requires a critical approach.

Documentation and monitoring must be carried out by experts with interdisciplinary skills. The data must be accompanied by metadata and paradata to ensure its correct use, quality and accuracy, and to trace the collection and processing steps (Wetzel et al., 2024).

The topic aligns with the Italian National Research Plan 2021–2027 (Programma Nazionale per La Ricerca|Ministero Dell'Università e Della Ricerca) in which 'Humanistic Culture, Creativity, Social Transformation, Society of Inclusion' are among the key research and innovation areas for Italy. The first research area is "Digitisation of Protection, Conservation and Valorisation Processes", focused on quantifying deterioration and calculating damage indices to prioritise conservation works (Randazzo et al., 2020).

5.2.1 Current EU Guidelines and Documents on 3D Digitisation of CH

As mentioned above, the European Union has supported 3D digitisation of cultural heritage over the years, funding projects, studies, research infrastructures and aggregators that have produced publications, dissemination events, guidelines, white papers, software and so on.

In summary, most of these documents present the state of the art in 3D digitisation and guidelines for the acquisition of artefacts for long-term preservation. While starting from the objective of conservation, an essential role is given to the use of 3D models in valorisation, education and communication projects. This leads to the transfer to the built heritage of workflows tailored to the content typical of GLAMs.

Conversely, buildings, archaeological sites, gardens, urban areas and other large assets not typically housed in a museum have similar needs for protection and valorisation, but their digitalisation requires a different approach, clearly linked to the tradition of architectural surveying as an operational tool for knowledge, design, and management.

A heritage digitisation project for preservation and management requires different techniques, is more expensive and time-consuming, but could be more sustainable by extracting contents for dissemination.

Although the first projects on 3D digitisation of cultural heritage[8] emphasised the need to develop repositories for archiving digital models by addressing critical

---

[8] https://digital-strategy.ec.europa.eu/en/library/study-quality-3d-digitisation-tangible-cultural-heritage

issues related to formats, visualisation, sharing, etc., the initial focus was strongly on describing tools and techniques for 3D digitisation, i.e. ‘how to do it’. Over time, the focus gradually shifted to the sharing of semantically enriched digital data, emphasising the need to define standards, ensure data quality, ensure process transparency, manage data ownership and establish efficient ways of sharing.

The advent of digital technologies has prompted a re-evaluation of the concept of digitalisation, with insights emerging from diverse contexts, particularly within the European scholarly community. Two notable contributions to this discourse were published in 2020:

1. Basic principles and tips for 3D digitisation of cultural heritage[9]
2. Study on quality in 3D digitisation of tangible cultural heritage—Mapping parameters, formats, standards, benchmarks, methodologies, and guidelines (European Commission, 2022)

The documents, which vary considerably in form, style and length, direct attention away from digitisation tools and techniques and towards issues related to the complexity and quality of the digitalisation process, and thus the sharing of digital data. Therefore, digitalisation is embedded in a broader, preservation-oriented strategy that cannot afford to lower standards of preservation. This strategy encompasses the semantic enrichment of models, the generation of a broad spectrum of data and metadata, and the provision for long-term preservation, with proper planning and management of digital archives to ensure FAIRness (Findable, Accessible, Interoperable, Reusable).

5.3 Digital Documentation of Tangible Cultural Heritage

The European Commission has highlighted a crucial paradigm shift driven by digitisation and new governance models (Brunet et al., 2022). Over time, the concept of ‘cultural heritage’ has been progressively broadened to include not only tangible and intangible assets, but also digital resources, in the dual sense of native digital and products and services derived from digitisation processes.

Cultural heritage digitalisation has been underway since the 1990s, but here is no overall data on the extent of this work by numerous institutions. The National Plan for the Digitisation of the Cultural Heritage 2022–2023 reports that the central institutes’ information systems contain over 37 million catalogue descriptions and 26 million images. It is impossible to give a precise estimate, but it is likely that significantly fewer objects have been digitised in 3D.

The reasons include, but are not limited to:

- Less technological maturity
- Less standardisation
- Higher production costs

---

[9] https://digital-strategy.ec.europa.eu/en/library/basic-principles-and-tips-3d-digitisation-cultural-heritage

- More recent standardisation of digital data
- Higher storage requirements

Although progress has narrowed many gaps, major differences still exist, particularly between the digitisation of immovable and movable assets and especially those in museum collections.

Technological advances have made 3D digitisation more extensive. However, the focus has shifted from the practical aspects of digital reference production to broader policies and strategies, including data management, process sustainability, communication and sharing, and the digital services that can be derived from them.

Classification of digitised cultural heritage is incomplete and approximate due to the diversity of objects and contexts. The Europeana Network Association Task Force on 3D Content (Europeana, 2020) has defined five categories of 3D content, based partly on the techniques used and partly on the intended use. Italy's PND distinguishes between movable and immovable works, as proposed in the UNESCO Conventions on the Hague discussing "cultural property" (UNESCO, 1954).

Some preliminary considerations on the concepts of complexity and quality, which are generally applicable to a wide range of situations and objects, are presented below. A classification of these concepts is also proposed, that synergistically (but not bi-univocally) considering the dimension of the object and the level of detail of the description to be obtained, suggesting the adoption of a multi-scale and multi-source approach. Finally, the most up- to-date declination of digital models is proposed, no longer understood merely as numerical replication but as a Digital Twin of the cultural heritage under analysis.

Some preliminary thoughts on complexity and quality are presented below. A classification of these concepts is proposed that synergistically (but not univocally) considers the dimension of the object and the level of detail considered. A multi-scale, multi-source approach is also suggested, and the digital twin is proposed as an evolved form of digital model.

5.3.1 The Concepts of "Quality" and "Complexity"

The "quality" of a digitisation project depends on the ability to handle different aspects of complexity; therefore, it is important to define the concepts of "complexity" and "quality" in this context.

Complexity

Factors of complexity can be identified:

- in the process
- in the object and context of the survey
- in the management of the data produced.

Reality-based models, which are at least the potential geometric support for a digital twin, transforms surveying from a one-off operation into a workflow that recursively produces, maintains, updates and enhances 3D spatial data.

The digitisation process goes beyond creating a digital copy. It addresses digital transformation, involving the collection, organisation and extraction of not only geometric information. Thus, being at the convergence of economic, technical and scientific resources, it constitutes an effective support for decision-making.

Cultural, historical, economic, and technological aspects of cultural heritage can be viewed as a "system" (Ripp & Rodwell, 2018), a concept applicable to other domains of knowledge.

Systems (Cilliers, 1998; Grieves & Vickers, 2017) can be distinguished into:

- simple, when they present evident cause-effect relationships between a few components, therefore being completely understandable and predictable.
- complicated, composed by many more components, linearly and straightforwardly connected.
- complexes, made by a multiplicity of interacting components, many-to-many connections, often producing surprises (generally unwelcome).

The layering of aspects that characterise a cultural property (history, artistic value, conservation of materials, current and past use, etc.) leads to the recognition of complexity in the process itself. It is also possible to highlight elements of complexity in the management of the results of the digitisation process (Martin, 2012), because of the multiplicity of investigations and data.

Current research topics concern how the now widely shared FAIR principles can be put into practice. Many projects are under development to define shared infrastructures, in Europe they include ARIADNE Research Infrastructure AISBL (ARIADNE RI), the European research infrastructure on Heritage Science (E-RIHS) and the Digital Research Infrastructure for the Arts and Humanities (DARIAH). Their main objective must be to overcome the fragmentation of digitisation experiences defining a real digital ecosystem, to enable the use of digital tools and methods of data analysis. In Italy, the National Plan for Cultural Heritage Digitization (PND) aims to define a strategic vision to promote and organise the digital transformation process up to 2026.

The open questions concern transforming a multidisciplinary approach into a deep interaction between studies with different competences. The practical obstacles include:

- the still unsatisfactory interoperability of data.
- medium and long-term data archiving strategies and sustainability.
- the methods of scientific validation, also due to the lack of reference standards.

Quality

Data quality assessment generally relates to compliance with standards and criteria, which the cultural heritage digitisation field lacks.

Any digitisation process involves sampling, and this inevitably leads to an approximation of geometric or other values to the analogue original, with an analogue/digital dualism becoming an integration (Levy, 1998). Furthermore, quality assessment can be subjective (Zhou et al., 2024) or objective (Javaheri et al., 2021), depending on the role of human observers. Most literature (Di Filippo et al., 2023), with a few exceptions (Zhang et al., 2022), refers to comparison with a reference model obtained separately.

5.3.2 Evaluation of the Digitisation Process

There are no standardised methods for producing digital documentation and most projects begin without prior agreement on procedures or results. Technological innovation and the variety of software and hardware favour a performance-based approach rather than a prescriptive one, as happened in the past in the sporadic technical specifications prepared (Monti et al., 2000). However, the approach used in classical topography and photogrammetry, where roles and competences are better defined, could also be applied to architecture and archaeology. The specifications, which translate the customer's requirements into technical language, are the operational reference for the contractor, and the inspector checks the processes and the end products. However, the drafting of specifications and final inspections are sacrificed due to limited resources in the heritage sector.

In terms of specifications, one solution might be to establish common guidelines for similar built heritage assests, as the Digital Library is doing for movable ones. (Istituto Centrale per la Digitalizzazione del Patrimonio Culturale, 2022).

5.3.3 Evaluation of the Digitisation Product (Reality-Based 3D Models)

To quantify quality, it is necessary to identify the geometric and semantic relevant aspects of a reality-based 3D model, in particular:

resolution, considered as the level of detail in both geometry and texture, which contains information on materials and conservation.

completeness, which refers to the complete coverage of all surfaces of the object and the integrity of thematic attributes in a specific domain.

The concept of accuracy comes from metrology and is applied to geometric aspects, considering that texture projection errors are almost negligible (for example, due to poor calibration between the image acquisition sensor and the one used for shape digitisation). The correct evaluation of this statistical parameter requires a set of error-free reference measurements, i.e. much more accurate than those to be evaluated. On the other hand, the term precision refers to the repeatability of results obtained using different methods of measuring.

In summary, in addition to the aspects mentioned above, it is essential to consider the suitability of 3D models for reuse, as intended by the FAIR principles. So, it is proposed to add to the FAIR principles the concept of "suitability", which plays a key role in facilitating data reuse. This addition will refer to the parameters that define which reuses are suitable for a given 3D model, in order to overcome the idea of the documentation process as a one-off. Encouraging data reuse increases sustainability, so the suitability parameters will facilitate reuse itself and the overall "FAIRification" process of reality-based 3D models. Suitability therefore suggests the application of objective methods of process assessment, while preserving flexibility in the evaluation of the product, for which specific characteristics must be rated but considering, each time, compatibility and performance aspects of 3D models with respect to the users, the goal, the framework of use. Supporting suitability assessment helps data producers, clients and all stakeholders to speed up the production of digital deliverables, promoting the sustainability of the documentation, preservation and valorisation of cultural heritage.

5.3.4 Multi-scale and Multi-sensors Approach

In the digital documentation of tangible cultural heritage, a multi-scale approach is crucial for capturing the diverse aspects of both large-scale urban environments and the fine details of individual artefacts or buildings. Traditional analogue designs, such as orthogonal projections, were always linked to a fixed scale. However, with the advent of digital tools, users can zoom in and out freely, breaking the rigid connection between graphic scale and the level of detail. Nevertheless, the need for maintaining consistency in the level of detail remains. Concepts like Level of Detail (LoD) and Level of Development (LOD), familiar from Building Information Modelling (BIM), are increasingly being applied to heritage documentation. Specifically, in the field of built heritage, frameworks such as Level of Geometry and Grade of Accuracy help ensure precision across different scales.

At the urban scale, large-scale cartography has shifted towards 3D city models, which depict the built environment and natural elements in detail. Geographic Information Systems (GIS) are often employed in these models to study the relationships between different urban features. Such systems are essential for understanding the broader spatial contexts in urban heritage studies, as well as in archaeology, where documentation typically starts with large-scale territorial analyses before moving into more detailed investigations of smaller sites or artefacts.

When digitizing individual artefacts or collections, the approach differs from that of buildings, particularly because georeferencing is not always necessary for movable objects. Institutions like museums, galleries, and libraries play a central role in this field. For example, the Smithsonian Museum has developed a comprehensive digitization program and metadata model, while the British Museum has recently committed to digitizing its entire collection within 5 years. These large-scale digitization efforts are not only about preservation but also have economic and cultural tourism benefits. The European Union's Europeana platform promotes access to digital cultural resources, with the ambition of digitizing millions of objects.

Photogrammetry and 3D scanning are the most commonly used techniques for digitizing artefacts, offering high-resolution, detailed representations. However, these processes require specialized equipment and expertise, especially when dealing with delicate or valuable objects. Handling, supports, and rotation systems must be carefully managed to ensure the accuracy of the final digital models.

For the documentation of historic buildings, Historic Building Information Modelling (HBIM) is gaining popularity. It typically integrates data from photogrammetry and 3D scanning to create comprehensive digital models of heritage structures. Georeferencing and accurate control networks play a fundamental role in ensuring the precision of these models, especially when aligning scans or incorporating data from multiple sources. Though HBIM is still evolving, it shows great potential in supporting the conservation and management of historical buildings. Alternative approaches focus on integrating building data into GIS systems, which allow spatial information to be managed and visualized, with greater flexibility for exploring detailed data.

At the urban scale, documentation and monitoring efforts address both natural and human-induced risks, which require a combination of aerial and ground-based technologies. UAVs (Unmanned Aerial Vehicles) equipped with RTK modules and SLAM (Simultaneous Localization and Mapping) technology are essential tools for surveying and documenting urban environments. These devices can provide both aerial and ground-level data, offering a comprehensive view of historic sites. For example, the historical centres of cities like L'Aquila and Firenze, a UNESCO World Heritage Site, have been extensively studied to monitor their transformations over time and to mitigate risks from natural disasters and human activities.

On a broader territorial scale, documentation must consider both natural landscapes and the transformations brought about by human activity. The European Landscape Convention defines landscapes as key elements within territories, shaped by the interactions between natural and human factors. Documenting these areas often requires a multi-sensor approach. UAVs equipped with LiDAR, thermal, and multi-spectral cameras are particularly useful for capturing data in large, complex, or high-risk areas, such as those prone to landslides, floods, or fires. Submerged or aquatic areas require specialized surveys, such as bathymetric mapping, often conducted using autonomous vessels that can simultaneously gather data above and below the water surface.

The digital documentation of cultural heritage demands the integration of multiple data sources and technologies. This multi-source and multi-sensor approach helps in understanding the structural behaviour, identifying damage, and evaluating the overall performance of heritage sites. Monitoring technologies, including satellites, drones, and ground-based sensors, are essential for creating a holistic view of these sites. By combining such tools with historical research, databases, and visual documentation, conservationists can ensure the long-term preservation and management of cultural heritage.

5.4 Georeferencing of Geometric and Thematic Data

Georeferencing is a fundamental aspect of this documentation process. Integrating and consolidating significant information and data of a territory is feasible if their geospatial coordinates are expressed within the same reference system.

The datums listed in the EPSG (European Petroleum Survey Group Geodetic Parameter Dataset), which collects the set of geodetic parameters that define the geographic reference systems and coordinates used to represent the Earth's surface on maps and in navigation systems, are commonly used when considering large study areas where relationships with the territorial context are critical.

The EPSG dataset, developed in 1986, has become a widely used standard for the management of geospatial data and geodesy. It contains a wide range of coordinate systems, geodetic datums, and other information related to map projection and coordinate transformation. The combinations of these elements are identified by numerical codes that uniquely identify the coordinate systems and geodetic parameters. This encoding type is extensively used within Geographic Information Systems (GIS). Within a single nation, such as Italy, maps may reference different geodetic datums and projections., because if the temporal evolution of the territory and the advancements in scientific knowledge (Istituto Geografico Militare, 2022). Currently using the ETRF2000 system as of epoch 2008.0 is mandatory for the public administration in Italy (D.M. November 10, 2011), as also indicated in the European INSPIRE directive.

Local reference systems may also be used, depending on the extent of the area and the purpose of the study. However, at least approximate referencing is always desirable to allow multi-scale measurements. In the case of large complexes, typically cartographic aspects must be considered, such as the choice of the projection surface to be adopted and its characteristics, in order to ensure the best congruence between field measurements and their graphic restitution (Bonora et al., 2021).

In the case of details of a building or movable objects, referencing has a different meaning, and it is more helpful to specify their location in a larger context than to define their absolute position. Proto-spatial referencing systems such as the Raumbuch (Bonora et al., 2023), which consists of the progressive breakdown and coding of the building into increasingly simple portions, can be useful for this. An essential feature of the Raumbuch is a progressive and unambiguous identification of the spaces and surfaces of a building. The identification codes, which form the master strings, allow the link to the thematic data relating to the different scales in which the buildings are articulated. In this way is possible to capillary describe the building and constitute a structured container capable of collecting and returning the various cognitive contributions, facilitating their progressive implementation.

Also, thematic information can be referenced, such as materials, state of preservation, presence of sensors/installations, etc. This can be realised with many solutions including point clouds annotated with uncontrolled textual descriptions or 3D enriched models in which thematic information is organised with controlled and standardised data structures.

Machine and deep learning can support the extraction of semantic information from geometric information (Matrone et al., 2020), but this field requires further investigation because of the amount of data produced by photogrammetric and laser scanning surveys and the high number of semantic classes to be identified.

5.5 Metadata and Paradata

In the case of built heritage, conservation and valorisation are inextricably linked to fruition. So the issue is not only generating a 3D model for visualisation, but also of developing tools that simultaneously address the knowledge, conservation and management. We are at the crossroads of a digital and ecological transition (Münster et al., 2021), where the pressures of climate change and natural hazards need to be responded to with a new cognitive approach that innovates digital documentation processes (Bosone et al., 2021).

The Digital Twin paradigm is emerging (Jouan & Hallot, 2020) as a multiscalar information model continuously enriched in time and space. This includes all types of information, from geometric and archival information to real-time data collected by monitoring sensor networks. BIM-GIS domains are examples of the integration of heterogeneous data into a geometric model of buildings and environment.

Within the workflow for the digitisation of the built heritage attention has been mainly focused on the model and its information content, neglecting the part related to the documentation of the survey process.

Surveying a heritage building is a complex and expensive task and, in the past, their documentation has been episodic.

Digital documentation of the built heritage is not an automated process but still requires an error-prone interpretation of acquired data, so monitoring of the workflow is necessary to validate, integrate and possibly correct the information as soon as possible. A scientific approach requires that the methods and paths adopted are verifiable and repeatable.

There are no standards to check is the documentation of a building is complete. At the national level, the most detailed checklist (focussed on structural analysis) is the "path of knowledge" contained in the "Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale".[10]

Often the survey of large buildings takes a long time, so it is advisable to systematically archive data, metadata and paradata related to (i) previous information, (ii) new acquisitions and (iii) data processing.

A BIM model of a new building, without information on masonry stratigraphies, construction characteristics, LODs, etc., is just a silent geometry. At the same time, the metadata and paradata are the information that certify the reliability of a digital

---

[10] https://cultura.gov.it/comunicato/linee-guida-per-la-valutazione-e-riduzione-del-rischio-sismico-del-patrimonio-culturale-allineate-alle-nuove-norme-tecniche-per-le-costruzioni-d-m-14-gennaio-2008

survey of an existing building. HBIM systems link building information to geometries, but they do not link information about the survey. Storing the survey data would help to update the geometry.

To date, this information is not consistently recorded by surveyors, except from annotations on sketches and collection of raw data according to unspecified criteria, usually in proprietary formats. Data collected in different workflows (topography, laser scanner, photogrammetry, etc.) are usually recorded separately, in non-standard formats, so survey data are often dispersed.

Some commercial proposals go in the direction of integrating different information, but these are strictly hardware and software dependent applications and not fully usable for complex projects. In principle, metadata cannot be efficiently found and stored.

The documentation of the workflow and metadata related with processing and production of the final outputs is even less common and standardised. Especially when the processing is not only a plot or a 3D model, as in the case of HBIM, it is essential to preserve the raw data on which the information content is based for possible corrections or additions.

Other issues are related with the use of machine and deep learning for data analysis and processing (Pellis et al., 2022) because the final results may depend on unsupervised processes. Nowadays, workflows are used by operators without specific training, making it even more important to retain the procedures and metadata to validate the results.

There is no universally accepted metadata system (Pamart & de Luca, 2020). It should be noted that many diffused metadata profiles (including Simple Dubin Core Metadata structure) do not include 3D file descriptors.

5.6 Open Challenges and Future Trends

Digitisation projects often face problems sharing data and results due to unclear Digital Rights Management laws. Despite the increasing diffusion of the FAIR principles, in Italy, reference is made to copyright law, whose regulatory framework is still referable to Law 633 of 22 April 1941, while in the digital context, the EU Directive 790/2019 and Legislative Decree 177/2021 have recently intervened. The creator of the digital model is considered the sole owner of all rights and economic exploitation. This is in contrast to the multiple actors in multidisciplinary processes, who are often only associated for the duration of the project, without paying attention to the maintenance of the result.

Many projects are frustrated by underestimating copyright and data protection issues, underestimating the cost of hosting services, publication rights or penalties, or making verbal agreements without written specifications. Bureaucracy and approval processes can also affect the timing of a project by hindering planning. Ineffective communication between team members leads to misunderstandings and delays. Uncontrolled changes to the project scope can lead to scope creep, affecting schedules, budgets and resources.

Budgeting for digitisation projects is challenging. Each project must also consider contributions to the expansion of the infrastructure and its needs, so that long-term valorisation results must be highlighted to potential funders.

Budgeting for digitisation projects is challenging. Each project must consider contributions to infrastructure and its specific needs. Long-term benefits must be emphasised to potential funders.

Future trends can be traced back to:

- Data acquisition methods, both in the sense of multi-sensor integration and the use of faster mobile sensors.
- The use of AI for the integration of semantic content into geometry.
- The definition (from a theoretical and regulatory as well as practical and operational point of view) how to share and use, especially online.
- The definition of de facto or regulatory standards.
- The creation of digital contents, i.e. the process of freeing pieces of a collection from the limits of their physical materiality and enabling them to exist in a virtual space.
- To open access aspects, making digitised cultural resources available for everyone to use without restriction.

References

Alessandri, L., Baiocchi, V., Del Pizzo, S., Di Ciaccio, F., Onori, M., Rolfo, M. F., & Troisi, S. (2019). Three-dimensional survey of Guattari cave with traditional and mobile phone cameras. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 42*(2/W11), 37–41.

Alessandri, L., Baiocchi, V., Del Pizzo, S., Di Ciaccio, F., Onori, M., Rolfo, M. F., & Troisi, S. (2020). The fusion of external and internal 3D photogrammetric models as a tool to investigate the ancient human/cave interaction: The La sassa case study. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences-ISPRS Archives, 43*(B2), 1443–1450.

Barrado-Timón, D. A., & Hidalgo-Giralt, C. (2019). The historic city, its transmission and perception via augmented reality and virtual reality and the use of the past as a resource for the present: a new era for urban cultural heritage and tourism?. *Sustainability, 11*(10), 2835.

Bitelli, G., Balletti, C., Brumana, R., Barazzetti, L., D'Urso, M. G., Rinaudo, F., & Tucci, G. (2019). The GAMHER research project for metric documentation of cultural heritage: Current developments. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 42*(2), 239–246. https://doi.org/10.5194/isprs-Archives-XLII-2-W11-239-2019

Bonazza, A., & Sardella, A. (2023). Climate change and cultural heritage: Methods and approaches for damage and risk assessment addressed to a practical application. *Heritage, 6*(4), 3578–3589.

Bonazza, A., Messina, P., Sabbioni, C., Grossi, C. M., & Brimblecombe, P. (2009). Mapping the impact of climate change on surface recession of carbonate buildings in Europe. *Science of the Total Environment*, *407*(6), 2039–2050.

Bonora, V., Maseroli, R., Mugnai, F., & Tucci, G. (2021). GNNS control network supporting large historical building architectural survey. *The International Archives of the Photogrammetry,* *Remote Sensing and Spatial Information Sciences, XLVI-M-1-2021*, 87–91. https://doi.org/10.5194/isprs-archives-XLVI-M-1-2021-87-2021

Bonora, V., Meucci, A., Conti, A., Fiorini, L., & Tucci, G. (2023). Knowledge representation of built heritage mapping an ad hoc data model in OGC standards: The case study of Pitti Palace in Florence, Italy. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVIII-M-2-2023*, 281–288. https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-281-2023

Bosone, M., Nocca, F., & Fusco Girard, L. (2021). The circular city implementation: Cultural heritage and digital technology. In M. Rauterberg (Ed.), *Culture and computing. Interactive cultural heritage and arts. HCII 2021* (Lecture Notes in Computer Science) (Vol. 12794). Springer. https://doi.org/10.1007/978-3-030-77411-0_4

Brunet, P., De Luca, L., Hyvönen, E., et al. (2022). *Report on a European collaborative cloud for cultural heritage: Ex—ante impact assessment*. https://data.europa.eu/doi/10.2777/64014

Cilliers, P. (1998). *Complexity & Postmodernism: Understanding Complex Systems*. New York: Routledge.

Del Pizzo, S., Di Ciaccio, F., Gaglione, S., Galassi, F. M., Papa, V., Varotto, E., & Troisi, S. (2024). The 3D reconstruction of the Sansevero Chapel anatomical machines: A geomatics challenge. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 48*, 173–179.

di Filippo, A., Gujski, L.M., Cappetti, N., Villecco, F. (2023). Traceability of uncertainty in building information modelling processes for existing structures. In Gerbino, S., Lanzotti, A., Martorelli, M., Mirálbes Buil, R., Rizzi, C., Roucoules, L. (Eds.), *Advances on Mechanics, Design Engineering and Manufacturing IV. JCM 2022. Lecture Notes in Mechanical Engineering*. Springer, Cham. https://doi.org/10.1007/978-3-031-15928-2_78

Directorate-General for Communications Networks, Content and Technology (European Commission). (2022). *Study on quality in 3D digitisation of tangible cultural heritage: Mapping parameters, formats, standards, benchmarks, methodologies, and guidelines: Executive summary*. Publications Office of the European Union. ISBN 978-92-76-51316-2. https://data.europa.eu/doi/10.2759/581678

Directorate-General for Education, Youth, Sport and Culture (European Commission). (2022). *Strengthening Cultural Heritage Resilience for Climate Change: Where the European Green Deal Meets Cultural Heritage*. Publications Office of the European Union. Luxembourg. ISBN 978-92-76-48205-5

Europeana. (2020). https://pro.europeana.eu/project/3d-content-in-europeana

Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In J. Kahlen, S. Flumerfelt, & A. Alves (Eds.), *Transdisciplinary perspectives on complex systems*. Springer. https://doi.org/10.1007/978-3-319-38756-7_4

Hervás Soriano, F., & Mulatero, F. (2010). Knowledge policy in the EU: From the Lisbon strategy to Europe 2020. *Journal of the Knowledge Economy, 1*, 289–302. https://doi.org/10.1007/s13132-010-0020-9

Istituto Centrale per la Digitalizzazione del Patrimonio Culturale—Digtal Library Piano Nazionale Di Digitalizzazione Del Patrimonio Culturale 2022–2023. Versione 1.1. Available online: https://digitallibrary.cultura.gov.it/wpcontent/uploads/2023/10/PND_V1_1_2023-1.pdf

Istituto Geografico Militare, Direzione Geodetica. (2022). *Nota per il corretto utilizzo dei sistemi geodetici di riferimento all'interno dei software GIS*. https://www.igmi.org/++theme++igm/pdf/nuova_nota_EPSG.pdf

Javaheri, A., Brites, C., Pereira, F., & Ascenso L. (2021). Point Cloud Rendering After Coding: Impacts on Subjective and Objective Quality. In *IEEE Transactions on Multimedia, 23*, 4049-4064. https://doi.org/10.1109/TMM.2020.3037481

Jouan, P., & Hallot, P. (2020). Digital twin: Research framework to support preventive conservation policies. *The ISPRS International Journal of Geo-Information, 9*, 228. https://doi.org/10.3390/ijgi9040228

Lévy, P. (1998). *Becoming virtual: Reality in the digital age*. Boston: Da Capo Press, Inc.

Khodeir, L. M., Aly, D., & Tarek, S. (2016). Integrating HBIM (Heritage Building Information Modeling) tools in the application of sustainable retrofitting of heritage buildings in Egypt. *Procedia Environmental Sciences, 34*, 258–270. https://doi.org/10.1016/j.proenv.2016.04.024

Kioussi, A., Karoglou, M., Labropoulos, K., Bakolas, A., & Moropoulou, A. (2013). Integrated documentation protocols enabling decision making in cultural heritage protection. *Journal of Cultural Heritage, 14*(3), e141–e146. https://doi.org/10.1016/j.culher.2013.01.007

Martin, H. (2012). How much information is there in the 'information society'? *Significance, 9*(4), 8–12.

Martínez-Espejo Zaragoza, I., Caroti, G., Piemonte, A., Riedel, B., Tengen, D., & Niemeier, W. (2017). Structure from motion (SfM) processing of UAV images and combination with terrestrial laser scanning, applied for a 3D-documentation in a hazardous situation. *Geomatics, Natural Hazards and Risk, 8*(2), 1492–1504.

Matrone, F., Grilli, E., Martini, M., Paolanti, M., Pierdicca, R., & Remondino, F. (2020). Comparing Machine and Deep Learning Methods for Large 3D Heritage Semantic Segmentation. *ISPRS International Journal of Geo-Information, 9*, 535

Monti, C., Guerra, F., Balletti C., & Galeazzo G. (2000). *Capitolato speciale d'appalto per l'esecuzione di un rilievo in forma numerica alla scala 1:50 Venezia: IUAV*.

Münster, S., Utescher, R., et al. (2021). Digital topics on cultural heritage investigated: How can data-driven and data-guided methods support to identify current topics and trends in digital heritage? *Built Heritage, 5*, 25. https://doi.org/10.1186/s43238-021-00045-7

Pamart, A., & de Luca, L. (2020). A metadata enriched system for the documentation of multimodal digital imaging surveys. *Studies in Digital Heritage, 6*(1), 1–24.

Pellis, E., Murtiyoso, A., Masiero, et al. (2022). An image-based deep learning workflow for 3D heritage point cloud semantic segmentation. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVI-2/W1-2022*, 429–434. https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-429-2022

Ramalhinho, A. R., & Macedo, M. F. (2019). Cultural heritage risk analysis models: An overview. *International Journal of Conservation Science, 10*(1), 39–58.

Randazzo, L., Collina, M., Ricca, M., Barbieri, L., Bruno, F., Arcudi, A., & La Russa, M. F. (2020). Damage indices and photogrammetry for decay assessment of stone-built cultural heritage: The case study of the San Domenico Church main entrance portal (South Calabria, Italy). *Sustainability, 12*, 5198. https://doi.org/10.3390/su12125198

Ripp, M., & Rodwell, D. (2018). Governance in UNESCO world heritage sites: Reframing the role of management plans as a tool to improve community engagement. In S. Makuvaza (Ed.), *Aspects of management planning for cultural world heritage sites*. Springer. https://doi.org/10.1007/978-3-319-69856-4_18

Rovelli, C. (2018). Meaning and intentionality = Information + evolution. In A. Aguirre, B. Foster, & Z. Merali (Eds.), *Wandering towards a goal: How can mindless mathematical laws give rise to aims and intention?* (pp. 17–27). Springer. ISBN 978-3-319-75726-1.

Sotirova-Valkova, K. (2024). A pilot conceptualisation of the data space ecosystems for cultural heritage. *Mathematics Education, 53*, 92–98. https://doi.org/10.55630/mem.2024.53.092-098

UNESCO. (1954). *Convention for the Protection of Cultural Property in the Event of Armed Conflict* (The Hague Convention of 1954). Paris: United Nations Educational, Scientific and Cultural Organization, 1954.

Wetzel, S., Mäs, S., Bernard, L., Vorobevskii, I., & Kronenberg, R. (2024). Spatial data infrastructure components to provide regional climate information services. *Climate Services, 34*, 100473. https://doi.org/10.1016/j.cliser.2024.100473

Wijesuriya, G., Thompson, J., & Young, C. 2013. *Managing cultural world heritage* (152p). UNESCO. ISBN 978-92-3-001223-6. Retrieved May 24, 2024, from https://whc.unesco.org/en/managing-cultural-world-heritage/

Wilson, L., Rawlinson, A., Frost, A., & Hepher, J. (2018). 3D digital documentation for disaster management in historic buildings: Applications following fire damage at the Mackintosh building, The Glasgow School of Art. *Journal of Cultural Heritage, 31*, 24–32. https://doi.org/10.1016/j.culher.2017.11.012

Zhang, Z., Sun, W., Min, X., Zhou, Q., He, J., Wang, Q., & Zhai, G. (2022). *MM-PCQA: Multi-modal learning for no-reference point cloud quality assessment*. arXiv preprint arXiv:2209.00244, https://doi.org/10.48550/arXiv.2209.00244

Zhou, C., Jiang, Y., Liu, H., Cao, J., & Gu, K. (2024). Subjective and objective quality evaluation-for industrial images. *Displays, 85*, 102858.

Chapter 6
Towards a Protocol for Tangible Cultural Heritage Digital Twin

F. Ottoni, M. Betti, N. Bruno, R. Ceravolo, M. A. Chiorino, S. Coccimiglio, G. Miraglia, S. Monchetti, M. Parente, and E. Pellis

Abstract Cultural heritage includes a large variety of historical masonry constructions. The identification of their structural behaviour is challenging due to the complexities of the masonry constructions and the evolution of multiple phases of construction. Advanced tools for geometric surveying and structural analysis can facilitate the preservation of the cultural heritage but transferring data between these tools remains an issue. In this chapter, we propose a critical discussion on the integration between informative models and digital twins by underling open issues e future perspectives.

Keywords Digital twin · H-BIM open issues · cultural heritage modelling · structural health monitoring · historical masonry structures

---

F. Ottoni · N. Bruno · M. Parente
Department of Engineering and Architecture, University of Parma, Parma, Italy
e-mail: federica.ottoni@unipr.it; nazarena.bruno@unipr.it; maria.parente1@unipr.it

M. Betti · S. Monchetti (✉) · E. Pellis
Department of Civil and Environmental Engineering, University of Florence, Florence, Italy
e-mail: michele.betti@unifi.it; silvia.monchetti@unifi.it; eugenio.pellis@unifi.it

R. Ceravolo · M. A. Chiorino · S. Coccimiglio · G. Miraglia
Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Turin, Italy
e-mail: rosario.ceravolo@polito.it; stefania.coccimiglio@polito.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_6

6.1 Introduction

Historic buildings are the result of intricate craftsmanship and varied practices, evolving through architectural alterations, multiple phases of construction, and the natural wear of materials over time. These transformations are often difficult to measure, and the behaviour of masonry presents significant complexity. Consequently, modern numerical models often struggle to capture the nuanced behaviour of these structures, especially those with layered historical developments. Despite this, large-scale numerical models of prominent historical buildings continue to be widely used. However, these models frequently yield results that do not accurately reflect the actual structural dynamics of these monuments. In many instances, calculation methods are applied directly to a detailed 3D representation of the building—often derived from highly accurate surveys—without a prior critical evaluation. It is widely recognized that increasingly accurate methodologies and automated tools are now available in the fields of geometric surveying and structural analysis, serving as essential instruments for understanding and preserving cultural heritage. Both these tools and technologies are integral to the overarching process of knowledge that underpins any conservation project for cultural heritage. However, despite the high levels of accuracy and automation achieved by both technologies and software, transferring data between them remains a challenge, and determining the most reliable methods for translating and exchanging information without data loss continues to be an unresolved issue. The research, in both cases, focuses on improving the accuracy of these important tools to create virtual replicas, the Digital Twins (DT), that closely resemble historic buildings and can simulate their actual structural behaviour with quantitative precision and detail.

Surprisingly, what is often needed is the reverse process.

The real challenge lies in understanding how to reduce the level of accuracy and the amount of information gathered about cultural heritage to enable more reliable analysis and a better, almost qualitative, understanding of its actual behaviour. In fact, while it's evident that precise instruments and methods, which provide increasingly detailed geometric data on historic buildings and allow for complex structural calculations, are essential for enhancing the restoration design process, the growing volume of data requires a careful and critical simplification. This simplification should be informed by other disciplines, such as history, structural intuition, and a blend of empirical knowledge, to develop reliable conceptual models of the buildings, starting from their virtual representations. However, the specificities of historical heritage present challenges in terms of surveying and modeling, primarily due to the need to strike a balance between geometric accuracy, resource input (time and cost), and the manageability of outcomes (file size). Indeed, "research on the so-called 'Historic BIM' should avoid being confined to merely representing historic architecture. Instead, it should leverage the capabilities of electronically interoperable tools to streamline conservation phases" (Della Torre, 2020).

6.2 State of Art in H-BIM and DT: Some Open Issues

Considering the unique nature of historical heritage, it is not feasible to develop a one-size-fits-all system applicable to every case study. However, establishing certain guidelines could assist in structuring operational and conservation-focused information models. To effectively achieve this, it is crucial to address the ongoing challenge of data management, which involves identifying the most suitable procedures for critically selecting, organizing, and archiving information to ensure it becomes an easily accessible resource for the preservation process.

Recent research on the relationship between geomatics and restoration has focused on the continual advancement of surveying and modelling technologies (Brumana et al., 2018; Banfi et al., 2017; Castagnetti et al., 2017; Tommasi et al., 2016; Bonazza and Sardella, 2023). However, to further enhance the effectiveness of the H-BIM methodology as a tool to support conservation activities, it is important to also focus on the information framework that complements the 3D model (Bruno & Roncella, 2019). Specifically, identifying the most valuable data for conservation purposes and determining how best to organize it to facilitate inspection and maintenance planning would be particularly useful. There are many challenging issues that must be addressed in defining a model, starting from information systems (BIM), which, when applied to historic buildings, must contend with an underlying irregularity that stems from semantic issues.

Semantic Issues The international standard IFC (Industry Foundation Classes), recognized as ISO 16739-1, is an open format for data exchange designed to facilitate interoperability between different software systems, such as BIM and structural analysis tools. However, these standards, which are primarily intended for new construction projects, currently lack specific classifications for elements typical of historic buildings (e.g., arches, vaults, and wooden trusses), making a comprehensive definition of all construction elements in built heritage unattainable (Adami et al., 2023; Spanò et al., 2023; Quattrini et al., 2023; Previtali et al., 2020). Additionally, assigning semantic meaning to objects that represent the conservation status of building elements, such as surface decay or structural cracks, remains a challenge. Therefore, one unresolved issue in this field (maybe the main one) is the development of a common vocabulary that, through the creation of specific ontologies, could provide a conceptual framework not only for physical elements but also for the properties, relationships, and actions involved in the conservation process (Acierno et al., 2017). The CIDOC-CRM ontology is a key example, but it requires further development to meet these needs.

Geometric Accuracy or Level of Detail

Unexpectedly, geometric accuracy in a model does not always guarantee the most reliable interpretation of reality, especially in the context of historic buildings. Unlike modern structures, historic buildings are irregular, making parametric modelling difficult and computationally expensive. Reproducing these irregularities with high metric accuracy can be time-consuming, and often, metric precision must be deprioritized to better support conservation activities. Some studies (Ottoni et al., 2017; Bruno, 2017; Brumana et al., 2019; Monchetti et al., 2023) emphasize that the level of detail should be determined by the intended purpose, and geometric precision should align with specific goals rather than always aiming for the highest accuracy. A conceptual model is often more effective for providing access to the necessary information for preservation efforts. The inherent irregularity of historic buildings often necessitates a Mixed Modelling (MM) approach, which combines 3D modelling software for precise geometric reconstruction with BIM authoring software for enhanced information management. The level of geometric detail and accuracy in a model should align with its specific purpose. Federated models, which consist of a geometrically simplified version and a more schematic repository of non-geometric data, are particularly effective for historic structures: the first model captures the full complexity of geometry derived from point clouds, while the second model focuses on detailed information linked to specific geometric elements. Incorporating false colour maps can enhance modelling by representing geometric accuracy. Therefore, although digital surrogates are metrically accurate, they may not adequately interpret the building, unlike simplified interpretative models that provide meaningful insights based on the creator's process. These models serve, instead, as spatially referenced data archives, connecting documents to specific building elements and enhancing the understanding of the building's history. However, a challenge remains regarding the appropriate level of metric accuracy and geometric detail needed for interoperability with structural analysis models. Excessive detail complicates model management and can lead to errors during import, necessitating manual corrections (Barazzetti et al., 2015). In some cases, full morphological complexity is maintained for export, while in others, simplification is required for compatibility with structural analysis software (Oreni et al., 2014; Brumana et al., 2017). It's fundamental to stress that geometric simplification goes beyond merely accelerating the modelling process and reducing complexity; it requires a critical interpretation of the building to justify specific simplifications that enhance the representation of the structure. This challenging process is essential for transforming vast amounts of data into a model that accurately reflects the original information. By incorporating insights gained from understanding the building, critical simplification enriches the model and facilitates the complex task of structural analysis.

Materials and Mechanical Characteristics

BIM entities can have materials assigned through specialized tools in commercial software. While predefined materials are common, they often do not suit historical buildings, prompting users to create new materials (Oreni et al., 2013) or include material information as textual data in custom properties (Celli & Ottoni, 2023; Monchetti et al., 2023). This information can be organized within a specific ontology, allowing details like masonry texture to replace the need to model each individual stone or brick unit (Brumana et al., 2018). Additionally, managing stratigraphy poses a challenge; users can define various layers of construction elements when using a parametric object-oriented modeling strategy (Banfi et al., 2022), facilitating the integration of thermal properties for research on building energy performance (Trani et al., 2021; Thravalou et al., 2023). Mechanical properties of structural elements can be included as attributes in BIM software, with predefined parameters for entities like walls and slabs. Custom properties enable the inclusion of essential mechanical characteristics for structural assessment (Croce et al., 2022). In Archicad, certain values are calculated using mathematical expressions (Moyano et al., 2022; Bruno & Fatiguso, 2018). For wooden structures, properties can be assigned based on visual inspections per the Italian UNI 11119:2004 standard, identifying defects in timber (Celli & Ottoni, 2023; Santos et al., 2022). Research is focused on incorporating properties for the Masonry Quality Index (MQI), which links masonry construction characteristics to structural properties. This classification uses Visual Programming Language for automatic calculation of MQI categories, assigning specific colors to masonry elements based on their category (Calvano et al., 2022). It is important to emphasize that both the geometry and mechanical properties of materials can be defined using the IFC property scheme and later exported. However, a limitation arises because FEM software (such as Abaqus or Ansys) does not support the open IFC format, resulting in the import of only geometry while losing the informational components of the BIM during data exchange. To mitigate information loss, potential improvements include using precompiled tables to translate BIM model properties into formats compatible with the structural model.

Damage: Cracks and Deformation In BIM environment, methodologies for crack mapping are tailored to the model's objectives. One method involves modelling cracks as Superimposed Customized Objects (SOs), with studies generally favouring geometrically accurate representations of damage (De Falco et al., 2024; Chiabrando et al., 2017). In some cases, a simplified model is preferred, supplemented by a detailed information framework. Cracks can also be created in 3D modelling software like Rhinoceros and then imported into BIM authoring software with custom classifications (Spanò et al., 2023). However, correlating cracks with their underlying structures, such as walls or vaults, presents challenges. Edificius software offers an interesting solution by automatically linking crack objects to symbolic representations in plan view, including properties like crack type, width, and potential causes, which align closely with structural restoration needs (Lanzara et al., 2021). Another approach simplifies crack representation using markers attached to walls, providing properties for damage interpretation and risk assessment for intervention planning (Barontini et al., 2022; Mora et al., 2021). Subtracting a Solid (SS) from the affected structural element is a more time-consuming method that allows for variable crack widths (Castellazzi et al., 2023). Additionally, correlating cracks with established collapse mechanisms through associated data sheets is a potential avenue for development (Quattrini et al., 2017). Structural damage is not limited to cracks; deformations are often identified through instrumental surveys. Detailed 2D drawings represent these deformations, sometimes using symbolic notations for clarity (such as out-of-plumb walls, deflections in beams, vaults, or pavings) (Barontini et al., 2022). The modeling of structural deformations in BIM is a topic of debate; while some research aims for high metric accuracy by replicating irregularities in historic buildings, others prefer idealized representations to enhance interoperability and manageability of the information model. In rectified modelling, precise assessments of deformations are made by comparing the ideal BIM model to point cloud data. This distinction emphasizes the roles of point clouds, which accurately reflect reality, and HBIM models, which, although simplified in geometry, contain valuable information for interpreting ongoing phenomena. For example, interpretative modelling allows for differentiation (and provides various representations) between deformations that occurred during the construction phase—which are not necessarily indicative of ongoing failure—and those closely linked to stability issues within the building, thus holding greater significance for planned conservation (Lo Turco et al., 2017). In simplified models, properties like beam deflections or out-of-plumb walls are recorded within rectified geometry, enabling thematic queries and the inclusion of detailed 2D drawings. Interoperability between BIM and finite element models is currently limited by IT and semantic challenges within software and exchange formats.

Diagnostics As far as investigation results, they are more readily accessible when they are spatially referenced within HBIM models and directly linked to the building element on which the test was conducted. Two main approaches can be identified: test results can either be incorporated as properties of the elements—which prevents precise localization since the results apply to the entire object—or represented through superimposed objects that symbolically correspond to the diagnostic investigation. However, the latter option complicates the semantic connection between the investigation and the construction element. In this second scenario, these objects can be linked to a set of customized properties, including test type, execution date, instrumentation used, summarized quantitative results, brief interpretations, and links to images and reports. The choice of the most appropriate method depends on the objective of the model, but above all on the type of test: some tests require precise localization (such as endoscopies, flat jacks, penetrometric tests, hygrometric ones, some sonic tests, etc.); others involve larger surfaces (thermography, investigations with radar or metal detectors, etc.). Additionally, the outputs differ significantly: quantitative data can easily be integrated into the properties of the objects and correlated with other information, such as mechanical characteristics; conversely, raster images (like thermography) need accompanying qualitative annotations for proper interpretation. A mixed approach is feasible (Mandelli et al., 2017): utilizing a developed platform, the representation method varies based on the test type: specific information is incorporated alongside symbolic objects, while investigations covering larger areas are mapped as an additional layer on the surface. Furthermore, thermography images and Ground Penetrating Radar (GPR) results for extensive surfaces can be directly projected onto wall objects (86), forming a new custom material (CM) whose properties align with the descriptive data of the test. This visualization facilitates immediate correlation between thermographic investigations and surface degradation within the three-dimensional model.

Lastly, the ontology developed in previous studies (Fiorani & Acierno, 2017) enables the conceptualization of diagnostic activities by defining the "Investigation Process" domain. Customized entities and properties are established to relate the tests to the architectural surfaces being investigated, emphasizing conservation efforts.

Some Notes: From HBIM to DT In simple terms, there appear to be two main approaches to translating reality into reliable models. The first approach involves refining the outcomes of even the most sophisticated numerical analyses by observing the actual behaviour of structures over time through both static and, more importantly, dynamic monitoring. This method is reminiscent of the techniques employed by ancient master builders, whose primary tools were experience and direct observation of past damage and collapse mechanisms. When opting to retain all available information for precise 3D numerical models, the geometry must be adjusted, and irregularities reconstructed to ensure reliable analysis results, especially regarding stress. The second approach emphasizes simplifying the redundant information from a highly accurate 3D model from the outset, enabling better control over the final analysis results. However, the simplification process itself is complex; it requires a clear understanding of the most likely collapse mechanisms, which can vary between different structures and often follow a typology-based approach. Furthermore, it demands the ability to predict expected outcomes, at least qualitatively. This level of understanding is only achievable through deep empirical knowledge, which remains the most fundamental and effective means of understanding and preserving cultural heritage.

6.3 Digital Twins, Prediction Capabilities, and Structural Health Assessment of Cultural Heritage

The use of DT in structural engineering has become increasingly widespread in recent years, providing a comprehensive framework to emulate and understand the behaviour of complex systems, including historical and monumental buildings. A key factor in any model, whether physical or mathematical, is its ability to accurately describe the essential features of the system it represents. This requires a methodical approach, involving multiple phases of model development, beginning with the analysis of available data, followed by synthesis to filter out unnecessary information, and culminating in the creation of the model. Physical models, while not suitable for representing structural systems when the scale becomes too small, are highly effective in simulating extremely complex behaviours, especially when replicated on a scale as close to the original as possible. In contrast, numerical models, such as Finite Element (FE) models, are well-suited for solving problems where theory aligns well with real-world observation, as in the case of linear elasticity, within the limits of instrumental or computational approximations. The relevance of physical models becomes particularly evident when they corroborate numerical models with experimental data. Numerical models, therefore, play a crucial role in supporting these tests, incorporating data gathered from archival research and geometric surveys. Regarding experimental data, they play a fundamental role in enriching the model, enabling the virtual representation to mirror real-world conditions more accurately. Among the techniques for collecting experimental data, vibration-based methods are especially important, as they allow the dynamic characterization of structures. Such measurements provide valuable insights into the global behaviour (Ceravolo et al., 2016; Ierimonti et al., 2023; Monchetti et al., 2024a, 2024b) of a structure at reduced costs and with minimal invasiveness (ICOMOS, 2003), a critical factor for historical structures, where preserving material integrity is essential (Ceravolo et al., 2019; Lorenzoni et al., 2016). Furthermore, as both the structural system and the surrounding environment are constantly evolving, models must be designed with the ability to update and incorporate new information from monitoring systems. Continuous or periodic monitoring can detect changes in system properties, such as those caused by environmental factors like temperature fluctuations and differentiate between physiological (normal) and pathological (abnormal) changes in behavior (Deraemaeker et al., 2008; Ubertini et al., 2017; Zini et al., 2024; Marafini et al., 2023). When such pathological behaviors occur, they should be reflected in the models by updating the constitutive laws of materials, or even geometric and topological properties. Through the process of Model Updating (MU) (Mottershead & Friswell, 1993; Ierimonti et al., 2023; Pepi et al., 2020; Monchetti et al., 2024a, 2024b), the predictive capabilities of these numerical models can be enhanced, particularly by aligning them with the experimental results obtained from vibration measurements. The goal is to develop a continuously updated model with predictive capabilities. However, simply updating a model does not automatically grant predictive abilities. These capabilities must be demonstrated through physical interpretations and experiments, at which point the updated model can be considered verified. A predictive numerical model can then be employed for high-level Structural Health Monitoring (SHM), including prognosis and estimation of the residual life of a structure. Within a civil SHM framework, this twinning perspective can be enabled by the assimilation of data through data-driven structural health diagnostics, possibly accommodating the quantification and propagation of relevant uncertainties, such as measurement noise, modelling assumptions, and environmental and operational variabilities. The resulting updated digital state should then allow for the prediction of the physical system evolution.

Considering the above, the concept of DT in structural engineering should embody a model that is simultaneously probabilistic, so accounting for the inherent uncertainties that define the nature of structural systems, capable of rapid updates to track real-world changes in real time or even anticipate them, and, lastly, should be a multiphysics model characterized by extremely high fidelity. Developing a digital model with the ability to precisely capture real-world variations requires the collection of a wide range of data types. Their integration and fusion enable a comprehensive view of the environment in which the structure is situated. In fact, it is crucial to recognize that each structure is embedded in a surrounding system, directly influenced by environmental conditions such as temperature, humidity, and precipitation, and indirectly by changes in the soil, which can alter its overall behaviour. The overall aim is to integrate data from various sources, including experimental and environmental monitoring, to create an evolving model that not only reflects current conditions but also predicts future behaviours (Fig. 6.1). The continuous updating of these models based on real-time data is what gives DT their advanced predictive capabilities. Among the data that can be used to enrich the model to make it a predictive DT, there are the data that directly characterize the structure (frequencies, cracks, temperature, displacement, rotations) (Ceravolo et al., 2017) and then the ground on which it stands (humidity, water table height) and the surrounding environment (temperature, rain, etc.) (Ceravolo et al., 2021). This data can be acquired on-site via on-site sensors or via remote technologies. The latter include data acquired through satellite remote sensing, which enables the collection of information on various structures or regions without the need for installing monitoring systems on-site, an approach particularly beneficial for historic buildings. Satellite data are highly beneficial for measuring displacements (Coccimiglio et al., 2024) and other parameters, such as soil moisture or temperature (Coccimiglio et al., 2022), particularly in situations where ground measurements are unavailable. They facilitate cost savings and, in some cases, reduce time requirements, as this data is often readily accessible.

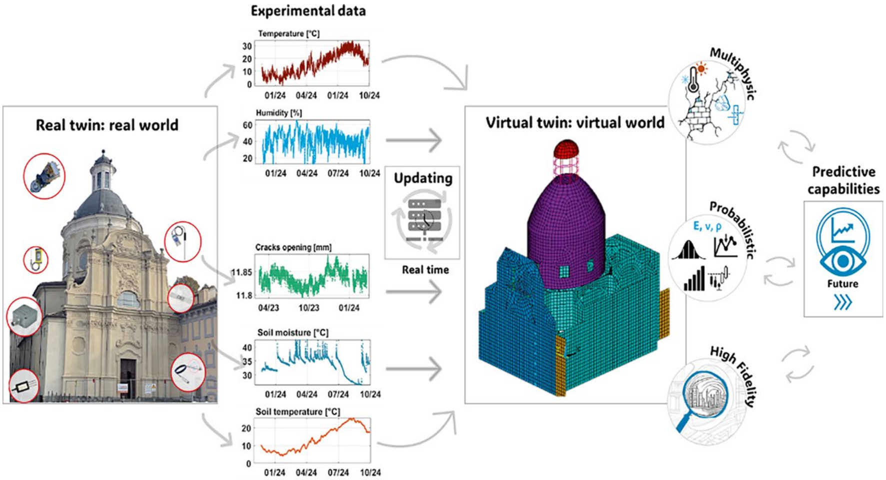


Fig. 6.1 The concept of digital twinning in structural engineering: the process towards predictive capabilities

References

Acierno, M., Cursi, S., Simeone, D., & Fiorani, D. (2017). Architectural heritage knowledge modelling: An ontology-based framework for conservation process. *Journal of Cultural Heritage, 24*, 124–133.

Adami, A., Scala, B., Treccani, D., Dufour, N., & Papandrea, K. (2023). HBIM approach for heritage protection: First experiences for a dedicated training. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVIII-M-2–2023*, 11–18.

Banfi, F., Fai, S., & Brumana, R. (2017). BIM automation: Advanced modeling generative process for complex structures. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, IV-2/W2*, 9–16.

Banfi, F., Brumana, R., Landi, A. G., Previtali, M., Roncoroni, F., & Stanga, C. (2022). Building archaeology informative modelling turned into 3D volume stratigraphy and extended reality time-lapse communication. *Virtual Archaeology Review, 13*, 1–21.

Barazzetti, L., Banfi, F., Brumana, R., Gusmeroli, G., Oreni, D., Previtali, M., Roncoroni, F., & Schiantarelli, G. (2015). BIM from laser clouds and finite element analysis: Combining structural analysis and geometric complexity. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-5/W4*, 345–350.

Barontini, A., Alarcon, C., Sousa, H. S., Oliveira, D. V., Masciotta, M. G., & Azenha, M. (2022). Development and demonstration of an HBIM framework for the preventive conservation of cultural heritage. *International Journal of Architectural Heritage, 16*, 1451–1473.

Bonazza, A., & Sardella, A. (2023). Climate change and cultural heritage: Methods and approaches for damage and risk assessment addressed to a practical application. *Heritage, 6*(4), 3578–3589.

Brumana, R., Della Torre, S., Oreni, D., Previtali, M., Cantini, L., Barazzetti, L., Franchi, A., & Banfi, F. (2017). HBIM challenge among the paradigm of complexity, tools and preservation: The Basilica Di Collemaggio 8 years after the earthquake (L'Aquila). *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W5*, 97–104.

Brumana, R., Condoleo, P., Grimoldi, A., Banfi, F., Landi, A. G., & Previtali, M. (2018). HR LOD based HBIM to detect influences on geometry and shape by stereotomic construction techniques of brick vaults. *Applied Geomatics, 10*, 529–543.

Brumana, R., Banfi, F., Cantini, L., Previtali, M., & Della Torre, S. (2019). HBIM level of detail-geometry-accuracy and survey analysis for architectural preservation. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W11*, 293–299.

Bruno, N., Coïsson, E., & Cotti, M. (2017). Laser-scanner survey of structural disorders: An instrument to inspect the history of Parma cathedral's central nave. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 42*(5W1), 167–174.

Bruno, S., & Fatiguso, F. (2018). Building conditions assessment of built heritage in historic building information modeling. *International Journal of Sustainable Development and Planning*.

Bruno, N., & Roncella, R. (2019). HBIM for conservation: A new proposal for information modeling. *Remote Sensing, 11*, 1751.

Calvano, M., Martinelli, L., Calcerano, F., & Gigliarelli, E. (2022). Parametric processes for the implementation of HBIM—Visual programming language for the digitisation of the index of masonry quality. *IJGI, 11*, 93.

Castagnetti, C., Dubbini, M., Ricci, P. C., Rivola, R., Giannini, M., & Capra, A. (2017). Critical issues and key points from the survey to the creation of the historical building information model: The case of Santo Stefano Basilica. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-5/W1*, 467–474.

Castellazzi, G., Cardillo, E., Lo Presti, N., D'Altri, A. M., De Miranda, S., Bertani, G., Ferretti, F., & Mazzotti, C. (2023). Advancing cultural heritage structures conservation: Integrating BIM and cloud-based solutions for enhanced management and visualization. *Heritage, 6*, 7316–7342.

Celli, S., & Ottoni, F. (2023). Managing information to improve conservation: The HBIM of the wooden chain of Santa Maria Del Fiore. *Sensors, 23*, 4860.

Ceravolo, R., Pistone, G., Fragonara, L. Z., Massetto, S., & Abbiati, G. (2016). Vibration-based monitoring and diagnosis of cultural heritage: A methodological discussion in three examples. *International Journal of Architectural Heritage, 10*(4), 375–395.

Ceravolo, R., De Marinis, A., Pecorelli, M., & Zanotti Fragonara, L. (2017). Monitoring of masonry historical constructions: 10 years of static monitoring of the world's largest oval dome. *Structural Control and Health Monitoring, 24*(10), 2017.

Ceravolo, R., De Lucia, G., Lenticchia, E., & Miraglia, G. (2019). Seismic structural health monitoring of cultural heritage structures. In *Seismic structural health monitoring: From theory to successful applications* (pp. 51–85).

Ceravolo, R., Coletta, G., Miraglia, G., & Palma, F. (2021). Statistical correlation between environmental time series and data from long-term monitoring of buildings. *Mechanical Systems and Signal Processing, 152*, 107460.

Chiabrando, F., Lo Turco, M., & Rinaudo, F. (2017). Modeling the decay in an HBIM starting from 3D point clouds. A followed approach for cultural heritage knowledge. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W5*, 605–612.

Coccimiglio, S., Coletta, G., Lenticchia, E., Miraglia, G., & Ceravolo, R. (2022). Combining satellite geophysical data with continuous on-site measurements for monitoring the dynamic parameters of civil structures. *Scientific Reports, 12*(1), 2275.

Coccimiglio, S., Miraglia, G., & Ceravolo, R. (2024). On the fusion between interferometric satellite data and in situ measurements for the monitoring of built heritage. *The E-Journal of Nondestructive Testing, 29*, 1–8.

Croce, P., Landi, F., Puccini, B., Martino, M., & Maneo, A. (2022). Parametric HBIM procedure for the structural evaluation of heritage masonry buildings. *Buildings, 12*, 194.

De Falco, A., Gaglio, F., Giuliani, F., Martino, M., & Messina, V. (2024). An HBIM approach for structural diagnosis and intervention design in heritage constructions: The case of the Certosa Di Pisa. *Heritage, 7*, 1850–1869.

Della Torre, S. (2020). Italian perspective on the planned preventive conservation. *Frontiers of Architectural Research.*

Deraemaeker, A., Reynders, E., De Roeck, G., & Kullaa, J. (2008). Vibration-based structural health monitoring using output-only measurements under changing environment. *Mechanical Systems and Signal Processing, 22*(1), 34–56.

Fiorani, D., & Acierno, M. (2017). Conservation process model (CPM): A twofold scientific research scope in the information modelling for cultural heritage. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-5/W1*, 283–290.

ICOMOS-ISCARSAH. (2003). ICOMOS Charter—Principles for the analysis, conservation and structural restoration of architectural heritage. In *Proc. ICOMOS 14th General Assembly and Scientific Symposium, Victoria Falls, Zimbabwe* (Vol. 2731).

Ierimonti, L., Cavalagli, N., Venanzi, I., García-Macías, E., & Ubertini, F. (2023). A Bayesian-based inspection-monitoring data fusion approach for historical buildings and its post-earthquake application to a monumental masonry palace. *Bulletin of Earthquake Engineering, 21*(2), 1139–1172.

Lanzara, E., Scandurra, S., Musella, C., Palomba, D., Di Luggo, A., & Asprone, D. (2021). Documentation of structural damage and material decay phenomena in H-BIM systems. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVI-M-1–2021*, 375–382.

Lo Turco, M., Mattone, M., & Rinaudo, F. (2017). Metric survey and BIM technologies to record decay conditions. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-5/W1*, 261–268.

Lorenzoni, F., Casarin, F., Caldon, M., Islami, K., & Modena, C. (2016). Uncertainty quantification in structural health monitoring: Applications on cultural heritage buildings. *Mechanical Systems and Signal Processing, 66*, 268–281.

Mandelli, A., Achille, C., Tommasi, C., & Fassi, F. (2017). Integration of 3D models and diagnostic analyses through a conservation-oriented information system. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W5*, 497–504.

Marafini, F., Matteini, A., Betti, M., Zini, G., & Bartoli, G. (2023). Transdisciplinary conservation of Sant'Andrea Pulpit in Pistoia (Italy): The structural perspective. In *International Conference on the Theory of Machines and Mechanisms* (pp. 65–77). Springer.

Monchetti, S., Betti, M., Borri, C., Gerola, C., Matta, C., & Francalanci, B. (2023). Insight on HBIM for conservation of cultural heritage: The Galleria dell'Accademia di Firenze. *Heritage, 6*(11), 6949–6964.

Monchetti, S., Pepi, C., Viscardi, C., & Gioffrè, M. (2024a). Approximate Bayesian computation for structural identification of ancient tie-rods using noisy modal data. *Probabilistic Engineering Mechanics, 77*, 103674.

Monchetti, S., Viscardi, C., Betti, M., & Clementi, F. (2024b). Comparison between Bayesian updating and approximate Bayesian computation for model identification of masonry towers through dynamic data. *Bulletin of Earthquake Engineering, 22*(7), 3491–3509.

Mora, R., Sánchez-Aparicio, L. J., Maté-González, M. Á., García-Álvarez, J., Sánchez-Aparicio, M., & González-Aguilera, D. (2021). An historical building information modelling approach for the preventive conservation of historical constructions: Application to the historical library of Salamanca. *Automation in Construction*.

Mottershead, J. E., & Friswell, M. I. (1993). Model updating in structural dynamics: A survey. *Journal of Sound and Vibration, 167*(2), 347–375.

Moyano, J., Carreño, E., Nieto-Julián, J. E., Gil-Arizón, I., & Bruno, S. (2022). Systematic approach to generate historical building information modelling (HBIM) in architectural restoration project. *Automation in Construction, 143*, 104551.

Oreni, D., Brumana, R., Georgopoulos, A., & Cuca, B. (2013). HBIM for conservation and management of built heritage: Towards a library of vaults and wooden bean floors. *The ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, II-5/W1*, 215–221.

Oreni, D., Brumana, R., Della Torre, S., Banfi, F., Barazzetti, L., & Previtali, M. (2014). Survey turned into HBIM: The restoration and the work involved concerning the Basilica Di Collemaggio after the Earthquake (L'Aquila). *The ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, II–5*, 267–273.

Ottoni, F., Freddi, F., & Zerbi, A. (2017). From models to reality, and return. Some reflections on the interaction between survey and interpretative methods for built heritage conservation. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 42*, 457–465.

Pepi, C., Gioffre, M., & Grigoriu, M. (2020). Bayesian inference for parameters estimation using experimental data. *Probabilistic Engineering Mechanics, 60*, 103025.

Previtali, M., Brumana, R., Stanga, C., & Banfi, F. (2020). An ontology-based representation of vaulted system for HBIM. *Applied Sciences, 10*, 1377.

Quattrini, R., Pierdicca, R., Morbidoni, C., & Malinverni, E. S. (2017). Conservation-oriented HBIM. The BIMEXPLORER web tool. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-5/W1*, 275–281.

Quattrini, R., Sacco, G. L. S., De Angelis, G., & Battini, C. (2023). Knowledge-based modelling for automatizing HBIM objects. The vaulted ceilings of Palazzo Ducale in Urbino. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVIII-M-2–2023*, 1271–1278.

Santos, D., Cabaleiro, M., Sousa, H. S., & Branco, J. M. (2022). Apparent and resistant section parametric modelling of timber structures in HBIM. *Journal of Building Engineering, 49*, 103990.

Spanò, A., Patrucco, G., Sammartano, G., Perri, S., Avena, M., Fillia, E., & Milan, S. (2023). Digital twinning for 20th century concrete heritage: HBIM cognitive model for Torino Esposizioni Halls. *Sensors, 23*, 4791.

Thravalou, S., Michopoulos, A., Alexandrou, K., & Artopoulos, G. (2023). Energy retrofit strategies of built heritage: Using building information modelling tools for streamlined energy and economic analysis. *IOP Conference Series: Earth and Environmental Science, 1196*, 012115.

Tommasi, C., Achille, C., & Fassi, F. (2016). From point cloud to BIM: A modelling challenge in the cultural heritage field. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLI-B5*, 429–436.

Trani, M. L., Ruschi, M., & Ripamonti, F. (2021). Cross information and BIM interoperability tools for energy retrofit analysis. *IOP Conference Series: Earth and Environmental Science, 863*, 012049.

Ubertini, F., Comanducci, G., Cavalagli, N., Pisello, A. L., Materazzi, A. L., & Cotana, F. (2017). Environmental effects on natural frequencies of the San Pietro bell tower in Perugia, Italy, and their removal for structural performance assessment. *Mechanical Systems and Signal Processing, 82*, 307–322.

Zini, G., Betti, M., Bartoli, G., Morano, S. G., & Spinelli, P. (2024). Structural health monitoring of a masonry arch bridge: Modal identification and model updating. *International Journal of Masonry Research and Innovation, 9*(1-2), 42–53.

Chapter 7
The Pulpit of Giovanni Pisano in Sant'Andrea Church in Pistoia

G. Bartoli, M. Betti, A. Conti, L. Fiorini, A. Meucci, S. Monchetti, E. Pellis, G. Tucci, and G. Zini

Abstract This paper presents a detailed analysis and conservation of the pulpit of the church of Sant'Andrea in Pistoia, a masterpiece by Giovanni Pisano, created between 1298 and 1301. The pulpit, remarkable for its intricate design and sculptural richness, has been modified and restored over the centuries and is currently in a critical state. The research employs a multidisciplinary approach to document and assess its structural integrity using 3D laser scanning and SfM photogrammetry. These techniques, along with dynamic and static structural tests, facilitate a comprehensive understanding of the pulpit's condition, highlighting previously undocumented fractures and structural weaknesses. The study includes a finite element model (FEM) to simulate the pulpit's dynamic behaviour under seismic loads, comparing it with actual recorded accelerations. Results show the model's high fidelity in capturing the pulpit's structural responses during seismic events. This approach, combining architectural analysis, digital modeling, and structural testing, contributes to the ongoing conservation and preservation efforts of this significant medieval work of art.

Keywords Sculpture · Laser scanning · Structure from motion · FEM · Monitoring · Giovanni Pisano

---

G. Bartoli · M. Betti · A. Conti · L. Fiorini · S. Monchetti (✉) · E. Pellis · G. Tucci · G. Zini
Department of Civil and Environmental Engineering, University of Florence, Florence, Italy
e-mail: gianni.bartoli@unifi.it; michele.betti@unifi.it; alessandro.conti@unifi.it; lidia.fiorini@unifi.it; silvia.monchetti@unifi.it; eugenio.pellis@unifi.it; grazia.tucci@unifi.it; giacomo.zini@unifi.it

A. Meucci
Department of Civil and Environmental Engineering, University of Florence, Florence, Italy

La Sapienza University of Rome, Rome, Italy
e-mail: adele.meucci@unifi.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_7

7.1 The Pulpit and Its Context

The pulpit of the church of Sant’Andrea in Pistoia, a masterpiece by Giovanni Pisano and one of the most important Italian sculptures, is an extraordinary example of medieval art and architecture (Siedel, 2012). In churches of the period, the pulpit was a raised structure intended for the reading of the Gospel. The church of Sant’Andrea, built in Romanesque style in the twelfth century, is distinguished by its massive walls, an austere and dimly lit interior, divided into three narrow naves culminating in an apse with single-lancet windows.

The pulpit, made of marble between 1298 and 1301, has a hexagonal plan and a structure divided into three orders: bases and columns, arches and pendentives, and parapets. With a side of about 1.4 m and a total height of 3.95 m, the tribune rises 3 m from the ground, supported by seven slender columns. Six of these are located at the corners, while one occupies the central position. The columns, of different heights and decorated with Corinthian capitals, rest on bases or sculptures depicting animals and human figures, a recurring element also in the works of Nicola Pisano, Giovanni’s father, in Pisa and Siena.

The parapets, carved in high relief, depict scenes from the life of Christ, religious symbols, sibyls and prophets. The marble sculptures have a glazed surface and gilded details, such as the edges of the robes. At the base of the pulpit, an inscription in leonine verses, also gilded, reports the date, the name of the author and the patrons.

Originally placed to the right of the altar, the ambo was dismantled and rebuilt in the fifth space between the columns of the southern nave following the Counter-Reformation, when many pulpits were removed. During the reassembly, its parts were arranged differently from the original, partially compromising its stability (Carli, 1986; Jászai, 1968; Mellini, 1969; Gnudi, 1972).

Over the centuries, various restoration interventions have been carried out, such as the addition of iron brackets in the nineteenth century to strengthen the structure. Since 1947, the Opificio delle Pietre Dure has been monitoring and conserving it. In 2007, in-depth analyses were conducted, including morphometric studies, tests on the materials (marble, gilding, glass), geological and geomechanical investigations on the foundations, as well as geophysical and gammagraphic tests, to assess the state of the work and prevent further deterioration.

In 2019, the Superintendence promoted a Scientific Committee composed of scholars with different skills for a careful evaluation of the state of conservation and stability of the work. Table 7.1 reports some general information on the Pulpit.

Table 7.1 General information

Object	Pulpit
Reference scale	Art object
Original/Current Destination	Pulpit (AAT: grottoes/ID: **300003790**/Page Link: http://vocab.getty.edu/page/aat/300003790
Author	Giovanni Pisano
Location	Parish Church of Sant’Andrea in Pistoia (PT) Via Sant’Andrea, 21
Geographical Coordinates	43°56′08.02″N10°54′51.11″E (Pieve)
Chronology	Fourteenth century, 1301 Seventeenth century dismantling of the pulpit
Ownership	Diocese of Pistoia
ICCD Sheet	ICCD5013954 (https://catalogo.beniculturali.it/detail/HistoricOrArtisticProperty/0900013029-0)
Authority responsible for protection	Superintendency for Archaeology, Fine Arts and Landscape for the Metropolitan City of Firenze and the Provinces of Pistoia and Prato
Keywords	Giovanni Pisano, Sculpture, Laser scanning, Structure from Motion, FEM, Monitoring,
Risk map	ID 187025 (the church)
Type of risk	Anthropogenic risks negligent rehabilitation/maintenance interventions; vandalism and/or socio-political events Climate change effects: rainfall increase; temperature changes Indirect risks: seismic vulnerability of the parish church of Sant’Andrea which already has some lesions

(continued)

Table 7.1 (continued)

Object	Pulpit
Goals	The objectives of the documentation campaign were multiple: • produce reliable metric documentation that documents the shape and appearance of the artifact. (The pulpit had already been investigated in 2010 with scanning systems by the DIAPREM of Ferrara—https://www.unife.it/centri/diaprem/archivio-progetti/pistoia-giovanni-pisano/pagina_standard—but except for the orthogonal projection drawings, the other data have been lost) • carry out mapping of the state of conservation and crack patterns • identify the individual parts that make up the work • create three-dimensional models at different resolutions for structural assessments • allow assessments of the stability of the work in relation to a possible dismantling and reassembly of the pulpit • create three-dimensional models for communication • support the monitoring system
Research team	This research was conducted following an agreement between the Superintendence of Archaeology, Fine Arts and Landscape for the metropolitan city of Florence, the Friends of Florence foundation, the Department of Civil and Environmental Engineering (DICEA) and the Department of Earth Sciences (DST) of the University of Florence., Opificio delle pietre dure OPD

7.2 Research Campaign Objectives

The pulpit, due to its dimensions similar to those of a small architecture, and the minute details of the figures sculpted in the individual panels, represents a work that combines formal complexity and artistic richness. These characteristics required a holistic research approach, based on a multidisciplinary set of skills.

The main objectives of the three-dimensional digitization campaign were multiple:

- Creating a common basis for the knowledge path, (Tucci et al., 2018) useful for the analysis and documentation of the artifact.
- Create three-dimensional models at different resolutions, suitable for different purposes, from structural analysis to project communication.
- Produce these models at different timeframes, allowing different teams to start their activities without delays.
- Generate documents in orthogonal projections with high-resolution orthophotos, to evaluate thicknesses, centers of gravity and map the state of conservation of the work, including the crack pattern and previous interventions.

These preliminary objectives were supported by a careful analysis of the critical issues related to both the morphology and physical characteristics of the artifact, and to the environmental conditions of the church. This allowed us to define the most appropriate acquisition methods, integrating laser scanning systems and SfM (Structure from Motion) photogrammetry techniques, referred to a single coordinate system established through a closed topographic network.

Each technology adopted has specific advantages and limitations (Bonora et al., 2021).

- **Laser scanning:** it is distinguished by its high acquisition speed, but it encounters difficulties in the detection of marble surfaces, which tend to disperse the light signal and reduce the accuracy of the measurements. This phenomenon depends on variables that are not easily predictable, such as the internal structure of the marble, the acquisition distance and the angle of incidence. Furthermore, the cameras integrated into laser scanners offer a generally limited chromatic quality (Godin et al., 2001; Guidi et al., 2009).
- **SfM photogrammetry:** represents a more flexible solution, ensuring better color quality, but requires diffused lighting, longer acquisition and processing times, and a greater number of targets for positioning.

The integration of these techniques has allowed us to overcome specific critical issues, ensuring an accurate survey and complete documentation of the pulpit.

7.3 Model Resolution and Accuracy for Granular Assessment of Artifact Fit

The critical issues, design and implementation of the survey have been extensively discussed in previous papers (Bartoli et al., 2020; Conti et al., 2022).

Instead, it is worth emphasizing here that the outputs of the resolution and accuracy of the 3D digital model have allowed us to detect some structural characteristics that cannot be computed in the FEM models described later, in particular regarding the floor of the pulpit which presents a fracture not documented in previous study campaigns and visible only in the walkable part.

The floor was not made as a single block but is composed of six elements arranged in a segment, which converge on a central hexagonal element positioned in correspondence with the central column beyond a central hexagonal element in correspondence with the central column. The six elements of the floor end triangularly on the vertices of the hexagon. The availability of such a resolute three-dimensional model allowed us to evaluate the thickness of the floor slabs and analyze the joints between them in both the upper and lower view (top and bottom).

This showed that the plates were simply affixed and not interlocked.

The lesion present between the third and fourth slab (see Fig. 7.1a) is not visible on the intrados as it extends along one side from the triangular marble element placed above the capital of the central column which distributes the loads and hides the fracture.

A map of the deviation between the actual position of the floor and an ideal horizontal plane has shown how the six segments do not lie on a horizontal plane but there is a difference in height of about 0.05 m (see Fig. 7.1b) between the opposite sides of the pulpit. This difference in height and the presence of the triangular element on the intrados could, during the reconstruction phase or later, have favoured the breakage of the third slab, greatly reducing its support surface.

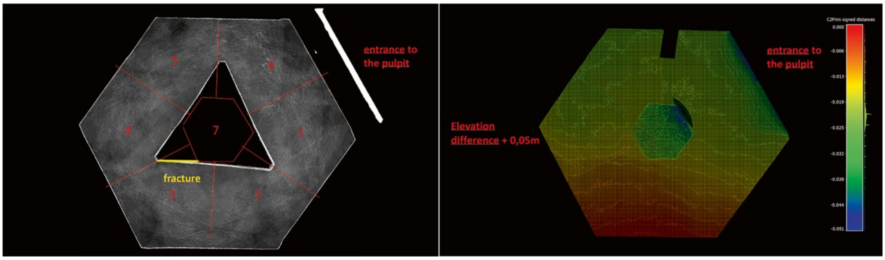


Fig. 7.1 (**a**) transparent view of the point model of the extrados and intrados of the floor of the pulpit. The view highlights the matching of the joints on the intrados and extrados sides: the crack on slab No. 3 is visible only from above because on the opposite side is hidden by the triangular abacus of the central column. (**b**) The deviation map shows how the pulpit floor plane is not horizontal

The resolution of the orthoimages describing the six sides allowed to continuously map the lesions present on the pulpit. The comparison with the only punctual photographic documentation carried out in the 2007 investigation campaign highlighted that the lesions remained stable (Fig. 7.2).

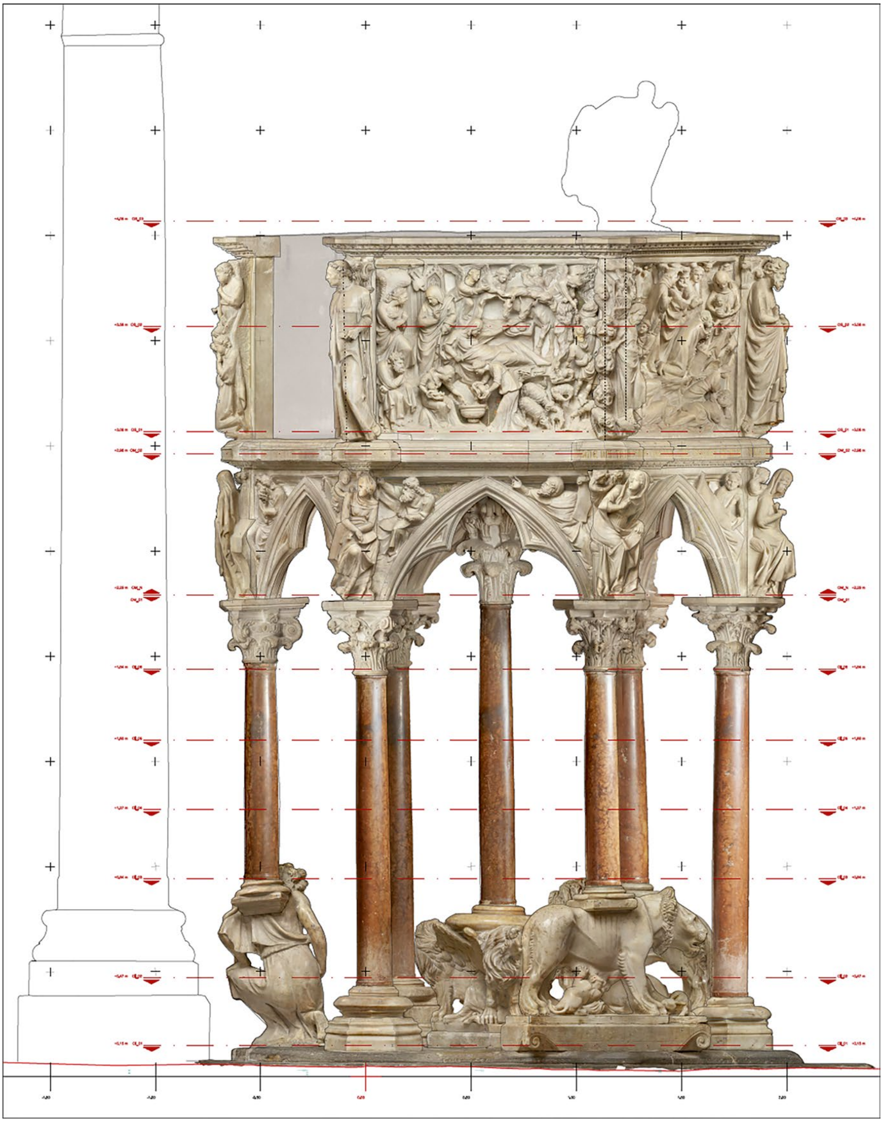


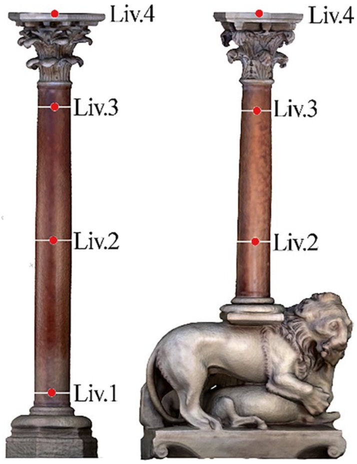
Fig. 7.2 Extract from the elevation drawing with orthoimage (GSD 0.005 m). Original scale 1:5

7.4 Dynamic Identification Tests

Dynamic identification tests aim to assess the structural integrity and dynamic behavior of a structure (Lacanna et al., 2020). These tests help to understand how a structure responds to environmental loads such as earthquakes or vibrations, revealing its natural frequencies, damping ratios, and mode shapes. This data, integrated with properly calibrated numerical models, is crucial for diagnosing potential vulnerabilities, guiding conservation efforts, and ensuring the long-term preservation and safety of significant structures (Bartoli et al., 2015; Bassoli et al., 2018; Pavlovic et al., 2019).

The experimental campaign on the structure of the pulpit was carried out by the University of Florence. Global measurements were taken under ambient vibrations, where the tops and midpoints of the columns were instrumented simultaneously. Additionally, the dynamic behavior of each column was analyzed through impulse tests, using small strikes from an instrumented hammer on the floor of the church in front of the pulpit. The tests were conducted with seven pairs of accelerometers fixed at the midpoints of the columns using plastic straps. For the local tests on each individual column, the columns were instrumented at four different levels (Fig. 7.3) for the ordinary columns (Col_1, Col_2, Col_3), whereas for the columns with the statue (Col_4, Col_5, Col_6), the lowest level was no longer instrumented, while the three upper levels remained unchanged. The spectral analysis revealed that, within a frequency band between 0.3 and 50 Hz, the structure exhibits three distinct modes of vibration: (i) the first mode, a primarily translation in the Y direction with a frequency of 5.115 Hz, (ii) the second mode, a purely translation in the X direction with a frequency of 5.341 Hz, and (iii) the third mode, a torsion with a slight translational component with a frequency of 6.586 Hz. In all the modal shapes, significant local components are observed in the columns, which translate in seemingly random directions, resulting in an imperfect rigid body motion between them. This is likely due to the varying stiffness of the connections, which grant a certain degree of freedom to the movement of the columns.

Fig. 7.3 Sensor placement on the columns of the pulpit



7.5 Monitoring System

Based on extensive measurement campaigns that reveal the characteristic behaviour of a rigid block dynamic system, a monitoring system has been designed to analyse the structural behaviour of the pulpit. This system includes both static measurements, which track the relative displacements between the various elements forming the pulpit's base, and dynamic accelerometric measurements. These dynamic measurements are recorded at two specific locations: at ground level and at the top of the structure. The location and type of sensors used are shown both in Fig. 7.4.

The monitoring system is based on two different types of data acquisition: (i) a scheduled daily acquisition and (ii) an event-triggered acquisition upon reaching a specific threshold value. The first group includes both static (SLOW) and dynamic (FAST) recordings, while the second group consists of dynamic recordings triggered by threshold exceedance. The scheduled static recordings provide a reading every hour starting from the beginning of the daily acquisition, while the dynamic recordings capture 20 min of data at a sampling frequency of 100 Hz. In contrast, the unscheduled dynamic recordings capture 4 min of data at a sampling frequency of 100 Hz upon threshold activation. Additionally, during each SLOW recording, environmental parameters such as temperature, relative humidity, and water table depth at the site are recorded. As a result, a data point is available every hour throughout the day. The acquired data is then transferred to a remotely accessible server, allowing for easy data download. The measurement system, which remains operational, also captured the response of the pulpit during two recent seismic events. The first event occurred on May

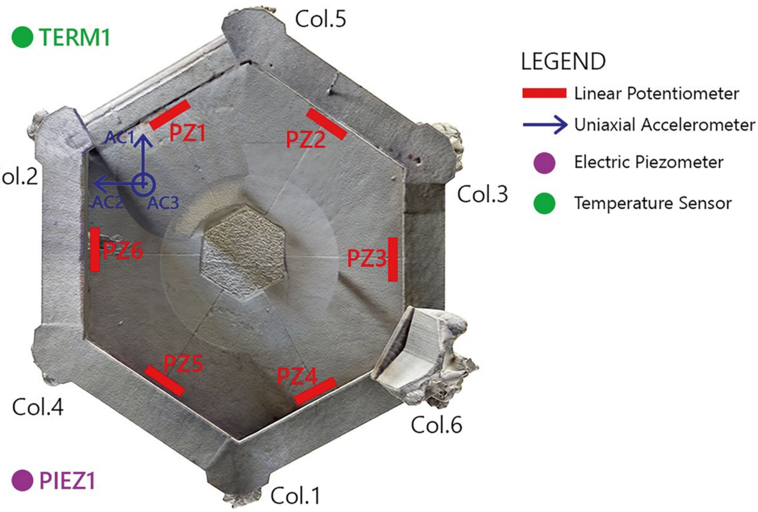


Fig. 7.4 Location and types of sensors used for the monitoring system

2022, at 05:51, with an epicenter 4 km from San Casciano Val di Pesa (FI) and a magnitude of 3.5 on the Richter scale. The second event took place on September 2023, at 05:12, in the upper Mugello region near Marradi, in the province of Firenze, with a magnitude of 4.8.

7.6 Numerical Models and Analysis

To assess the stresses induced under both static and dynamic conditions, it was necessary to develop a finite element numerical model capable of adequately representing the actual behavior of the structure (Bartoli et al., 2023). In this regard, the dynamic experimental campaign proved to be of utmost importance, as it allowed for the calibration of the finite element model in terms of frequencies and mode shapes.

To construct an accurate FEM model, various models with different levels of simplification were developed (Fig. 7.5): (i) a model entirely composed of 3D finite elements (Model 1, Fig. 7.5a), (ii) a model where the columns were replaced by 2D beam elements (Model 2, Fig. 7.5b) and (iii) a model where the arches and capitals are modelled by two-dimensional elements (Model 3, Fig. 7.5c). The decision to adopt simplified models was driven by the need to capture the joint behaviour while mitigating the excessive computational cost of the 3D model. Indeed, simplification significantly reduced computational time, but it also reduced the level of detail concerning the structural elements.

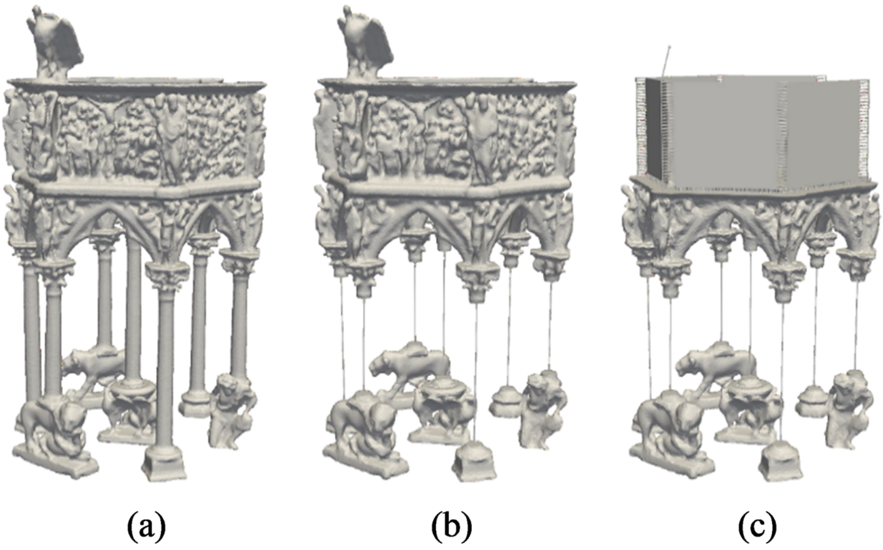


Fig. 7.5 Numerical model of the Pulpit

To verify the consistency of behaviour across the various models and the real structure, modal analyses were performed on each model, with the base-column and column-capital joints in the simplified models considered as fixed. The most striking finding was that, while the mode shapes differed from the real ones, the natural frequencies were found to be approximately twice those of the real structure. Table 7.2 presents the frequency values obtained from the analyses and a comparison of the models in terms of the Modal Assurance Criterion (MAC) (Pástor et al., 2012). From the data in the table, it can be observed that all the simplified models are nearly equivalent to the fully three-dimensional model in terms of modal features with maximum frequency deviations of less than 2.64%.

To better understand the behavior of the pulpit based on the stiffness of the connections, repeated modal analyses were performed on the simplified Model 3. At each iteration, stiffness values were adjusted, modal analyses were conducted, and deviations from the real model were calculated using MAC and frequency comparison. The analyses were carried out using beam-type connections for the base-column and column-capital joints.

After several series of tests, it became clear that friction plays a primary role in the stiffness of the connections and thus in the overall behavior of the structure. A linear static analysis was also performed to assess the normal stresses acting on the connections. This allowed for the establishment of a relationship between the stiffness of the various connections, which resulted in frequencies and mode shapes comparable to the real model. The results are shown in Table 7.3. The average error in terms of frequency is 0.065%, though the MAC values remain suboptimal, indicating that various unpredictable or unquantifiable factors, such as the quality of the joints, contribute to the stiffness of the connections.

Given the accelerograms measured both at the ground and on the pulpit during the earthquake on May 10, 2022, a time history analysis was performed. The model was subjected to the measured ground accelerations, and the resulting accelerations on the pulpit were compared to ensure they matched the real measurements. The analysis was performed over a duration of 20 s to capture the peak ground acceleration, which occurred around the tenth second. It was repeated several times with varying damping values to estimate a representative damping value based on the peak closest to the actual measurements. The results showed maximum displacements that were consistent with the real ones and accelerograms closely matching those measured at the top of the pulpit, in both the X and Y directions. The fidelity of the FEM model to the real one is therefore considered satisfactory.

Table 7.2 Comparison in terms of frequencies and MAC between the models

Model	Freq. 1 (Hz)	Freq. 2 (Hz)	Freq. 3 (Hz)	MAC 1	MAC 2	MAC 3
1	11.63	12.44	14.66	1.00	1.00	1.00
2	11.94	12.61	14.67	0.99	0.99	0.99
3	11.75	12.41	14.51	0.99	0.99	0.99

Table 7.3 Frequency and MAC values obtained from the finite element model

	Freq. 1 (Hz)	Freq. 2 (Hz)	Freq. 3 (Hz)	MAC 1	MAC 2	MAC 3
Real	5.115	5.341	6.586	1.000	1.000	1.000
Model 3	5.111	5.344	6.589	0.915	0.926	0.857
Deviation	0.08%	0.06%	0.05%	–	–	–

Acknowledgments This research was financially supported by the foundation “Friends of Florence” (www.friendsofflorence.org) that is gratefully acknowledged.

References

Bartoli, G., Betti, M., & Borri, C. (2015). Numerical modelling of the structural behaviour of Brunelleschi’s dome of Santa Maria del Fiore. *International Journal of Architectural Heritage, 9*, 408–429. https://doi.org/10.1080/15583058.2013.797038

Bartoli, G., Betti, M., Bonora, V., Conti, A., Fiorini, L., Kovacevic, V. C., et al. (2020). From TLS data to FE model: A workflow for studying the dynamic behavior of the Pulpit by Giovanni Pisano in Pistoia (Italy). *Procedia Structural Integrity, 29*, 55–62.

Bartoli, G., Betti, M., Facchini, L., & Monchetti, S. (2023). Rocking response and vulnerability of the pulpit by Giovanni Pisano in Pistoia (Italy). In *COMPDYN 2023-9th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering* (Vol. 1, pp. 259–270). National Technical University of Athens (NTUA).

Bassoli, E., Vincenzi, L., D’Altri, A. M., de Miranda, S., Forghieri, M., & Castellazzi, G. (2018). Ambient vibration-based finite element model updating of an earthquake-damaged masonry tower. *Structural Control and Health Monitoring, 25*, e2150. https://doi.org/10.1002/stc.2150

Bonora, V., Tucci, G., Meucci, A., & Pagnini, B. (2021). Fotogrammetria e stampa 3D per repliche di statue in marmo: Questioni critiche e valutazione. *Sostenibilità, 13*(2), 680.

Carli, E. (1986). *Giovanni Pisano. The Pulpit of Pistoia*. Giorgio Mondadori Ed. EAN:2560028468315.

Conti, A., Fiorini, L., & Tucci, G. (2022). The Ambon of Sant’Andrea in Pistoia: A comparison between laser scanner and photogrammetric digitization of marble surfaces. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 46*, 159–166.

Gnudi, G. (1972). Giovanni Pisano’s pulpit in Pistoia. In *The Gothic in Pistoia in its relations with Italian Gothic art. Proceedings of the 2nd International Conference of Studies, Pistoia 1966, Rome* (pp. 165–179).

Godin, G., Rioux, M., Beraldin, J., Levoy, M., Cournoyer, L., & Blais, F. (2001). Una valutazione della misurazione della portata laser su superfici di marmo. In *Proc. 5th Conf. su tecniche di misurazione ottica 3D, Vienna, 49-56 NRC 44210*. NRC-CNRC.

Guidi, G., Remondino, F., Russo, M., & Spinetti, A. (2009). Sensori di distanza su superfici di marmo: Valutazione quantitativa di artefatti. In *Proc. SPIE 7447, Videometrics, Range Imaging, and Applications X, 744703*. https://doi.org/10.1117/12.827251

Jászai, G. (1968). Die Pisaner Domkanzel. *Neuer Versuch zur Wiederherstellung ihres ursprünglichen Zustandes, München, Dabnubia*

Lacanna, G., Betti, M., Ripepe, M., & Bartoli, G. (2020). Dynamic identification as a tool to constrain numerical models for structural analysis of historical buildings. *Frontiers in Built Environment, 6*. https://doi.org/10.3389/fbuil.2020.00040

Mellini, G. L. (1969). *The pulpit of Giovanni Pisano in Pistoia*. Electa.

Pástor, M., Binda, M., & Harčarik, T. (2012). Modal assurance criterion. *Procedia Engineering, 48*, 543–548. https://doi.org/10.1016/j.proeng.2012.09.551

Pavlovic, M., Trevisani, S., & Cecchi, A. (2019). A procedure for the structural identification of masonry towers. *Journal of Nondestructive Evaluation, 38*, 38. https://doi.org/10.1007/s10921-019-0575-8

Siedel, M. (2012). *Father and son*. Nicola and Giovanni Pisano.

Tucci, G., Conti, A., & Fiorini, L. (2018). Geomatics for structural assessment and surface diagnosis of CH. *Procedia Structural Integrity, 11*, 2–11.

Chapter 8
The Sanctuary of Vicoforte

Rosario Ceravolo, Mario Alberto Chiorino, Stefania Coccimiglio, and Gaetano Miraglia

Abstract Renowned for its massive masonry oval dome, the largest worldwide, the Sanctuary of Vicoforte has faced significant structural issues, including settlement and cracking. Since the 1980s, a sophisticated monitoring system has evolved, incorporating static and dynamic measurements, supported by geotechnical surveys. Recent advancements include the integration of satellite data. The collection and the analysis of these different kind of data aimed at developing a robust Digital Twin for real-time diagnostics and predictive analysis, paving the way for resilient management of architectural heritage. Temperature-induced behaviors, such as changes in vibration frequencies and crack dynamics, reveal complex interactions between environmental conditions and structural responses. Future upgrades will focus on further integrating remote sensing capabilities to enhance this innovative approach.

Keywords Structural health monitoring · Cultural heritage · Static and dynamic monitoring · Digital twin · Data integration

---

R. Ceravolo (✉) · G. Miraglia
Department of Structural, Geotechnical and Building Engineering, Politecnico Di Torino, Turin, Italy

Responsible, Risk, Resilience Interdepartmental Centre (R3C), Politecnico Di Torino, Turin, Italy
e-mail: rosario.ceravolo@polito.it; gaetano.miraglia@polito.it

M. A. Chiorino · S. Coccimiglio
Department of Structural, Geotechnical and Building Engineering, Politecnico Di Torino, Turin, Italy
e-mail: mario.chiorino@polito.it; stefania.coccimiglio@polito.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_8

8.1 Description

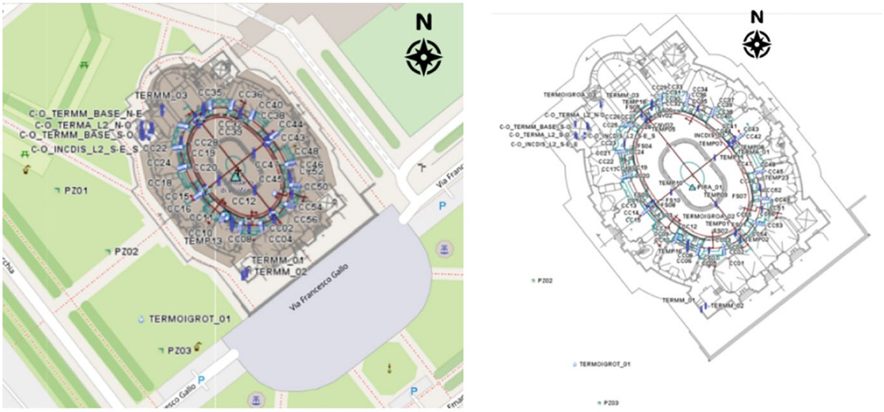
The Basilica “Regina Montis Regalis,” also known as the Sanctuary of Vicoforte, is located near Mondovì in Northern Italy (Fig. 8.1a, b). Construction began in 1596, initially under the direction of architect Ascanio Vitozzi, following a design conceived by Duca Emanuele I di Savoia, who intended the Basilica to serve as the mausoleum for the Savoia’s. The structure is famous for its oval dome, the largest of its kind in the world, with internal dimensions of 37.23 by 24.89 m (Fig. 8.1c). The construction halted for several decades, stopping at the level of the base of the drum of the dome. It was only in the early eighteenth century that Francesco Gallo (1672–1750) resumed the project, overseeing the erection of the high drum and the


(a)
(b)
(c)

Fig. 8.1 The Sanctuary of Vicoforte: (**a**) Top view, (**b**) façade, and (**c**) internal view of the oval dome majestic dome. Gallo also incorporated a system of iron rings, consisting of three rings with a total section of approximately 140 cm^2, designed to absorb some of the horizontal thrust. The dome was disarmed in 1732 (Cozzo et al., 2017), and the lantern was completed in 1735, marking the Basilica inauguration. Over time, the dome and drum system experienced significant structural challenges, largely due to ongoing settlements and the daring structural configuration of the dome. In 1983, severe concerns regarding settlement and cracking led to detailed inspections, monitoring, and strengthening interventions. From 1985 to 1987, an extensive survey gathered comprehensive data on the foundation conditions, dome geometry, and geotechnical aspects. In parallel, previous structural investigations had begun in the late 1960s, notably following surveys by engineer Martino Garro in 1962. In the 1970s, the scientific community began to systematically investigate the structural health of the Sanctuary, which ultimately informed restoration efforts focused on maintaining its stability.

8.2 Static and Seismic Monitoring

In the early 1980s, a hooping system was installed to prevent the widening of cracks, primarily concentrated in the dome-drum system. The system consists of four high-strength steel bars arranged in each of the 14 tangential directions. Steel frames connect the ends of the bars in two adjacent stretches. The tie bars, slightly prestressed to 50 kN using jacks, were retensioned in 1997 to compensate for physiological load losses (Chiorino et al., 2008). Geological and geophysical investigations, conducted between 1976 and 2008, confirmed that the subsoil of the Sanctuary is composed of different materials (Scandella et al., 2011). A marl layer slopes downwards from the northeast to the southwest, while a clay layer exists beneath the rest of the building, causing serious cracking patterns. Monitoring of the Vicoforte Sanctuary began in 1983 with the installation of instruments to investigate crack pattern evolution. Since then, the static monitoring system has undergone several updates, culminating in 2004 with an automated data acquisition system; this system was comprised of 133 instruments specifically placed on the dome-drum structure (Ceravolo et al., 2017). The system continuously operated from 2004 to 2015, after which it was restored and reactivated in November 2023. Today, the static monitoring of the Vicoforte Sanctuary consists of 56 load cells, 2 laser distance meters, 2 distance meters, 12 crack meters, 28 thermometers, 1 barometer, 1 pyranometer, 3 thermo-hygrometers, and 3 piezometers (Fig. 8.2). In 2015, a dynamic monitoring system was added, consisting of 12 accelerometers (Ceravolo et al., 2016) (Fig. 8.3) distributed at different heights to monitor the overall structural behaviour, which also underwent adjustments and updates in 2023. The dynamic acquisition system at the Sanctuary of Vicoforte records data based on two criteria: time and threshold. The time criterion involves recording for 20 min every hour to limit data storage, while the threshold criterion records data when ground horizontal acceleration exceeds 0.042 g, in line with Italian seismic hazard



(a) (b)

Fig. 8.2 Layout of the low-rate system of the Sanctuary and the mixed monitoring system of the West bell tower

regulations. This ensures the dynamic response of the structure during seismic events is captured.

Finally, in 2023, a mixed monitoring system was installed in the West bell tower, including 2 MEMS triaxial accelerometers, 2 inclinometers combined with biaxial laser distance meters, 6 thermometers, and 4 strain gauges.

8.3 Results and Discussion

The data collected by the dynamic monitoring system are automatically processed to determine the main frequencies and modal shapes of the Sanctuary. In these automatic identification processes, a cluster analysis is applied to group the potential physical modes into uniform sets that represent the same mode (Pecorelli et al., 2020). The analysis of the static and dynamic monitoring data of the Sanctuary, including correlations with environmental data, showed that both types of behavior are strongly influenced by changes in ambient temperature. At the moment, no significant correlation was found with other environmental factors, such as humidity or rainfall. The study revealed that temperature increases lead to corresponding rises in the internal masonry temperature, with delays of 10–30 days due to thermal inertia. This also causes cracks at the balcony level to widen and the load on the bars to decrease, as steel expands more than masonry under heat. Furthermore, the first vibration frequencies of the structure were found to increase with rising temperatures, except for low temperatures where a bilinear behavior was observed. This may be linked to the stiffening effect of ice on the structure. Interestingly, an unexpected relationship was identified between dynamic and static data: higher temperatures led to both increased vibration frequencies and more significant crack

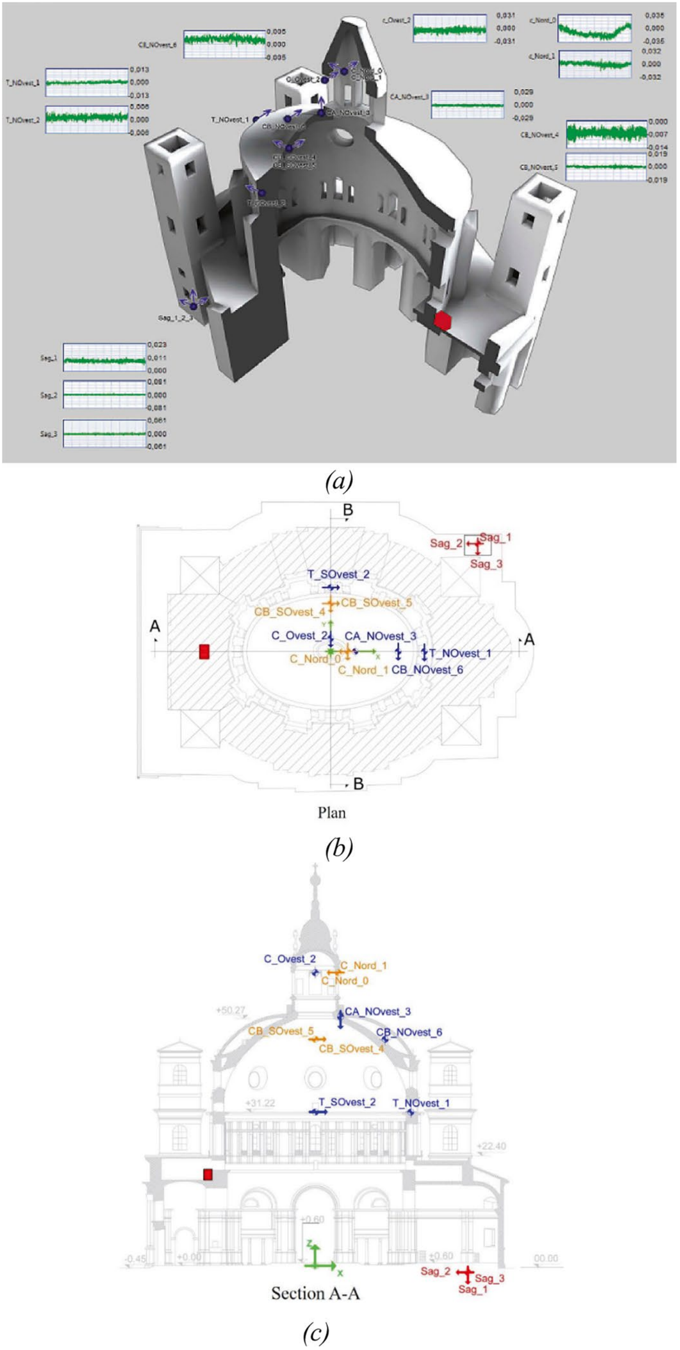


Fig. 8.3 Dynamic monitoring system of the Sanctuary of Vicoforte: (**a**) Dynamic monitoring system software interface, (**b**) Layout of the configuration the accelerometers, and (**c**) Section A-A of the configuration of dynamic monitoring system

openings, as well as reduced bar tension. This suggests additional, unmodeled phenomena, such as micro-cracks or soil seasonal cycles, particularly affecting the first vibrational modes. A plausible interpretation concerns the effect of ice, which is known to significantly increase structural rigidity (Peeters & De Roeck, 2001) (Fig. 8.4).

Then, the data acquired from the monitoring system can be used for the updating of the Finite Element Model (FEM) of the Sanctuary. The first model updating of the Sanctuary was based on the results of a dynamic test campaign conducted in 2008 (Chiorino et al., 2011). Successively, in order to consider the structural, typological and historical peculiarities of each component of the structure, a more accurate FE model was built that consisted of 9 homogeneous macro-elements: 7 for the building (lantern, dome, drum, basement, but-tresses, belltowers and iron ties) and 2 for the soil (marl and clay). Then a thermo-elastic updating was performed using multiphysics data, including the thermal analysis to obtain the temperature distribution of the drum-dome system as related to the forces acting in the tie-bars (Ceravolo et al., 2020). This distribution was determined by applying local temperature measurements to the thermal FE model.

The update of the FEM model (Fig. 8.5) through experimental data allows the model to be as close as possible to reality, enabling it to accurately reflect the actual behaviour of the structure while always considering the uncertainties inherent in its nature. The more types of data are used to enrich the model and study the behaviour of the structure (Figs. 8.4 and 8.6), the greater the fidelity of the model to its real-world counterpart. Thus, it was decided to equip the Sanctuary of Vicoforte with instruments capable of characterizing its behaviour from multiple perspectives. In addition, when dealing with SHM, it is essential to consider the influence that the environment and the soil can have on the structure response. For this reasons, the Sanctuary of Vicoforte presents a complex monitoring system (Table 8.1) that

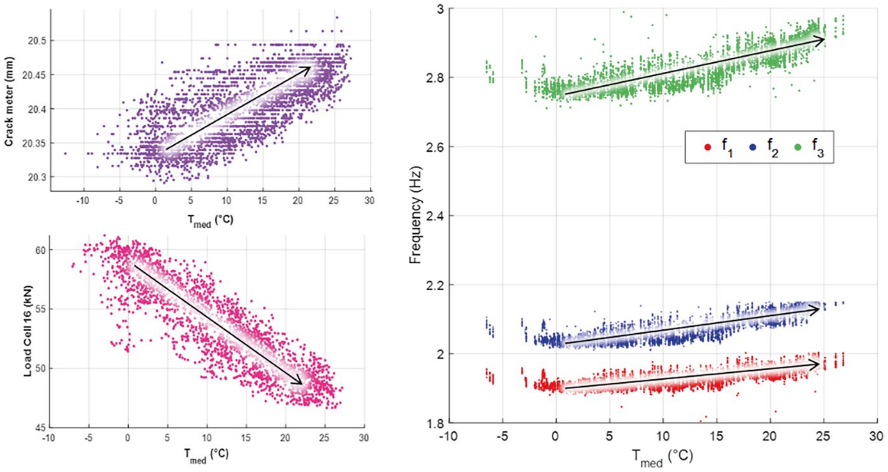


Fig. 8.4 Comparison of the results coming from the static and the dynamic monitoring systems

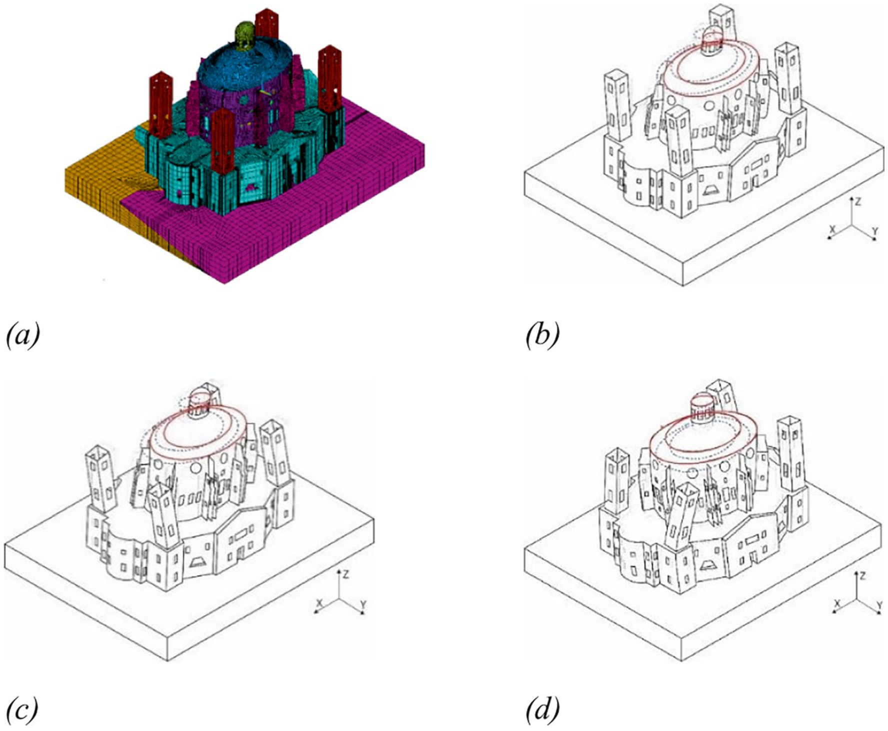


Fig. 8.5 (**a**) FEM of the Sanctuary of Vicoforte, (**b**) first modal shape (longitudinal along Y direction), (**c**) second modal shape (longitudinal along X direction), and (**d**) third modal shape (torsional)

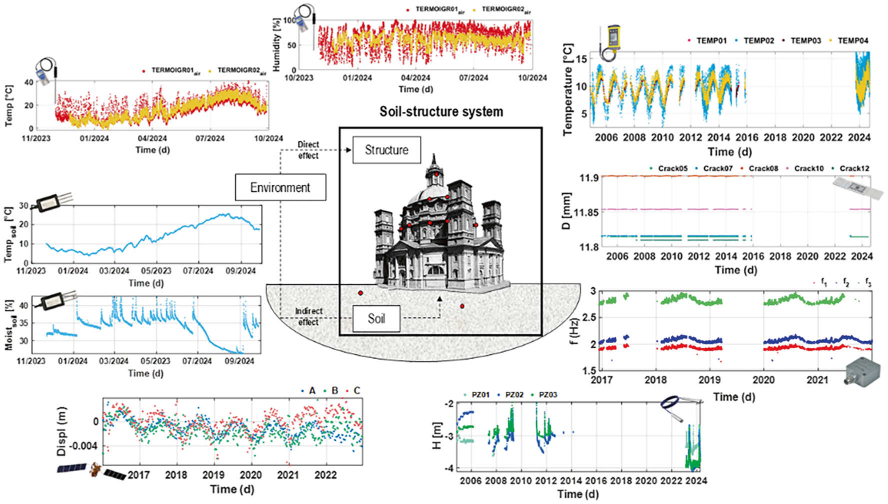


Fig. 8.6 The Sanctuary of Vicoforte with some time series obtained from in situ sensors (static and dynamic) and remote sensors

Table 8.1 Output and instruments

Type of monitoring	Static, environmental and seismic
Outputs	Updated multiphysics Finite Element Models Structural safety levels Seismic vulnerability indices Crack patterns Soil parameters and settlements
Instruments	Monitoring system of the structure Low rate (static and environment system): 1 barometer 56 load cells 2 laser distancemeters 2 distancemeters 12 crackmeters 28 thermometers 1 pyranometer 5 thermo-hygrometers 3 piezometers High rate (dynamic system): 12 accelerometers West bell tower monitoring system (low and high rate): 2 MEMS triaxial accelerometers 2 inclinometers combined with laser distance meters (biaxial) 6 thermometers 4 strain gauges

provide useful information to complete the global overview of its health state. In addition to data obtained directly from sensors installed on-site, data collected through satellite surveys, such as displacement data (DInSAR), are also added. This supplementary data is valuable for gathering information that may not be available from the installed sensors (Fig. 8.6).

8.4 Future Works

In conclusion, the Sanctuary of Vicoforte currently benefits from an extensive array of sensors that facilitate a comprehensive characterization of its structural behaviour (Fig. 8.6). The data obtained are essential for validating the numerical model, enhancing its accuracy, and enabling real-time tracking of structural changes while accounting for inherent uncertainties. This development has culminated in an effective Digital Twin capable of not only monitoring current structural conditions but also predicting future behaviours. Looking ahead, the installation of corner reflectors on the four towers will enhance the system's capabilities by enabling continuous data collection through satellite remote sensing, specifically utilizing CosmoSkyMed (ReLUIS, 2023) acquisitions. This upgrade will provide valuable additional data regarding the structure's integrity. Moreover, the integration of these displacement measurements with data from in-situ sensors will allow for comprehensive correlations and validations. This approach not only bolsters the reliability of the Digital Twin but also represents a significant advancement in the application of satellite data for structural monitoring, paving the way for more resilient and informed management of heritage structures.

References

Ceravolo, R., Pistone, G., Fragonara, L. Z., Massetto, S., & Abbiati, G. (2016). Vibration-based monitoring and diagnosis of cultural heritage: A methodological discussion in three examples. *International Journal of Architectural Heritage, 10*(4), 375–395.

Ceravolo, R., De Marinis, A., Pecorelli, M., & Zanotti Fragonara, L. (2017). Monitoring of masonry historical constructions: 10 years of static monitoring of the world's largest oval dome. *Structural Control and Health Monitoring, 24*(10), 2017.

Ceravolo, R., De Lucia, G., Miraglia, G., & Pecorelli, M. L. (2020). Thermoelastic finite element model updating with application to monumental buildings. *Computer-Aided Civil and Infrastructure Engineering, 35*(6), 628–642.

Chiorino, M. A., Spadafora, A., Calderini, C., & Lagomarsino, S. (2008). Modeling strategies for the world's largest elliptical dome at Vicoforte. *International Journal of Architectural Heritage, 2*(3), 274–303.

Chiorino, M. A., Ceravolo, R., Spadafor, A., Zanotti Fragonara, L., & Abbiati, G. (2011). Dynamic characterization of complex masonry structures: The Sanctuary of Vicoforte. *International Journal of Architectural Heritage, 5*(3), 296–314.

Cozzo, P., De Lucia, G., & Longhi, A. (2017). Un prodigio "sfortunato"? Valori e ambizioni disattese di un luogo "miracolato": Il Santuario di Vicoforte (Mondovì). In *Conoscere, conservare e valorizzare. Il patrimonio religioso culturale* (pp. 63–70). Aracne Editrice.

Pecorelli, M. L., Ceravolo, R., & Epicoco, R. (2020). An automatic modal identification procedure for the permanent dynamic monitoring of the Sanctuary of Vicoforte. *International Journal of Architectural Heritage*.

Peeters, B., & De Roeck, G. (2001). One-year monitoring of the Z24-Bridge: Environmental effects versus damage events. *Earthquake Engineering & Structural Dynamics, 30*(2), 149–171.

ReLUIS. (2023). *Pubblicata la Prima Versione delle Linee Guida per l'Utilizzo dei Dati Interferometrici Satellitari Ai Fini dell'interpretazione del Comportamento Strutturale delle Costruzioni*. https://www.reluis.it/news/news-2023/830/linee-guida-per-l-utilizzo-dei-dati-interferometrici-satellitari-ai-fini-dell-interpretazione-del-comportamento-strutturale-delle-costruzioni/

Scandella, L., Lai, C. G., Spallarossa, D., & Corigliano, M. (2011). Ground shaking scenarios at the town of Vicoforte, Italy. *Soil Dynamics and Earthquake Engineering, 31*(5–6), 757–772.

Chapter 9
The Ponari Nymphaeum of Cassino: First Steps Towards a New Approach

Eugenio Polito, Arturo Gallozzi, Vincenzo Graffeo, Francesca Pierdominici, and Alessandra Ferrara

Abstract The Ponari Nymphaeum, dating from the first century BC to second century AD, is an important example of Roman residential architecture located in the ancient Roman town of Casinum, at the foothill of Montecassino Abbey. It has a rectangular structure with nine square niches, and was originally decorated with rustic mosaics evoking caves and caverns. Later, the walls were covered with painted plaster imitating marble, consistent with the evolution of Roman taste. The nymphaeum opens onto an atrium with an impluvium, paved with a white mosaic and decorated with paintings simulating a garden (paradeisos) and an isodomic wall structure. The presence of the atrium makes the Ponari nymphaeum unique, distinguishing it from the more common type of nymphaeum as an independent structure. Besides illustrating the different construction and decorative phases of the nymphaeum, the paper describes the survey and documentation techniques used, including laser scanning and photogrammetry, to create 3D digital models and a 2.5D virtual tour. Furthermore, it highlights the critical issues related to the nymphaeum structure and the need for conservation interventions. It emphasises the importance of an in-depth analysis of structural materials and the definition and cataloguing of critical processes and risks, both natural and man-made, that threaten the integrity of the archaeological asset. Finally, it proposes the implementation of multi-criteria

---

E. Polito
Roma Tre University, Roma, Italia
e-mail: eugenio.polito@uniroma3.it

A. Gallozzi (✉)
University of Cassino and Souhtern Lazio, Cassino, Italy
e-mail: arturo.gallozzi@unicas.it

V. Graffeo · F. Pierdominici · A. Ferrara
DTC Lazio—Cultural Heritage and Activities Technological District—Center of Excellence, Rome, Italy
e-mail: alessandra.ferrara@unicas.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_9

monitoring procedures to continuously assess the state of conservation of the Ponari Nymphaeum, thus ensuring its long-term preservation.

Keywords Ponari Nymphaeum · Rustic mosaic · Heritage Building Information Modelling (HBIM) · Digital twin · Structural Health Monitoring (SHM) · Cassino

9.1 The Ponari Nymphaeum of Casinum: Architecture, Decoration and Restoration of a Roman Monumental Complex

The Ponari Nymphaeum (Fig. 9.1) is located upstream of the urban system of ancient Casinum, a short distance from the Theatre, occupying one of the northern quadrants where the main domus of the Roman city were located (Fig. 9.2) (Carettoni, 1940; Polito, 2013; Tanzilli, 2016).

The monument dates from between the first century BC and the second century AD. It is a rectangular room, partially recessed into the slope, closed on three sides and completely open on the front, and covered by a cement barrel vault. The three straight walls are enlivened by the presence of nine square niches with a flat roof. The floor of the Nymphaeum is decorated with a refined polychrome mosaic floor, forming a chessboard in which fragments of coloured marble are inserted. The weaving, despite the numerous inserts, is quite regular and accurate, even if the

Fig. 9.1 3D point cloud processing with textures

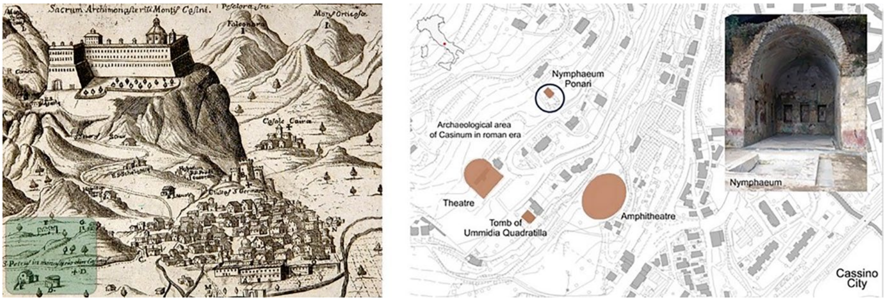


Fig. 9.2 Location of the Ponari Nymphaeum in the context of the archaeological area of the Roman Casinum

Fig. 9.3 Left: polychrome mosaic floor in the Nymphaeum—right: black dotted white mosaic floor and marble inserts in the entrance area

colours of the tesserae are randomly distributed, with only the alternation between the white and coloured ones being strictly respected (Fig. 9.3). The use of coloured marbles, the horizontal warp and the chequered pattern seem to point to comparisons attested in the late Republican period (Valenti, 1992).

The walls, on the other hand, preserve the remains of two different decorations: the first is called rustic mosaic, which, in a second phase, is covered with painted plaster imitating marble (Valenti, 1992, 1994). The rustic decoration, made with the intention of artificially evoking caves and underground caverns connected with water (Neuerburg, 1965), is executed with the application on the wall of shells, coloured glass in geometric shapes, limestone fragments, Egyptian blue and white quartz tiles (Fig. 9.4 left). It has been possible to identify a tripartite decorative scheme: in the upper part it is organised in parallel bands, in the middle part it is marked by the presence of niches surmounted by triangular pediments, and in the lower part, which develops below the floor of the niches, it is delimited at the top by a band with alternated circular and rhomboidal polychrome glass tiles, characterised by a lozenge grid pattern that recalls cocciopesto and wrought stone floors of the late Republican period (Valenti, 1994).

Fig. 9.4 Left: detail of the rustic mosaic warp—right: right wall of the Nymphaeum, painted plaster imitating marble slabs

The Ponari Nymphaeum probably underwent a series of renovations that also affected the rustic mosaic wall decoration, which was replaced with painted plaster. This change reflects the evolution of taste and decorative techniques in the Roman period: as time went by, painted plaster established itself as the main technique for interior decoration, thanks to its versatility and the possibility of creating increasingly refined pictorial effects (Falzone, 2007). In the case of the Ponari Nymphaeum, painted plaster is characterised by imitations of coloured marble slabs. This decorative style, typical of the first century AD, was characterised by the elegance and refinement of its compositions (Fig. 9.4 right).

The extension of the excavation towards the area in front of the nymphaeum revealed that the room opened onto an atrium with an impluvium (rainwater collection basin), bordered by side walls marked vertically on the façade by pilasters (Betori, et al., 2009; Betori, 2009). The area is paved with a white mosaic and is arranged around a square compluvium basin lined with white marble. The painted decoration of the walls of the atrium is marked by two registers: at the bottom runs a paradeisos-themed baseboard in a deep red colour, on which beasts are depicted against a background of shrubs, intended to simulate a garden scene (Fig. 9.5 left) (Guiral & Mostalac, 2005). Above this runs an imitation in painting of an isodomic wall apparatus. On the right head of the nymphaeum half of a standing figure apparently moving towards the entrance of the nymphaeum is preserved (Fig. 9.5 right). Due to the considerable stylistic difference from the feline figures on the plinth, it is probably a later insertion testifying to a further decorative phase of the com-plex. The presence of the atrium in front of the nymphaeum and the adjacent masonry structures suggests a more complex organism, hypothesising a large domus inserted into the fabric of the late republican city (Betori et al., 2009; Betori & Vincenti, 2017).

Fig. 9.5 On the left detail of the plinth of the atrium—on the right detail of the standing figure incident on the right head of the Nymphaeum

9.2 Specific Achievable Objectives

OO1: Evolution of the state of the art and semantic organisation
The evolution of the state of the art and semantic organisation in the Ponari Nymphaeum is evident in the different decorative phases that affected the structure (Valenti, 1992, 1994). Initially, the Nymphaeum had a rustic mosaic decoration, using simple materials such as shells, coloured glass and fragments of limestone. This decorative choice, typical of an older taste, aimed to evoke the natural environment of caves and underground caverns, in line with the Nymphaeum's function as a place dedicated to water (Neuerburg, 1965; Cifarelli, 1995; Cifarelli & Valenti, 1999). Later, the Nymphaeum underwent a significant transformation, with the abandonment of rustic mosaic and the introduction of painted plaster. This new decorative technique, typical of the first century AD, reflected the evolution of taste towards greater refinement and elegance. The imitation of coloured marble slabs in the plaster testifies to the search for greater preciousness and a more sophisticated aesthetic. The semantic organisation of spaces also underwent an evolution. Initially, the Nymphaeum appeared as a rectangular room with nine niches, entirely dedicated to rest and pleasure of the senses.

The extension of the excavation then revealed the presence of an atrium in front of it, also decorated on the walls, in a first phase, by rustic mosaic, later covered by paintings simulating a garden (*paradeisos*-themed), the floor instead presenting a white mosaic and an *impluvium* (Betori, 2009; Betori et al., 2009). The presence of the atrium suggests a very precise organisation of spaces, which served as a reception area and passage to the Nymphaeum. The choice of representing a *paradeisos*-themed in the atrium, with its connotations of abundance and serenity, contributed to creating a pleasant and relaxing atmosphere, typical of a place dedicated to conviviality and pleasure.

OO2: Analysis of available experimental data
OO3: Definition of a Digital Twin
OO4: Definition of a Web GIS model
OO5: Preparation of a monitoring system.

The objectives of the documentation campaign are:

Table 9.1 Master data

Object	Nymphaeum
Scale of reference	The Ponari Nymphaeum in the archaeological area of *Casinum*
Original/current use	Nymphaeum Probable annexe of a Roman domus
Author	–
Location	Archaeological site of Casinum, via Montecassino SR 149, Cassino (FR)
Geographic coordinates	41.484450097717385 N—13.822469593767584 E
Chronology	First century BC—First century AD
Property	Università degli Studi di Cassino e del Lazio Meridionale (formerly owned by the Ponari family)
ICCD file	–
Conservation authority	Soprintendenza Archeologia, belle arti e paesaggio per la provincia di Frosinone e Latina
Constraints	Archaeological constraint: “Ninfeo Ponari, strutture murarie” (Ex Lege 1089/39:D.M. 05.10.1974)—Identificativi Regione Lazio: ID RL arp_0202—Beni del patrimonio archeologico—puntuale—art.10 *d.lgs.* 42/04 (Fig. 9.6 left) At the edge of the Montecassino Natural Monument, established by Presidential Decree Lazio 11 March 2010, n. 154 (B.U.R. of 14 April 2010, n. 14), significant naturalistic and historical-archaeological interest - Management Body: Ente Parco Monti Aurunci
Keywords	Cultural Heritage; Ponari Nynphaeum of Cassino; Heritage Building Information Modelling (HBIM); Structural Health Monitoring (SHM); Finite Element Modelling; Structural Analyses; Web Gis comunication
Risk Map (MiC) Directorate General for Cultural Heritage Security	Cultural Heritage: not signalled Vulnerability/risk: not signalled Hydrogeological risk—ISPRA: Landslide risk, potentially high risk area (Fig. 9.6 right)
Type of risk	Anthropogenic risk: discontinuous maintenance Natural/environmental risks: marked steepness of the site with risk of landslides, risk of damage from wild animals (wild boar) Effects of climate change: increased atmospheric precipitation Indirect risks: seismic vulnerability of the Cassino area

(continued)

Table 9.1 (continued)

Research team	CdE DTC Lazio (Distretto Tecnologico beni e attività Culturali—Centro di Eccellenza) Scientific Advisors: prof. Eugenio Polito; prof. Arturo Gallozzi UNICAS (Università degli Studi di Cassino e del Lazio Meridionale): – Dipartimento di Scienze Umane, Sociali e della Salute – DART Laboratorio di Documentazione, Analisi, Rilievo e Tecnica dell'Architettura, responsabile: prof. Michela Cigola – LaRSArA Laboratorio di Ricerche Storiche e Archeologiche dell'Antichità, responsabile: prof. Eugenio Polito Researchers CdE DTC Lazio: dr. Vincenzo Graffeo (Senior); dr. Francesca Pierdominici (Junior); dr. Alessandra Ferrara (Junior) Collaboration: – LAPS—UNICAS—Laboratorio di Analisi e Progettazione Strutturale: prof. Maura Imbimbo (Responsabile); prof. Valentina Tomei; prof. Ernesto Grande; dr. Marina Serpe – LaGGS—UNICAS—Laboratorio di Geotecnica, Geologia e Strade, responsabile: prof. Giuseppe Modoni – ENEA—Centro Ricerca Frascati: dr. Michele Arturo Caponero; dr. Cristina Mazzotta; dr. Davide Vicca; dr. Rosaria D'Amato – CRITEVAT—UNIROMA Sapienza—Centro Reatino di ricerca di Ingegneria per la Tutela e Valorizzazione dell'Ambiente e del Territorio: prof. Leonardo Paris; prof. Maria Laura Rossi

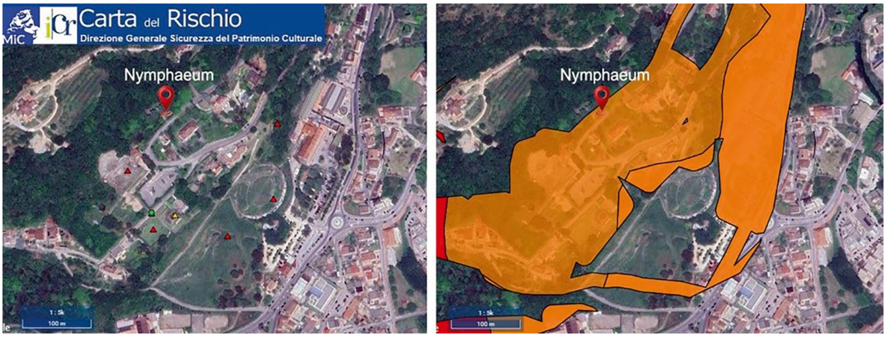


Fig. 9.6 Risk Map: General Directorate for the Safety of Cultural Heritage—Ministry of Culture. On the left a map of the Cultural Assets reported in the archaeological area of Casinum—on the right ISPRA Hydrogeological Risk map, Landslide Risk

- production of a metric representation of the shape and appearance of the artefact, (to carry out mapping of the state of preservation and crack paintings).
- production of a three-dimensional model to assess environmental and anthropic risks.
- realisation of a three-dimensional model for the representation of the crack framework.
- realisation of a three-dimensional model for communication.
- support the monitoring system for structural diagnostics (Table 9.1).

9.3 Survey, Monitoring and Diagnostic Techniques

Considering the research objectives, it was decided to produce different types of digital models aimed at investigating specific aspects (Gallozzi et al., 2017). Surveys were carried out to analyse the site's environmental conditions: terrain acclivity and level of accessibility, exposure and any interference from conterminous vegetation: the Ponari Nymphaeum site is composed of archaeological remains ranging from masonry works to floor and wall decorations, so it is important to use the best data acquisition and processing strategies, depending on the individual archaeological specificities.

For the survey campaign, the combined use of laser scanning and photogrammetry was chosen (Gallozzi et al., 2017; Caponero, 2021). Laser scanning allows the production of a digital model with good definition that can be used for the cognitive purposes of dimensional and material aspects. Photogrammetry makes it possible to obtain a restitution with a higher resolution and more detailed textures. On the Ponari nymphaeum, the laser scanner survey is integrated with spherical panoramas realised with an external camera on a panoramic head. In this way, thanks to the use of the High Dynamic Range (HDR) technique, the image from the 3D scanner's internal camera is replaced with a higher resolution image with better exposure compensation.

In the next post-processing step, the point cloud is processed (Figs. 9.7 and 9.8). The quality of the surface model depends on both the quality of the point cloud and the algorithm used to generate the mesh surface from the point sets (in this case the Poisson algorithm is used). From the textured 3D model, 2D graphics are extracted: horizontal and vertical sections containing the specific information. The 3D model obtained in this way can be used for the monitoring of the asset over time, for the evaluation of the crack framework and for the purposes of dissemination for the creation of virtual tours.

A second output is the creation of a 2.5D model: a virtual tour of the nymphaeum realised with spherical panorama photos and hotspots to navigate the environment and access information content. Two types of hotspots can be created: (1) Dynamic: moving model; (2) Static: photos and cards (Fig. 9.9).

Finally, the georeferenced 3D model placed on the web GIS at the spatial scale, accompanied by the database and links to retrieve the information collected can be published and shared on the web (Fig. 9.10) (Pierdominici, 2020).

Workflow

- inspections and instrument testing
- acquisition planning
- laser scanner acquisitions
- measurement of photogrammetric targets placed on the artefact and photographic acquisitions
- download and archiving of raw data (scans and photographs)
- pre-processing of raw data (colour allocation to scans and radiometric correction of photos)

Fig. 9.7 3D processing from point cloud—zenith view

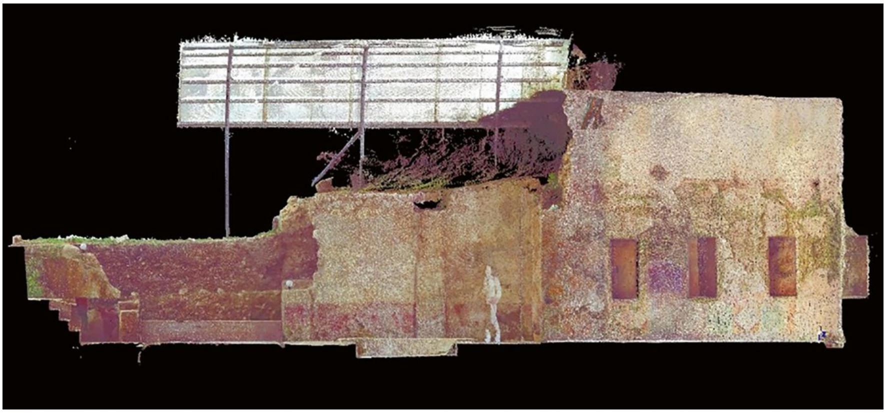


Fig. 9.8 3D processing from point cloud—longitudinal section

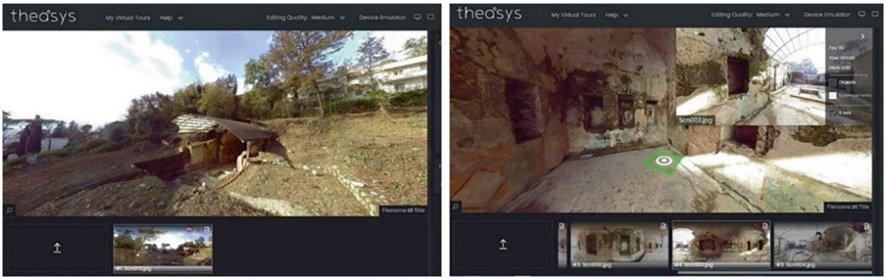


Fig. 9.9 Virtual Tour 2.5D processing by Theasys

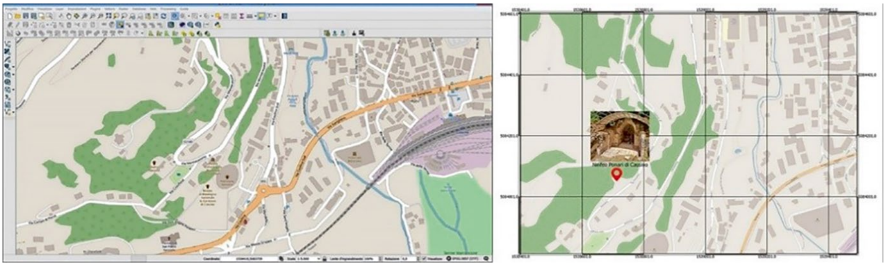


Fig. 9.10 QGIS cartographic processing from Open Street Map

Table 9.2 Outputs and tools

Scale of representation, resolutions	Graphics Rapp.: 1:100; 1:50; 1:20 Resolution of three-dimensional models Diagnostics, Structures
Expected outputs	Orthogonal projection drawings (plans, elevations, sections) Thematic mapping Surface models Diagnostics, Structures
Instruments (HD/SW)	Instrumentation available at the DART and LaRSArA laboratories, together with the instrumentation available at the collaborating structures (ENEA, LAPS and LaGGS laboratories of UNICAS, CRITEVAT UNIROMA Sapienza laboratory

- alignment of scans
- photogrammetric processing
- panoramic photo acquisition
- virtual tour processing with 2.5D model
- realisation of a GIS web model with inclusion of digital twin and collected data
- realisation of the expected deliverables
- setting up of monitoring systems and procedures (Table 9.2).

9.4 Results and Discussion

The Ponari Nymphaeum, with its rectangular hall structure and nine square niches, represents an important example of how Roman aristocratic families integrated rooms dedicated to rest and pleasure within their dwellings (Polito, 2013). The walls, initially decorated with rustic mosaics that recalled caves and caverns, were later covered with painted plaster imitating marble, evidence of the evolution of taste in Roman times (Valenti, 1992, 1994; Falzone, 2007). The atrium in front, with its impluvium marble basin, was paved with a white mosaic and decorated with paintings simulating a garden (*paradeisos*) and an isodomic wall apparatus, creating an elegant and refined atmosphere (Betori, 2009; Betori et al., 2009). The presence of the atrium, together with its function as a summer *coenatio*, makes the Ponari Nymphaeum unique in its kind, distinguishing it from the more common type of nymphaeum as an independent structure.

Following the recent cleaning of the decorative apparatus, it is now possible to assess more carefully the state of conservation of the artefact and the criticalities caused by the lesions on the nymphaeum structure, in order to plan the conservation actions to be undertaken on the archaeological asset and the possible preparations to be made for its preservation (Caponero et al., 2020, 2021; Modoni et al., 2022).

9.5 Future Works

The Ponari Nymphaeum represents an important example of Roman residential architecture. Its different building and decorative phases, together with the richness of its mosaics, provide valuable information on the history of Cassino and its territory (Polito, 2013; Tanzilli, 2016). The polychrome floor of the Nymphaeum could prove fundamental in clarifying certain doubts concerning the different phases of its history (Betori & Vincenti, 2017). For this reason, in agreement with the Soprintendenza Archeologia, Belle Arti e Paesaggio for the provinces of Frosinone and Latina, an exploratory survey will be conducted. In addition, upon closer examination, the polychrome floor shows a series of ancient renovations, and it would therefore be useful to carry out a mapping of the floor, highlighting the restorations carried out.

In summary, the following future operational steps are identified:

- Integrated Structural Materials Investigation: Perform an in-depth and integrated analysis of structural materials, in order to understand their nature, physical-mechanical characteristics and degradation conditions, through non-destructive investigations and techniques.
- Define, analyse and catalogue critical processes and risks, both natural and man-made. Identify and analyse all critical and risk processes that threaten the integrity of the archaeological asset, considering both natural factors (such as erosion, earthquakes, atmospheric phenomena) and anthropic factors (such as vandalism,

urbanisation or tourism activities). Cataloguing these risks to develop mitigation strategies and preventive management plans, ensuring the long-term preservation of the site.

- Completing the Post-Processing Phase. Complete the post-processing process of the data collected during the survey and investigation activities to convert this information into a useful and usable format. This step includes the validation, systematisation and organisation of the data into appropriate databases for future analysis and conservation work.
- Implementation of the creation of Digital Models (Virtual Twins). Develop digital models of the Nymphaeum, acting as virtual twins, to accurately replicate the object and allow for detailed analyses, simulations of conservation interventions, and the dissemination of knowledge about the site. Such models are essential to monitor the evolution of the condition of the property and to engage the public through interactive visualisation tools (Gallozzi et al., 2017).
- Preparation of Multi-Criteria Monitoring Procedures. Define and implement multi-criteria monitoring procedures to continuously assess the state of conservation. These procedures should include monitoring of structural, environmental conditions and risk factors, through the integration of advanced sensing techniques (such as environmental sensors and remote sensing technologies) to obtain a holistic view of site dynamics (Caponero et al., 2020, 2021; Modoni et al., 2022).

9.6 Available Metadata and Paradata: Sources of Exchange

For the realisation of the 3D model, the integrated laser scan and photogrammetry survey technique was adopted, which makes it possible to acquire the geometric data and the material/decorative components of the artefact being researched (Gallozzi et al., 2017).

The data available to date, which are currently being processed, are those derived from the survey campaign carried out in 2020, born out of the collaboration between DART (Laboratory for the Documentation, Analysis, Survey and Technique of Architecture) and CRITEVAT (Centre for Research on Engineering for the Protection and Enhancement of the Environment and Territory).

In order to permanently monitor the structures for possible deterioration, the data of the survey campaign carried out by ENEA (Frascati research centre) in collaboration with the LAPS of the University of Cassino and Southern Lazio was acquired; the survey was aimed at mapping the state of the cracking framework, also documenting the areas attacked by mould and lichens, the presence of gaps and detachments, and the qualitative state of the colouring (Caponero et al., 2020, 2021).

The geotechnical monitoring was carried out with the cooperation of the LAGGS of the University of Cassino and Southern Lazio (Modoni et al., 2022).

The Ponari Nymphaeum, like many other archaeological structures, is exposed to various natural and man-made hazards that may threaten its integrity and conservation. Among the natural hazards, landslides and soil erosion pose a significant danger, especially considering its embedded position in the slope. Weathering, including heavy rainfall and temperature variations, can damage decorations and wall structures, compromising the mosaic and painted plaster. In addition, climate change may accentuate these risks by increasing the frequency and intensity of extreme weather events, such as floods and droughts, which may compromise the stability of foundations and the microclimate of the environment.

On the other hand, anthropogenic risks include the impact of tourism, which can cause physical wear and tear and direct damage to structures, as well as potential environmental contamination. Fortunately, there are no modern structures in the vicinity that could affect the local ecosystem and archaeological context, altering drainage conditions and increasing the risk of water infiltration.

To address these risks, it is crucial to implement sustainable management strategies, including monitoring and conservation programmes, to protect the Ponari Nymphaeum and ensure that this important historical site can be enjoyed by future generations (Modoni et al., 2022).

For the assessment of anthropogenic and environmental risks, a spatial-scale GIS model was chosen. GIS systems allow for the acquisition of varied data in terms of both format and quality aspects. In a first step, a data/attribute grid will be created for the construction of a QGIS model based on overlay mapping, after which the model will be published and shared online (Pierdominici, 2020).

References

Betori, A. (2009). Cassino, novità dal Ninfeo Ponari. La pavimentazione dell'atrio. In *AISCOM XIV* (pp. 195–199).

Betori, A., & Vincenti, V. (2017). Nuovi pavimenti dalla Domus del Ninfeo Ponari di Cassino. In *AISCOM XXIII* (pp. 447–459).

Betori, A., Valenti, M., & Tanzilli, S. (2009). Ninfeo Ponari di Cassino: Nuove acquisizioni e prospettive di valorizzazione. In G. Ghini (Ed.), *Lazio e Sabina 5* (pp. 483–498). Atti del convegno Quinto Incontro di Studio sul Lazio e la Sabina.

Caponero, M. A., Corsi, C., Mongelli, M., Imbimbo, M., Polito, E., Modoni, G., & Grande, E. (2020). Tecnologie per il monitoraggio strutturale del Ninfeo Ponari di Cassino. Una sperimentazione in collaborazione tra ENEA ed Università di Cassino. In C. Arcangioli & M. S. Sarto (Eds.), *Centro di eccellenza DTC Lazio. Atti del I Convegno annuale (Roma, 30 settembre 2019), Roma 2020* (pp. 69–71).

Caponero, M. A., Mongelli, M., Imbimbo, M., Polito, E., Modoni, G., & Grande, E. (2021). Structural monitoring of the Ninfeo Ponari by fibre optic sensors, photogrammetry and laser scanning. *Archeologia e Calcolatori*, 223–232. CNR, ISSN: 1120-6861.

Carettoni, G. F. (1940). Casinum, presso Cassino. In *Italia romana: Municipi e colonie, s. I* (Vol. II).

Cifarelli, F. M. (1995). Un ninfeo repubblicano a Segni con la firma di Q. Mutius architetto. In *Tra Lazio e Campania. Ricerche di Storia e di Topografia antica* (pp. 159–188). Università degli Studi di Salerno. Quaderni del Dipartimento di Scienze dell'antichità, 16 – Serie Storia Antica e archeologia, II.

Cifarelli, F. M., & Valenti, M. (1999). Due nuovi ninfei decorati nel Lazio meridionale. In *La Mosaïque Gréco Romaine VII, Actes du VII Colloque International pour l'Étude de la Mosaïque Antique, 3–7 octobre 1994, Tunis* (pp. 673–680).

Falzone, S. (2007). *Ornata aedificia. Pitture parietali dalle case ostiensi, Roma.*

Gallozzi, A., Paris, L., & Wahbech, W. (2017). 3D models and interactive communication for archaeology: The Nymphaeum Ponari in Cassino. In *Conference: Digital Archaeologies, Material Worlds (Past and Present)—CAA 2017, Atlanta, GA* (pp. 401–411).

Guiral, C., & Mostalac, A. (2005). Representació d'arbres, flors i plantes en la pintura romana. In J. d'Empupùrie (Ed.), *La jardineria en època romana, Girona* (pp. 53–60).

Modoni, G., Imbimbo, M., Serpe, M., Polito, E., Saccucci, M., Spacagna, R. L., Grande, E., Caponero, M. A., Mongelli, M. L., & Valenti, M. (2022). Geotechnical-structural engineering for the preservation of Ninfeo Ponari in Roman Casinum. In *Engineering for the Preservation of Monuments and Historic Sites III—Proceedings of the 3rd International ISSMGE TC301 Symposium, 2022 Open Access, Napoli 22 June 2022 through 24 June 2022* (pp. 583–594).

Neuerburg, N. (1965). L'architettura delle fontane e dei ninfei nell'Italia antica. In *Memorie dell'Accademia di Archeologia, Lettere, e Belle Arti di Napoli 5, Napoli.*

Pierdominici, F. (2020). La raccolta dati in ambiente QGIS per un modello territoriale nazionale dei ponti antichi. In C. Inglese & L. Paris (Eds.), *Arte e tecnica dei ponti romani in pietra* (pp. 77–100).

Polito, E. (2013). Il complesso archeologico di Cassino: uno sguardo d'insieme nel segno di Ummidia. In P. Gabriella (Ed.), *Studi in ricordo di Gabriella Braga, III, a cura di Marco Palma e Cinzia Vismara* (pp. 1453–1469). Edizioni Università di Cassino.

Tanzilli, S. (2016). *Cassino. Architettura, archeologia, arte, storia*. Formia.

Valenti, M. (1992). Il "Ninfeo Ponari" di Cassino (FR): Analisi stilistica e cronologica delle decorazioni. In *Archeologia Classica XLIV, Roma* (pp. 51–80).

Valenti, M. (1994). Il mosaico rustico a conchiglie e il ninfeo Ponari di Cassino. Riflessioni su una moda decorativa di età tardo-repubblicana. In *AISCOM II* (pp. 49–60).

Chapter 10
Operational Methods Implemented for the Monitoring of the Artworks Preserved in the Museum and the Conclave Hall of the "Colle del Duomo Museum Complex" of the Viterbo Diocese, Lazio—Italy

Luca Lanteri and Claudia Pelosi

Abstract The present contribution is developed within the Spoke 7 of the project CHANGES and focuses on the "Colle del Duomo Museum Complex", a monumental contest located in the city of Viterbo, Central Italy, which includes: the so-called Palace of the Popes, the Saint Lawrence Cathedral and the Museum Colle del Duomo. Objectives of the project are: (1) the monitoring of the microclimate through various sensors in order to highlight the aspects related to anthropic and climatic risk on the objects preserved in the Conclave Hall and in the art-historical section of Colle del Duomo complex, and to find possible solutions to solve or at least mitigate the problems; (2) the creation of 3D diagnostic digital twins on the polychrome wooden reliquary busts by using ultraviolet radiation. This allows to create a virtual gallery and to evaluate the state of preservation of the museum selected objects. The acquisition of ultraviolet fluorescence (UVF) frames was performed on six reliquary busts by using a photogrammetric approach. The microclimate monitoring was performed through both traditional dataloggers and Wi-Fi systems controlled by a PC or mobile phone application. A synthesis of the most relevant results is reported in the paper.

Keywords Small museums · Ultraviolet 3D models · Digital twins · In-cloud microclimate monitoring

---

L. Lanteri
Technological District of Cultural Heritage of Lazio Region, Lazio, Italy
e-mail: llanteri@unitus.it

C. Pelosi (✉)
University of Tuscia, Viterbo, Italy
e-mail: pelosi@unitus.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_10

10.1 Description of the Artifact

The present contribution is developed within the Spoke 7 of the project CHANGES and focuses on the “Colle del Duomo Museum Complex”, a monumental contest located in the city of Viterbo, Central Italy, which includes: the so-called Palace of the Popes, the Saint Lawrence Cathedral and the Museum Colle del Duomo (Fig. 10.1) (Signorelli, 1964).

The Palace of the Popes is the most important monument in the city of Viterbo, built when the transfer of the seat of the Papal Curia (Pinzi, 1910). In 1257 the cardinals took up “permanent residence” in Viterbo by decision of Pope Alexander IV who, due to political instability in Rome, was forced to flee and took refuge in Viterbo where he died in 1260. The curia also moved with him and remained there at least until 1281.The architectural structure of the Palace of the Popes is the result of the expansion of the seat of the Episcopal Curia supervised by the nobleman from Viterbo Raniero Gatti, Captain of the People, who also built a large audience hall, today known as the “Conclave Hall”. This name is linked to the fact that the hall hosted the first and longest Conclave in the history of the Catholic Church (1268–1271) ended with the election of Pope Gregory X. During the conclave, the magistrates of Viterbo tired of bearing the expenses of the interminable meeting, which lasted 33 months, decided to remove the roof of the hall; the cardinals, exposed to the external climatic conditions, the following day elected the Pope. Another characteristic part of the Palace is the Loggia of the Popes built in 1267 and characterized by a series of trilobed point arches, as visible in the Fig. 10.1, right image.

Important sacred artworks of significant artistic and symbolic value are exhibited in the Conclave Hall: first, the vestments of Saint Boniface, made in linen, silk and gold embroidery. According to historical tradition, the robe arrived in Viterbo in 1172 after the conquest and destruction of the nearby city of Ferento. It is composed of four elements: the “alba”, the white liturgical vestment in linen; the amice, the rectangle again in linen that covers the priest’s shoulders; the stole, that represents the distinctive sign of the order and is made up of a strip of cloth that goes around

Fig. 10.1 The Cathedral of St. Lawrence with the entrance of the Diocesan Museum (left image), and The Conclave Hall in the so-called Palace of the Popes (right image)

the neck and falls on the chest; lastly the cincture, the cord with which the priest cinctures his hips over the alb. Another sacred object, is the Pallium belonging to Pope John XXI, born Pietro Hispano (1210–1277). The materials, the execution technique and the decorative motifs are typical of the second half of the thirteenth century, although there are no documents attesting to its certain provenance. Other important liturgical artworks are the so-called Antiphonaries. These are books (dimension: 75 × 55 cm) made of parchment and dated back to a period between thirteenth and fifteenthcentury. The Antiphonaries, written with various coloured inks and illuminated, are liturgical books used in the celebration of the Catholic rite for the canonical hours that contain the sung parts of the liturgy.

Adjacent to the “Conclave Hall” is the so-called “Sala Gualtiero”. The room, entirely frescoed and characterized by the presence of the coat of arms of Pope Clement VIII (1592–1605), is the result of the works decided by the Bishop Sebastiano Gualterio from Orvieto (1551–1566) who wanted to expand his Curia by adapting the two ancient rooms next to the Conclave Hall. At the beginning of the seventeenth century, Cardinal Tiberio Muti, bishop of the city of Viterbo in the years 1612–1636, made further expansions to the Palace, with the opening of two new doors in the room and with the insertion of his coat of arms on the architraves of these doors and in the frescoes.

The Colle del Duomo Museum was created in the Jubilee Year 2000 by the Episcopal Curia to preserve and expose the heritage of the diocese of Viterbo. The museum is divided into three sections: (1) the archaeological section with artefacts dating back to the Villanovan and medieval periods: (2) the art-historical section hosting important paintings from the twelfth to the eighteenthcentury, mainly attributed to artists operating the in territory of Viterbo; (3) the sacred art section containing metal objects and textiles as well as some paintings of Viterbo’s bishops and a collection of the twentieth century artist Francesco Nagni from Viterbo (Mechelli, 2000; Parisi et al., 2018).

Between the most relevant paintings of the art-historical section, it is worth noting the so-called “Madonna della Carbonara”, a panel tempera artwork dated back to the late twelfth—early thirteenth century. It was attributed to an artist from the Roman school and measures 40 × 80 cm. The panel painting owes its name to the homonymous church where originally it was stored. According to the local tradition the painting was left in Viterbo by the Knights of Rhodes with two other artworks. Other important paintings are “The Madonna with Child”, a tempera panel painting dated to the fifteenth century (dimensions 60 × 43 cm), by Benvenuto di Giovanni and “The Crucifixion”, attributed to the workshop of Michelangelo Buonarroti (50 × 40 cm). The “Crucifixion”, an oil panel painting, is dated back to the first two decades of sixteenth century, thanks to the deep investigations performed on it both concerning the wooden support and the painting layers, also by using innovative techniques (Laureti et al., 2019; Pelosi et al., 2020). Another important artwork is “The Deposed Christ” attributed to Pietro Vanni. The panting is an oil on canvas measuring 210 × 50 cm dated back and signed by the artist in 1876. It was donated by the Ascenzi family to the Cathedral of Viterbo. The “Saint Mark” tempera panel painting was made by the artist Francesco d’Antonio Zacchi from Viterbo well-known as “Il Balletta”. This panel painting, measuring 44 × 103 cm, is probably a later creation of the artist, dating back to the last years of his activity, therefore before 1476, the year of the author’s death (Lo Monaco et al., 2024).

Lastly, in the art-historical section, is exposed an interesting group of painted and gilded wooden reliquary busts, dedicated to martyrs and saints (Lanteri et al., 2019). The busts have been recently restored in the laboratory of the University of Tuscia and re-located in a specific area of the art-historical section of the museum. The busts were used in the past to decorate the cathedral of St. Lawrence, but, since 2000, they were moved to the Museum, becoming part of its collections.

10.2 Specific Reachable Goals

The chosen case study contains many works of art and monumental contexts that can be studied, thanks to the agreements already in place between University of Tuscia and the Diocese of Viterbo as well as with the Archeoares Society who manages the complex. In addition to the artworks inside the Colle del Duomo Museum and halls, there are architectural elements of great importance such as the staircase and the loggia of the popes who present major conservation problems caused by environmental but also anthropic factors (unsuitable past interventions). Regarding the problems of the loggia, a technical table was created by the Diocese of Viterbo in which University of Tuscia and also the Superintendence are involved, precisely to seek suitable solutions to save this important architectural context. Conservation strategies are also in place within the Colle del Duomo Museum to identify risk factors for the artworks conserved inside, both climatic and anthropic. Monitoring activities already carried out inside the Museum have concerned various rooms such as that of sacred vestments, that of papier-mâché busts, and the art-historical section. The monitoring has sometimes highlighted a non-good state of the artworks due to poor maintenance, lack of adequate fixtures, lack of adequate shielding of the windows, lack of air conditioners for RH and T. In some cases, the monitoring has highlighted critical issues linked above all to the thermo-hygrometric conditions, such as the case of the Crucifixion and of various other paintings exhibiting detachments of pictorial film and structural alterations of the support.

For these reasons, starting from what already exists, the design idea of University of Tuscia aims to achieve the following objectives, within the project CHANGES:

Objective 1: Completion and improvement of the monitoring of the microclimate through various sensors in order to highlight the aspects related to anthropic and climatic risk on the objects preserved in the Conclave Hall and in the art-historical section of Colle del Duomo complex, and to find possible solutions to solve or at least mitigate the problems.

Objective 2: Creation of 3D diagnostic digital twins on the polychrome wooden reliquary busts by using ultraviolet radiation. This allows to create a virtual gallery and to evaluate the state of preservation of the museum selected objects. The

3D documentation, performed at various times, has been used to check the effect of exposition environment on the artworks and of the restoration, recently concluded. The goal is to evaluate the anthropic risk and its possible combination with that of the microclimate linked to sudden changes in the environmental parameters.

10.3 Working Methodology and Instrumental Details

The acquisition of ultraviolet fluorescence (UVF) frames was performed on six reliquary busts by using a Nikon D5300 digital SLR camera 24 MP resolution, equipped with an 17/35 mm multifocal lens (focal length dx sensor = 52 mm) setting the following parameters: f/12, exposure time 30 s, ISO-200 sensitivity. UV irradiation was provided by two UV led lamp (peak emission 365 nm) positioned at 45° to the subject. On the camera optics, two filters (UV-IR cut, filter A) were mounted in order to eliminate the reflections of the UV and to attenuate the dominant blue typical of ultraviolet shots. The camera and lamps are fixed during acquisition, and the object is rotated (Fig. 10.2) (Lanteri & Pelosi, 2021; Bonizzoni et al., 2023).

The three-dimensional UVF models were obtained using Agisoft Metashape®, a user-friendly software package that provides a comprehensive Structure from Motion (SfM) approach which integrates digital photogrammetry and the computer vision facilities with the ability to process unsorted photographs into photorealistic,

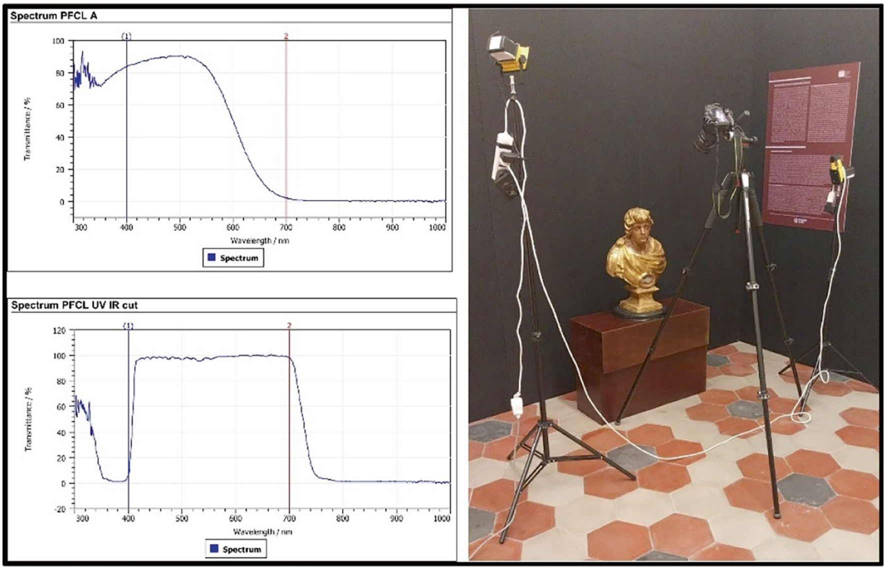


Fig. 10.2 % transmittance spectra of the two filters used for UVF photography and the operating setup in the museum for the bust's acquisition

geometrically accurate 3D models. The technique allows for the generation of the 3D structure using an image set acquired in a similar way to traditional photogrammetry, but with the advantage that the phases of the internal and relative orientation of the frames are completely automatized. SfM employs images overlapping and captured from multiple points of view with the further ability to simultaneously determine the internal geometry of the camera, its position, and orientation automatically. The high degree of overlapping of the frames, useful to cover the entire geometry of the object, gives rise to the name "structure derived from a motion sensor". The acquired frames were saved in .Jpg format with a resolution of 24MP, sRGB 24-bit depth, each frame size was 5.80 MB. The images were processed on a workstation with the following features: 11th Gen Intel (R) Core processor (TM) i7-11800H CPU @ 2.30 GHz; Ram 64 Gb; 64-bit system, Windows 11 Pro®; GeForce RTX 3060 6 Gb video card. To create the six 3D UVF models of the reliquary busts, approximately 50 shots for each object were taken, to obtain very detailed dense point clouds—on average approximately 40 million points depending on the complexity of the morphology. The rendered models were saved in .ply format (Fig. 10.3) and can be seen on Sketchfab at the following links:

https://sketchfab.com/3d-models/san-icodono-ridotto-623eeb3a3e6c40888f0c9663c5fc4adf;
https://sketchfab.com/3d-models/san-filomelo-3ef74f8fe0af4d2291b6898d6f72d391
https://sketchfab.com/3d-models/santo-stefano-ac0f26ccea1d466a822a499df5df1d3b
https://sketchfab.com/3d-models/san-leonardo-7bcff9ed23ae4221a50ba52b06285679
https://sketchfab.com/3d-models/santa-rosalia-8b4cf6c05837433c8c383b6266bf46fb
https://sketchfab.com/3d-models/san-rodonio-tempo-1-187ef9beb2de45388bde63390591a778

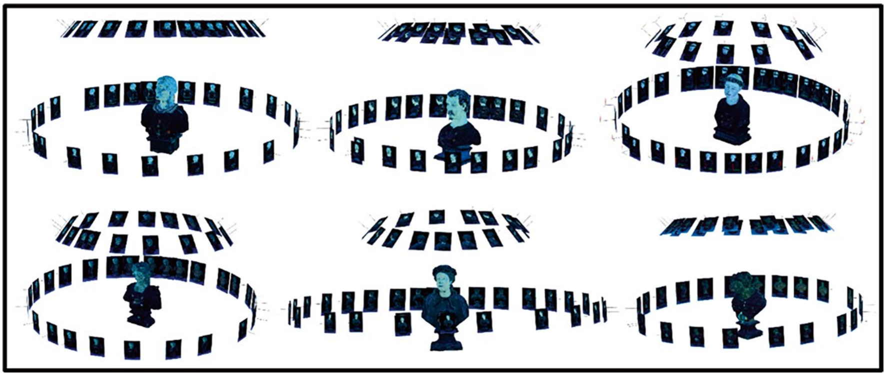


Fig. 10.3 The 3D UVF models of the six investigated busts

The combined methodology used to obtain 3D models in UVF has been developed for the first time in the Laboratory of Imaging of University of Tuscia and published in a 2019 paper (Lanteri et al., 2019).

For the climate monitoring project of the Museum art-historical section and of the Conclave Hall the following sensors were installed: two traditional datalogger Testo 175-H2; three Wi-Fi datalogger Testo 160 TH and two Testo 160 THL. The dataloggers Testo 175-H2 and 160 TH measure relative humidity (RH%) and temperature (°C), the datalogger 160 THL measure further the illuminance expressed in lux. In respect to the traditional Testo datalogger 175-H2, the new instrument 160 TH acquires also dew point temperature and absolute humidity. The measuring range of the Testo 175-H2 dataloggers is from 0% to 100% for RH% and precision ±3.0%, and from −20 °C to +70 °C for temperature with a precision of ±0.5 °C. The measuring range of the Testo 160 dataloggers is from 0% to 100% for RH% with precision ±2%, from −10 °C to +50 °C for temperature with a precision of ±0.5 °C, and from 0 lux to 20.000 lux with a precision of ±3 lux for illuminance.

The acquisition was set for registering the values of RH% and T (°C) at hour intervals so that 24 measures were gathered each day.

The data acquired by the datalogger Testo 175-H2 are downloaded manually on a portable computer by a specific Testo accessory. A first year of acquisition was completed for the art-historical section.

The new Wi-Fi dataloggers, Testo 160 TH and THL, are controlled by a PC or mobile phone application. In particular, the "Testo 160" monitoring system controls the climatic conditions inside the main room of the Conclave Hall and transmits the measurement values via the Wi-Fi network present in the Hall to the online archive (Testo Cloud, Fig. 10.4).

In case of alert the responsible of the Museum are immediately advised in order to intervene with solution that could eliminate or at least mitigate the problem. Specifically, the system launches alarms when the thermo-hygrometric thresholds, set according to the museum standards, are exceeded and an email alarm is

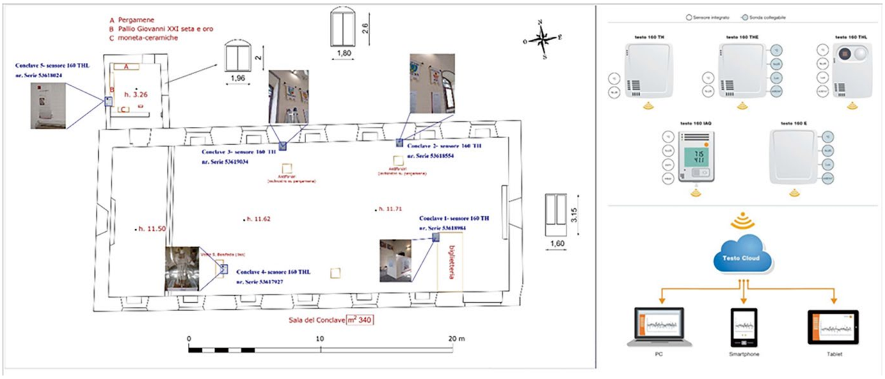


Fig. 10.4 The microclimatic monitoring project in the Conclave Hall (left) and the Testo 160 system operating scheme on the right

immediately sent. For illumination, it is possible to send an alarm even when the amount of light accumulated in a day, a week or a month exceeds one of the set thresholds. The threshold values are: for temperature minimum 10 °C and maximum 25 °C; for RH% minimum 35% and maximum 65%; for illuminance maximum 50 lux.

10.4 Results and Discussion

The microclimatic monitoring in the Museum Colle del Duomo for 1 year gives the results shown in the Figs. 10.5 and 10.6. By observing the trends of RH% and T, it is immediately clear that the values of these two parameters follow the seasonal changing, as normally occurs in the absence of conditioning systems, like the case of Colle del Duomo complex. Moreover, the values of RH% exhibit higher fluctuations in respect to those of temperature.

This situation is not recommendable for a correct preservation of the artworks, but also for the wellness of the visitors (too high temperatures in summer and too low in winter) (Pelosi et al., 2022). At the moment, the fluctuations have been limited by applying an isolating black film on the glass door (the emergency exit located immediately close to the painting attributed to the workshop of Antoniazzo Romano).

The real-time monitoring in the Conclave Hall highlighted an alarm situation concerning the illuminance values in the showcase of the St. Boniface vestment

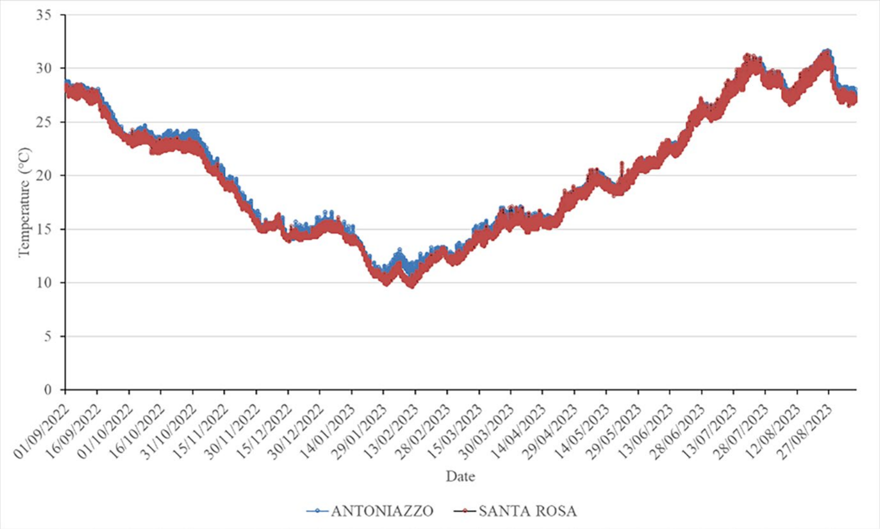


Fig. 10.5 Graph of the temperatures measured by two datalogger Testo 175-H2 positioned on the painting representing Santa Rosa and on the painting attributed to the school of Antoniazzo Romano

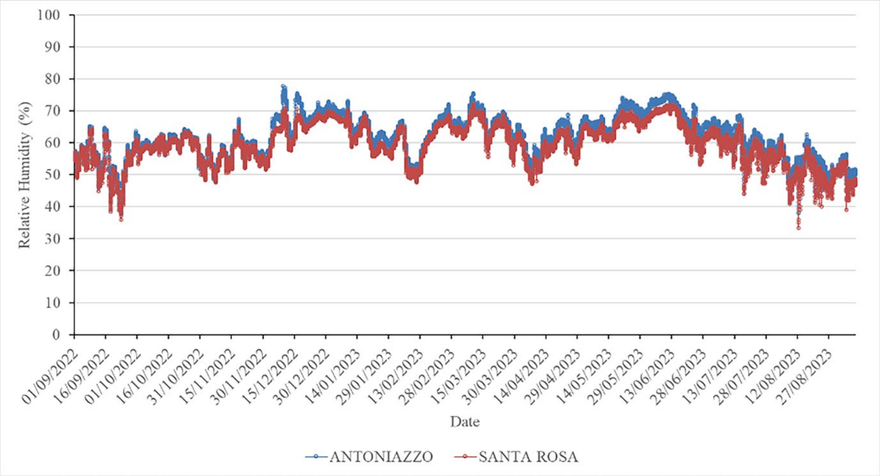


Fig. 10.6 Graph of the relative humidity values measured by two datalogger Testo 175-H2 positioned on the painting representing Santa Rosa and on the painting attributed to the school of Antoniazzo Romano

(Fig. 10.7). Here the datalogger registered excessive values of illuminance caused by the entrance of external sunlight from the large windows located on the south wall of the Hall. This problematic situation, promptly revealed by the sensos, requested an immediate intervention to mitigate the illuminance values. The emergency intervention consisted in the shielding of the window with a curtain. This decreased significantly the values of illuminance as shown in the Fig. 10.7.

The microclimatic conditions inside the Conclave Hall highlight trends similar to those registered in the art gallery of the Museum Colle del Duomo (see Figs. 10.5 and 10.6). In the Conclave Hall the fluctuations of thermoigrometric parameters are more evident due to the presence of large entrance door (always open to guarantee the visitors entrance), and large windows on both side (south and north) of the hall, which cause a constant thermic exchange with the outside. The windows have got normal glasses and non-insulating fixtures so that the external weather conditions determine those inside the Conclave Hall and, in general, in all Museum rooms.

10.5 Future Works

The future developments of the activities in the Colle del Duomo complex may be summarized as follows:

- Continue the monitoring, specifically in the room of the reliquary busts where they are now exposed, after the restoration.

Data - Ora	testo 160 THL_53617927 CONCLAVE 4 [lx]
07/03/2024 18:00:00	3,9
07/03/2024 17:00:00	68,4
07/03/2024 16:00:00	129,8
07/03/2024 15:00:00	160,5
07/03/2024 14:00:00	425,5
07/03/2024 13:00:00	280,9
07/03/2024 12:00:00	340,9
07/03/2024 11:00:00	477,4
07/03/2024 10:00:00	19953,3
07/03/2024 09:00:00	489,9
07/03/2024 08:00:00	134,4
07/03/2024 07:00:00	26,1
07/03/2024 06:00:00	0,0
07/03/2024 05:00:00	0,0
07/03/2024 04:00:00	0,0

Data - Ora	testo 160 THL_
02/06/2024 21:00:00	0,0
02/06/2024 20:00:00	13,1
02/06/2024 19:00:00	20,1
02/06/2024 18:00:00	84,7
02/06/2024 17:00:00	109,2
02/06/2024 16:00:00	104,7
02/06/2024 15:00:00	115,6
02/06/2024 14:00:00	127,4
02/06/2024 13:00:00	95,6
02/06/2024 12:00:00	87,6
02/06/2024 11:00:00	91,4
02/06/2024 10:00:00	26,6
02/06/2024 09:00:00	12,3
02/06/2024 08:00:00	20,5
02/06/2024 07:00:00	14,2

Fig. 10.7 Comparison between the values of illuminance before and after the mitigating emergency intervention in two sunny days

- Constitute a working group with the society Archeoares and with the Diocese in order to plan long lasting solutions in substitution of emergency interventions.
- Dissemination and training activities addressed to the museum operators on best practices to mitigate climatic and anthropic effects on artworks.
- Musealization of diagnostic results and monitoring campaigns addressed to the public with the aim at stimulating the visitors to the knowledge of the safeguard processes for cultural heritage.

References

Bonizzoni, L., Caglio, S., Galli, A., Lanteri, L., & Pelosi, C. (2023). Materials and technique: The first look at Saturnino Gatti. *Applied Sciences, 13*(11), 6842. https://doi.org/10.3390/app13116842

Lanteri, L., & Pelosi, C. (2021). 2D and 3D ultraviolet fluorescence applications on cultural heritage paintings and objects through a low-cost approach for diagnostics and documentation. In *Proc. SPIE 11784, Optics for Arts, Architecture, and Archaeology VIII, 1178417*. https://doi.org/10.1117/12.2593691

Lanteri, L., Agresti, G., & Pelosi, C. (2019). A new practical approach for 3D documentation in ultraviolet fluorescence and infrared reflectography of polychromatic sculptures as fundamental step in restoration. *Heritage, 2*, 207–215. https://doi.org/10.3390/heritage2010015

Laureti, S., Colantonio, C., Burrascano, P., Melis, M., Calabrò, G., Malekmohammadi, H., Sfarra, S., Ricci, M., & Pelosi, C. (2019). Development of integrated innovative techniques for the examination of paintings: The case studies of The Resurrection of Christ attributed to Andrea Mantegna and the Crucifixion of Viterbo attributed to Michelangelo's workshop. *Journal of Cultural Heritage, 40*, 1–16. https://doi.org/10.1016/j.culher.2019.05.005

Lo Monaco, A., Lanteri, L., Rusu, I., & Pelosi, C. (2024). The panel painting of Saint Mark by the Italian Renaissance artist 'The Balletta' a study for the restoration. *European Journal of Science and Theology, 20*(2), 151–164.

Mechelli, B. (2000). *Il Museo Colle del Duomo di Viterbo*. Ambrosini.

Parisi, C., Agresti, G., & Pelosi, C. (2018). The rediscovery of religious art in Francesco Nagni and the diagnostic study of selected artefacts. *European Journal of Science and Theology, 14*(1), 159–171.

Pelosi, C., Lo Monaco, A., Bernabei, M., Agresti, G., Colantonio, C., Perri, A., Comelli, D., Valentini, G., & Manzoni, C. (2020). Beyond the visible: The Viterbo Crucifixion panel painting attributed to Michelangelo Buonarroti. *Microchemical Journal, 154*, 104636. https://doi.org/10.1016/j.microc.2020.104636

Pelosi, C., Lanteri, L., & Blanco, B. (2022). Monitoraggio microclimatico nel Museo della Città e del Territorio di Narni (Terni, Italia): esigenze di fruizione ed aspetti di conservazione di dipinti su tavola. In *Il comfort indoor nel patrimonio edilizio esistente. Tecnologie e metodi per gli ambienti di vita, a cura di Elvira Nicolini* (pp. 351–366). La scuola di Pitagora editrice.

Pinzi, C. (1910). *Il Palazzo di Papale di Viterbo nell'arte e nella storia*. Tipografia Agnesotti.

Signorelli, M. (1964). *Guida di Viterbo. Monumenti del centro cittadini*. Tipografa Agnesotti.

Chapter 11
The Grotta degli Animali in the Garden of Villa di Castello in Firenze

M. Castellini, E. Cantisani, A. Conti, L. Fiorini, R. Manganelli Del Fà,
A. Meucci, C. Riminesi, and G. Tucci

Abstract The Grotta degli Animali, an artificial grotto located in the garden of Villa di Castello in Firenze, is a significant example of sixteenth-century Mannerist garden design. Commissioned by Cosimo I de' Medici, the grotto was designed by Niccolò Pericoli (Il Tribolo) and later completed by Giorgio Vasari, with contributions from renowned artists such as Jean de Boulogne (Gianbologna) and Ammannati. Featuring marble fountains and animal sculptures symbolizing natural elements, the grotto's hydraulic system once created the dramatic "Scherzo del Diluvio" water effect. Over the centuries, the grotto underwent multiple restorations, and recent work (completed in March 2024) utilized advanced digital documentation and 3D surveying techniques to reactivate the water features and improve its preservation. The project also integrated virtual reconstructions and addressed material degradation by creating a monitoring system for the grotto's microclimate and structural health. Diagnostic surveys and advanced surveying methods, including laser scanning and photogrammetry, revealed key structural challenges and offered insights into the historical evolution of the water system. This work emphasizes the importance of monitoring semi-confined heritage environments like the Grotta degli Animali, where complex microclimatic conditions can lead to localized material deterioration. The CNR-ISPC, in collaboration with other institutions, has developed a methodological approach for diagnosing and monitoring such sites, focusing on assessing conservation states, identifying active decay processes, and

---

M. Castellini (✉) · E. Cantisani · R. M. Del Fà · C. Riminesi
Institute of Heritage Science, National Research Council, Firenze, Italy
e-mail: martacastellini@cnr.it; emma.cantisani@cnr.it; rachele.manganellidelfa@cnr.it; cristiano.riminesi@cnr.it

A. Conti · L. Fiorini · G. Tucci
Department of Civil and Environmental Engineering, University of Florence, Florence, Italy
e-mail: alessandro.conti@unifi.it; lidia.fiorini@unifi.it; grazia.tucci@unifi.it

A. Meucci
Department of Civil and Environmental Engineering, University of Florence, Florence, Italy

La Sapienza University of Rome, Rome, Italy
e-mail: adele.meucci@unifi.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_11

predicting risks linked to environmental changes. Using non-destructive techniques like infrared thermography and moisture detection, along with the establishment of a digital twin of the grotto, the project aims to ensure long-term preservation. Continuous monitoring and analysis of microclimatic variations will inform conservation strategies, helping mitigate potential decay risks while supporting more sustainable preservation practices.

Keywords Artificial grotto · Historic water supply systems · Diagnostics · Monitoring · 3D model

11.1 Description of the Artifact

The Grotta degli Animali, also known as the Grotta del Diluvio, is located in the garden of Villa di Castello in Firenze, a significant example of an artificial grotto in the mannerist gardens of the sixteenth century (Fig. 11.1). Its construction is closely tied to the project commissioned by Cosimo I de' Medici, who sought to transform the villa, where he spent part of his life, into a sumptuous example of Renaissance architecture and hydraulics. The project was initially overseen by Niccolò Pericoli, known as Il Tribolo, and completed after his death by Giorgio Vasari, with the

Fig. 11.1 Villa di Castello (Firenze), view of the interior of the Grotta degli Animali after the water supply system reactivation

collaboration of artists such as Jean de Boulogne (Gianbologna) and Ammannati, who were responsible for the sculptural decorations. Table 11.1 reports some general information.

The grotto's structure consists of a single chamber measuring 13 m in length, 8 m in width, and 8 m in height, divided into three main niches. Each niche houses large marble fountain, topped by reliefs depicting animal statues made from various stone materials, symbolizing the realms of nature: water, earth, and air. The vault is decorated with porous stones, pebbles, shells, and other natural elements typical of Renaissance artificial grottoes. The grotto's distinctiveness lies particularly in its intricate hidden hydraulic system, which powered water jets placed in the vault and floor, surprising visitors with spectacular water effects.

The complex hydraulic system that powered the grotto was made up of lead pipes and terracotta conduits, hidden within the walls and the vault. This system was connected to a series of channels that allowed water to flow through the decorations, creating fountains and a rain-like effect inside the grotto, known as the "Scherzo del Diluvio" (Flood Trick). These hydraulic and decorative elements were symbolic, representing the control of nature through technology and human ingenuity, a central concept in Renaissance thought.

The grotto's history is marked by numerous maintenance and restoration interventions. Already in the eighteenth century, under the Lorraine dynasty, significant changes were made to the garden and the grotto's structure, which also led to the abandonment of part of the original hydraulic system. In 1745, a report described the grotto's deterioration, with a damaged vault and ruined niches. Further work in 1779 permanently sealed parts of the original hydraulic system when the terrace above the grotto was paved. In the twentieth century, there were additional attempts to restore the grotto, including the restoration work in the 1990s, promoted by the Superintendency. These interventions brought to light part of the original hydraulic system, when essays were carried out on the extrados of the vault that allowed for the removal of a concrete roof, carried out in the 1970s. This period was important for the documentation of the site, especially thanks to the use of more modern surveying and analysis techniques.

More recently, a new phase of restoration work was initiated due to further deterioration of the various interior decorative materials and the collapse of the decorations. This phase saw the use of three-dimensional surveying techniques, including laser scanning, to map the grotto's structure and the hydraulic system conduits. The objective was to support the restoration of the water features by locating the path of the water in the lead pipes from the extrados to the intrados, so that the existing pipes could be used without damaging and altering the structure of the grotto. Investigations revealed that many of the existing pipes were corrupted or obstructed, so these were removed and replaced with a new, more modern hydraulic system that respected the original aesthetic configuration of the grotto. The work was completed in March 2024, with the reactivation of the water features.

In addition to the physical restoration, the project also included a series of digital documentation and conservation initiatives. A three-dimensional model of the grotto was created to accurately document its structure and decorations, allowing

Table 11.1 General information

Object	Artificial grotto
Scale of reference	Architecture/Sculptural Group
Original/Current Destination	Grotto (AAT: grottoes/ID: 300006807/Page Link: http://vocab.getty.edu/page/aat/300006807)
Author	Pericoli Niccolò known as Tribolo (from 1538), Davide Fortini, and Giorgio Vasari (from 1550)
Location	Garden of the Villa di Castello, Via di Castello, 44, 50141 Firenze (FI)
Geographic Coordinates	43°49′14″N 11°13′49″E
Chronology	First half of the sixteenth century
Ownership	Public Property
ICCD Sheet	ICCD15176713 (https://catalogo.beniculturali.it/detail/HistoricOrArtisticProperty/0900281675-0)
Authority responsible for protection	Superintendency for Archaeology, Fine Arts and Landscape for the Metropolitan City of Firenze and the Provinces of Pistoia and Prato
Keywords	Mannerist gardens, Artificial grottoes, Historic water supply systems
Risk map	ID 923 (Villa di Castello)
Type of risk	Anthropogenic risks: inadequate aur conditioning, micro-climate effects Climate change effects: weathering increasing, speeding up erosion processes, increased wetness Natural risks: landslides, ground water, weed vegetation
Research team	This research was conducted following an agreement between the Polo Museale della Toscana and the Department of Civil and Environmental Engineering (DICEA) for the creation of the three-dimensional survey, and with CNR-ISPC (Istituto di Scienze del Patrimonio Culturale) for the identification and characterization of the chemical-physical properties of the constituent materials

restorers to visualize and study the monument's condition in detail. This 3D model not only facilitated the planning of restoration interventions but also paved the way for virtual reconstructions of the grotto and its original appearance. Among the proposals is the idea to virtually reintegrate the bronze bird sculptures, now housed in the Bargello Museum, which once adorned the grotto's walls.

11.2 Specific Reachable Goals

OO1: Development of guidelines for the management and maintenance of complex, multi-material garden structures.

OO2: Study for the creation of a prototype 3D information system for the localization of materials that make up the grotto, spot analyses, degradation, and restoration interventions, in collaboration with other research groups and restorers, for the study and monitoring of microclimatic variations in the Grotta degli Animali.

OO3: Evaluation of the durability of replicas made from different materials and finishes exposed to atmospheric and environmental agents.

11.3 Survey, Monitoring and Diagnostic Techniques: Best Practices

11.3.1 Best Practices for the 3D Surveying of the Hydraulic System

The multiple transformations that have affected the garden of the Villa Medicea di Castello and the Grotta degli Animali complex over the centuries are extensively documented by significant iconographic evidence and surveys, spanning a long period from the early sixteenth century to the 1990s (Tucci et al., 2018). However, surveying such complex works, characterized by organic and articulated forms like those found in gardens and their architectures, particularly in grottos, has always posed a significant challenge. The surveying technologies used in the past, while contributing to the historical understanding of the site, did not provide the accuracy and completeness needed to fully capture the richness and complexity of the details.

Since 2012, commissioned by Superintendence, the Laboratory of Geomatics for the Environment and the Conservation of Cultural Heritage at the University of Firenze has undertaken a series of surveying operations, organized into several campaigns, the latest of which took place in March 2021 (Table 11.2). During these 12 years, the main objective has not only been to document the current state but also to monitor ongoing work, adapting to the needs of the construction site and supporting diagnostic investigations.

Table 11.2 Summary table of the various survey campaigns carried out over the years

Survey campaigns	Scans	N. of points	Avg. resolution
08-2012: Intrados vault and containing wall	22	370.714.688	0.005 m at 5 m
02-2013: Grotto	8	369.353.135	0.005 m at 5 m
10-2013: Extrados and SLAM test on tunnels	18	713.732.636	0.006 m at 10 m
09-2015: Extrados and ph. acq.	25	864.683.723	0.006 m at 10 m
12-2017: Conduits, upper tunnel	23	354.049.412	0.12 m at 10 m
09/10-2018: Conduits, lower tunnel, tunnel “del Gennaio”, left and right tunnels	83	1.834.724.922	0.006 m at 10 m
03-2021: Excavation in the “Limonaia” plane	19	388.198.231	0.006 m at 10 m
Total	198	4.895.456.747	

11.3.2 The Survey of the Grotto and the Extrados Area

The survey of the Grotta degli Animali represented a significant challenge, overcoming the epistemological difficulties related to the measurement and representation of organic forms, a problem that had arisen in the documentation of Mannerist gardens and their associated water architectures. Thanks to the adoption of three-dimensional digitization technologies, it was possible to obtain high-resolution digital models capable of capturing complex details with great accuracy. From the digital model, obtained through the acquisition and processing of spatial data, the materials for documentation and the drafting of the recovery project were extrapolated, derived from a mixed 2D and 3D graphic representation: the high-resolution surface model (triangular mesh) (Fig. 11.2), which effectively represents the organic lines of the sculptures and the sponge cladding, was sectioned to produce orthogonal views that clarify the constructive rationale of the cave.

In parallel, the survey of the extrados and lead pipes was carried out during the excavation campaign, with initial acquisitions in 2013 and further checks in 2015. Thanks to the three-dimensional model, it was possible to conduct analyses that would not have been feasible with only two-dimensional representations, correlating the pipes of the extrados with the internal pockets of the cave, which are essential for activating the “Diluvio” effect. Additionally, a close-range photogrammetry campaign thoroughly documented the pipe system, allowing for the analysis of the various components of the hydraulic system, including water supply and distribution.

Fig. 11.2 Mesh model, view of the front tank

11.3.3 The Survey of the Underground Ducts

The project continued with the survey and analysis of the complex water conduit system that supplies the grotto and the other fountains in the park. This task was particularly significant, as these conduits, dating back to the construction of the Grotta degli Animali in the early sixteenth century, had never been thoroughly analyzed. Their intricate layout, combined with the difficulties of accessing narrow spaces, had made it challenging to create a detailed map of the underground hydraulic system that powers the monumental works in the garden of the Villa Medicea di Castello. Given the morphological complexity of the tunnels, some of the most advanced surveying techniques available at the time were tested, particularly those based on automated mobile scanning, supported by Simultaneous Localization and Mapping (SLAM) technology. To document the grotto's tunnels, the Zeb1 device by GeoSLAM was used, equipped with a Hokuyo UTM-30LX profiler mounted on a rotating handle, allowing the operator to maneuver it easily. The point cloud model generated, which was acquired quickly, accurately described the geometry of the spaces. However, the point cloud's resolution was significantly lower than that obtained through static scans, proving insufficient for precisely detailing the surfaces of the tunnel structures or generating a sufficiently detailed continuous mesh model. The surveys conducted over several campaigns between 2017 and 2021 revealed important factors useful for understanding the function of the water features and the changes they underwent over time. Initially, the lower tunnels running along the three sides of the grotto were examined, with two branches leading to niches behind the side nymphaea, and a third branch leading to the chamber below the "Gennaio" basin, accessible via a stone spiral staircase that exits directly at the base of the statue. The survey then proceeded to cover the tunnel running beneath the grotto's entrance floor, followed by laser scanning acquisitions of the perimeter tunnels on the upper level, accessible through two openings on the extrados. The point cloud model (Fig. 11.3) facilitated an understanding of the relationship between the internal and external spaces of the entire architectural complex. Further investigations revealed additional conduits and currently inaccessible spaces, which are believed to correspond to a second level of tunnels above the two side branches leading to the lateral nymphaea of the grotto. The survey of the trees also allowed for an analysis of how the roots impact the ground and, in turn, the conduits, which in some cases are directly affected by the root system, compromising their structural integrity.

11.3.4 Best Practices for Diagnostic and Monitoring for a Semi-confined Environment

Cultural heritage located in semi-confined environments represents a unique and underexplored area of study, distinct from the more extensively researched indoor and outdoor environments. Semi-confined environments are characterized by spaces that are partially exposed to external conditions, resulting in specific microclimatic variations within the structure (Becherini et al., 2010). These variations can result in differential deterioration, such as localized high humidity levels, which can accelerate the deterioration of materials in certain parts of a monument. For example, areas with poor ventilation may trap moisture and promote biodeterioration, while other areas may remain dry (Cuzman et al., 2023). Similarly, differential exposure to sunlight can lead to uneven discolouration or fading of surface materials. These effects are particularly pronounced in environments such as cloisters, caves, or partially enclosed galleries where external weather patterns still influence the

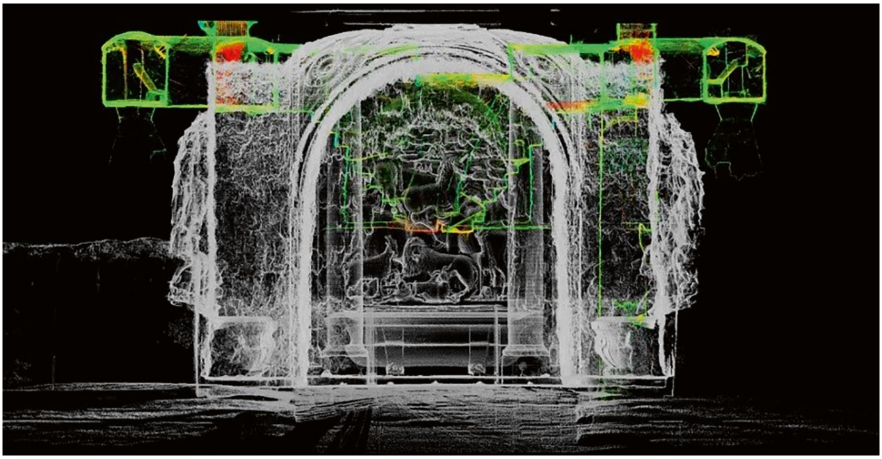


Fig. 11.3 Image of the point cloud model as of September 2018, showing the grotto and the perimeter conduits of the second level

preservation conditions but are mitigated by architectural features. The lack of focused research on semi-confined environments has left significant gaps in understanding of how best to preserve heritage in these sites, which exhibit a complex interaction between natural factors and built materials. Addressing these challenges requires interdisciplinary approaches that consider not only the material conservation and structural integrity of the monuments, but also the microclimatic and environmental dynamics at play. Changes of the microclimate condition due to restoration works or maintenance can also affect the equilibrium conditions for the conservation between materials and environment. In this way, the case study of the Grotta degli Animali in the garden of the Villa di Castello presents some significant aspects, since the hydraulic system supporting water features has been recently reactivated after at least two centuries of dismission (Tesi, 2018).

The activity of CNR-ISPC in collaboration with UNIFI, OPD and ICR aims to establish a reliable methodological approach for controlling the state of conservation of heritage assets located in a semi-confined environment such as the artificial grotto of Villa di Castello. In particular, the proposed approach must consider the following steps:

- to determine the state of conservation of the surfaces and structures.
- to evaluate the presence of active alteration/decay processes and their correlation with the changing of the micro-environment
- to assess the potential risks for the conservation related with changing of the environmental condition due to Climate Change or man-made changes such as the reactivation of water features.
- to monitor the risks for the conservation finalized preventive conservation planning (see Chap. 14).

When it considered heritage materials exposed to water action, different decay mechanisms can be activated also consider the strength of sorption due to free water (as water sprayed from the grotto's ceiling), capillary water, and hygroscopic water (due to the environmental condition: relative humidity and temperature).

In the case-study, the main sources of the decay can be categorized as direct and indirect. In the first group of sources are included falling water that impacts directly on the stone surfaces of the sculptures, on the spongy stone cladding and on the multi-material floor. This can affect the stone materials in different ways, among which:

- mechanical damage promoted by the strength of the sprayed water resulting in loss of cohesion and potential detachments.
- the water retention can promote microbial colonization and biodeterioration (algae, fungi, biofilm, etc.) (Li & Gu, 2022; Lamenti et al., 2000; Peraza Zurita et al., 2005).

The combination of the previous mechanisms puts a strain on the effectiveness of the protective treatment eventually applied on the surfaces for their conservation (Hansen et al., 2003; Sacchi et al., 2020).

As indirect source, for example, the water supply is responsible in the changing of the micro-climate inside the grotto, since the increased humidity level could promote the dissolution process, salts migration, and, combined to the temperature and wet-dry cycles, the biodeterioration and bioactivity.

Starting from an exhaustive diagnostic survey, here described in terms of methodological strategy complete with the description of the measurement equipment which can be used, the alteration/decay mechanisms potentially induced by the water games reactivation are described, so an effective monitoring strategy is proposed. To this aim, two main research aspects are addressed:

- the identification of the materials' key parameters to be accounted in the monitoring as result of the diagnostic survey.
- the design criteria to develop a monitoring sensors system for providing a clear description of the microclimatic changes inside the grotto and particularly in the areas where the three fountains are located.

As a final purpose, the acquired multidisciplinary data will be entirely managed using a digital platform (see Chap. 14) for the storage, processing and analysis of acquired data. The platform will host the digital twin of the grotto, where the 3D model will be completed with the sensors network for a real-time description of the parameters of interest. This perspective will allow the data visualization and interrogation through the geomatic digital twin of the grotto (Tucci et al., 2020). The tool will provide a remote-control system for the state of conservation against the risks of environmental damage, supporting the decision-making process for the definition of a preventive conservation strategy. The tool can contribute to a more sustainable planning the onsite survey and diagnostic campaigns, limiting them only when necessary.

11.4 Results and Discussion

11.4.1 Simplifying Complexity: The Grotto and Hydraulic System Model

Based on the data collected during the various survey campaigns of the grotto and the surrounding conduit system, a simplified model was developed using NURBS surfaces, which was subsequently divided into a hierarchy of elements identified within the conduits (Fig. 11.4). The 3D surface model was initially broken down into macro-elements, starting with the broader context, which includes the surrounding terrain and the retaining walls of the Grotta degli Animali, before moving on to the various conduits that encircle it. A further breakdown was then carried out, focusing on the main masonry structures, secondary conduits, vertical conduits communicating with the exterior, supporting walls for the open-air conduits,

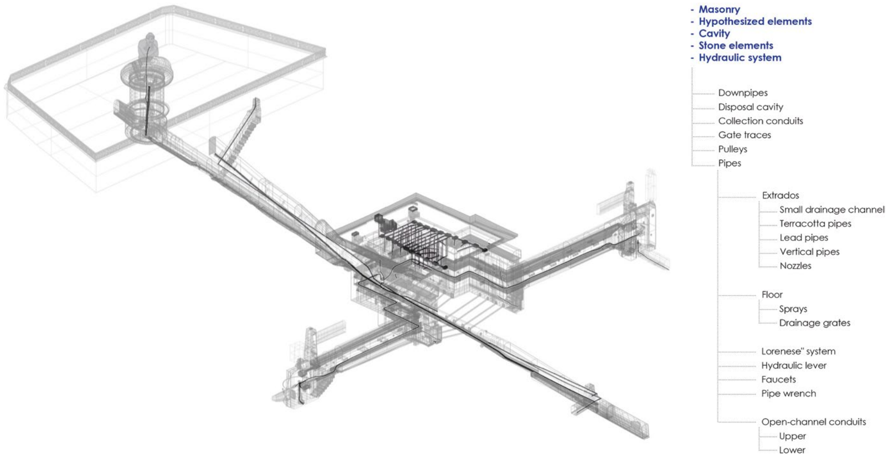


Fig. 11.4 Overview of the surface model highlighting the decomposition of the hydraulic system layers

buttresses, staircases, and more. In future work, the terminology within the model's semantic structure will be selected from a controlled vocabulary.

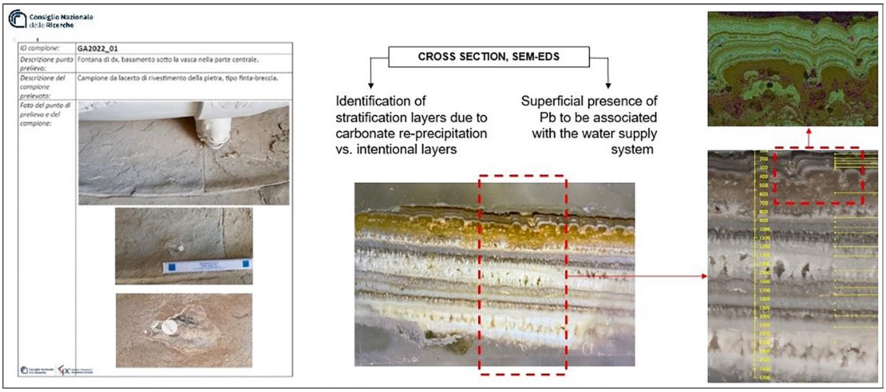
The simplification of the modeling process has made it easier to understand the complex hydraulic system, which would otherwise be difficult to interpret due to fragmented historical sources and hard-to-access survey data. This model helps restorers plan interventions with precision, reducing the risk of unnecessary or excessive actions that could compromise the site. Additionally, the model holds great communicative value, allowing visitors to visualize and understand the hidden conduits and how water was channeled to create spectacular visual effects. Beyond serving as an educational and engaging tool, it could also serve as the foundation for a digital twin of the hydraulic system, useful not only for monitoring its conservation against environmental risks but also for gathering and preserving the historical and technical data accumulated over time.

11.4.2 Diagnostic Results by the Planned Multi-disciplinary Approach: State of Conservation and Risk for the Conservation

The characterization and the correct knowledge of the state of conservation of the materials inside the grotto are therefore important and necessary to estimate the process of decay in terms of entity and rate. In fact, the characterization of the state of conservation at the initial stage of monitoring (time 0, T0) is mandatory for the prediction of the incoming problems of conservation and as a first step of the monitoring plan for risk assessment. The state of conservation has been investigated by a proper diagnostic campaign based on a multi-technique and multi-scale approach.

Sampling and non-destructive analysis for the characterization of the stone materials of sculptures and fountains were performed. On the 31 samples collected from the surface of the sculptures and from the stone apparatus, the analytic investigation was performed by Fourier-Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Raman Spectroscopy, Scanning Electronic Microscopy (SEM) combined with Energy Dispersive X-ray Spectroscopy (EDS), and Optical Microscopy (OM). Pigments, white-washings, decay-processes were identified, revealing some deposits resulting from the old activations of the water features. In particular, the analysis of fragments sampled from the stone slabs under the right-hand marble fountain pointed out some interesting evidence. In fact, in Fig. 11.5, the cross-section of the sample reveals a stratification of multiple layers. The outer layers appear as alterations due to the successive re-precipitations of calcium-carbonate, probably due to the wet-dry cycles that occurred at the early stage of the hydraulic system activation. While the presence of Lead, recognized by SEM-EDS mapping, is probably associated with the water supply system on and off. The inner layers, although still carbonate, appear to be plastering layers, due to their morphology.

A measurement campaign by non-destructive techniques was also performed to detect differences in heat emitting and possible areas of moisture retention (Fig. 11.6a), to localize the metal supports of the animals' sculptures and the walls of the grotto, and to assess the rate of biological growth. For the above targets the InfraRed Thermography (IRT), Pacometric Surveys and bioluminometer (for the Adenosine Triphosphate detection) were employed. In particular, the thermal survey was also performed for monitoring by thermal images the different surfaces' drying time after water spraying. Due to the water run-off on the stone sculptures' surface, the occurrence of corrosion phenomena had to be considered since the



Consiglio Nazionale delle Ricerche

ID campione:	GA2022_01
Descrizione punto prelievo:	Fontana di dx, basamento sotto la vasca nella parte centrale.
Descrizione del campione prelevato:	Campione da lacerto di rivestimento della pietra, tipo finta-breccia.
Foto del punto di prelievo e del campione:	

Fig. 11.5 Results of the diagnostic analysis performed on a sample of the stone slabs under one of the marble fountains

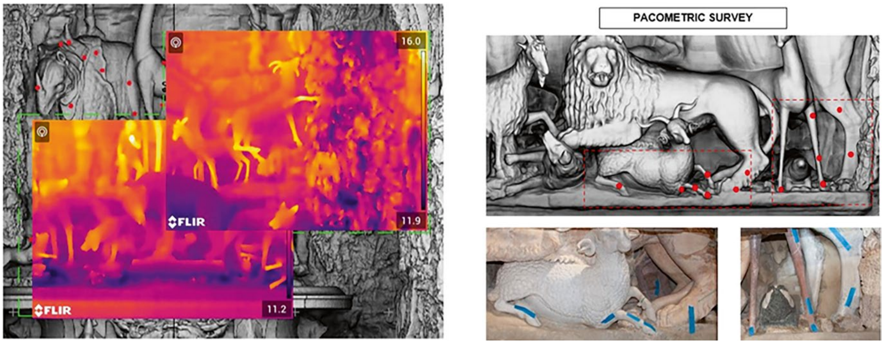


Fig. 11.6 (**a**) Thermal survey performed on the sculptures; (**b**) internal reinforcement elements detected by the pacometric measurements

presence of internal reinforcement consisting of iron pins and iron brackets. To achieve this aim, a pacometric survey was performed exploiting the principle of the magnetic field absorption measurement to locate the metal elements and their state of conservation (the diameter of the pin can be estimated). On Fig. 11.6b, the map of the detected pins (Ø 8–16 mm) and brackets, is shown. Their presence is mainly due to the previous interventions for the consolidation, strengthening, and replacement of damaged parts (more fragile parts, such as the animals' paws, the animals' ears). Moreover, the grouts and mortars used for filling the fractures and junctions among different parts will be monitored to prevent water infiltrations and corrosion risk.

11.5 Prospective for New Research

11.5.1 From History to Virtuality: From the Replicas of the Birds to the Digital Future of the Grotta

Among the upcoming developments is the planned creation of replicas of some bird statues that adorned the Grotta. Many of the bronze sculptures, attributed to Ammannati, Giambologna, and Giovan Battista Ferrucci Del Tadda, are currently housed in the Museo del Bargello. This is following the theft of the bronze pigeon figure, which was taken from the grotto on August 1919. For this reason, measures were taken to secure the other five figures still present inside the grotto at that time (Frommel, 2018; Mozzo, 2018). The creation of faithful copies of the birds, to be installed on the ceiling to reconstruct the original iconographic and figurative integrity of the grotto, represents a complex methodological challenge. Although the replacement with replicas may raise debates about the authenticity and aesthetic experience of the artwork, it is increasingly regarded as a necessary measure to protect cultural heritage for future generations. While there are no explicit rules regarding the use of copies to safeguard the originals, decisions regarding their use depend on a combination of international regulations, professional guidelines, and national regulations. To date, some of the statues preserved at the Museo del Bargello have been acquired through SFM photogrammetry, particularly the owl and falcon attributed to Ammannati. A print is planned that will serve as a countermold for subsequent bronze casting. The "digital cast," resulting from the three-dimensional survey, will meet various needs in both the conservation of the original and its enjoyment and dissemination.

Furthermore, with regard to the knowledge, conservation, and maintenance of the original assets, the possibility to create a digital copy completed with the scientific results organized in "layers", allows to simulate the "state of conservation" based on the environmental parameters. 3D modeling enables georeferentiation of all the performed analyses, thereby facilitating tailored thematic mapping.

Finally, the digital relocation of the copies of the birds within a complete digital twin of the Grotta degli Animali represents not only an opportunity for visual restoration, but also a powerful tool for communication and cultural sharing. Although the realization of faithful copies to reconstruct the original iconographic and figurative integrity remains a complex challenge, the fascinating suggestion of this project becomes tangible today thanks to virtual reality.

11.5.2 From the Diagnostic Survey to the Monitoring Strategy: A Methodological Approach

The results of the diagnostic survey at time 0 (T0) suggested the relevant materials' parameter to be considered during the monitoring activities: colorimetric alterations, biological growth, drying rate of the surfaces. Those indicators will be correlated with data collected by the environmental monitoring, showing that whether microclimate changes can resume the previous decay processes or rise additional ones. To this aim, a monitoring setup will be established measuring the main descriptive environmental parameters from a microclimatic point of view: temperature and relative humidity. Other parameters will be useful for monitoring:

- The level of water stagnation, in the sandstone slabs under the marble fountains, after the closing of the water features.
- The surface temperature of some animal sculptures checks the presence of condensation phenomena.
- The solar radiation on exposed surface (in particular, darker stone), since it affects the drying time through the increase of temperature. Moreover, solar radiation can contribute to the growth of autotrophy organisms (algae, moss, etc.) in the area subjected to water retention.

As a result, the differences in microclimate within the grotto among the niches of the fountains—in particular, close to the three fountains—will be deeply understand and related to decay processes of the heritage materials.

The above results will be completed with radiometric data captured on the wetted surface by IR thermography camera. The spot temperature measure is useful to calibrate the radiometric image to obtain information on the drying dynamics of the surface. Continuous thermal monitoring will be provided by the integration of the thermal sensors within the environmental monitoring system (see Chap. 14). This will allow to better investigate the critical aspects, such as areas subjected to water stagnation or subjected to mechanical damage for the impact of falling water (Fig. 11.7).

In conclusion, the monitoring strategy focuses on the correlation of selected parameters, investigated before the water games are switched on, during and after their switch-off, to determine the cyclic variation of the micro-climate conditions inside the grotto; moreover, different drying rates of the stone surfaces will be considered, to detect vulnerabilities and preventive conservation interventions.

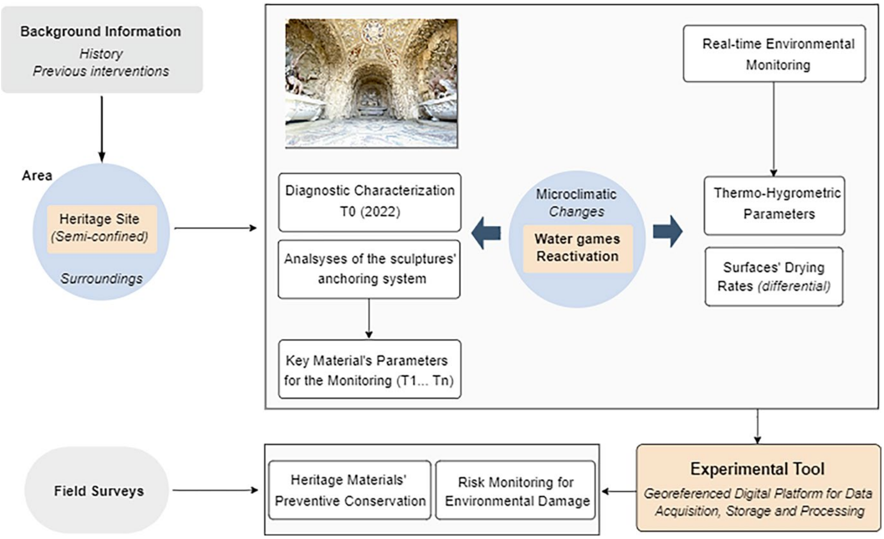


Fig. 11.7 Overview of the methodological approach leading to the development of the Risk Monitoring Tool for Cultural Heritage in semi-confined environments exposed to microclimate changes

References

Becherini, F., Bernardi, A., & Frassoldati, E. (2010). Microclimate inside a semi-confined environment: Valuation of suitability for the conservation of heritage materials. *Journal of Cultural Heritage, 11*(4), 471–476. https://doi.org/10.1016/j.culher.2010.01.005

Cuzman, O. A., Luvidi, L., Colantonio, C., Raio, A., & Taiti, S. (2023). Biodiversity and conservation correlation in the case of a Roman fresco located in a semi-confined environment. *International Biodeterioration & Biodegradation, 181*(2023), 105605. https://doi.org/10.1016/j.ibiod.2023.105605

Frommel, S. (2018). Preface. In E. Ferretti & S. Lore (Eds.), *Opvs incertvm, Il Rinascimento delle Grotte* (pp. 8–11). Officine grafiche Giannini.

Hansen, E., Doehne, E., Fidler, J., Larson, J., Martin, B., Matteini, M., Rodriguez-Navarro, C., Sebastian Pardo, E., Price, C., De Tagle, A., Teutonico, J. M., & Weiss, N. (2003). A review of selected inorganic consolidants and protective treatments for porous calcareous materials. *Studies in Conservation, 48*(sup1), 13–25. https://doi.org/10.1179/sic.2003.48.Supplement-1.13

Lamenti, G., Tiano, P., & Tomaselli, L. (2000). Biodeterioration of ornamental marble statues in the Boboli Gardens (Florence, Italy). *Journal of Applied Phycology, 12*, 427–433. https://doi.org/10.1023/A:1008135501265

Li, Y.-H., & Gu, J.-D. (2022). A more accurate definition of water characteristics in stone materials for an improved understanding and effective protection of cultural heritage from biodeterioration. *International Biodeterioration & Biodegradation, 166*(2022), 105338. https://doi.org/10.1016/j.ibiod.2021.105338

Mozzo, M. (2018). La decorazione della grotta degli Animali: Note sulle vicende conservative dall'epoca sabauda ad oggi. In E. Ferretti & S. Lore (Eds.), *Opvs incertvm, Il Rinascimento delle Grotte* (pp. 74–81). Officine grafiche Giannini.

Peraza Zurita, Y., Cultrone, G., Sánchez Castillo, P., Sebastián, E., & Bolívar, F. C. (2005). Microalgae associated with deteriorated stonework of the fountain of Bibatauín in Granada, Spain. *International Biodeterioration & Biodegradation, 55*(1), 55–61. https://doi.org/10.1016/j.ibiod.2004.05.006

Sacchi, B., Vettori, S., Andreotti, A., Rampazzi, L., Colombini, M. P., & Tiano, P. (2020). Assessment of water repellent treatments for the stone of the Matera Cathedral Facade (Italy). *International Journal of Architectural Heritage, 16*(3), 365–373. https://doi.org/10.1080/15583058.2020.1782532

Tesi, V. (2018). Il restauro dell'impianto idraulico della grotta degli Animali, a Castello. In E. Ferretti & S. Lore (Eds.), *Opvs incertvm, Il Rinascimento delle Grotte* (pp. 94–99). Officine grafiche Giannini.

Tucci, G., Conti, A., & Fiorini, L. (2018). "Canne di piombo ascose". Tecniche geomatiche per un nuovo rilievo della grotta degli Animali della villa medicea di Castello. In E. Ferretti & S. Lore (Eds.), *Opvs incertvm, Il Rinascimento delle Grotte* (pp. 82–89). Officine grafiche Giannini.

Tucci, G., Bonora, V., Conti, A., & Fiorini, L. (2020). Geomatics for studying historic supply systems: The Grotta degli Animali case study. *IOP Conference Series: Materials Science and Engineering, 949*, 012083. https://iopscience.iop.org/article/10.1088/1757-899X/949/1/012083/pdf

Part III

Monitoring, Assessment and Preventive Conservation of Heritage Against Climate Change

Chapter 12
Enhanced Modeling Approaches to Introduce the Effects of Environmental and Mechanical Damage

D. Addessi and C. Gatta

Abstract This contribution focuses on modeling procedures to describe damage mechanisms evolving in masonry structures under mechanical and environmental actions. After introducing the proposed protocol developed to analyze the overall mechanical response of masonry historical constructions, a macromechanical constitutive model coupling damage and plasticity effects is presented in detail. Two case studies are analyzed, concerning a masonry façade subjected to tunneling-induced settlements and the Tortona town hall, selected as real cases to evaluate the effects of environmental and man-made loads on the structural response of buildings with historical relevance.

Keywords Masonry · Macromechanical approach · Damage · Plasticity · Finite element

12.1 Introduction

Protection and conservation of cultural heritage (CH) against climate changes, natural and anthropic risks is a challenging task for the scientific community. In fact, natural landscapes, historical cities and works of art improve the citizens' life quality by promoting social inclusion and fighting alienation. Therefore, the development of a multidisciplinary approach, including advanced structural, chemical and

---

D. Addessi (✉) · C. Gatta
Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Rome, Italy
e-mail: daniela.addessi@uniroma1.it; cristina.gatta@uniroma1.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_12

architectural analyses is necessary to preserve the CH, and this is the final aim of this work.

As for the structural heritage, a protocol for enhanced modeling approach is proposed, which combines the advantages of modeling strategies based on different scales of analysis. Indeed, ordinary residential buildings and monumental structures, like towers, castles and churches, made of heterogeneous materials can be studied with increasing level of accuracy moving from phenomenological to detailed analysis. Focusing on masonry, which is an ancient construction material widely used throughout history and still used nowadays, the modeling strategies schematically shown in Fig. 12.1 can be employed.

Although several criteria can be adopted (Roca et al., 2010; Addessi et al., 2014; D'Altri et al., 2020), the approach classification in Fig. 12.1 refers to the modeling scale used (masonry material or structural elements), thus distinguishing between macro-element, macromechanical, multiscale and micromechanical models (Addessi et al., 2014; Lagomarsino & Cattari, 2015).

The so-called micromechanical strategy appears to be the most accurate modeling approach, as this describes the composite nature of the material, made of bricks/blocks connected with or without mortar layers. All masonry components (units, mortar joints and interfaces between them) are separately modeled and the information about the microstructure, in terms of geometry and constitutive responses, are accounted for. However, although the modern computer developments, the applicability of this approach is limited to small elements or structural details due to the high computational burden required by the analysis.

To speed up numerical simulations and model large-scale structures, continuum models, also referred to as macromechanical models, are usually employed. These consider masonry as a continuum deformable body, without distinction between the constituent materials. In this framework, the constitutive response of the homogenized medium, whose proper calibration is a hard task, is expressed through relationships between the average masonry strains and stresses that phenomenologically describe the main degrading processes of the material, mainly due to the onset and evolution of micro- and macro-cracks and frictional mechanisms.

Between macro and micro approaches, multiscale models have become widespread in recent decades. These split the structural problem in two scales: at the

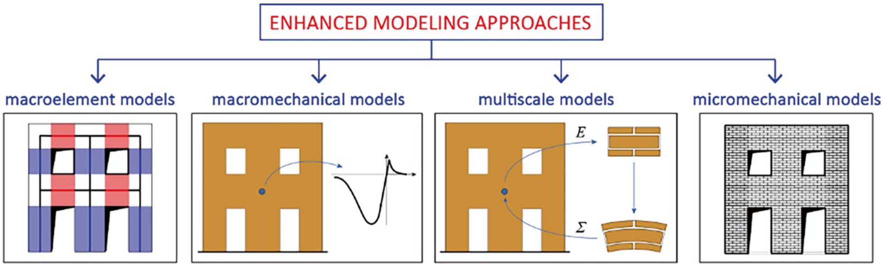


Fig. 12.1 Modeling approaches based on different scales of analysis of the structure

macroscopic level, a homogeneous material is considered, whose constitutive response is derived by the analysis of a properly selected masonry representative volume element (RVE) modeled at the microscopic level and, thus, accounting for the detailed description of components, geometry and arrangement. Weak or strong coupling between the two scales can be established, based on the scale separation concept (Lloberas-Valls et al., 2012).

The macro-element strategy, designed for performing accurate and fast nonlinear simulations, discretizes the masonry walls and structures in their main resistant structural members, each of them modeled as a single deformable element. According to empirical criteria inspired by the observation of post-earthquake damage patterns, piers and spandrels (blue and red portions Fig. 12.1) are usually identified as the main load-bearing components. The piers, vertical elements, are assumed to be capable of carrying both vertical and horizontal loads, whereas the spandrels, horizontal elements, are usually regarded as 'secondary', strongly affecting piers boundary conditions. To date, the effectiveness of this modeling strategy has been proved in the case of simple and regular structures, but its application to more complex geometry, also involving the presence of arched systems, needs to be further investigated.

All the mentioned modeling approaches require the definition of proper constitutive laws to describe the response of each material component or of the homogenized masonry material. In fact, masonry exhibits a complex mechanical behavior characterized by anisotropy, brittleness and non-symmetric response in tension and compression. To capture these features, the formulations commonly adopted are based on the introduction of proper inner variables in the stress-strain relationships. In particular, models based on Damage Mechanics allow to describe the degrading phenomena by making use of the consolidate principles of Continuum Mechanics and, differently from models based on Fracture Mechanics Theory, do not explicitly represent the cracks but introduce damage variables in the constitutive law. Usually, damage models are coupled with plasticity formulations, with the aim of better reproducing the hysteretic dissipation properties. Smeared smack models are also adopted in the framework of the macromechanical strategy (Rots, 1991; Jirásek, 2011).

As far as numerical tools are concerned, the modeling strategies mentioned are commonly implemented into Finite Element (FE) codes, this numerical method being the most widespread for solving differential equations governing structural analysis. In this framework, one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) formulations have been developed. Recently, also models based on the innovative Virtual Element Method (Beirão da Veiga et al., 2013) have taken hold with the aim of obtaining simple formulations able to preserve the polynomial accuracy, merging the features of the polygonal finite element method.

It clearly appears that the modeling techniques described largely differ in terms of accuracy and computational costs. To date, the choice of the approach to use for analyzing historical constructions has been related to the available input data, personal intuitions and experiences, without resorting to an organized and integrated procedure. In order to fill this lack, this work develops a protocol for advanced modeling approaches of architectural heritage, with special focus on masonry structures. Particularly, the modeling strategies schematically depicted in Fig. 12.1 are integrated into a procedure providing guidelines on the workflow to be adopted on the basis of geometric characteristics and available data of the structure to be analyzed.

The contribution is organized as follows. Section 12.2 describes the protocol proposed for structural modeling, providing details on the damage-plastic material model used in the numerical applications later presented. Section 12.3 is dedicated to the results obtained for the selected case studies, analyzing the effect of anthropic-induced loads and variation of environmental conditions on the response of masonry constructions with historical relevance. Finally, concluding remarks are given in Sect. 12.4.

12.2 Methodology

Figure 12.2 schematically shows the workflow proposed to analyze the overall mechanical response of masonry historical constructions to external loads of anthropic and natural origin. The methodology attempts to combine the advantages of various modeling strategies and select the most appropriate one on the basis of the available mechanical and geometric data.

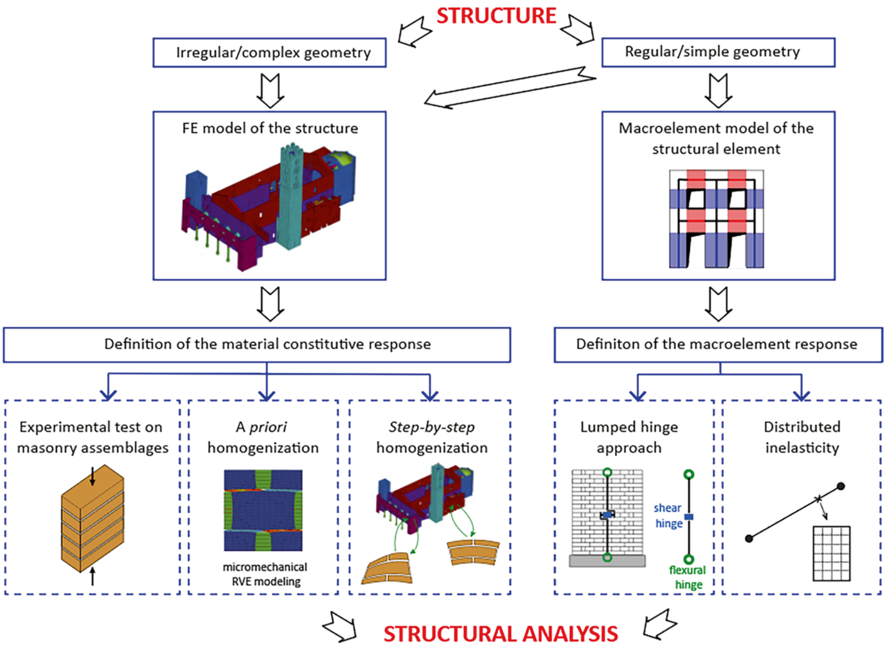


Fig. 12.2 Protocol for enhanced structural modeling approach

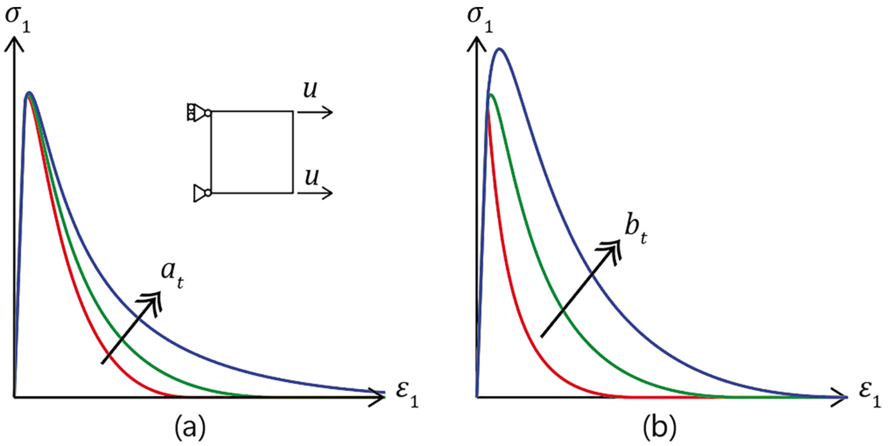


Fig. 12.3 Uni-axial tensile stress-strain law: effect of the parameters (**a**) a_t and (**b**) b_t

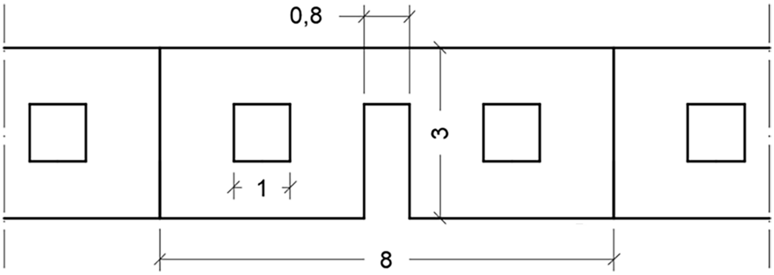


Fig. 12.4 Schematic representation of one dwelling composing the analyzed façade (dimensions in meters)

Firstly, the complexity of the structural system has to be evaluated, considering the building vertical and plan regularity, location and shape of openings and the possible presence of arched systems.

In the case of simple geometries, with periodic opening layout, the structure could be efficiently modeled as the assembly of few macro-elements or with a dense finite element discretization.

However, if many nonlinear analyses need to be performed and limited material characterization is available, the use of the macro-element strategy is recommended, as this allows for fast numerical simulations and requires the identification of few mechanical parameters. In the spirit of this method, masonry buildings have to be divided in horizontal diaphragms and vertical walls, which, in turn, consist of rigid undamageable areas and deformable panels. Each panel, pier or spandrel, is typically represented by a single 1D, 2D or 3D finite element and accounts for the material nonlinearity. However, differently from the continuum finite element models that try to reproduce the mechanical behavior of masonry material, the constitutive law of macro-elements should describe the mechanical response of the panel-scale structural components. Focusing on the equivalent beam models, which idealize masonry panels as nonlinear beams, the analyst can refer to lumped (Lagomarsino et al., 2013; Addessi et al., 2015; Sangirardi et al., 2019) or distributed (Raka et al., 2015) approaches. The first captures the nonlinear response of the macro-element using lumped flexural and shear hinges, usually located at the ends and in the central part of the element, respectively; the last considers phenomenological nonlinear laws for the beam section, often introduced in a fiber-based formulation. The choice of the strategy to adopt depends on the available material data. In case of knowledge of few mechanical parameters, the lumped hinge approach appears to be a good choice as this requires little information, often derivable from building codes on the basis of the masonry typology, to define the hinge nonlinear response. Advanced distributed formulations are more general and versatile, but their accuracy strongly depends on the selected constitutive laws.

The proper identification of pier and spandrel dimensions is also primary for the use of the macro-element method and the related structural safety assessment. To date, rigorous rules are still missing, but detailed review of the criteria that could be adopted is reported in Quagliarini et al. (2017). Among others, proposals by Dolce (1991), Augenti (2006) and Lagomarsino et al. (2013) deserve to be mentioned, as they are widely used in practice for the individuation of the deformable length of piers.

The possibility of using the macro-element method for the analysis of complex structures must be carefully evaluated, due to the uncertainties connected to the wall discretization in the case of irregular opening patterns and the presence of curved structural elements, like arches, domes and vaults (Quagliarini et al., 2017). Therefore, in such a case, the creation of the finite element model of the structure is recommended, as this permits to simulate any type of structural element and describe the material constitutive response more in detail. Certainly, a fairly complete geometric characterization is required for the model creation. In this framework, to avoid the computationally demanding micromechanical description of the material, masonry is represented as a homogenized medium and its constitutive response is described by means of the simplified hypothesis of isotropic behavior or the more realistic assumption of anisotropic response. In particular, the material behavior can be identified according to the various methodologies described below.

The first, referred to as *direct approach*, involves the definition of phenomenological constitutive laws calibrated on the basis of experimental results on masonry assemblages or the indications provided by the building codes with reference to the various masonry typology. This approach has been successfully employed for the analysis of historical masonry constructions and the reader can refer, among the many examples, to Valente and Milani (2016) and Addessi et al. (2021b).

Alternatively, the material constitutive response to be introduced in the structural-scale model can be defined by performing an a priori homogenization at RVE level, thus determining the homogenized masonry properties in terms of elastic moduli and strength parameters (see for instance Anthoine, 1995; Zucchini & Lourenço, 2004). It is clear that this method requires detailed knowledge of the dimensions and mechanical properties of the constituent materials. Moreover, it is suitable for regular masonry patterns where the RVE can be identified deterministically as the smallest masonry portion that generates the regular arrangement by repeating itself in the continuum domain.

Finally, step-by-step RVE-based homogenization procedures could be adopted to determine the constitutive response of the material at the structural scale. These multiscale procedures solve a boundary value problem on the RVE at each integration point of the structural-scale model and, therefore, they may require high computational cost if integrated into the so-called FE^2 procedure. In fact, the latter is based on the solution of the micromechanical finite element problem on the RVE at each step, iteration and integration point of the analysis (Massart et al., 2007; Petracca, 2016). As another option, the Transformation Field Analysis (TFA) technique could be adopted. This multiscale procedure deals with a nonlinear homogenization problem based on the superposition of the effects and requires the computation of localization and transformation tensors, avoiding the micromechanical modeling of the RVE during the analysis with computational cost saving. Several TFA versions for masonry are today available, tailored to modeling the in-plane (Addessi et al., 2020; Marfia & Sacco, 2012) and out-of-plane (Addessi et al., 2021a) mechanical response of masonry elements, also characterized by curved geometry (Addessi et al., 2023).

The presented protocol for enhanced modeling of CH, is applicable to both 2D and 3D structural analysis and it can be enriched with micromechanical analysis of structural details or small masonry portions, particularly relevant for the structural safety.

In the following, attention is dedicated to the description of the damage-plastic constitutive model characterizing the finite element model of the case study here analyzed.

12.2.1 Damage-Plastic Constitutive Model

In the spirit of the macromechanical approach, the real heterogeneous masonry material, composed by blocks, stones or bricks, connected with or without mortar, is modeled as a fictitious 2D homogeneous medium. Its constitutive response is described by the damage-plastic law proposed by Gatta et al. (2018), which assumes the hypothesis of small displacements and strains. The model is capable of describing, in a phenomenological manner, the degradation of the mechanical properties of the material caused by the propagation of tensile cracks, the crushing phenomenon and the onset of frictional strains at the interface of the constituent materials.

Assuming a plane stress formulation and adopting the equivalence energy principle of the Damage Mechanics, the stress-strain law is expressed as follows:

$$\sigma = \left(1 - D\right)^2 \mathbf{C}\left(\varepsilon - \varepsilon^{\mathrm{p}}\right) \tag{12.1}$$

where $\boldsymbol{\sigma} = \{\sigma_1\ \sigma_2\ \tau_{12}\}^T$ is the stress vector defined at each material point located at $\mathbf{x} = \{x_1\ x_2\}^T$ on the surface A of the body; $\boldsymbol{\varepsilon} = \{\varepsilon_1\ \varepsilon_2\ \gamma_{12}\}^T$ and $\varepsilon^p = \left\{\varepsilon_1^p\ \varepsilon_2^p\ \gamma_{12}^p\right\}^T$ are the associated total and plastic strain vectors, respectively; $\boldsymbol{C}$ is the elastic stiffness matrix of the isotropic material, classically evaluated using the Young's modulus E, and the Poisson coefficient ν.

The scalar damage variable D in Eq. (12.1) is computed as the proper combination of a damage parameter in tension, D_t, and in compression, D_c, that is: $D = \alpha_t D_t + (1 - \alpha_t)D_c$. The weighting coefficient α_t, later defined, combines the effect of the two damage variables. According to their physical meaning, associated to the reduction of the cross-sectional area due to microcracking, the two damage parameters range between 0, corresponding to undamaged state of the material, and 1, attained when the material is completely degraded. These variables satisfy the thermodynamic irreversibility condition of the degrading process, such that $\dot{D}_t \geq 0$ and $\dot{D}_c \geq 0$. Furthermore, the constraint $D_t \geq D_c$ is imposed to proper describe the stiffness recovery occurring under cyclic loads and due to the re-closure of tensile cracks under compressive states.

The evolution process of the damage parameters, D_t and D_c, is ruled by associated variables, Y_t and Y_c, defined as:

$$Y_t = \sqrt{\sum_{i=1}^{3} \left\langle e_i \right\rangle_+^2} \qquad Y_c = \sqrt{\sum_{i=1}^{3} \left\langle e_i \right\rangle_-^2 + \frac{\kappa}{2} \sum_{i=1}^{3} \sum_{j\neq i=1}^{3} \left\langle e_i \right\rangle_- \left\langle e_j \right\rangle_-} \tag{12.2}$$

In Eq. (12.2), κ is a material parameter influencing the shape of the damage domain in compression; the brackets $\langle \blacksquare \rangle_{+/-}$ select the positive/negative part of the quantity $\blacksquare$ and e_i is the equivalent strain measure, evaluated on the basis of the total principal strains $\hat{\varepsilon}_i$, as:

$$e_i = \left(1 - 2\nu\right)\hat{\varepsilon}_i + \nu \sum_{j=1}^{3} \hat{\varepsilon}_j \tag{12.3}$$

The third component $\hat{\varepsilon}_3$ required in Eq. (12.3) is computed by adding to the corresponding principal elastic strain $\hat{\varepsilon}_3^e = -\nu\left(\hat{\varepsilon}_1^e + \hat{\varepsilon}_2^e\right)/\left(1 - \nu\right)$ the plastic strain $\hat{\varepsilon}_3^p$.

Two damage limit functions, F_t and F_c, are introduced to govern the onset of the damage variables. These are defined as follows:

$$\begin{aligned} F_t &= Y_t - Y_{t0} - D_t\left(a_t Y_t + b_t\right) \\ F_c &= Y_c - Y_{c0} - D_c\left(a_c Y_c + b_c\right) \end{aligned} \tag{12.4}$$

and are ruled by the classical Kuhn-Tucker and consistency conditions. In Eq. (12.4), parameters $Y_{t0/c0}$ represent the initial damage thresholds governing the onset of the tensile and compressive damaging processes; $b_{t/c}$ and $a_{t/c}$ are parameters affecting mainly the peak strengths and the slope of the descending post-peak branches of the stress-strain relationships. Figure 12.3 schematically shows the effect of varying these parameters on an example of uni-axial tensile response.

The weighting coefficient α_t, ruling the combined effect of D_t and D_c, is computed as:

$$\alpha_t = \frac{Y_t^e / Y_{t0}}{Y_t^e / Y_{t0} + Y_c^e / Y_{c0}} \tag{12.5}$$

being $Y_{t/c}^e$ parameters evaluated by using formula (12.2), but on the basis of the principal elastic strains $\hat{\varepsilon}_i^e$.

As far as the plasticity formulation is concerned, a classical Drucker Prager plasticity model is adopted, equipped with kinematic hardening.

The damage-plastic model described is implemented into a quadrilateral isoparametric finite element in the FEAP code (Taylor, 2017), adopting a nonlocal integral formulation (Pijaudier-Cabot & Bažant, 1987) to overcome the mesh-dependency numerical issue, typical of strain-softening response. Hence, the integral definition of the damage associated variables is introduced in Eqs. (12.4) and (12.5). This depends on the nonlocal radius L_c which is a characteristic dimension of the microstructure and the FE mesh.

12.3 Results

The modeling strategy proposed in Sect. 12.2 is here used to analyze response of historical buildings in view of their protection and conservation. In particular, the studies refer to masonry façades with historical relevance for the European heritage.

12.3.1 Damage Assessment of Masonry Façades Subjected to Tunneling-Induced Settlements

Ground settlements caused by excavation activities represent a significant example of human-induced hazard for the existing structures. In fact, underground constructions are often resorted to meet the need of new and improved infrastructures for people and transportation energy purpose. However, their construction process inevitably induces ground displacements that cause cracks on the surface structures, mainly made of masonry. Hence, a proper prediction of the structural damage level is needed to ensure safety conditions with targeted protection measures, which, ultimately, translate into non-negligible economic benefits. This final aim can be achieved by combining results derived from the simplified methodologies commonly used in the underground construction design with more sophisticated analyses based on a realistic description of the material response and geometry of the structures.

Basing on the above considerations, in the following the structural response of masonry buildings to ground movements is analyzed by adopting the macromechanical model presented in Sect. 12.2.1, which allows for accurate modeling of material and geometry.

The case study selected refers to the construction of the L9 Metro tunnel in Barcelona (Camós et al., 2014) and, in particular, to the one-story small dwellings lying in proximity to the tunnel track.

Dwellings represent a building typology frequently used in Barcelona's outskirts. Figure 12.4 schematically shows geometry and dimensions of one of the six dwellings composing the analyzed façade, made of ceramic brick masonry with unit size of 29 × 14 × 4 cm.

The macromechanical FE model of the structure is shown in Fig. 12.5. This is composed of 444 4-node isoparametric finite elements, based on the plane stress hypothesis, and assumes the horizontal and vertical degrees of freedom of the nodes at the base as restrained. Façade thickness is set equal to 20 cm, although some thicker elements are adopted to account for the presence of the transversal partition walls.

The identification of the material mechanical parameters is performed by combining results derived from experimental tests on masonry constituents and homogenization procedures. As described by Camós et al. (2014), mortar strength was determined from penetration tests, while compressive strength of the ceramic bricks was evaluated according to the procedures of EN 772-1 (2002). Then, the strength values of each material component were combined to estimate that of masonry, resulting equal to 4.9×10^3 kN/m^2. Furthermore, the masonry vertical elasticity modulus was found to be equal to 2680×10^3 kN/m^2.

On the basis of the experimental evidence described above and some typical assumptions made for masonry, the model parameters reported in Table 12.1 are adopted for the numerical simulation. These correspond to tensile and compressive strengths equal to 0.08×10^3 kN/m^2 and 4.1×10^3 kN/m^2, respectively. In fact, according to the isotropic characteristic of the model, the assumed elasticity and strength values represent an average quantity among those defined along the masonry natural axes, i.e. the tangential and normal direction to bed joints, by Camós et al. (2014).

The response of the façade to the ground movements experienced during the construction of the L9 Metro tunnel is studied by performing two-step uncoupled soil-structure interaction analysis. Firstly, the gravity loads are applied and, then, keeping these constant, the vertical settlement profile is imposed at the base of the structure by gradually increasing the intensity of the displacements until their final value. In detail, self-weight is determined according to the typical value of masonry

Fig. 12.5 Macromechanical FE model of the six dwellings composing the analyzed façade

Table 12.1 Model parameters assumed for the analyzed façade

E [kN/m^2]	ν	Y_{t0}	Y_{c0}	b_t	b_c	$a_t = a_c$
3015×10^3	0.2	1.5×10^{-5}	2.5×10^{-4}	4.1×10^{-5}	3.5×10^{-3}	0.99

density (1800 kg/m^3) and roof load is represented with a uniform load on the façade equal to 10 kN/m.

As for the settlement profile, this is determined according to the procedure adopted by Peck (1969) and O'Reilly and New (1982), for the general case of an advancing tunnel with axis at depth z_0 below the ground level. Accordingly, the transverse settlement, s_v, is expressed by a Gaussian distribution curve as:

$$s_v = s_{\max} \exp\left(\frac{-x^2}{2i^2}\right) \tag{12.6}$$

In Eq. (12.6), s_{max} is the maximum settlement on the tunnel central line, x is the horizontal distance from the centre line and i is the horizontal distance from the tunnel central line to the point of inflexion on the settlement.

To achieve the best correspondence with the settlement profile in-situ measured, the following parameters are assumed for the Gaussian function: i=7.18, s_{max}= 41 mm. Furthermore, expression of the Gaussian curve is slightly modified to account for the rotation of the wall with respect to the reference section orthogonal to the tunnel axis. Referring to Fig. 12.6 (on the left), the settlement is evaluated in section A-A′ and then transferred to section B-B′ by simple trigonometry. The significant part of the resulting vertical displacement profile and the relative position of the structure are shown in Fig 12.6 on the right.

The results of the numerical simulation are shown in Fig. 12.7 in terms of distribution of the damage variable D on the deformed configuration of the structure. It appears that the most degraded zones are located at the bottom right corner of the building and its middle-right top part, corresponding to the sagging (upward concavity of the settlement profile) and hogging (downward concavity) regions. The

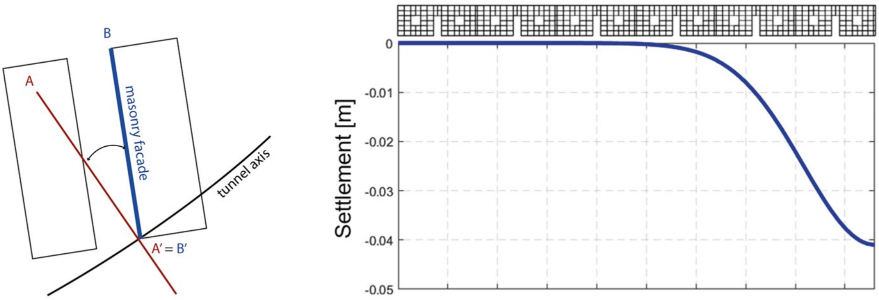


Fig. 12.6 Position of the façade with respect to the tunnel axis (left); applied vertical settlement profile (right)

Fig. 12.7 Distribution of the damage variable D at the end of the analysis

predicted damage scenario well represents the real one, although the real cracks are described phenomenologically by means of smeared damaged zones in the numerical model. A schematic representation of the real damage path at the last three dwellings is shown in Fig. 12.8. This is characterized by several diagonal and vertical cracks, starting from corners of windows and doors till the lintel of the façade. Real crack widths were comprised between 1 and 3 mm.

Numerical outcomes in Fig. 12.9 are represented in terms of distribution of maximum principal strains. This representation allows the damage category to be estimated by exploiting the classification proposed by Boscardin and Cording (1989) and Burland et al. (1977), reported in Table. 12.2. Accordingly, the overall damage in the building can be classified as Slight, both in the hogging and sagging zones, on the basis of the occurring tensile strains.

Finally, the estimated damage category is compared to that identified by adopting other numerical models and procedures. In particular, Camós et al. (2014) determined the degradation level using both the equivalent beam approach commonly used in tunnel design, and advanced FE analysis.

In the first case, the structure response was predicted by applying the free-field settlement profile to a linear elastic beam with building-equivalent stiffness. In the last case, semi-coupled interaction analysis was performed simulating the interaction between soil and foundations with a set of nonlinear springs and representing masonry with a macromechanical model accounting for the material orthotropic behavior.

A summary of the prediction of all models, compared with the real damage categories, is contained in Table 12.3. It emerges that results obtained with the proposed nonlinear FE model are in good agreement with actual evidence and the damage assessment resulting from other sophisticated models. Therefore, the developed macromechanical model represents a useful tool for damage prediction due to tunneling induced cracking for masonry architectural heritage.

12.3.2 Tortona Town Hall Structural Response

A real case study is here selected to evaluate the effects of natural and man-made loads on the structural response of buildings with historical relevance. This is the Tortona town hall.

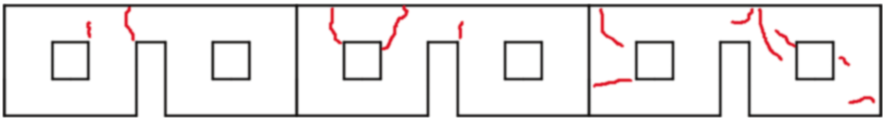


Fig. 12.8 Schematic representation of the real damage occurred at the last three dwellings. [Adapted from Camós et al., 2014]

Fig. 12.9 Distribution of the maximum principal strains at the end of the analysis

Table 12.2 Classification of visible damage to walls proposed by Burland et al. (1977) and Boscardin and Cording (1989)

Category of damage	Normal degree of severity	Description of typical damage	Crack width [mm]		Limiting tensile strain [−]	
			min	max	min	max
0	Negligible	Hairline cracks	0.0	0.1	0.0	5.0×10^{-4}
1	Very slight	Fine cracks which can easily be treated during normal decoration	0.1	1.0	5.0×10^{-4}	7.5×10^{-4}
2	Slight	Cracks easily filled. Re-decoration probably required. Some re-pointing may be required externally.	1.0	5.0	7.5×10^{-4}	1.5×10^{-3}
3	Moderate	The cracks require some opening up and can be patched by a mason. Recurrent cracks can be masked by suitable lining. Repointing of external brickwork and possibly a small amount of brickwork to be replaced	5.0	15	1.5×10^{-3}	3.0×10^{-3}
4	Severe	Extensive repair work involving breaking-out and replacing sections of walls, especially over doors and windows	15	25	3.0×10^{-3}	∞
5	Very severe	This requires a major repair job involving partial or complete re-building	25	∞	–	–

Table 12.3 Comparison between real damage categories and those predicted with equivalent beam and nonlinear macromechanical FE models

	Reality	Equivalent beam model (Camós et al., 2014)	Nonlinear FE model (Camós et al., 2014)	Proposed nonlinear FE model
Damage category sagging	Slight	Very slight	Slight	Slight
Damage category hogging	Slight	Slight	Slight	Slight

Tortona is an Italian city, with about 28,000 inhabitants, located in the province of Alessandria in Piedmont, on the right bank of the Scrivia (see Fig. 12.10 on the left). Throughout history, the city has had military importance due to its strategic position between the Gulf of Genoa and the Po Valley. Evidence of this is the presence of an important castle, which was destroyed and periodically rebuilt until its final demolition, the subsequent construction of barracks, and finally the infantry barracks named after General Passalacqua.

Passalacqua Barracks, which lost its military role becoming a refugee center for Italian displaced persons in the second after war, is the actual location of the Tortona town hall. The building complex, square in plan, consists of four main edifices (see Fig. 12.10 on the right), all characterized by three floors above ground. In this work, the focus is on the biggest building, 137.40 m long and 14.50 m wide, located on Corso Alessandria and oriented to the north. In particular, the structural response of the main façade is analyzed by performing finite element analyses. To this scope, material properties and geometric features of the structure are identified on the basis of information directly derived from the municipal archives and literature studies (Zamperini, 2014). The main construction characteristics, useful to define the intensity of the acting vertical loads, are also summarized in the following:

- double-pitched roof with wooden truss structure;
- horizontals with brick vaults on the ground, first and second floors;
- under-roof slab partly with brick vaults and partly with false wooden vaults.

As far as the construction material is concerned, rubble masonry interspersed with brick strip courses is identified. Indeed, the load-bearing walls of the building were built with stones recovered from the demolition of the ancient castle, alternated with courses of bricks.

The 2D finite element model of the Tortona town hall main façade is shown in Fig. 12.11. This is composed of 14116 4-node isoparametric elements relying on the classical displacement-based formulation. It can be noticed that the model reproduces in detail the window and door layout, while it neglects the slight overhang of the central part of the façade. Moreover, as shown in Fig. 12.11, the macromechanical modeling approach is employed for masonry, as the real heterogeneous material is modeled as a homogenized medium and its main mechanical parameters are

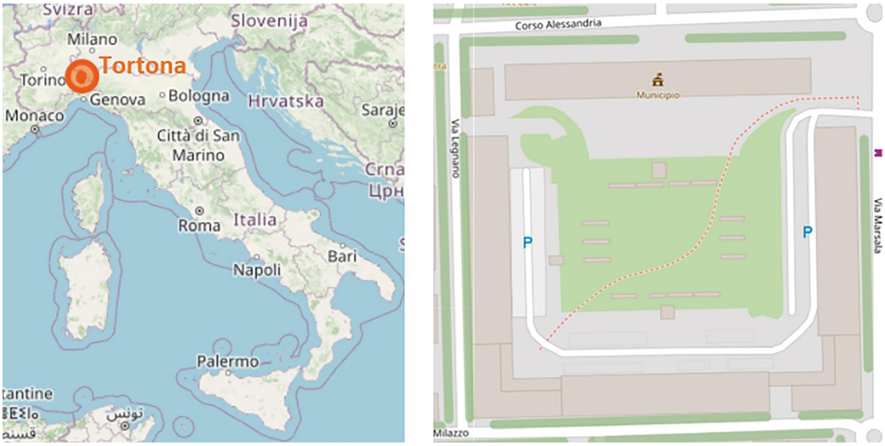


Fig. 12.10 Location of Tortona in Italy (left) and Tortona town hall (right) [Open Street Map source]

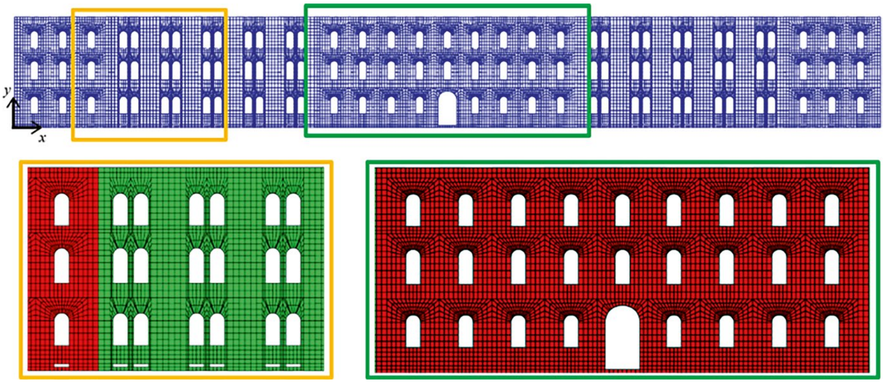


Fig. 12.11 Finite element model of the whole façade (top) and details of some parts (bottom)

identified on the basis of the masonry typology and the indications contained in the Italian Building Code (MITC, 2018, 2019). Hence, isotropic linear elastic constitutive response is assumed, setting Young's and shear moduli equal to 1000×10^3 kN/m^2 and 333×10^3 kN/m^2, respectively.

The response of the façade under vertical forces is analyzed with reference to the following load combinations:

- Combination 1: dead loads.
- Combination 2: dead and live loads.

The value estimated for each load is reported in Tables 12.4 and 12.5. These values are, then, properly traced back to body forces and boundary tractions in the finite

Table 12.4 Intensity of the dead loads

	Masonry self-weight	Wooden roof	Brick vaults	Under-roof brick vaults	Decorative frame in the middle top part
Load intensity	20 kN/m^3	1.2 kN/m^2	5.6 kN/m^2	3 kN/m^2	28.7 kN/m

Table 12.5 Intensity of the live loads

	Snow	People	Crowd
Load intensity	1.2 kN/m^2	2 kN/m^2	4 kN/m^2

element model. Dead loads include the masonry self-weight (thickness of the wall is assumed equal to 0.75 m), the wooden roof, the floor slabs and, also, the contribution of the decorative frame in the middle upper part of the façade, where the inscription ‘Tortona city, town hall’ is located.

The intensity of the live loads, contained in Table 12.5., is evaluated on the basis of the indication contained in the Italian Building Code (MITC, 2018, 2019), considering the effect of snow and live load acting on the slabs and due to human occupancy. The latter is set equal to 2 kN/m^2, except on the second floor in the area where the conference room is placed. There a higher value is considered, that is 4 kN/m^2, to account for the possible presence of crowds of people.

Figures 12.12, 12.13 and 12.14 show the distributions of the vertical stresses, principal maximum and minimum stresses for load combination 1, respectively. The corresponding stress maps for load combination 2 are contained in Figs. 12.15, 12.16 and 12.17. In both situations, a good match between the vertical and the minimum principal stresses emerges. Furthermore, quite similar stress distributions are obtained for the two loading conditions considered, even though increment of stress intensity is detected moving from load combination 1–2. Particularly, an increment of about 15% of the compressive stresses occurs.

Finally, it emerged that, apart from some numerical stress concentration areas, also caused by the presence of restraints, the highest compressive stresses, concentrated around the central door and equal to approximately -9.4×10^2 kN/m^2 (see Fig. 12.15), do not exceed the material's strength, estimated to be between 1.3×10^3 and 2.6×10^3 kN/m^2 on the basis of the masonry typology and the Italian Code indications.

Fig. 12.12 Distribution of the vertical stress, σ_y[kN/m^2], for load combination 1

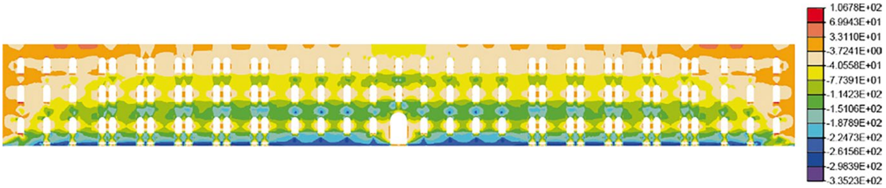


Fig. 12.13 Distribution of the maximum principal stress, σ_{max}[kN/m^2], for load combination 1

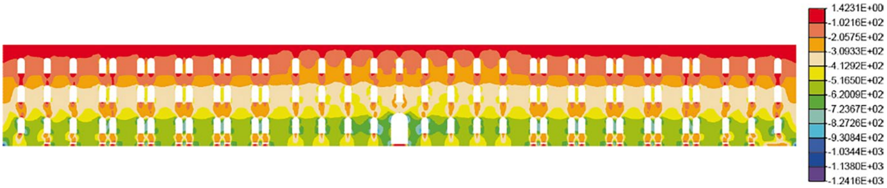


Fig. 12.14 Distribution of the minimum principal stress, σ_{min}[kN/m^2], for load combination 1

Fig. 12.15 Distribution of the vertical stress, σ_y[kN/m^2], for load combination 2

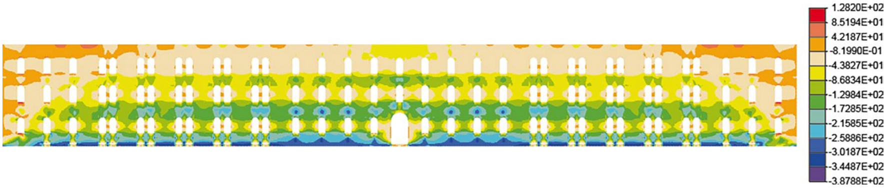


Fig. 12.16 Distribution of the maximum principal stress, σ_{max}[kN/m^2], for load combination 2

12.4 Conclusions

The study discusses the conservation and protection of cultural heritage, focusing on challenges posed by climate change and natural and human-induced risks. Preserving historical buildings, particularly masonry structures, requires a multidisciplinary approach that integrates structural, chemical, and architectural analyses. The methodology developed adopts advanced models that combine strategies at various scales, from the highly detailed but computationally demanding

Fig. 12.17 Distribution of the minimum principal stress, σ_{min}[kN/m^2], for load combination 2

micromechanical approach to more simplified macro-element models suited for rapid simulations and simpler structures.

The proposed methodology proves effective in predicting damages caused, for instance, by underground excavations that induce ground settlements, a significant risk for masonry structures. Through macromechanical models applied to historical façades, such as those analyzed in the case studies, a match was observed between numerical results and actual observed damage, demonstrating the reliability of this approach for predicting structural degradation. The analysis of other cases, like the Tortona town hall, allowed for the evaluation of structural stresses due to natural and man-made loads, concluding that the induced loads do not exceed the material's strength.

This work proposes a protocol for the analysis of historical structures that, by integrating results at different scales, provides a systematic basis for identifying the most suitable modeling strategy according to the available geometric and mechanical data. The presented methodology adapts to both 2D and 3D structures and also allows for detailed analysis of specific structural portions through a micromechanical approach. This protocol, therefore, not only ensures an accurate assessment of vulnerabilities in historical structures but also serves as a valuable tool for planning targeted protection and conservation interventions, guaranteeing the sustainability and preservation of cultural heritage over time.

References

Addessi, D., Marfia, S., Sacco, E., & Toti, J. (2014). Modeling approaches for masonry structures. *The Open Civil Engineering Journal, 8*(1).

Addessi, D., Liberatore, D., & Masiani, R. (2015). Force-based beam finite element (FE) for the pushover analysis of masonry buildings. *International Journal of Architectural Heritage, 9*(3), 231–243.

Addessi, D., Gatta, C., Marfia, S., & Sacco, E. (2020). Multiscale analysis of in-plane masonry walls accounting for degradation and frictional effects. *International Journal for Multiscale Computational Engineering, 18*(2).

Addessi, D., Di Re, P., Gatta, C., & Sacco, E. (2021a). Multiscale analysis of out-of-plane masonry elements using different structural models at macro and microscale. *Computers & Structures, 247*, 106477.

Addessi, D., Gatta, C., Nocera, M., & Liberatore, D. (2021b). Nonlinear dynamic analysis of a masonry arch bridge accounting for damage evolution. *Geosciences, 11*(8), 343.

Addessi, D., Di Re, P., Gatta, C., & Sacco, E. (2023). Non-uniform TFA reduced multiscale procedure for shell-3D modeling of periodic masonry structures. *Mechanics Research Communications, 130*, 104122.

Anthoine, A. (1995). Derivation of the in-plane elastic characteristics of masonry through homogenization theory. *International Journal of Solids and Structures, 32*(2), 137–163.

Augenti, N. (2006). Seismic behaviour of irregular masonry walls. In *Proceedings of the 1st European Conference on Earthquake Engineering and Seismology*.

Beirão da Veiga, L., Brezzi, F., Cangiani, A., Manzini, G., Marini, L. D., & Russo, A. (2013). Basic principles of virtual element methods. *Mathematical Models and Methods in Applied Sciences, 23*(01), 199–214.

Boscardin, M. D., & Cording, E. J. (1989). Building response to excavation-induced settlement. *Journal of Geotechnical Engineering, 115*(1), 1–21.

Burland, J. B., Broms, B., & De Mello, V. F. B. (1977). Behaviour of foundations and structures. State of Art Report. Session 2. In *Proceedings of the 9th International Conference on Soil Mechanics and Foundation Engineering* (Vol. 2, p. 495).

Camós, C., Molins, C., & Arnau, O. (2014). Case study of damage on masonry buildings produced by tunneling induced settlements. *International Journal of Architectural Heritage, 8*(4), 602–625.

D'Altri, A. M., Sarhosis, V., Milani, G., Rots, J., Cattari, S., Lagomarsino, S., et al. (2020). Modeling strategies for the computational analysis of unreinforced masonry structures: Review and classification. *Archives of Computational Methods in Engineering, 27*, 1153–1185.

Dolce, M. (1991). Schematizzazione e modellazione degli edifici in muratura soggetti ad azioni sismiche. *Industria delle costruzioni, 25*(242), 44–57.

EN 772-1. (2002). *Methods of test for masonry units. Part 1: Determination of the compressive strength*. European Committee for Standardization.

Gatta, C., Addessi, D., & Vestroni, F. (2018). Static and dynamic nonlinear response of masonry walls. *International Journal of Solids and Structures, 155*, 291–303.

Jirásek, M. (2011). Damage and smeared crack models. In *Numerical modeling of concrete cracking* (pp. 1–49). Springer.

Lagomarsino, S., & Cattari, S. (2015). PERPETUATE guidelines for seismic performance-based assessment of cultural heritage masonry structures. *Bulletin of Earthquake Engineering, 13*, 13–47.

Lagomarsino, S., Penna, A., Galasco, A., & Cattari, S. (2013). TREMURI program: An equivalent frame model for the nonlinear seismic analysis of masonry buildings. *Engineering Structures, 56*, 1787–1799.

Lloberas-Valls, O., Rixen, D. J., Simone, A., & Sluys, L. (2012). Multiscale domain decomposition analysis of quasi-brittle heterogeneous materials. *International Journal for Numerical Methods in Engineering, 89*(11), 1337–1366.

Marfia, S., & Sacco, E. (2012). Multiscale damage contact-friction model for periodic masonry walls. *Computer Methods in Applied Mechanics and Engineering, 205*, 189–203.

Massart, T. J., Peerlings, R. H. J., & Geers, M. (2007). An enhanced multi-scale approach for masonry wall computations with localization of damage. *International journal for numerical methods in engineering, 69*(5), 1022–1059.

MIT Ministero delle infrastrutture e dei trasporti. (2018). Decreto 17 gennaio 2018. *Aggiornamento delle "Norme tecniche per le costruzioni"*.

MIT Ministero delle infrastrutture e dei trasporti. (2019). Circolare 21 gennaio 2019, n.7. Istruzioni per l'applicazione dell'Aggiornamento delle "Norme tecniche per le costruzioni" di cui al decreto ministeriale 17 gennaio 2018.

O'Reilly, M. P., & New, B. M. (1982). *Settlements above tunnels in the United Kingdom-their magnitude and prediction*.

Peck, B. B. (1969). Deep excavation and tunnelling in soft ground, State of the art volume. In *7th ICSMFE* (Vol. 4, pp. 225–290).

Petracca, M. (2016). *Computational multiscale analysis of masonry structures*. Polytechnic University of Catalonia. Ph.D. thesis

Pijaudier-Cabot, G., & Bažant, Z. P. (1987). Nonlocal damage theory. *Journal of engineering mechanics, 113*(10), 1512–1533.

Quagliarini, E., Maracchini, G., & Clementi, F. (2017). Uses and limits of the equivalent frame model on existing unreinforced masonry buildings for assessing their seismic risk: A review. *Journal of Building Engineering, 10*, 166–182.

Raka, E., Spacone, E., Sepe, V., & Camata, G. (2015). Advanced frame element for seismic analysis of masonry structures: Model formulation and validation. *Earthquake Engineering & Structural Dynamics, 44*(14), 2489–2506.

Roca, P., Cervera, M., Gariup, G., & Pela', L. (2010). Structural analysis of masonry historical constructions. Classical and advanced approaches. *Archives of Computational Methods in Engineering, 17*, 299–325.

Rots, J. G. (1991). Smeared and discrete representations of localized fracture. *International Journal of Fracture, 51*, 45–59.

Sangirardi, M., Liberatore, D., & Addessi, D. (2019). Equivalent frame modelling of masonry walls based on plasticity and damage. *International Journal of Architectural Heritage, 13*(7), 1098–1109.

Taylor, R.L., (2017). *FEAP—A Finite Element Analysis Program*. Version 8.5. Department of Civil and Environmental Engineering, University of California, Berkeley.

Valente, M., & Milani, G. (2016). Seismic assessment of historical masonry towers by means of simplified approaches and standard FEM. *Construction and Building Materials, 108*, 74–104.

Zamperini, E. (2014). Caserme recuperate a usi pubblici. Caserma Passalacqua a Tortona: Conversione a sede municipale. In *Le caserme e la città. I beni immobili della difesa tra abbandoni dismissioni e riusi* (pp. 431–436). Palombi Editori.

Zucchini, A., & Lourenço, P. B. (2004). A coupled homogenisation–damage model for masonry cracking. *Computers & Structures, 82*(11–12), 917–929.

Chapter 13
Wine Cultural Landscape's Adaptation: A Method-Logical Framework for the Dynamic Conservation of Cultural Heritage

Alessandra Battisti, Herbert Natta, Maria Valese, Eva Vergara, and Angelo Figliola

Abstract Cultural Landscapes, resulting from a long history of interaction between people and nature, are a well-recognized resource for improving the quality of life and promoting sustainable economic chains. However, the current Climate Change process, putting the fragile equilibrium between the natural and human environment at risk, represents one of the most significant threats to their conservation. In particular, due to their dependence on specific combinations of cultural and environmental factors, the Wine Cultural Landscapes requires effective strategies to safeguard their tangible and intangible components. In this context, the research aims to provide decision-makers with a methodological framework for exploiting the potential of geospatial data in evaluating the adaptability of Wine Cultural Landscapes to the environmental transformation produced by Climate Change. Moving from the existing policies and the most common indicators for landscape assessment in the European framework, the research proposes a data-driven workflow to evaluate the transformation of Wine Cultural Landscapes to support the activation of dynamic conservation strategies (ICOMOS, ICOMOS-IFLA principles concerning rural landscapes as heritage, 2017). The paper considers, as applicative case studies, two European Wine Cultural Landscapes through a comparative

---

This contribution appears as "Battisti A., Natta, H., Valese, M., Vergara, E., Figliola A. (2024), Wine Cultural Landscape's Adaptation: A Methodological Framework for the Dynamic Conservation of Cultural Heritage Wine Cultural Landscape's Adaptation: A Methodological Framework for the Dynamic Conservation of Cultural Heritage, Journal of Digital Landscape Architecture, 9–2024, pp. 552–569, https://doi.org/10.14627/537752051". It is published in Open Access under Creative Commons-CC by 4.0—authors' permission.

A. Battisti (✉) · H. Natta · M. Valese · E. Vergara · A. Figliola
Sapienza University of Rome, Department of Planning, Design, Technology of Architecture, Rome, Italy
e-mail: alessandra.battisti@uniroma1.it; herbert.natta@ge.imati.cnr.it; maria.valese@uniroma1.it; eva.vergara@uniroma1.it; angelo.figliola@uniroma1.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_13

approach: the Rioja (Spain), included in the UNESCO candidate list, and the Colli Tortonesi (Italy), an Italian Protected Origin Denomination wine production area.

Keywords Cultural landscape · Climate change · Wine · Data-driven processes · Multi-criteria analysis

13.1 Introduction

Cultural Heritage (CH), as a concept to identify items with recognized Outstanding Universal Values (OUVs), appeared in the international debate in dichotomic juxtaposition with Natural Heritage (NH), distinguishing the "work[s] of man" (UNESCO, 1972) from geological/physical formations, specific habitats of animal species, etc.

However, soon, this separation appeared too restrictive and dependent on a Western cultural framework, opening the road for a hybridization that emphasizes the link be-tween human beings and their environment. In this sense, the revision of the World Herit-age Convention (WHC) introduced the concept of Cultural Landscape (CL) as the result of the combined work of nature and man (UNESCO, 1992).

This extension of CH to CLs has been a result of a broader debate, fostered to shift the attention from CH as a valuable, isolated object to its interrelation with the context (UNESCO, 1972, 2003, 2005): a living system (UNESCO, 2005), inclusive of intangible components and the active action of people (UNESCO, 2005, 2012).

The concept of CL initially prevails on the 'rural landscape' one (Cameron & Mechtild, 2013), present from the 1980s in UNESCO's documents (Scazzosi, 2018) with a similar purpose: to include in the protection mechanism activated by the World Heritage List (WHL) properties with both natural and cultural OUVs.

However, in time, the meaning and role of Rural Landscape (RL) have been specified as a subcategory of CLs: one of the most common types of 'continuing cultural landscapes', coproduced by human-nature interaction for the production of food and another renewable natural resource (ICOMOS, 2017).

In defining RLs as complex systems of different kinds of valuable elements (both physical and intangible), ICOMOS underlines their continuous, irreversible, and inevitable processes of transformation (ICOMOS, 2017), introducing the concept of 'dynamic conservation' as a best practice to safeguard the heritage values respecting the intrinsic RL's dynamism.

In Europe, despite the immense scale of socio-economic changes that have accompanied industrialization and urbanization in many parts of the continent (EEA, 1995), RLs represent 95% of the territory (Agnoletti, 2014). Due to their historical interconnection with European cultural development in several countries, they have a quantitative and qualitative relevance that paradoxically has to face the current and foreseen urbanization trends. About 28% of the EU population lives mainly in inner peripheries and rural areas, 31.6% live in small and suburban areas (intermediate areas), and the remaining 40.4 are concentrated in larger cities (Eurostat, 2017). Across the world, the trend towards urbanization seems unstoppable. Forecasts indicate that by 2050, city dwellers will increase by 24.1 million, while the population of mainly rural areas will decrease by 7.9 million (OECD, 2016). In the following decades, depopulation will affect the internal European areas of Spain, France, Germany, Poland, Slovenia, Romania, Czech Republic, Greece and Italy (Verburg et al., 2010), following two different modalities: the first caused by the emigration of a class demographic in working age towards the big cities, the second connected with the progressive ageing of the population of the places. A low birth rate generally accompanies this phenomenon by a low birth rate (Golini, 2000).

Consequently, the depopulation, land abandonment, and urban expansion (and the related infrastructure) threaten the conservation of the significant or characteristic features of RLs due to an acceleration of their transformation promoted by the European Land-scape Convention (Council of Europe, 2000).

Furthermore, the system of processes defined by the umbrella term of Climate Change (CC) substantially impacts the conservation of RLs as living systems of cultural and natural elements. If, by definition, the climate is a temporal stability of environmental conditions, its sudden variation deeply affects the long-lasting interaction between human presence/action and its environmental context.

In the update of the "Policy Document on Climate Action for World Heritage" (UNESCO, 2021), the member states identify CC as one of the most significant threats to CH and define guidelines and specific goals for activating urgent preservation strategies.

The document also recognizes CLs as places that might significantly contribute to climate mitigation, providing land use management solutions and traditional knowledge with a solid and harmonious human connection to the natural environment.

Thus, CLs represent something to preserve and a driver for activating adaptation strategies to face the environmental changes generated by CC.

From the Cork Declarations (EU, 1996, 2016) to the EU's Common Agricultural Policy (CAP) and the specific long-term vision for EU's Rural Areas (European Commission, 2022), the exploitation of rural potential as a driver of sustainable development and as a vector of mitigation and adaptation strategies to face CC stands at the core of several European policies for rural areas, targeted at encouraging their economic development, promoting counteraction against depopulation, ageing and land abandonment trends. The main pillars of this action are economic diversification, digitalization (both in terms of education and infrastructure) and the activation of job creation and positive generation renewal trends.

However, the enhancement of rurality as a driver of sustainable socio-economic development overlaps and, sometimes, interferes with the policies more related explicitly to landscape preservation, at the point that, even though the debate has been in progress for years, a specific European agreement about the protection of RLs is still to be defined (EEA, 1995b).

Some attempts have been made to develop indicators to identify and classify RLs for monitoring the integration of environmental concerns into European policies (Paracchini & Capitani, 2011; Ungaro et al., 2014; Medeiros et al., 2021; Sabbioni et al., 2006). The growing availability of spatial data at high spatial and temporal resolution encourages the development of data-driven approaches to landscape monitoring, providing adequate and flexible methods and tools to support decision-making processes, helping in defining what to be preserved in RLs through a multi-dimensional measurement of their status and their transformation.

This possibility becomes fundamental in the perspective of dynamic conservation of RLs in the context of CC, where the environmental transformation threatens the existing landscapes but generates new potential landscapes (Myga-Piątek & Rahmonov, 2018).

The core of this research is evaluating the current RLs' status and their adaptation to new environmental contexts, aiming to provide a methodological framework based on geospatial analysis to support the development of dynamic conservation strategies.

The integration of digital technologies, both as tools and methods, offers the opportunity to exploit the potential of the growing availability of spatial data to turn the RL's complexity into a computable object, supporting the monitoring of its condition and trans-formation, along with the simulation of future scenarios.

13.2 Methodology

The research focuses on Wine Cultural Landscapes (WCLs), a specific kind of RL produced by developing viticulture traditions. Currently, the WHL includes fourteen proper-ties related to winemaking (Pijet-Migoń & Migoń, 2021), among which eight are classified as CLs, almost all in Europe.

Winemaking is a traditional practice and a leading economic sector in several European countries; however, WCLs are particularly vulnerable to CC due to their high dependence on climatic and environmental conditions (Carroquino et al., 2020).

The soil erosion impacts the traditional shape of wine hills, while the water stress and temperature increase affects all the bio-cultural processes, from grapes maturation to wine quality and the seasonality of winemaking (Iglesias et al., 2010; Jones & Alves, 2012; Fraga et al., 2016; Ramos, 2017).

Thus, it becomes fundamental to simulate predictive scenarios of the environmental transformation to understand how WCLs will be affected and how conservation/adaptation strategies can reduce the loss of current WCLs, taking advantage of new suitable areas.

The proposed methodological framework is based on a data-driven approach, focused on using the available geospatial repositories for a multidimensional measurement of RLs, both in a descriptive and predictive perspective.

The composite nature of RLs has required a preliminary selection of indicators based on the existing literature on landscape modelling at the European and national levels (Eurostat, 2010; Paracchini & Capitani, 2011; ISTAT, 2021; Agnoletti et al., 2019; Battisti et al., 2022).

Three main dimensions have been identified: (i) ecology, to qualify the geophysical structure of RLs, its diversity and the equilibrium of human presence and activity with the natural environment; (ii) culture, focused on the social awareness of the RL’s relevancy for the community; (iii) dynamicity, considering the current, past and forthcoming transformation processes.

These dimensions have been analyzed through three indicators (Table 13.1), including quantitative and qualitative parameters. The indicators are intended as an open measurement tool to activate the workflow, providing the model to structure the initial input. However, during the expected iteration of the process, they should be integrated, engaging the stakeholders involved in the RL’s management (public administration, private companies, associations, citizens, etc.).

The dimensions and indicators support both an analytic description and synthetic classification of RLs, providing the necessary information to understand the RL’s behavior about specific phenomena, supporting as such the definition of coherent adaptation/mitigation strategies and a synthetic classification of the RLs in terms of naturalness (ecology), perception (culture) and transformation (dynamicity), setting a comparative framework for the definition of differentiated policies, respectful of the heterogeneous nature of RLs.

In addition to the general indicators defined for the RLs’ preliminary analysis, specific parameters have been selected for the WCLs to understand, according to the different dimensions, the relevancy of vineyard cultivations and winemaking practices (Table 13.2).

Table 13.1 Dimensions and indicators for RL’s analysis

Dimension	Indicator code	Indicator
Ecology	E1	% surface rural landcover
	E2	Rural entropy
	E3	Degree of hemeroby
	E4	Landscape units’ diversity
	E5	Orography
Culture	C1	% surface of protected areas
	C2	Number of recognized valuable landscape elements
	C3	Number of tourist attractions
Dynamicity	D1	Depopulation
	D2	Urbanization
	D3	% crop surface change
	D4	Normalized Difference Vegetation Index (NDVI) change
	D5	Leaf Area Index (LAI) change

Table 13.2 Specific indicators for WCL's analysis

Dimension	Indicator code	Indicator
Ecology	EW1	% vineyards surface
	EW2	Vineyards distribution
	EW3	Grapes variety
	EW4	% surface for vitis vinifera cultivation
	EW5	Number of trees/ha
	EW6	Grapes production/ha
Culture	CW1	Age of the vineyard cultivation
	CW2	Number of PDO's farming activities
	CW3	Number of trees/ha in PDO's farming activities
	CW4	Grapes production/ha in PDO's farming activities
	CW5	Number of tourist attractions related to winemaking
	CW6	Number of tourist services (accommodations, restaurants) related to the vineyard's farming activities
Dynamicity	DW1	Number of workers in winemaking farming activities (trend)
	DW2	Population trend in vineyard areas
	DW3	% built-up surface change in vineyard areas
	DW4	% crop surface change in vineyard areas
	DW4	Normalized Difference Vegetation Index (NDVI) change in vineyards areas
	DW5	Leaf Area Index (LAI) change in vineyards areas

This model activates the workflow, articulated in four steps:

1. Identification of the RL: This is the initial, fundamental phase to define the object of the analysis spatially and conceptually. They can be used as a reference to the existing policies which provide a territorial base and a brief description of the protected area (e.g. UNESCO buffer and core zones, PDOs, etc.);
2. Data collection: selection of the data sources for populating the model. They can be considered repositories of spatial data at different scales, both international (to allow the comparison between different countries) and national or sub-national (to work on a higher level of detail), giving priority to (i) comparable datasets, (ii) higher resolution and (iii) update. The selected sources have to be harvested through an Extraction/Transformation/Load (ETL) process, starting from the definition of query parameters (spatial and temporal range, variables, etc.), proceeding to a normalization of the datasets (reprojection, data cleaning, downscaling, etc.) to achieve an integrated spatial database where to store and update the collected data, making them available for the next step;
3. Analysis: elaborating the collected data, according to the model's dimensions and indicators, provides a parametric description of the area. This base of knowledge permits to characterize the RL, considering its structural elements and transformation dynamics. This classification defines (i) a comparative framework for identifying similarities and differences between RLs in different con-

texts, as such supporting (ii) the development of specific adaptation/mitigation strategies targeted to clusters defined by recurrent configurational patterns;

4. Simulation: the outcomes of the third analytic phase define the present status of the RL, along with its current and past transformation dynamics. In the fourth phase, in terms of suitability, this system is evaluated by simulating transformation scenarios. Changing some parameters in the RL's natural and human environment generates a virtual context where the possibility of the existence of the RL, as it is or in a different configuration, can be tested. This phase provides, as output, a visualization of (i) the RL's elements that are suitable to survive in the simulated scenario, (ii) the features that are most vulnerable to the transformation dynamics and require adaptation strategies, (iii) areas that are currently peripheral in the RL's system, but that, in the new environmental conditions, are suitable for the generation of a potential RL.

The workflow is intended as an iterative process to guide decision-making through identifying the main components of RLs and their transformation trends, visualizing the simulated scenarios and discussing the outcomes with the stakeholders in participatory activities. This iteration is fundamental for collecting new inputs, data and parameters to integrate the model with more granular information or specific indicators. In this way, it is possible to evaluate different strategies in an open process fostered at supporting ad hoc safeguarding strategies, that working on specific components through targeted actions could encourage dynamic conservation of RLs.

The paper proposes a comparative application of this workflow, from the data collection to the simulation, to two European WCLs identified by a similar system of protection (the wine PDOs) but diverse in their characteristics and included in different protection systems.

13.3 Case Studies

13.3.1 Comparison Framework Overview

The two selected case studies are the Rioja (Spain) and the Colli Tortonesi (Italy), defined by the discipline of a European and nationally recognized wine PDO. The comparison aims to understand if and how the protection policy of a registered excellent product impacts the conservation of the landscape in the same international framework but in different national and local systems of policies.

The methodological framework developed by the research aims to provide a system of measurement that, parametrizing the WCL, helps identify differences and similarities between the two cases, supporting the definition of standard best practices along with specific actions.

The four workflow steps have been developed for the two cases, moving from a similar identification of the territorial base, determined by the definition provided by the PDOs' documents, and considering the conservation policies at different levels.

The two areas differ in qualitative and qualitative terms, considering the extension, the population and the normative centrality as protected areas. The Rioja is broader, more populated and included in the UNESCO WHL's tentative list (properties which the UNESCO members consider as cultural and/or natural heritage and therefore suitable for inscription on the WHL, UNESCO, 2020), while the Colli Tortonesi is in a low-density rural area, at the outskirts of the more famous "Wine Cultural Landscapes of Langhe, Roero and Monferrato", recently included (2014) in the UNESCO WHL.

However, among the rejection reasons for Rioja's application to WHL is the fragmentation of the WCL in some of its areas, a structural characteristic also documented in the description of landscape units in the Colli Tortonesi area (Regional Landscape Plan of Piedmont Region, 2017). Furthermore, the Colli Tortonesi will receive a new centrality, with potential opportunities and threats, by activating the European connection between Genova and Hamburg (via Milan).

In the data collection phase, moving from the above-listed indicators, data sources have been selected and integrated at the European, national, and local levels to support the comparative framework while maintaining the level of detail provided by regional repositories (Table 13.3).

Table 13.3 Selected data sources for the two case studies

Indicator codes	Data source
E1, E2, EW1, EW2	elaboration from CLC 2018
E3	reclassification of CLC 2018 (Paracchini & Capitani, 2011)
E4	Regional Landscape Plan of Piedmont Region 2017 (Colli Tortonesi), Rioja Province 2011 (Rioja)
E5	elaboration from 10m DEM (Piedmont Region 2011) and 5m DEM (CNIG 2008)
C1	European Natura 2000
C2	Regional Landscape Plan of Piedmont Region 2017, Rioja Province 2011
C3, CW5, CW6	Tripadvisor
D1, DW2	Global Human Footprint (GHF)
D2, DW3	Copernicus Land Cover Built-up Fraction (BF 2015–2019)
D3, DW4	Copernicus Land Cover Crop Fraction (CF 2015–2019)
D4, DW5	elaboration from Sentinel-3 OLCI (2020–2023)
D5, DW6	elaboration from Sentinel-3 OLCI (2020–2023)
EW3, EW5, EW6, CW1, CW2, CW3, CW4	Regional Agricultural Cadaster (Piedmont), Rioja PDO
EW4	elaboration from 10m DEM (Piedmont Region 2011) and 5m DEM (CNIG 2008)
DW1	Italian National Institute of Statistics (2015–2019), Instituto Nacional de Estadistica (INE)

Integrating different sources has been fundamental to achieving an adequate spatial resolution for a comparative territorial analysis of the two selected areas. However, this heterogeneity has implied a normalization of different spatial resolutions: 1kmx1km (GHF), 100 m × 100 m (CLC), 10 m × 10 m (Piedmont DEM) and 5 m × 5 m (CNIG DEM).

Furthermore, the simulation scenarios have been considered the main climatic indica-tors published by the European COordinated Regional Climate Downscaling EXperiment (EURO-CORDEX) and collected through the Copernicus Climate Change Service (C3S) API (Copernicus Climate Change Service, 2019). This dataset has a spatial resolution of 0.11° × 0.11° (approximately 10 km × 10 km).

In the normalization process, the EURO-CORDEX and GHF datasets have been downscaled to a 100 m × 100 m resolution, maintaining the value per cell of the first and distributing the population value of the second. At the same time, the DEM has been up-scaled, considering an average value per cell.

For the suitability analysis of WCL, the Representative Concentration Pathway (RCP) scenarios 2.6 and 8.5 at 2050 have been considered, calculated through the CNRM-CERFACS-CM5 model, considering, as variables, the air temperature (maximum, mini-mum and average), relative humidity and mean precipitation. These indicators have been integrated into the calculation of the Huglin Index, Winkler index, growing season temperature (Bai et al., 2022), dryness index and hydrothermic index (Sgubin et al., 2023) as well as recognized dimensions for measuring the climatic suitability to the development of the grapevine's phenological phases. However, the WCL stands on more than just the environmental possibility for the Vitis vinifera to grow; it also requires the consideration of anthropic trends (D1, D2, D3) and adequate vegetation status (D4 and D5). These variables have been integrated into the simulation model as risk indicators.

The integration has been realized in two steps: firstly, it has been composed of the suitability index (Sgubin et al., 2023), and then it has been multiplied by a composite index calculated through the normalization of D1–D5 through the information entropy weighting method (Shannon, 1948). In this way, the future scenario generated by climatic projections, which defines the potential suitability for WCL, is adjusted by positive and negative factors, which can support the preservation of WCL or contribute to deter-mining its loss.

This model aims to set an open framework for activating the iterative process defined in the methodology, which can produce different simulations supporting the decision-making process by integrating new indicators.

13.3.2 La Rioja

The Rioja PDO's area is located in Northeastern Spain, crossed by the River Ebro, which generates two different physiographical sides (a system of reliefs and valleys on the West side and a network of tributaries on the East) and is protected (in the North) by the massif of the Sierra Cantabrica (Fig. 13.1).

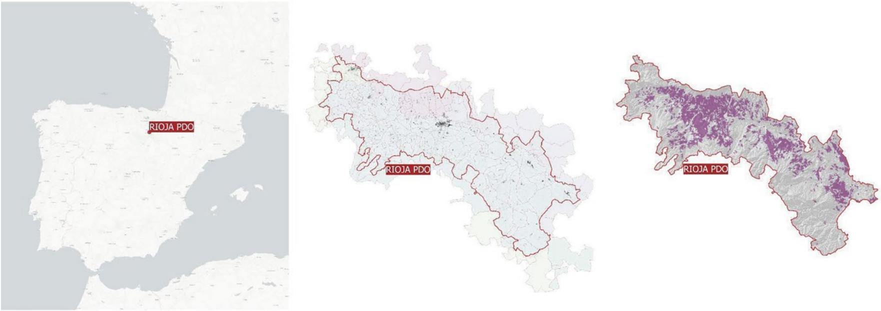


Fig. 13.1 (**a**) Rioja is located in the North-East of Spain. (**b**) It includes 205 municipalities, and it crosses the three autonomous regions of Navarra, La Rioja and the Basque Province of Alava; (**c**) the vineyards cross the region from East to West, covering 42% of the total surface (CLC, 2018). [Sources: Carto Positron Basemap, Open Street Map, CLC 2018, 5 m DEM, maps elaborated by the authors]

The Rioja includes 205 municipalities, distributed in the three autonomous communities of La Rioja, Navarra and the Basque Countries, with an overall population of around 315,000 inhabitants, half of which are located in the main centre of Logroño (150,020 in.) and other 80,000 distributed in the medium size municipalities of Calahorra, Arnedo, Haro, Lardero.

The territory has been used for vineyard cultivation since the pre-Roman age, generating, in time, traditional techniques related to winemaking and grapes growing.

13.3.2.1 Identification

Rioja is the most ancient PDO in Spain, dating back its origin to 1925 as a development of a previous, long history of promoting and protecting the local grapevine farming. The PDO first defined the production area as a territory, establishing an official regulation. Over time, the area progressively expanded, including new wine varieties. In 2017, the regulation included the geographical entity of the viñeto singular (singular vineyard): a territorial unit smaller than the municipality, with specific agrogeologic and climatologic characteristics that distinguish it from the surroundings.

The EU PDO's register included Rioja since 1986; since 2013, it has been a candidate as a WH site. One of the main reasons ICOMOS rejected the candidacy was territorial delimitation due to its fragmentation (UNESCO, 2015; ICOMOS, 2015).

Over the last 10–20 years, Rioja winemaking has added wine tourism as a new product. Among other activities visitors will carry out are visits and excursions through the vineyards, and their attractiveness is growing. The vineyard's landscape, aesthetic and cultural value have led the Government of La Rioja to consider the vineyard as a Landscape of Cultural Interest. However, some shadows arise after the landscape changes of the last decades, as the growing trend towards homogenization, defragmentation, expansion of espalier plantations, and migration of hillside vineyards towards flat and more fertile are-as threatens to transform a unique, cultural and beautiful landscape into a very general landscape, similar to other European vineyard landscapes. The environmental conditions and the tillage of generations of farmers gave rise to a diverse landscape, rich in biodiversity and aesthetics, unique and singular; a landscape that has evolved towards the homogenization imposed by mechanization and uniform European Union legislation, which constitutes a threat to the maintenance of the cultural landscape of the vineyard.

All this is combined with the need for more agreement for the historical management of the Rioja PDO territories due to the difference in criteria between the Autonomous Communities of La Rioja and the Basque Country.

13.3.2.2 Analysis and Simulations

The analytic phase characterizes Rioja's territory as predominantly rural, with 42.2% agricultural land cover (E1) and 15% vineyards (EW1). The average hemeroby index (E3) of 3.73 stands between the semi-natural (mesohemerobe) and relatively far from natural (β-euhemerobe) classes, revealing the impact of rural activity on the modification of the natural environment (Fig. 13.2a). The rural structure presents an average entropy index (E2) of 0.63, lowered by the predominance of vineyards (65% of rural landcover surface). The built environment follows a hierarchical network distribution, with higher-density urban areas and small villages dispersed in the rural environment (Fig. 13.2b). The depopulation trend in the last 5 years (D1) shows a cluster in the Northwest area (municipality of Miranda de Ebro), which is out of the central vineyards cluster and, more generally, this demographic phenomenon affects less the territories directly including vineyards landcover. The Rioja PDO recognizes 570 vineyard farming activities (CW2), around half of which (210) pro-vide tourist services and 360 providers of specific ecotourism experiences (CW5, CW6). The growth of the built environment in the last 5 years (DW3) affects

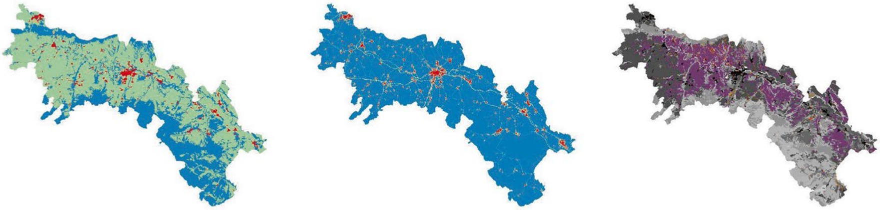


Fig. 13.2 (**a**) the hemeroby index qualifies the area considering the spectrum between the major (in red) and minor (in blue) impact of human presence/activity on the natural environment; (**b**) the distribution of the built environment as a fraction of the cell surface let emerge the presence of architectural/infrastructure elements in the predominantly natural context; (**c**) the map shows the higher changes (in red) in the built fraction between 2015 and 2019

more the south-ern part; however, close to the main centre of Logroño, there is an active urbanization process directly affecting the vineyards area (Fig. 13.2c).

The data-driven exploration has revealed a territory highly centred on the presence of vineyards, both from a quantitative and qualitative perspective: a rural element that characterizes the natural environment, with its historical presence, deeply connected with human activity. A dedicated protection system for high-quality winemaking has determined the growth of several economic activities in the sector, not only targeted to agricultural production but also to the activation of tourist services for enhancing the attractiveness of new economic chains. However, the urbanization trend and the transformation in the environmental condition can produce potentially dangerous dynamics for the WCL's conservation.

The simulation phase aims to put the WCL in new environmental conditions, determined by CC in correlation with anthropic dynamics. The comparison between the mini-mum (RCP 2.6, Fig. 13.3a) and maximum (RCP 8.5, Fig. 13.3b) increase in temperature in the short period (2050) reveals how the spatial distribution of the suitability areas does not significantly change in the two simulations, while there is a quantitative contraction in the most extreme one, with a potentially significant loss of almost the 90% of the existing vineyards area, with the compensation of only the 0.1% of new suitable zones (Fig. 13.3c).

The simulations identify a central cluster with a stable suitability condition and a distributed longitudinal loss of these characteristics across the whole area, with small variations determined by orographic conditions like the presence of higher reliefs, which can potentially mitigate the temperature increase. The structural homogeneity of the territory does not play in favor of the generation, inside of the territorial unit defined by the PDO, of new potential suitable areas.

The structural characteristics of the WCL that emerged in the identification phase are fundamental to evaluating the simulation's resulting scenarios and developing specific preservation strategies. The suitability index calculated through the elaboration of climatic projections shows an asymmetric development of environmental conditions in the area, with a higher Winkler index in the Eastern and Western areas and lower values in the Centre and South. However, the demographic trend and the expansion of the built environment negatively impact on the weighted index.

Fig. 13.3 The simulation has considered climate data projections in the (**a**) less dangerous (RCP 2.6) and (**b**) most dangerous scenarios, considering the relative variation in the suitable areas for vineyards cultivation (from yellow to blue), providing, for each scenario, (**c**) visualization of the vineyards areas in danger (in magenta) and the new potentially suitable areas (in green)

13.3.3 Colli Tortonesi

Colli Tortonesi is an Italian PDO located in the Northwest of the country (in the Piedmont region), in a geographical area where the Plain of the Po gradually shifts into the Apennine Mountains through a system of hills and river valleys (Fig. 13.4). Since the first human settlements, the area has been strategically located at the crossway of the communication network (rivers, roads, railroads). Tortona, the main urban center of the area, is a 25,000 inhabitants Roman age settlement situated in a strategic position for its centrality between the urban polarities of Turin, Genoa and Milan and its connection with the European TEN-T corridor n. 3, which aims at linking the North and the Mediterranean Sea.

On a local scale, Tortona works as a polarity for a network of around 30 villages (most under one thousand inhabitants) that populate the river valleys between the city and the Apennine Mountains.

13.3.3.1 Identification

The tradition of winemaking in Piedmont and the related landforms that characterize its RLs is rooted in the pre-Roman age, developing in connection with several aspects of the local culture. The PDO has been an active instrument of protection since 1974: it specifies the relationship between the wine and the production area, highlighting how the lithological characteristics of the ground generate the specific salinity of the wine.

In the regional policy framework, attention emerges to the RL's presence and relevancy in the area (e.g. the public interest recognized to the RL from Tortona to Novi Ligure), even if not explicitly targeted to WCLs. The Regional Landscape Plan (2017) divides the area into two landscape areas characterized by fragmented agricultural land use.

Fig. 13.4 (**a**) Colli Tortonesi is located in the Northwest of Italy. (**b**) Its main urban centre is Tortona, and it includes 30 other municipalities with less than 5000 inhabitants. (**c**) The vineyards are concentrated in the North-west, approximately 300–700 m above sea level

The Colli Tortonesi is also not included in the National Register of Historical Rural Landscapes (2012), which provides, at a national level, specific indicators for evaluating RLs in terms of landscape patterns, farming techniques, and architectural elements.

In 2014, the nearby WCLs of Langhe, Roero and Monferrato were included by UNESCO in the WHL, adding an international policy layer. Colli Tortonesi is not included in this property's core/buffer zone. However, as a side effect, in the last 8 years, four vinaries versanti (hillsides) of this area have been awarded with a high-quality prize inscribed in the promotion strategies activated by the UNESCO recognition.

Compared to Rioja, Colli Tortonesi remains a marginal WCL, in terms of protection systems, at different levels, characterized by fragmentation that makes it incomparable with the most famous Italian and, in particular, Piedmontese wine production areas. However, this weak protection system makes the case study interesting for considering its transformation dynamics. Furthermore, the ongoing work for the activation of the European TEN-T corridor, empowering the accessibility of the area, will probably give a new attractiveness to the area, both in economic and tourist terms, generating opportunities and threats for the WCL.

13.3.3.2 Analysis and Simulations

The analysis of the Colli Tortonesi area revealed a predominantly rural environment, which occupies 45% of the total land cover surface (E1). However, only 2.5% is dedicated to vineyards (EW1), which are not explicitly classified in the land cover (CLC, 2018). Integrating local data sources (regional land use map, regional agricultural cadastre), it has been possible to map the existing vineyards: the majority of them located in areas classified as complex cultivation patterns (CLC code 242) and land principally occupied by agriculture with significant areas of natural vegetation (CLC code 243), which are the predominant rural landcover (nearly 90% of the total), maintaining the rural entropy index in the average 0.58 (E2). The hemeroby index (E3) of 3.03 confirms the semi-natural quality of the area (Fig. 13.5a), where most of the total population is concentrated in the main urban/artificial environment of Tortona and the Western side, closer to the central axis of transportation network (railway and main roads). However, the spatial analysis of the built environment shows the capillary presence of small infrastructures and architectural elements even in the inner areas (Fig. 13.5b), particularly in the vineyards. The coexistence of natural and artificial elements in the Colli Tortonesi RL is well documented in the first documents of regional protection policies (1975), a significant part of its history. Thus, as the analysis of soil consumption trends (D2) has revealed, the growth of the built environment does not affect only the urban areas, generating also new constructions in the vineyards areas due to their closer location to the main urban areas (Fig. 13.5c).

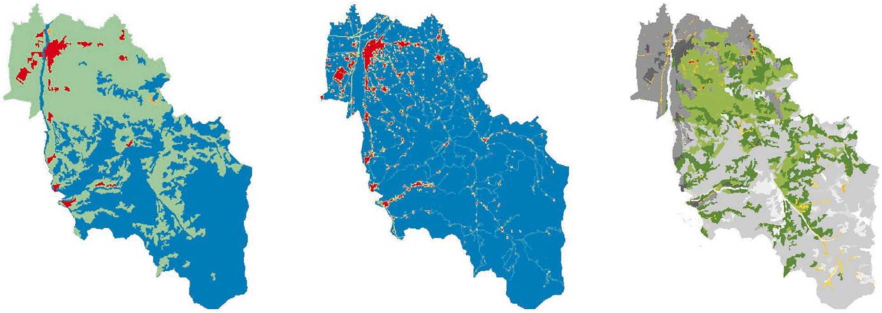


Fig. 13.5 According to (**a**) the hemeroby index, the Colli Tortonesi is divided into three areas, with a decreasing degree of artificiality, from the plain to the inner mountains; however, (**b**) the distribution of the built environment let emerge the presence of architectural/infrastructure elements also in the predominantly rural context; but (**c**) the higher changes in the built environment (increase between 2015 and 2019) are concentrated in the nearby of the urban areas, affecting also the nearby vineyards

The simulation phase has revealed how the physical heterogeneity of the Colli Tortonesi area works as a potential generator of new suitable conditions for vineyard cultivation.

Compared to the simulation scenarios for the Rioja, the potentially new suitable area (Fig. 13.3c) is relatively more extensive, representing 0.2% of the total PDO's surface. The RCP 2.6 (Fig. 13.6a) scenario reveals a substantial continuity between the current vineyards and the foreseen suitable areas, confirming their prevalent distribution in the North. The RCP 8.5 (Fig. 13.6b) shows a more fragmented configurational pattern, with a sensible endangerment of the current WCL. However, both the scenarios reveal a potential extension of the vitis vinifera cultivation in the inner area, where the elevation mitigates the temperature growth, and the territory is currently less affected by the urbanization phenomenon.

This condition, from one side, opens the possibility for the WCL to persist, but not without a significant systemic transformation: the potential extension of cultivated areas in previously natural ones affects human-natural equilibrium (impacting indicators like E3); on the other side, the hybridization between rural and built environment, which characterizes the WCL in the area, is questioned by the new configurational pattern.

Furthermore, the specific characteristics of the protected wine, which highly depends on the salinity of the soil, could be affected by the characteristics of the suitable areas, requiring, in this sense, the integration of geological and pedological indicators.

In this sense, the effectiveness of the PDO, as a mechanism of protection generated by the development of a collective interest in high-quality products, is deeply connected to the environmental context and its transformation. While it is capable of activating the required cultural and economic interests, able to orient the WCL's generation and preservation, it also has to follow its dynamic transformation, including, in its policies, strategies to maintain a balance between the excellence of the production chain and the environmental change.

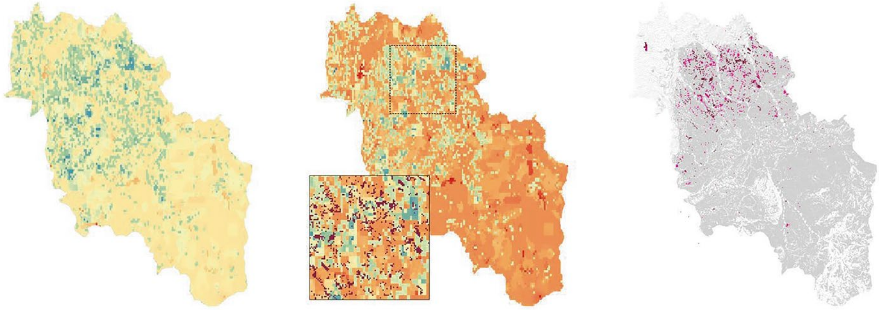


Fig. 13.6 The simulation of the (**a**) low and (**b**) maximum environmental transformation scenarios show how the suitability areas progressively decrease, generating (**c**) new potentially usable lands for vineyard cultivation (in green)

13.4 Conclusions

The comparison between two areas encompassed by a similar protection policy, targeted to define the production zone as a stable condition for the production of high-quality wine, has revealed how the configurational characteristics of the WCL impact the transformation scenarios, becoming, as such, significant information for developing safe-guarding strategies. In particular, the Colli Tortonesi, less characterized as a WCL due to the fragmentation and diversity of its rural environment, is more adaptive to the forthcoming transformations, providing more possibilities for vineyards to develop in new areas. This first hypothesis has to be verified, including new, more detailed microclimatic and agrometeorological indicators, to understand if and how the environmental change affects the characteristic salinity of the Colli Tortonesi wine, dependent on specific geo-physical properties of the site. On the other side, the WCL of Rioja, which is a predominant human/natural ecosystem of the area, having been and becoming a factor of economic development, stands on the fragile equilibrium determined by the combination of climatic and anthropic trends, requiring to develop conservation strategies balanced between the economic productivity of the area and its conservation as a rural landscape.

The further development of the proposed applications consists, from one side, of the iteration of the process, including the inputs received from the local stakeholders and automation of part of the workflow in a data infrastructure aimed at supporting the continuous update of the collected database, opening to the integration of real-time remote sensing and IoT data streams. This digital infrastructure aims to provide decision-makers with an operative tool that can simulate predictive scenarios to face the rapidity of current and future environmental changes.

However, the possibility of parametrizing the landscape as a measurable system of processes, encouraged by the growing opportunities offered by the continuous development of digital technologies, is highly dependent on and influenced by the definition of the analytic model. In particular, for a workflow aimed at turning heterogeneous data into operative information for decision-makers, selecting the indicators and the visual outcomes must pay attention to their partiality. Thus, flexibility, in terms of integrating new parameters and regeneration of the simulated scenarios, is fundamental to avoid the risk of overlaying the future perspective with insufficient accurate projections, with a significant potential countereffect.

Furthermore, the required downscaling of predictive datasets to an adequate spatial resolution for analyzing the selected areas generates a methodological bias with a limitation in terms of the accuracy of the results, in particular when the scale of the analysis tries to move from a general overview of the PDO's territorial base to landscape units, clusters of vineyards or isolated ones. Even if the proposed methodology is not targeted to precision farming, maintaining a holistic perspective on RLs and their complexity, as in terms of mutliscalarity, the possibility to integrate predictive datasets with a higher spatial resolution, or to derive projections from time series of Earth Observations imageries, represents a line of development. The possibility of quantifying, localizing and visualizing the balance between what is endangered by the ongoing transformation and potentially lost and what is potentially gained, in terms of suitable areas for imagining a WCL future development, opens the road for imagining and co-designing dynamic conservation strategies, where the landscape is safeguarded as a living system, potentially adaptable to different transformation scenarios.FundingThis research was funded by PNRR PE05-CHANGES-SPOKE 7 Protection and Conservation of Cultural Heritage against Climate Changes, Natural and Anthropic Risks CUP B53C22003780006.

References

Agnoletti, M. (2014). Rural landscape, nature conservation and culture: Some notes on research trends and management approaches from a (southern) European perspective. *Landscape and Urban Planning., 126*, 66–73. https://doi.org/10.1016/j.landurbplan.2014.02.012

Agnoletti, M., Emanueli, F., Corrieri, F., Venturi, M., & Santoro, A. (2019). Monitoring traditional rural landscapes. The case of Italy. *Sustainability, 11*, 6107. https://doi.org/10.3390/su11216107

Bai, H., Gambetta, G. A., & Wang, Y. (2022). Historical long-term cultivar×climate suitability data to inform viticultural adaptation to climate change. *Sci Data, 9*, 271. https://doi.org/10.1038/s41597-022-01367-6

Battisti, A., Valese, M., & Natta, H. (2022). Indicators as mediators for environmental decision making: The case study of Alessandria. *Land, 11*, 607. https://doi.org/10.3390/land11050607

Cameron, C., & Mechtild, R. (2013). *Many voices, one vision: The early years of the World Heritage Convention*. Ashgate.

Carroquino, J., García-Casarejos, N., & Gargallo, P. (2020). Classification of Spanish wineries according to their adoption of measures against climate change. *Journal of Clearer Production, 244*, 118874. https://doi.org/10.1016/j.jclepro.2019.118874

Copernicus Climate Change Service, Climate Data Store. (2019). *CORDEX regional climate model data on single levels*. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). Retrieved February 24, 2024, from https://doi.org/10.24381/cds.bc91edc3

Council of Europe. (2000). *European Landscape Convention* (Florence, 20 October 2000), ETS No. 176. Strasbourg: Council of Europe.

EEA. (1995a). *Europe's environment—The Dobris assessment*. Retrieved January 17, 2024, from https://www.eea.europa.eu/publications/92-826-5409-5

European Environmental Agency (EEA) (1995b). *Environment in the European Union - 1995 - Report for the Review of the Fifth Environmental Action Programme*. Retrieved February 14, 2024, from https://www.eea.europa.eu/en/analysis/publications/92-827-5263-1

EU. (1996). *Cork declaration*.

EU. (2016). *The Cork declaration—A living countryside*. Retrieved January 17, 2024, from https://ec.europa.eu/enrd/sites/default/files/cork-declaration_en.pdf

European Commission. (2022). *A long-term Vision for the EU's Rural Areas - Towards stronger, connected, resilient and prosperous rural areas by 2040*. Retrieved February 14, 2024, from

Eurostat. (2010). *Agri-environmental indicators*. Retrieved January 17, 2024, from https://ec.europa.eu/eurostat/web/agriculture/agri-environmental-indicators

Eurostat. (2017). *Statistics on rural areas in the EU*. Retrieved January 17, 2024, from http://ec.europa.eu/eurostat/statistics-explained/in-dex.php/Statistics_on_rural_areas_in_the_EU

Fraga, H., Inaki, G. de C. A., Aureliano, M. C., & Santos, J. A. (2016). Modelling climate change impacts on viticultural yield, phenology and stress conditions in Europe. *Global Change Biology, 22*(11), 3744–3788. https://doi.org/10.1111/gcb.13382

Golini A. (2000). Levels and trends of fertility in Italy: Are they desirable or sustainable?, Below replacement fertility. *Population Bulletin of the United Nations, Special Issue, 40/41*. https://www.ipss.go.jp/webj-ad/webjournal.files/population/2003_6/17.Golini.pdf

ICOMOS. (2015). *Evaluations of nominations of cultural and mixed properties to the world heritage list*. Retrieved February 14, 2024, from https://whc.unesco.org/document/135654

ICOMOS. (2017). *ICOMOS-IFLA principles concerning rural landscapes as heritage*. Retrieved January 17, 2024, from https://www.icomos.org/images/DOCUMENTS/General_Assemblies/19th_Delhi_2017/Working_Documents-First_Batch-August_2017/GA2017_6-3-1_RuralLandscapesPrinciples_EN_final20170730.pdf

Iglesias, A., Quiroga, S., & Schlickenrieder, J. (2010). Climate change and agricultural adaptations: Assessing management uncertainty for four crop types in Spain. *Climate Research, 44*(1), 83–94. https://doi.org/10.3354/cr00921

ISTAT. (2021). *Benessere equo e sostenibile (BES). Report 2021*. Retrieved January 17, 2024, from https://www.istat.it/it/files//2023/03/BES-2021-Report.pdf

Jones, G. V., & Alves, F. (2012). Impact of climate change on wine production: A global overview and regional assessment in the Douro valley of Portugal. *International Journal Global Warming, 4*, 383–406. https://doi.org/10.1504/IJGW.2012.049448

Medeiros, L. P., Song, C., & Saavedra, S. (2021). Merging dynamical and structural indicators to measure resilience in multispecies systems. *Journal of Animal Ecology, 90*, 2027–2040. https://doi.org/10.1111/1365-2656.13421

Myga-Piątek, U., & Rahmonov, O. (2018). Winery regions as the oldest cultural landscapes: Remnants, signs, and metamorphoses. *Miscellanea Geographica. Regional Studies on Development, 22*(2), 69–80. https://doi.org/10.2478/mgrsd-2018-0009

OECD. (2016). *Rural Policy 3.0. OECD Regional Outlook 2016: Productive regions for inclusive societies*. OECD Publishing. https://doi.org/10.1787/9789264260245-7-en

Paracchini, M.L., & Capitani, C. (2011). *Implementation of a EU wide indicator for the rural-agrarian landscape*. JRC Scientific and Technical reports, European Commission, Joint Research Centre, Institute for Environment and Sustainability. Retrieved January 17, 2024, from https://publications.jrc.ec.europa.eu/repository/bitstream/JRC68008/lbna25114enn.pdf

Pijet-Migoń, E., & Migoń, P. (2021). Correction to: Linking wine culture and geoheritage—Missing opportunities at European UNESCO world heritage sites and in UNESCO global geoparks? A survey of web-based resources. *Geoheritage, 13*, 76. https://doi.org/10.1007/s12371-021-00602-7

Ramos, M. C. (2017). Projection of phenology response to climate change in rainfed vineyards in north-east Spain. *Agricultural and Forest Meteorology, 247*, 104–115. https://doi.org/10.1016/j.agrformet.2017.07.022

Sabbioni, C., Cassar, M., Brimblecombe, P., Tidblad, J., Kozlowski, R., & Drdácký, M. (2006). Global climate change impact on built heritage and cultural landscapes. *Heritage, Weathering and Conservation, 1*, 401.

Scazzosi, L. (2018). Rural landscape as heritage: Reasons for and implications of principles concerning rural landscapes as heritage ICOMOS-IFLA 2017. *Built Heritage, 2*, 39–52. https://doi.org/10.1186/BF03545709

Sgubin, G., Swingedouw, D., Mignot, J., Gambetta, G. A., Bois, B., Loukos, H., Noël, T., Pieri, P., & Ollat, N. (2023). Non-linear loss of suitable wine regions over Europe in response to increasing global warming. *Global Change Biology, 29*(3), 808–826. https://doi.org/10.1111/gcb.16493

Shannon, C. E. (1948). A mathematical theory of communication. *Bell System Technical Journal, 27*, 379–423.

UNESCO. (1972). *Convention concerning the protection of the world cultural and natural heritage, adopted by the General Conference, Paris, 16 November 1972*. Retrieved January 17, 2024, from http://whc.unesco.org/en/conventiontext

UNESCO. (1992). Revision of the operational guidelines for the implementation of the World Heritage Convention: Report of the expert group on cultural landscapes, La Petite Pierre (France), 24–26 October 1992. Retrieved January 17, 2024, from http://whc.unesco.org/archive/pierre92.htm

UNESCO. (2003). *Cultural landscapes: The challenges of conservation*. World Heritage Paper, No. 7, UNESCO World Heritage Centre. Retrieved January 17, 2024, from http://whc.unesco.org/documents/publi_wh_papers_07_en.pdf

UNESCO. (2005). *Convention on the protection and promotion of the diversity of cultural expressions, adopted by the General Conference, Paris, 20 October 2005*. Retrieved January 17, 2024, from http://portal.unesco.org/en/ev.php-URL_ID=31038&URL_DO=DO_TOPIC&URL_SECTION=201.html

UNESCO. (2012). *Operational guidelines for the implementation of the World Heritage Convention*. UNESCO World Heritage Centre. Retrieved January 17, 2024, from http://whc.unesco.org/archive/opguide12-en.pdf

UNESCO. (2015). *Decisions adopted by the World Heritage Committee at its 39th session (Bonn, 2015)*. Retrieved February 25, 2024, from https://whc.unesco.org/document/137710

UNESCO. (2020). *Guidance on developing and revising world heritage tentative lists*. International Council on Monuments and Sites. Retrieved February 25, 2024, from https://whc.unesco.org/document/184566

UNESCO. (2021). Updating of the policy document on climate action for world heritage. In *23rd Session of the General Assembly of States Parties, Paris*.

Ungaro, F., Calzolari, C., Pistocchi, A., & Malucelli, F. (2014). Modelling the impact of increasing soil sealing on runoff coefficients at regional scale: A hydropedological approach. *Journal of Hydrology and Hydromechanics, 62*, 33–42. https://doi.org/10.2478/johh-2014-0005

Verburg, P. H., van Berkel, D. B., van Doorn, A. M., et al. (2010). Trajectories of land use change in Europe: A model-based exploration of rural futures. *Landscape Ecology, 25*, 217–232. https://doi.org/10.1007/s10980-009-9347-7

Chapter 14
An Experimental Approach for the Real-Time Monitoring of Semi-confined Environments Exposed to Microclimatic Changes for Preventive Conservation

Cristiano Riminesi, Marta Castellini, Emma Cantisani, and Rachele Manganelli Del Fà

Abstract The Grotta degli Animali in the garden of the Villa Medicea di Castello in Firenze is considered the first example of a rustic Mannerist artificial grotto. Its structure consists of a single vaulted chamber lined with spongy stones and decorated with pebbles, shells and animal sculptures made of various stone materials. The recent restoration project began with the results of an extensive diagnostic campaign. These results were used in the design of the restoration and further targeted investigations were carried out during the restoration. The knowledge base was completed with the installation of sensors to monitor environmental parameters (temperature, relative humidity, surface temperature of the sculptural elements and solar radiation) to study the impact of the micro-environmental changes on the conservation of the surfaces. Based on the case study, this paper describes the key aspects and the strategy that should be used to develop a plan for the risk assessment of the state of conservation of semi-confined environmental heritage assets. By the comparing of the monitoring data with the results of spot analysis carried out by portable and non-destructive instruments, and micro-sampling to characterize the constituent materials and alteration/decay products and archiving them in a digital twin, it is possible to define the guidelines and protocols for the management and preservation of heritage assets in a semi-confined environment.

Keywords Stone materials · Interdisciplinary approach · Climate change · Risk assessment managing · Preventive conservation

---

C. Riminesi · M. Castellini (✉) · E. Cantisani · R. M. Del Fà
Institute of Heritage Science, National Research Council, Firenze, Italy
e-mail: cristiano.riminesi@cnr.it; martacastellini@cnr.it; emma.cantisani@cnr.it; rachele.manganellidelfa@cnr.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_14

14.1 Introduction

Risk management in the context of cultural heritage involves identifying, analyzing, and mitigating risks that could lead to the deterioration or loss of heritage assets. This process is crucial due to the unique vulnerabilities of these properties, which can be affected by both natural disasters (like earthquakes and floods) and human activities (such as urban development) (Jigyasu, 2019). Below are described the risk assessment frameworks of interest for the pilot sites chosen as demonstrator:

- *Hazard Taxonomy Development*: A recent study emphasizes the need for a comprehensive hazard taxonomy to support risk assessment in outdoor heritage. This framework aims to classify various natural and anthropic risks affecting cultural heritage, facilitating a multidisciplinary approach to risk management. It allows stakeholders to incrementally add exposure and vulnerability data to enhance risk evaluations (Battisti et al., 2019).
- *Incident Scenarios and Mitigation*: Another approach involves familiarizing of conservators and restorers with risk assessment through case studies of outdoor heritage assets. This process identifies threats, develops incident scenarios, and proposes mitigation measures. A total of 78 different incident scenarios have been identified, highlighting the diverse risks that outdoor heritage assets face (Sunara, 2022).
- *Climate Change Impact Assessments*: Research has also focused on quantifying the impacts of climate change on cultural heritage. Various methodologies have been developed to assess damage from climatic variations and hydrometeorological events. The studies indicate a need for better data transfer to stakeholders for effective risk mitigation strategies (Bonazza & Sardella, 2023).

Monitoring, risk assessment and management, and preventive conservation are crucial for the protection and sustainability of outdoor heritage sites (Pedersoli et al., 2016). Monitoring involves the systematic observation of heritage assets to assess their condition over time. This process is essential for:

- Identifying Changes: detecting alterations in the site due to environmental factors, human activity, or natural degradation.
- Data Collection: gathering quantitative and qualitative data to inform conservation strategies.
- Informed Decision-Making: providing a basis for timely interventions to mitigate deterioration

The methods that can be used are listed below:

- Visual Inspections: regular site visits to visually assess conditions.
- Technological Tools: use of drones, GIS (Geographic Information Systems), and remote sensing technologies to gather data.
- Environmental Monitoring: tracking climate variables such as temperature, humidity, solar radiation, and rainfall that affect the heritage assets.

The monitoring is necessary to assess the effective risk of conservation. This involves identifying potential threats to outdoor heritage assets and evaluating their likelihood and impact. This includes:

- Natural Risks: floods, earthquakes, landslides, and climate change effects.
- Human-Induced Risks: vandalism, pollution, tourism pressures, and urban development.

Once risks are assessed, management strategies can be developed:

- Mitigation Measures: implementing interventions to reduce the likelihood or impact of identified risks.
- Emergency preparedness Plans: Developing response strategies for potential disasters.
- Stakeholder Engagement: involving local communities, governments, and organizations in conservation efforts.

The integration of monitoring, risk assessment and management, along with preventive conservation practices is vital for safeguarding outdoor heritage. By employing systematic approaches and engaging various stakeholders, we can enhance the resilience of these invaluable sites against both natural and anthropogenic threats.

Preventive conservation focuses on proactive measures to minimize deterioration and prolong the life of outdoor heritage. This involves:

- Environmental Control: managing factors such as light exposure, humidity levels, and air quality.
- Maintenance Programs: establishing regular maintenance schedules for cleaning, repairs, and monitoring.
- Documentation: keeping detailed records of the site's condition and any interventions made.
- Education and Training: providing training for staff and stakeholders on conservation techniques and the importance of preservation.
- Community Involvement: encouraging local communities to participate in monitoring and conservation efforts.

14.2 Methodologies for Monitoring

Environmental monitoring is crucial for conservation efforts, as it plays a vital role in preserving and protecting the invaluable artifacts, artworks, and exhibits that are housed within these institutions. By monitoring various environmental and variable factors, we can control that the state of conservation of each heritage asset is controlled in time to preserve it for future generations. Monitoring, logging and analysis helps in planning the conservation strategies improving their effectiveness. Real-time data acquisition and storage requires the establishment of integration between Digital Twins using an experimental repository designed as a platform for georeferenced consultation of diagnostic data.

The spatial heritage science online sensor environment platform has been specifically designed for real-time monitoring in heritage- sites, tailored to serve cultural heritage with its implicit challenges by CNR-ISPC in the framework of the project H2IOSC.[1] The platform must integrate sensors network (wireless and/or wired) for monitoring indoor and outdoor scenarios, making it adaptable for different monitoring schemes in sites such as museums, libraries, archaeological sites, and semi-confined environments too. The sensors/system platform are a solution particularly responsive to the description of the effects induced by microclimatic changes in the semi-confined environment as the Grotta degli Animali in Villa di Castello in Firenze—the selected pilot site for the Spoke 7 of the project CHANGES. Moreover, the research on this ICT solution is carried out on their equipping with advanced data processing and interpretation modules that transform collected data into valuable information useful for the conservator and restorer in the planning of the conservation activities. Upon installation, the platform must streamline the control process of the asset, saving significant time by minimizing human intervention and automating the in situ survey process through updating user via mobile smartphone as well as web applications. The data acquired can be processed to produce indices related to the state of conservation of the manufacts, and for each index an alert threshold will be programmed which, if exceeded, can trigger local alarms and send alarm SMS and email message to the designated user. The platform will provide the real-time access to data and tools for interrogating sensor outputs and, through data analysis, provide feedback on the state of conservation of the grotto. As regards the georeferencing and interrogation of diagnostic data collected for the case-study of the Grotta degli Animali, the platform must visualize the data through 3D geomatic or simplified digital twin model of the grotto (Chap. 11) together with the sensors. With regard to the consultation of the diagnostic data, their visualization should be carried out through a 3D geomatic model (see the section related to the grotto of the Villa di Castello in Chap. 11). For a complete representation of the dynamic process that can envolve the conservation of the artefacts in the cave, the information and data from the sensors and the survey measurement campaigns must be merged in the 3D model in order to obtain a true digital twin.

This approach defines a protocol and best practices applicable to similar case studies, allowing better data sharing and analyses by remote access to the site through the digital twin, favoring a better manage of resources (budget and personnel) for the conservation (maintenance intervention and restoration work), and for a sustainable valorization of the tangible cultural heritage.

---

[1] Humanities and cultural Heritage Italian Open Science Cloud, founded by the European Union Next Generation EU and the Italian Ministry of University and Research as part of the National Recovery and Resilience Plan, NRRP.

14.3 Towards a Risk Assessment Implementation and Preventive Conservation for the Semi-confined Environment

Tools for the geo-referencing of multidisciplinary data sets are a main topic in the field of the documentation of cultural heritage assets. As a fact, existing classification models (SIGECweb, SICaRweb as the main IT systems developed by the MiC) (Fiorino & Loddo, 2015) typically include limited parameters related to the diagnostic aspects, providing summary judgment on the state of conservation and general information about previous interventions. With a view to an effective protocol for the management of diagnostic data, the main expectations are related to the digital twin's exploitation as a repository of multidisciplinary data acquired at the initial time (T0) and in the monitoring phases following the reactivation of the hydraulic system.

As known, the digital twin should provide much information for the characterization of cultural heritage asset:

1. 3D reconstruction for knowledge purposes;
2. simulation model for analyses;
3. data storage for research sharing or virtual replica for an interactive experience.

In the view of a supporting decision-making tool for Preventive Conservation, main aspect is the merging/integration between the monitoring and data collection with the digital twin, this is one of the most important challenges in the framework of digital heritage field. The platform developed for this target should provide protocol foresees:

- punctual characterization of heritage assets, as the semi-confined environment;
- recording and storing of the data in a centralized repository;
- data transfer through an application programming interface (API) channel.

Then, the multidisciplinary data are associated with the digital twin model providing a multi-level virtual replica of the case study where the site-collected data are mapped into the 3D representation of the global asset. In this way, the digital working environment provides a "real" replica of the site and can potentially provide a risk assessment tool toward the incoming effects of the environmental changes and a supporting-decision instrument for the preventive conservation. Moreover, this potentially opens new frontiers for high-level computing of the collected data by employing artificial neural networking processing algorithms for artificial learning that will help in making timely decisions by providing risk analysis within the preventive conservation strategy.

14.4 The Case Study: Grotta degli Animali in the Villa Medicea di Castello in Firenze

For the case study of the Grotta degli Animali, a georeferenced database for the conservation management of the sculptures was firstly implemented by the SiCAR (Sistema Informativo per la Documentazione e la Progettazione dei Cantieri di Restauro) collecting the documentation of previous stages of intervention from 1969 to 2012. Major limitations of the system are the cluttered data organization, the non-availability of time-dependent data analyses (fundamental in the field of monitoring) and the limited data formats supported. Within the CHANGES Project an experimental multidisciplinary approach was performed to develop an effective protocol for the monitoring and risk assessment, with a view to maintenance actions and preventive conservation strategies. First step of the research procedure was the characterization and the correct knowledge of the state of conservation of the materials inside the grotto. This step is mandatory both for the prediction of the incoming problems of conservation and for the development of an effective monitoring plan for the risk assessment. The results of the diagnostic survey at time 0 (T0) are summarized in Chap. 11 in terms of the relevant parameters to be considered during the monitoring activities useful for the characterization of the materials over risk of conservation.

In Fig. 14.1 the characterization of a representative stone element/surface is represented, showing the correlation between the surface morphology (with previous conservation issues) and the incoming alteration phenomena. The first assessment of the conservation state pointed out some relevant areas where the environmental sensors have been located. The acquired environmental data (temperature and relative humidity, temperature of the surface, solar radiation) will be then correlated with the multi-technique diagnostic data measured during the monitoring stage. In particular, the colorimetric alterations, biological growth, drying rate of the surfaces were assumed as indicators to be correlated with data collected from the environmental monitoring, showing whether the microclimate changes can resume the previous decay processes or rise additional ones. The second step of the protocol involved the development of an effective monitoring strategy for the semi-confined heritage environment, through the punctual characterization of the key environmental aspect. To this aim, a wireless sensors network (WSN) that can be customized/tailored in accordance with the needs of the site and the planned preservation strategy must be studied and designed. In particular, the WSN should consist of localized, small and low power sensors that can monitor various environmental parameters such as temperature, environmental humidity, solar radiation and air quality. Considering the case study, the main descriptive environmental parameters from a microclimatic point of view were found to be the temperature and relative humidity. Solar radiation and water level were also detected in the areas subjected to water stagnation, together with the sculptures' surface temperature: these parameters were taken as main indicators of the characteristic drying time of the stone surfaces. Here comes the importance of real-time monitoring in providing a

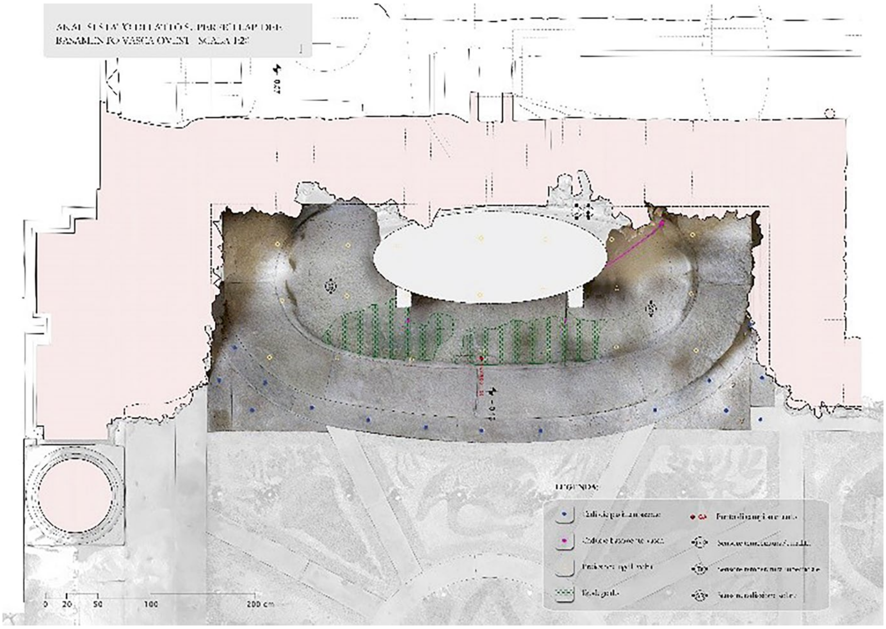


Fig 14.1 Photogrammetric representation of the particular of the stone slab under the niche's marble fountain

streamline of data that helps in taking timely decisions and properly evaluating the effectiveness of the conservation strategies. Since the sensors are connected to a wireless sensor network data can be accessed remotely, pointing out when limit values and/or alert thresholds are being exceeded. Among the key points of the research protocol is the physical implementation of the IT monitoring system to cover the whole site of the grotto. Figure 14.2 shows a schematic representation of the monitoring equipment, that includes as main elements:

- Access point is a crucial components that enhance local/temporary data collection and connectivity with the server for the permanent data storing and for the data consulting;
- Sensors Multisensory node are devices that can connect with multiple external sensors to gather diverse types of environmental or physical data. They serve as hubs within a WSN, facilitating data collection and communication with a central system or cloud server. These nodes help streamline the complexity of deploying and managing sensor networks by integrating various sensing capabilities into a single unit.

Due to the specific structural conformation of the case study, the design of the IT monitoring system uses existing small openings located in the masonry behind the three fountains for the eventually cables out of sight to connect the sensors to the multisensory node, so that the visual impact of the components is minimized. Each

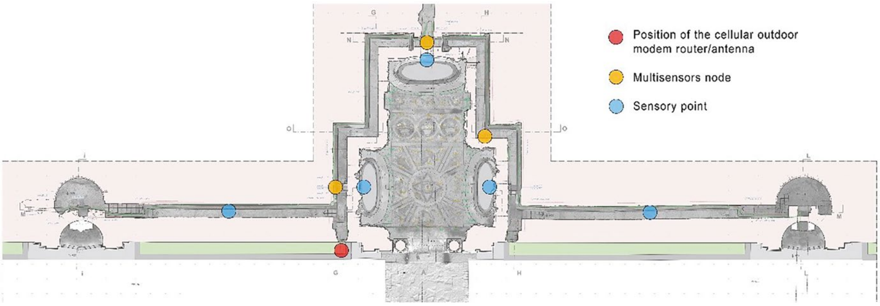


Fig. 14.2 Schematic representation of the IT monitoring system covering the grotto's niche; three Sensory points for environmental parameters acquisition are located close to the fountains

multisensory node will be equipped with 4 sensors located in each niche, so that the micro-environment can be properly described. In particular, the sensors for measuring temperature and humidity are integrated with solar radiation sensors, and surface temperature of the tub (Fig. 14.3).

In the view of an effective storage of the collected data and an intuitive UI to access data, the research aims at the digital twin's exploitation as the repository of multi-disciplinary knowledge acquired starting from the initial stage (T0) and in next monitoring phases following also the reactivation of the hydraulic system. Furthermore, the multi-level visualization interface, detailed in the following, will also allow the management of raster data acquired from monitoring (images and thermal images).

The opportunity to carry out this could be provided by the recent integration among 3D models and data visualization through semantic web application. This merging provides an interactive virtual working environment where the virtual representation gives real-time data visualization supported by a georeferencing feature. Through the API we can interrogate the real-time sensors data to the 3D visualization. The sensors data can be processed for their integration into 3D scene as semantic masks.

The platform must enable direct interaction with the end-user, providing an interface for user experience (UX) analysis and customization as per the use case. This layer must serve as the link between the end user and the platform, offering intuitive, user-friendly, and customizable dashboards on both mobile and web applications for data visualization and analysis.

14.5 Conclusion

The conservation of outdoor heritage is evolving through the integration of real-time diagnostic techniques (sensors and scheduled measurements) fitted on 3D model to realize digital twin of the asset. This scenario opens the route for an

Fig. 14.3 Location spots for Temperature and Relative Humidity sensors

advanced risk assessment framework useful to implement an efficient preventive conservation strategy. By addressing the multifaceted risks posed by environmental changes, human activities, and disasters, stakeholders can better protect cultural heritage for future generations. Continued research and collaboration among professionals are essential to refine these methodologies and implement effective management practices across diverse contexts.

References

Battisti, A., Figliola, A., & Santarelli, M. L. (2019). A framework for a hazard taxonomy to support risk assessment of tangible outdoor heritage. *Heritage, 7*(6), 2984–3012.

Bonazza, A., & Sardella, A. (2023). *Climate change and cultural heritage: Methods and approaches for damage and risk assessment addressed to a practical application*. Heritage.

Fiorino, D. L., & Loddo, M. (2015). Innovative tools for knowledge and management of the Italian Cultural Heritage: SICaR/web and SIGeC/web. In A. Kepczynska-Walczac (Ed.), *Envisioning architecture: Image, perception and communication of heritage (Proceedings 12th European Architectural Envisioning Association Conference, 23–26 September 2015, Lodz)* (pp. 348–359). Lodz University of Technology.

Jigyasu, R. (2019). Managing cultural heritage in the face of climate change. *Journal of International Affairs, 73*(1), 87–100.

Pedersoli, J. L., Antomarchi, C., & Michalski, S. (2016). *A guide to risk management of cultural heritage*. ICCROM-ATHAR.

Sunara, S. M. (2022). Familiarizing conservation-restoration students with risk assessment and risk management using outdoor sculptures as case studies. *Libellarium, 13*(1), 45–60.

Chapter 15
Vandalism on Cultural Heritage: Learning from the Past to Shape Future Prevention Strategies

Fabrizio Terenzio Gizzi, Cristina Cumbo, Agata Maggio, and Maria Rosaria Potenza

Abstract The article concerns ongoing research on cultural heritage vandalism in Italy, with a view to provide guidelines for policymaker and stakeholders to mitigate the risk. To achieve this goal, the research has been based on the historical analysis of both the acts of vandalism committed since the 1960s and the good practices implemented by institutions to face the risk. Therefore, the contribution discusses the progress of research also outlining prospects for the near future.

Keywords Heritage vandalism · Historical sources · Digital archives · Preventive conservation · Risk mitigation

15.1 Introduction

The term "vandalism" refers to a human phenomenon oriented at devastating or destroying other people's property for mere fun, carelessness or ignorance of the current rules (Schweickard, 2013). It involves committing a voluntary act of violence against a common good or, in general, someone else's property with the aim of not only to destroying it, but also simply damaging, defacing or staining.

Moving the attention towards cultural heritage, we are forced to refer to recent episodes of environmental activism (Bessette & Bessette, 2022; Vercesi, 2024) that have seen the security systems of international museums to be eluded in easy way to target important works of art and historical buildings. The reference is to the attacks on works of art that have taken place in some leading museums, fortunately only targeting protective glass in the case of paintings: the "Mona Lisa" at the Louvre, defaced by throwing a cake; Van Gogh's "Sunflowers" and "The Sower",

---

F. T. Gizzi (✉) · C. Cumbo · A. Maggio · M. R. Potenza
Consiglio Nazionale delle Ricerche, Istituto di Scienze del Patrimonio Culturale (CNR-ISPC), Potenza, Italy
e-mail: fabrizioterenzio.gizzi@cnr.it; cristinacumbo@cnr.it; agata.maggio@cnr.it; mariarosaria.potenza@cnr.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_15

pelted with soup at the National Gallery in London and during an exhibition at Palazzo Bonaparte in Rome, respectively; the “Laocoön” sculpture group at the Vatican Museums, on whose base activists literally glued their hands; Botticelli’s “Venere” and “Primavera” at the Uffizi, on which protective glasses protesters stuck photos of the floods that have recently occurred in Italy. We are also referring to vandalism that have taken place in urban contexts: the (washable) paint sprayed on the façade of Palazzo Madama in Rome and Palazzo Vecchio in Florence; the monument to Vittorio Emanuele II, defaced with yellow paint in Piazza del Duomo in Milan, and the paint used against the frontage of the Teatro alla Scala, in the same city. These acts, even if symbolic, have led some governments to promptly take countermeasures to cope with the risk. For example, the Italian Government has imposed a drastic change in the legal code by issuing Law No. 6 of 22 January 2024 dealing with “Sanctioning provisions on the destruction, dispersion, deterioration, defacement, soiling and illicit use of cultural heritage” (our translation). Therefore, depending on the context, we can observe different types of vandalism, both in the way people operate and in the materials and tools they use to infringe heritage. However, the ‘human factor’ (who is the author of the act) is also a variable that deserves to be deemed (Gamboni, 1997).

To throw light on heritage vandalism in Italy, this contribution concerns the ongoing research activities planned to investigate the phenomenon from a historical perspective to support policymakers and stakeholders with strategies for risk mitigation. The final outcomes will be reached after a scrutiny of the acts perpetrated in the past to learn useful lessons and thus recognise good mitigation practices. In this view, the article outlines the methodological approach pursued, arguing some preliminary results.

15.2 Previous Studies: A Quick Glance

While vandalism is a phenomenon with historically roots, the national and international scientific landscape appears to be partial, fragmented and sectoral. We often find psycho-sociological analyses related to vandalism committed by teenagers, where the contexts of education and daily life of kids are investigated relating them to the defacement carried out as a symptom of personal discomfort (Fusconi, 1981). There are also studies related to vandalism in urban areas which very often lead to the discussion of the broad subject of graffiti, correlated with analyses on the sometimes-blurred distinction, between street art and staining (Fig. 15.1). In this background, we underline the “endless foam or undertow” effect (a surface vandalized by graffiti, will later be covered in turn by other graffiti) (Panza, 2013) and the well-known “broken glass” theory, which acts as a “binder” between graffiti and urban degradation, the latter being predominant in suburbs (Kelling & Wilson, 1982).

Certainly, it is worth mentioning some major scholars who have taken care to offer a vision, albeit partial, of the phenomenon on an international scale. Cordess and Turcan (1993) examined the specific faces of art vandalism by conducting a

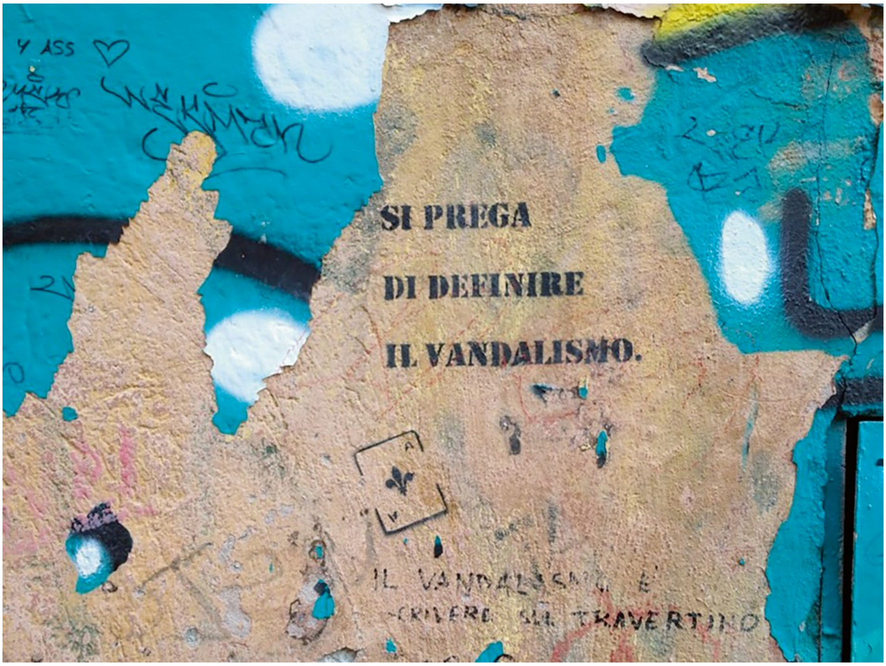


Fig. 15.1 Rome, Trastevere quarter. Example of a stencil on a wall building. (Upper) One can read "Please define vandalism" (translation) and (lower) a writing done with a black permanent marker where the answer is "Vandalism is writing on travertine". (Photo credits: C. Cumbo, 2024)

survey of the directors of 92 major museums and galleries in England, Scotland and Wales. The analysis allowed the authors to split the vandalism into two categories: "minor" and "major". On the one hand, the first category includes those small gestures, often unnoticed and ignored even by the press, such as engravings, scribbles, and lipstick marks, episodes that Bessette will later define as "microvandalism" (Bessette, 2021). On the other hand, the second category embraces cuts, canvas tears and other destructive behaviours towards works of art, committed by individuals seeking media notoriety, often judged as unbalanced people. Finally, the study of Cordess and Turcan (1993) found that three elements can predispose to vandalism. Indeed, the authors deduced that:

- particular works of art (e.g., nudes, political or religious representations) can generate adverse reactions in people;
- art encourages mentally ill visitors to commit reckless acts;
- the place where the work is preserved plays an important role in triggering and perpetrating vandalism.

An analysis that mirrors not only the phenomenon of vandalism, but also the psychological aspects is undoubtedly the work of McKim-Smith (2002). The researcher analysed some infamous acts committed since the 1980s, noticing that in some cases the art was attacked as the perpetrator symbolically saw in it a person or an institution against which he or she felt anger.

The most comprehensive work, although limited to the major crimes occurred in art galleries in Europe and North America between 1970 and 2013, is the research conducted by Bessette (2021) through journalistic sources. The analysis was carried out on about seventy episodes and led to recognize six different categories: creative vandalism; vandalism as a political, social or personal claim; psycho-pathological vandalism; vandalism in reaction to what is represented in a work; vandalism as aesthetic or institutional criticism and microvandalism.

15.3 Data and Methodology

The lack of analytical studies on vandalism related to Italy, where one needs consider the wealth and complexity of the heritage kept on galleries, museums, urban areas and historical centres, has driven the beginning of the historical research on the phenomenon.

The ongoing research has taken advantage of the systematic scrutiny of some newspapers published from the 1960s to June 2024. The newspapers consulted have been “la Repubblica” (https://ricerca.repubblica.it/repubblica/archivio/repubblica, accessed 28 September 2024) followed by the “Corriere della Sera” (https://archivio.corriere.it/Archivio/interface/landing.html, accessed 28 September 2024) and “La Stampa” (http://www.archiviolastampa.it/, accessed 28 September 2024). The historical archives of these national newspapers can be consulted online for a fee. The extraction of data from the digital archives has been allowed using specific keywords identified after a preliminary analysis of several articles to learn about the specific vocabulary. Likewise, based on a contextual reading of the articles, a specific census sheet of defacement acts has also been drawn up, consisting of fourteen fields. The sheet has also been useful for developing a geodatabase in which to archive the data. The fields considered in the cataloguing of vandalism are 14: (1) date of the episode, (2) period of the day in which the episode occurred (morning, afternoon, evening or night); (3) location, with address of the place and geographical coordinates; (4) number of damaged goods and their type; (5) type of vandalism; (6) motivation; (7) information on perpetrators of the act; (8) indication of any repetition of the act on the same good; (9) brief description of the episode; (10) information on the serial publication consulted; (11) date of the newspaper article; (12) web link to the specific source of information; (13) identification of other articles related to the selected episode; (14) photographs or videos of the act.

15.4 Results and Discussion

The analysis of the data collected and processed so far provides some clues on the nature of vandalism. To this end, we take particular attention on Florence, which has proven to be particularly exposed to vandalism. Actually, ninety-nine significant episodes have been identified so far (December 2024), providing a fairly detailed overview on the phenomenon. Among the affected monuments and architectures we have identified Ponte Vecchio, Duomo-Baptistery and works of art located in Piazza della Signoria (e.g., in Loggia dei Lanzi: Rape of Polyxena, Rape of the Sabine; Fountain of Neptune, Michelangelo's David, the copy exhibited in the square) and in the Uffizi.

A focus on the tools used can help to understand how intentional, usually demonstrative acts involve the use of objects (e.g., spray paint) that are not commonly available to tourists or occasional visitors. These gestures are carried out during over-crowding, both in confined spaces such as museums and in urban area. This category usually includes those gestures attributed to people with psychological disorders. Climbing statues or diving into fountains, but also racist gestures and graffiti, are more likely committed in the evening or at night, demonstrating that the offender is aware of the illegal action he or she is carrying out, but still plans to hide taking advantage of darkness. Tourists, on the other hand, being just passing through, are more interested in leaving a mark that recalls their stay in the city. They are mainly responsible for engravings or writings made on monuments respectively with small metal objects of common use (e.g., keys, coins) or with markers.

The analysis performed for Florence also allowed us to distinguish different categories of vandalism in relation to both the person committing the act and his or her intentions, for which we prefer to coin some specific terms, taking advantage of the literature (Bessette, 2021) only for "microvandalism" (Fig. 15.2). Therefore, we recognize the following types of vandalism:

- *tourist vandalism*, which mainly consists of writing initials or names on monuments to leave traces of one's stay in the city;
- *residential vandalism*, which leads to or is part of hooliganism. These acts are carried out by citizens, regardless of the presence of monuments, whose aim is to damage the city for fun, challenge or for reasons attributable to social discomfort;
- *vandalism in relation to demonstrations*, which occurs during political, religious or sporting events;
- *demonstrative or social vandalism*, the most well-known manifestations of which are the gestures of "eco vandals", which can occur both indoors and outdoors environment, provided that there is a large audience to witness it;
- *microvandalism*, which strikes both in controlled-access spaces and outdoors.

It includes scratches, cuts, and marks of various kinds made in secret and, often, unnoticed.

The historical analysis highlights that there were several attempts to mitigate the risk by the bodies responsible for managing and protecting heritage. For example,

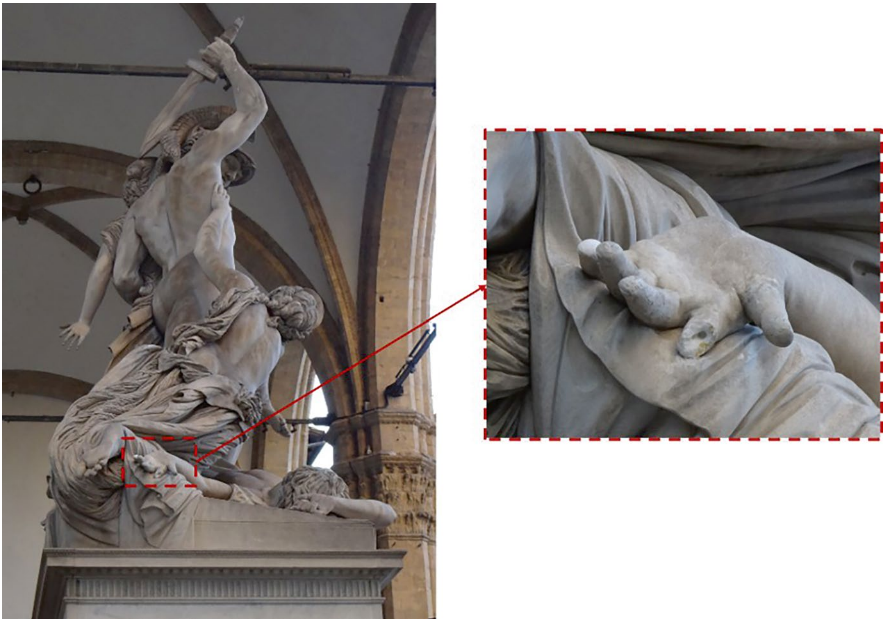


Fig. 15.2 Florence, Piazza della Signoria, Loggia dei Lanzi. The photos depict “The Rape of Polyxena” (Pio Fedi, 1855–1866), vandalized by a tourist (probably in 2013) with the breaking of the index finger of the left hand of Polite, the figure lying on the base of the sculptural group. The consequences of the act are still visible today. (Photo credits: F.T. Gizzi, 2024)

following the occurrence of many episodes of graphic vandalism on the interior and at the base of the lantern of the Dome, as well as inside the bell tower of the Florence Cathedral, the “Opera del Duomo” management body commissioned the development of the *Autography* App in 2016 (Opera Magazine, 2016). Three tablets were installed along the tour route of the dome/bell tower on which visitors could leave their digital signatures or messages, virtually choosing the type of surface (marble, wood, etc.), the colour and the graphic tool to be used (marker, aerosol, brush, etc.). These “signs of passage” were saved and archived online, recording as many as 135,307 messages between 2016 and 2019. During the same period, acts of vandalism decreased dramatically. Messages were all printed by the Opera, thus becoming part of the archival documentation of the Cathedral. Autography was very useful to counteract the vandalism, despite it no longer being in use. The initiative was aimed mainly to hinder the above-mentioned tourist vandalism, but at the same time allowing people to leave proof of their presence.

Since September 2024, the Municipality of Florence has also started the awareness campaign called #EnjoyrespectFirenze (Enjoy & Respect Firenze, 2024), promoted by the Italian Ministry of Tourism. The website, to which the visitor is redirected, hosts different tips for a respectful and conscious visit to the city, from the artistic, cultural, environmental and social point of view. One section of the web site reports advice and warnings to avoid dirtying the city and damaging the monuments.

Other actions were undertaken to mitigate the risk on a national scale. In addition to install advanced video surveillance systems, some attempts to raise awareness starting from schools have been undertaken over the years. In this regard, the joint venture between Municipality of Rome, International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) and Istituto Centrale per il Restauro (technical body of the Italian Ministry of Culture) in the period 1996–1997 and 2000–2001 is noteworthy. The initiative was aimed at hindering graphic vandalism committed by youths (ICCROM Archive, 1996–2001) involving students of Rome. Other preventive measures to reduce graphic vandalism in urban areas have been taken in Bologna, where the porticos are constantly subject to smearing (Bettocchi et al., 2010; Gandolfi, 2021). To fight and prevent the graphic vandalism, the rapid cleaning of the walls was put into the field to discourage further writers actions. Furthermore, to mitigate the effects of paints, the preventive application of protective films on walls was also considered thus preventing the absorption of pigments from exposed surfaces. In addition, many proposals to install high gates around monuments, in particular fountains (Boccacci, 2000; Pandolfi, 2000; Mattone, 2004; Cirillo, 2008) located in Rome, Florence and Naples were made. However, due to the significant visual impact that such structures would have caused, the gates were rarely raised. Alternative solutions have been adopted, such as the installation of lower fences that determine a buffer zone while keeping a clear view of the monument. A direct and multitemporal field surveys (2023 and 2024) by the authors of this contribution highlighted that most of monuments in Rome and Florence protected through these systems were no longer vandalised.

Some institutions, such as the Colosseum Archaeological Park in Rome, have chosen to install explanatory signs regarding the penalties provided for by Italian law in the event of vandalism, illustrating the correct behaviour to keep inside the monument (Fig. 15.3).

Other solutions implemented concern the replacement of original works of art with copies (see, in Rome, the case of Villa Borghese, whose originals are kept on deposit at the Pietro Canonica Museum), which were thus preserved. In fact, the appropriateness of this choice is demonstrated by the circumstance that the copies were vandalized over time.

15.5 Conclusions and Perspectives

The article has discussed the preliminary results of a historical research focusing on vandalism against cultural heritage in Italy, particularly in Florence. The analysis will continue and expand in the near future, considering the whole national territory to catalogue the vandalism acts, thus drawing up further suggestions to cope with the anthropic risk, highlighting the good practices implemented by the institutions over time to protect the heritage. Besides, the geodatabase of defacement events,

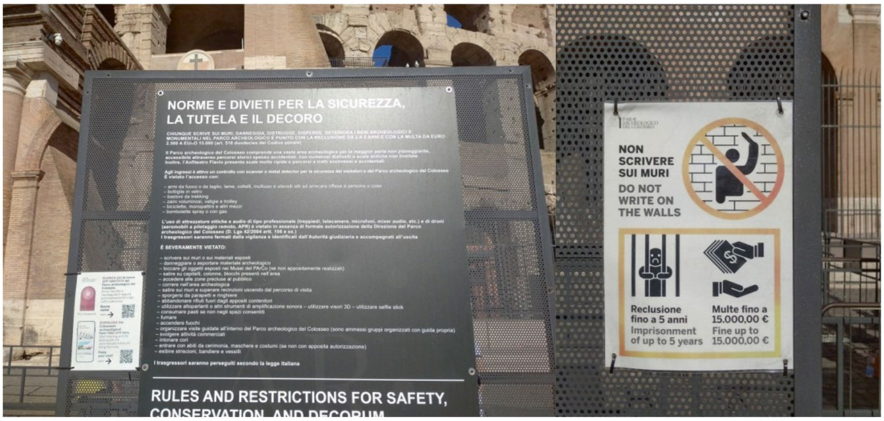


Fig. 15.3 Rome, Flavian Amphitheatre: detail of the monument and the indication with rules and prohibitions for protection and decorum. (Photo credits: Cristina Cumbo, 2024)

currently under construction, will also be provided to the local and national bodies to support them in managing heritage vandalism.

This study is part of a wider research activity on heritage vandalism whose further aims are to develop: (1) nanostructured coatings for surfaces protection, (2) mechanical and physicochemical-techniques and methods for graffiti removals using cold plasma treatments, (3) tailormade products to mitigate the risk of vandalism (see Sect. 15.5).

References

Archivio ICCROM Anti-graffiti, 1996–2001 (files 116–123) [In Italian].

Bessette, A. (2021). *Du vandalisme oeuvres d'art. Destructions, dégradations et interventions dans les musées en Europe et en Amérique du Nord depuis 1970, Paris*.

Bessette, A., & Bessette, J. (2022, December 6). *On environmental activism in Museums*. e-flux Notes. https://www.e-flux.com/notes/507828/on-environmental-activism-in-museums

Bettocchi, M., Di Francesco, C., Sardo, A., & Zigarella, P. (Eds). (2010). *Contro il vandalismo grafico. Il centro storico di Bologna: sperimentazione e linee guida, Argelato (BO)* [in Italian].

Boccacci, P. (2000). *Roma, l'arte dietro i cancelli*. https://www.repubblica.it/ [in Italian].

Cirillo, A. (2008). *'Le inferriate? Brutte ma a volte necessarie'*. https://www.repubblica.it/ [in Italian].

Cordess, C., & Turcan, M. (1993). Art vandalism. *The British Journal of Criminology, 33*(1), 95–102.

Enjoy & Respect Firenze. (2024). *Florence is alive, treat it with care*. https://enjoyrespectfirenze.it/it/

Fusconi, V. (Ed.). (1981). Il Vandalismo dei giovani. Aspetti sociologici, psicologici e giuridici. Messina 3–8 dicembre 1979. *Atti del IV Seminario Internazionale di Studio organizzato dal Centro Internazionale di Ricerche e Studi sociologici penali e penitenziari di Messina, Milano* [in Italian].

Gamboni D (1997) *The destruction of art. Iconoclasm and vandalism since the French Revolution, London*.

Gandolfi N (2021) I portici di Bologna e la candidatura a patrimonio UNESCO. In Baroncini E (a cura di) *Tutela e valorizzazione del patrimonio culturale mondiale nel diritto internazionale. Bologna* (pp. 539–586) [in Italian].

Kelling, G. L., & Wilson, Q. (1982). Broken windows: The police and neighborhood safety. *Atlantic Monthly*, 29–38.

Mattone, A. (2004, June 3). *Una cancellata anti-vandali per la statua di Giordano Bruno*. https://www.repubblica.it/ [in Italian].

McKim-Smith, G. (2002). The rhetoric of rape, the language of vandalism. *Woman's Art Journal (Springer), 23*(1), 29–36.

Opera Magazine. (2016, March 16). *Dal vandalismo alla testimonianza: Autography, è tutta una questione di segni...*. https://duomo.firenze.it/it/opera-magazine/post/4442/dal-vandalismo-alla-testimonianza-autography-e-tutta-una-questione-di-segni [in Italian].

Pandolfi, A. (Ed.). (2000). Prevenzione e difesa dei monumenti e degli spazi monumentali. *La conservazione del patrimonio monumentale. Il vandalismo grafico, Roma* (pp. 127–130) [in Italian].

Panza, P. (2013). La città tatuata, ovvero la schiuma di Milano. *ΑΝΑΓΚΗ, 68*, 28–41. [in Italian].

Schweickard, W. (2013). s.v. vàndali. *Deonomasticon Italicum, IV*, 733–735.

Vercesi, P. L. (a cura di). (2024). *La bellezza sfregiata. Un patrimonio da tutelare e difendere, Milano* [in Italian].

Chapter 16
Effects of Climate Change on Heritage in Maritime Contexts: The Case Study of the Island of Motya in Sicily

Lorenzo Nigro

Abstract This study examines the impact of climate change on the archaeological heritage of Motya, an ancient Phoenician settlement located in Sicily's Marsala Lagoon. The research highlights the vulnerability of coastal archaeological sites to rising sea levels, tidal oscillations, and wind erosion. Employing advanced technologies, including photogrammetry, UAV surveys, and GIS-based analyses, the study documents historical and current degradation patterns, offering detailed projections for the future. Particular attention is given to the Kothon, Tophet, and North Gate areas, which face significant threats from erosion and submersion. Strategies for preservation include naturalistic engineering solutions, such as re-planting coastal dunes and implementing protective barriers, alongside innovative techniques like virtual restoration and 3D modeling. These approaches not only safeguard the site but also enhance its accessibility and integration into the broader Mediterranean landscape. The findings emphasize the need for integrated management strategies to mitigate the effects of climate change while maintaining the cultural and environmental significance of this unique archaeological context.

Keywords Marine transgressions · Motya · Archaeology · Climate change mitigation · Coastal erosion

---

L. Nigro (✉)
Department of Sciences of Antiquities, Sapienza University of Rome, Rome, Italy
e-mail: lorenzo.nigro@uniroma1.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_16

16.1 Introduction

Heritage sites of coastal regions in the Mediterranean have been under attack for decades by forces and actions that undermine their integrity both due to nature and humans, including sea erosion and transgressions, coastal changes, the destruction of wetlands, population growth and rampant development, looting and other processes. Global warming is exacerbating the destruction of cultural resources in coastal areas through an accelerated sea level rise, intensified storm cycles and associated coastal erosion.

Although global sea levels, rising steadily for about 20,000 years, slowed significantly about 7000 years ago, rising sea level rates now appear to be increasing rapidly due to increasing anthropogenic emissions of carbon dioxide and other greenhouse gases. Global warming and rising seas, especially when combined with population growth and the implementation of measures to protect coastal property, threaten the deep maritime history of human migration, settlements, and adaptations in coastal areas around the world.

This continuous loss of coastal heritage is a widespread phenomenon, which has not been foreseen but is now happening and with increasingly devastating effects. If the global sea level rises by a meter or two (or more) in the twenty-first century, vast expanses of coastal plains rich in archaeological sites will be flooded around the world. In the decades to come, especially where steep coastlines are present, the general principles outlined in the Bruun rule (Bruun, 1962, 1983) suggest that many shorelines will see horizontal erosion 50 to 200 times higher, depending on local geology, of wave energy and other factors. If, as expected, global warming also increases the number and intensity of severe coastal storms around the world, losses will be amplified. Erosion on this scale could destroy hundreds of thousands of coastal archaeological sites around the world. The lack of concerted action can have two main causes: (1) the scale of the problem is simply overwhelming, especially for the staff of government agencies already accustomed to budget cuts and limited resources; (2) the misconception that coastal erosion is a completely natural process that does not require any mitigation.

In coastal regions around the world, archaeologists, conservatives, and land managers need to significantly increase their efforts to inventory, investigate and interpret the history of coastal sites in distress before they are lost forever. In the framework of the Italian PNRR Changes Project, Spoke 7, such phenomena have been investigated by the Sapienza Unit, Line 4, under the supervision of the writer choosing the case study in coastal Southern Italy: the island of Motya in the Marsala Lagoon (Trapani).

16.2 Climate Variation in Mediterranean from the Bronze to the Iron Ages

The Mediterranean Sea is an anti-estuarine semi-enclosed sea that can be subdivided into two sub-basins, the western and eastern Mediterranean separated by the Sicily Strait sill. Low salinity surface waters, called Modified Atlantic Water (MAW), enter in the Mediterranean Sea from the Strait of Gibraltar. MAW flows along the Algerian coast as the coastal Algerian Current and separates into two branches at the entrance of the Sicily Strait. The Strait of Sicily represents a physical barrier (about 500 m deep) of the eastern Mediterranean and implies considerable control over the biogeochemical processes occurring within the eastern basin. Most of the MAWs cross the Sicilian Channel to the south, while the rest flows into the Adriatic Sea, channelling right along the north-western coast of Sicily and thus lapping the waters where the island of Motya rises (Fig. 16.1).

The comparison of the Mediterranean SST records evidences very distinct regional patterns before the onset of Greek colonization (mid of eighth century BCE), with an overall cooling trend in the Aegean Sea, a warming trend in the Sicily

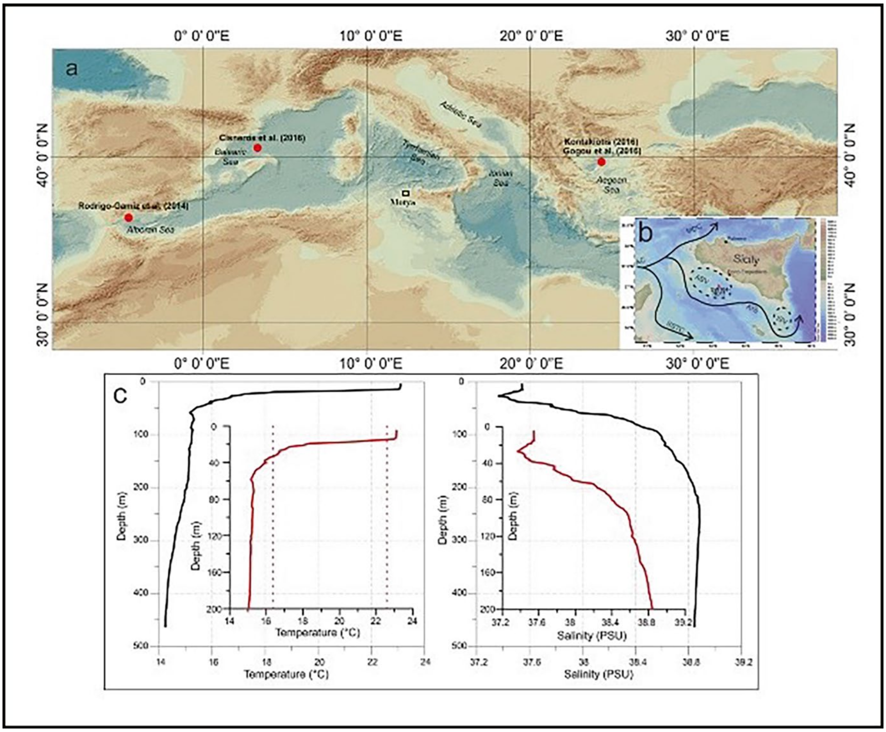


Fig. 16.1 Bathymetric map of the central-western Mediterranean Sea and the Sicily Channel. Black lines follow the path of surface water circulation

Strait and more stable conditions in the Alboran Sea. In the Sicily Channel, between the base of the record and the beginning of the Bronze Age period, the Mg/Ca*G. ruber* SST signal shows two warm events, at ca. 2913 BCE and ca. 2040 BCE, respectively. The first warm event, documented in the study record of Sicily Channel, although it does not fall within the 95% CI, has been tentatively associated to the Copper Age warm phase (ca. 2913 BCE) (Margaritelli et al., 2020). This event chronologically corresponds to a warming in the Aegean Sea SST record and agrees to the beginning of a gradual aridification process described in northern Egypt (Kaniewski et al., 2010). The second one (Early Bronze Age, ca. 2040 BCE) is associated with a further aridity phase, as documented by the strong decrease in arboreal pollen in the central Mediterranean (Di Rita et al., 2018). This latter event, chronologically corresponds to the fall of the Old Kingdom in Egypt and to the end of the Ur III Dynasty in Mesopotamia, associated with strong famines related to a dry climate and a strong aridity (Behringer, 2009). Later, Mg/Ca *Gruber* SST warmed between 1800 and 1100 BCE indicating relative warm conditions during Late Bronze Age (until 1190 BCE) (Nigro, 2014, Andreou, 2018) documented in the whole Mediterranean basin. Significant cultural changes are documented during this period, in fact, historical records indicate the collapsed several civilizations (Weiss, 1982). Most of the Minoan and Mycenaean Palatial centres were destroyed and/or abandoned. The Palatial centres were hit hard by the increase in aridity and the collapse of agriculture production making impossible for the population to sustain themselves (Drake, 2012). The transition from Bronze Age to Iron Age chronologically approximate the short-term cooling event associated to the Homeric (ca. 800 BCE) grand solar minimum. During this period, associated to negative NAO values, the climate condition was again favourable to agriculture expansion in the eastern Mediterranean (Kaniewski et al., 2010). Compared to the subsequent Roman period, the Mediterranean was characterized by a colder phase from ca. 500 BCE to 200 BCE, predating the rise of the Roman Empire. From a chronological point of view, this interval corresponds to the beginning of the so-called “sub-Atlantic phase” (Zolitschka et al., 2003), characterized by a cool climate and rainy winters which was propitious for the expansion of the Greek, Etruscan and Roman civilizations (Shaw, 1981). During this period, also global glacier advances are documented, and a negative NAO phase is recorded (Mayewski et al., 2004). The cool and humid climate of the sub-Atlantic phase lasted until ca. 100 BCE and covered the entire period of the Monarchy in Rome. In addition, this period is characterised by a short-term cooling event associated with the Greek (ca. 350 BCE) solar minimum (Fig. 16.2). However, at ca. 400 BCE, cultural changes were synchronised across the Mediterranean region. The Greek and Phoenician colonies expanded, and Rome and Carthage began their epic rise, a situation coincident with the establishment of more homogeneous temperature conditions across the Mediterranean regions.

According to this framework, based on the study of marine warming, the phase of Phoenician colonisation of the island of Motya corresponds to a period of cold weather that occurred around 800 BCE. It seems to coincide with a phase of climate change at the time, which resulted in a wetter Western Europe and a drier Eastern Europe. This had far-reaching effects on human civilisation, some of which are

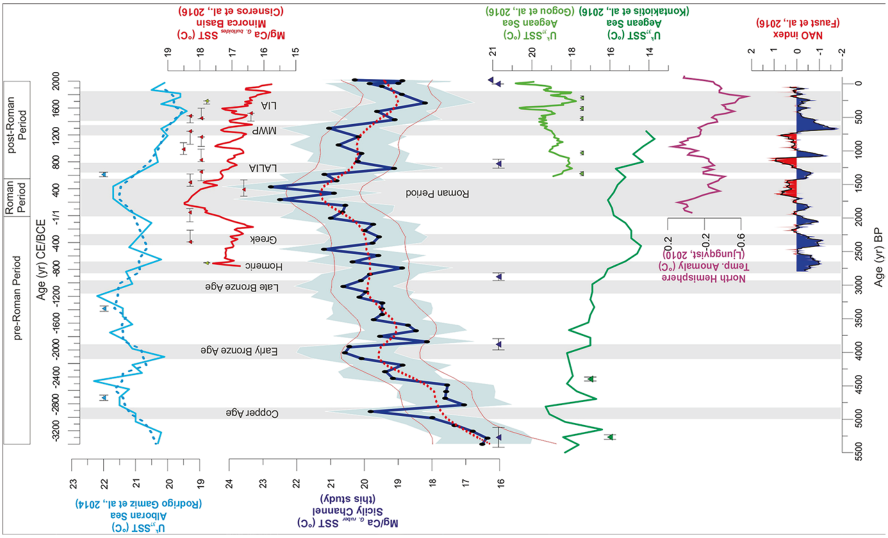


Fig. 16.2 Comparison in time domain of the SSTs records from Sicily Channel (blue line)

echoed in Greek mythology and the Old Testament. But above all, it is from 500 BCE until around 200 BCE. This trend of cooling with rainy winters and a generally cold climate is reflected in the archaeology of Motya.

16.3 Central Mediterranean Transgressions and its Effect on Motya

In order to sum up a multi-temporal visualisation of the effects of climate change on the cultural heritage contexts of the island of Motya in particular, we cannot fail to consider a series of studies on the rise of the sea level over the centuries, which have provided a series of fundamental data on the original coastline and consequently on the configuration of certain archaeological evidence. Due to the low elevated topography, the island and the archaeological ruins are very sensitive to sea-level changes, which at Motya interact with typical tides of the Marsala Lagoon, linked to lunar phases.

Sea rise at Motya and in the Marsala Lagoon in the last two millennia is well illustrated by the renowned Punic causeway connecting the North Gate of Motya to the nearby Sicilian coast, presently submerged to about 1.1 m (Schmiedt et al., 1972; Domen et al., 2023).

The three principal contributions to sea level change, measured with respect to land, along the Sicilian coast, are: (1) the sea level response to the past glacial cycle, including the response to the most recent glacial unloading of the major ice sheets and the European Alps and the response to the ocean floor loading by the melt water—the glacio-hydro-isostatic and eustatic contributions; (2) changes in ocean volume in more recent times from thermal expansion, recent glacier melting etc.; (3) vertical land movements, including uplift in Calabria and Sicily and consequent subsidence (Lambeck et al., 2011). Tectonic stability is assumed when the Last Interglacial (LIg) shorelines occur at about 6 m above present sea level. Where the LIg markers occur above or below this level, it is assumed that the area has been subjected to uplift or subsidence (Ferranti et al., 2006; Nisi et al., 2003). These analyses allow assessments of sea-level rise from 20,000 years (Fig. 16.3). These predictions are for the isostatic-eustatic components from the last glacial cycle only and their variability from site to site reflects both an approximately north–south component from the increasing distance from the former northern ice sheets and a more variable component from the water-loading contribution. Along the entire Italian coast, sea level is rising because of this ongoing response to the past deglaciations at rates of up to 0.6 mm/year (Lambeck & Purcell, 2005).

The study, which analysed the impact of climate change-induced sea-level rise on the coastal heritage site of Motya, made it possible to assess the effects of this phenomenon on human settlement over the past 2400 years, as well as to predict the scenario for the coming decades. A detailed flooding scenario for 2100 from direct observations and two models, taking into account the contribution of Vertical Land Movements (VLM), is provided by Ravanelli et al., 2019. The surface topography is derived from a novel high-resolution/high-accuracy digital surface model (DSM), which was performed through an Unmanned Aerial Vehicles (UAV) survey (Barradas Gutierrez, 2018), whereas the rate of VLM was estimated by the analysis of geodetic data at three Continuous Global Positioning System (CGPS) stations located close to the island. To estimate the local mean sea level and to correct the tide level (TL) (Antonioli et al., 2015; Sammari et al., 2006) at the epoch of UAV survey, the hydrometric recordings of the nearest sea level gauge station located at Porto Empedocle (Sicily), were used. The results of this analysis have produced a

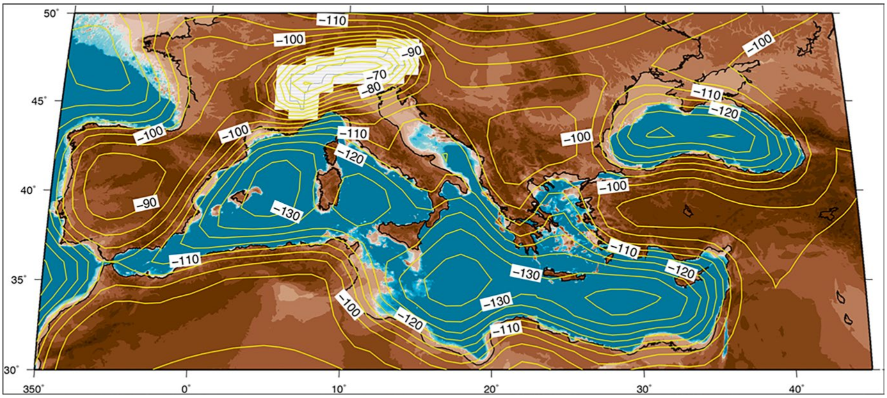


Fig. 16.3 Palaeogeographic reconstruction of the Mediterranean basin for the time of the Last Glacial Maximum at 20,000 years BP, (after Lambeck & Purcell, 2005). Contours show the sea-level change with respect to present sea level

fairly clear picture of the effect of climate change on the retreat of the coastline from the values that existed in Phoenician times and have provided archaeologists with useful information to better clarify the use of some of the structures discovered.

This is the case with the Kothon, an artificial inland basin that has been hypothesised to function as a marina or boat storage area, and which today is intermittently connected to the sea, depending on the level of the tide level. The sea-level curve proposed (Lambeck et al., 2011) estimates a sea-level rise for Motya of about 3.0 m over the last 3500 years (Fig. 16.4), in agreement with other RSLC estimates for the late Holocene in the central Mediterranean region (Furlani et al., 2013). Under the assumption that the VLM has been stationary during this long-time interval, we observed that the water level in the Kothon was approximately 0.8 m above past sea level and will reach 2.2 m (Nigro, 2023; Ravanelli et al., 2019). This process of uplift and consequent advancement of the sea along the island's coastal shoreline has been facilitated and accelerated by the anthropogenic impact on the territory, which has led to the elimination of the native coastal vegetation that constituted a natural barrier against the advancement of the sea, in the form of the coastal arboreal dune.

This in-depth study is related to the conservation and protection of the environmental, landscape and archaeological heritage of the island of Motya, which is seriously threatened by the sudden and already widely visible effects of climate change, affecting a small island in the centre of the Mediterranean. I refer to the main factors of degradation and deterioration of the archaeological evidence, which consist mainly of the constant rise in sea level, tidal oscillation and wind erosion involving archaeological deposits and exposed structures.

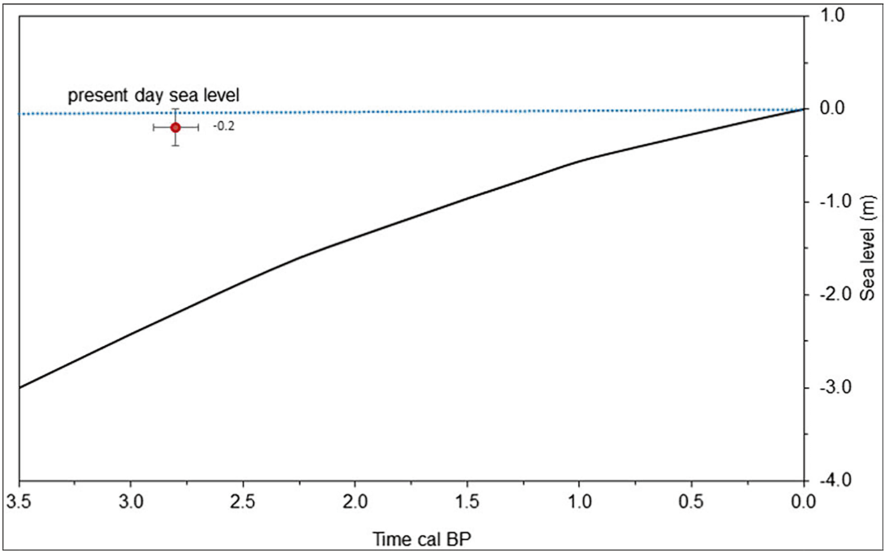


Fig. 16.4 The black curve is the sea-level prediction for the last 3.5 Kyears BP for Motya (Lambeck et al., 2011)

In this phase of the activity, work was carried out on two trajectories: on the one hand, the retrieval of existing documentation on the preservation and protection of archaeological monuments threatened by climate change, especially those located in marine and coastal environments (case studies, degree of impact assessment, models of actions to protect the archaeological asset), and on the other hand, the observation of the context under investigation, through detailed surveys to ascertain the state of the art and document the effects of climate change on archaeological areas. The aim is to propose models for monitoring the degradation of archaeological evidence, on the one hand by documenting the advance of climate change and on the other hand by assessing its effect on monuments.

Here, a dossier is presented that delves into the subject, i.e. the relationship between coastal archaeology and the impact of climate change, presents the case of the island of Motya through an analysis of the long-term effects of these phenomena and direct observations made during surveys. This is followed by a series of proposals on measures to be taken and actions to protect monuments, involving naturalistic engineering, architecture for archaeology and technologies applied to cultural heritage.

16.4 Degradation Factors in the Archaeological Site of Motya and Proposed Monitoring Techniques

The ongoing research focuses on the impact of rising sea levels caused by climate change on the coastal archaeological heritage of Motya, a Phoenician colony on the island of San Pantaleo, located at the western tip of Sicily. Specifically, the study evaluates the effects of sea level rise on human settlement over the last 2400 years, the current condition of the archaeological site (Nigro, 2018, 2023), and projections for the next decades (Ravanelli et al., 2019).

Coastal areas in the central Mediterranean Sea are particularly vulnerable to climate change and vertical land movements (VLM) of natural and anthropogenic origin, leading to relative sea level rise (Antonioli et al., 2017; Anzidei et al., 2017). These phenomena affect densely populated areas, infrastructure, and cultural heritage sites along the coasts, causing substantial damage. Archaeological sites are especially susceptible to structural degradation in these contexts.

San Pantaleo, a protected archaeological area in the province of Trapani (Sicily, Italy), is located 0.5 km from Sicily's west coast within the Marsala Lagoon (3 × 7 km), an area with a shallow seabed historically used for salt ponds. The small island spans 0.4 km^2 (approximately 40 hectares) and rises to a maximum elevation of 6 m above sea level. Since 2002, the archaeological expedition of Mozia by Sapienza University of Rome, under the present author's direction, has conducted systematic research and excavations on the island in collaboration with the "Whitaker Foundation" and the Superintendence of Trapani.

Due to its low topography, the island and its archaeological remains are highly sensitive to sea level rise and VLM. One notable indicator of this phenomenon is the ancient Punic causeway connecting Motya's northern gate to Sicily's coast, now submerged at approximately 1.1 m (Schmiedt et al., 1972).

High-resolution DSM mapping, using regional sea-level projections by the IPCC for the Mediterranean region, simulated two flooding scenarios for 2100. Under the RCP 8.5 climate model, an increase of approximately +59 cm above the current average local sea level is projected, which, combined with the average daily tidal amplitude of 30 cm, predicts a maximum flood scenario. This would significantly affect archaeological structures, particularly in the Kothon area and along the island's northwest coast (Figs. 16.5 and 16.6).

Observations on Motya's coastline have identified risk zones subject to erosive forces of water and wind, sea level rise, and tidal fluctuations (Fig. 16.7). Key vulnerable areas include the Kothon (Zone C) in the island's southern part and the northern portion near the North Gate of the Phoenician-Punic settlement (Zone MON). Additional concerns arise in the Tofet area, where wind erosion increasingly impacts the archaeological landscape.

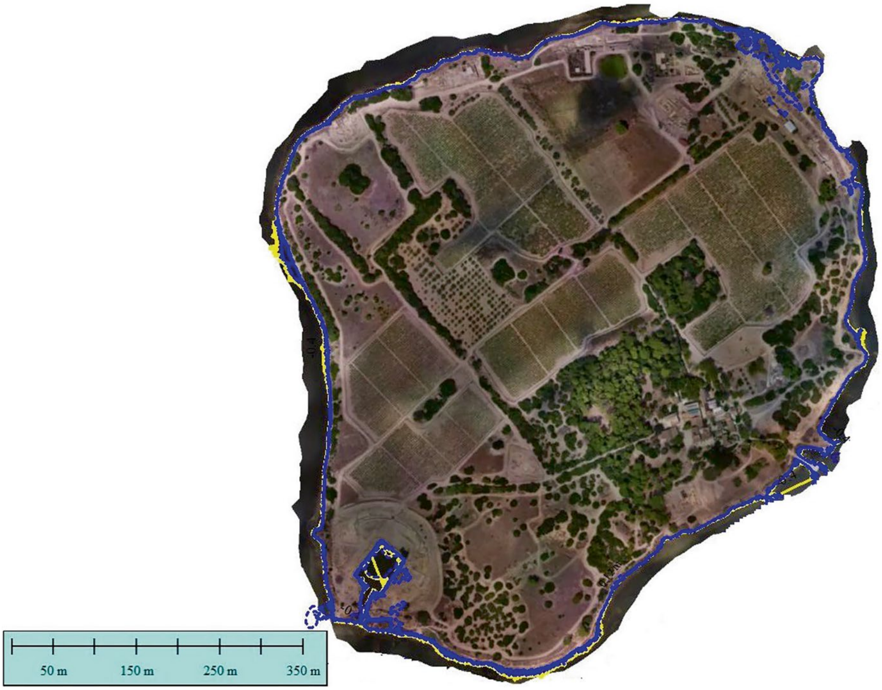


Fig. 16.5 2100 A.D. coastline projection for the RCP 2.6 + VLM scenario for Motya island: in yellow (continuous line) the current coastline, in blue the coastline projection (continuous line) with its minus/plus uncertainty (dashed lines)

Fig. 16.6 2100 A.D. coastline projection for the RCP 8.5 + VLM scenario for Motya island: in yellow (continuous line) the current coastline, in red the coastline projection (continuous line) with its minus/plus uncertainty (dashed lines)

The Kothon area faces flooding risks due to rising sea levels and tidal fluctuations, potentially resulting in the submersion of the ancient cultic site. Archaeological structures near the coast are already compromised by debris accumulation and advancing tides. The absence of Mediterranean vegetation, which naturally forms protective dunes, exacerbates this vulnerability.

The Tophet (Nigro, 2020), located on the island's northwest bank, suffers from wind and sea erosion, including the effects of salt aerosol. These processes damage archaeological deposits, exposing stratigraphy and artifacts to further deterioration and looting. Exposed limestone stelae show significant erosion and loss of detail. The area's low-lying coastline, devoid of protective vegetation, is particularly susceptible to continuous erosive forces.

The projected climate impact scenario for the Kothon area mirrors that of the northeastern coast near the North Gate and the adjacent boundary walls (Figs. 16.8 and 16.9). Erosion and rising sea levels threaten archaeological remains in this region, including substantial structures like the walls of the built-up area. Made from large limestone blocks, these walls are severely affected by wind and salt erosion, as evident from the degradation of the most exposed surfaces. This stretch, where the ancient road connected the island to Sicily, lacks robust vegetation, leaving it vulnerable to tidal and wave action.

Fig. 16.7 The orthophoto of Motya island. The current coastline is highlighted in yellow

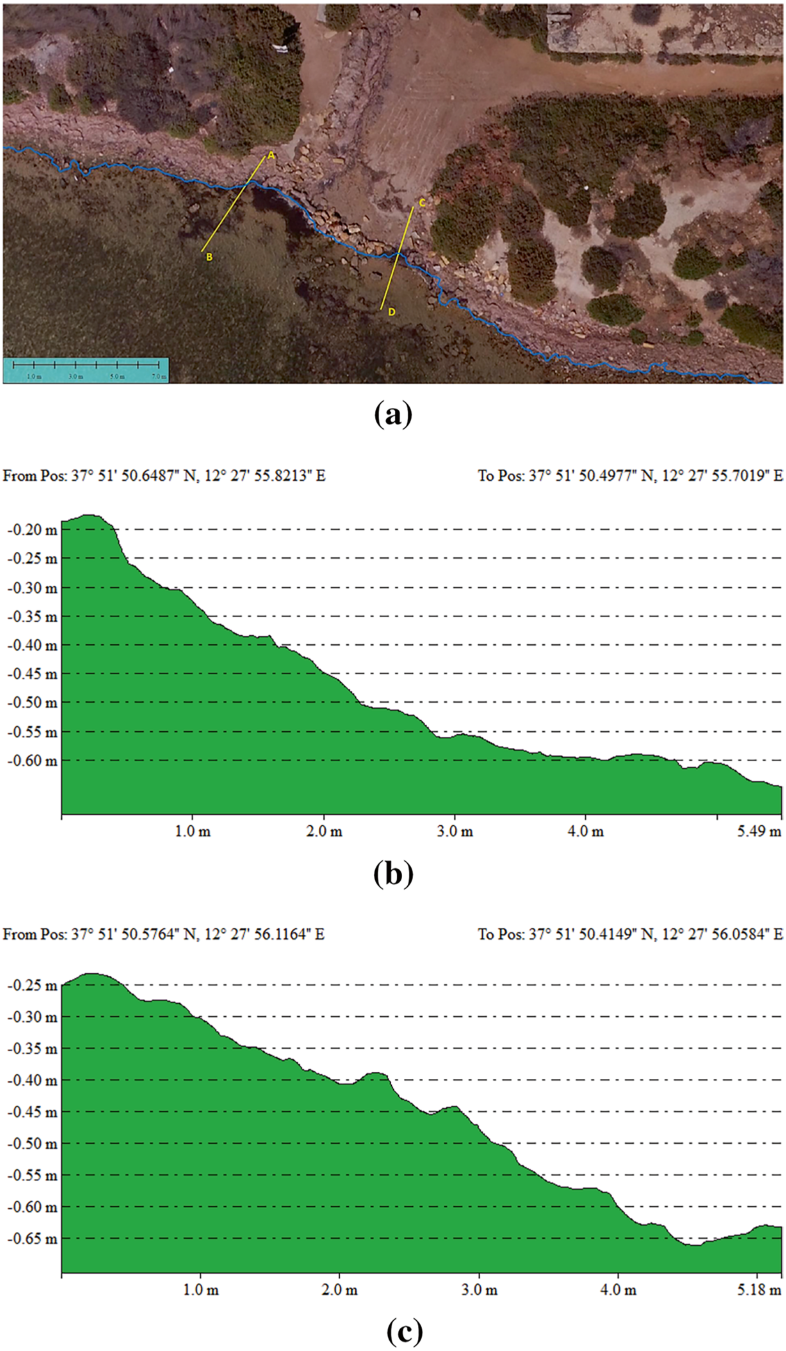


Fig. 16.8 Topographic sections in the Kothon area (in cyan, the current coastline): **a** location of the sections; **b** the A–B section; **c** the C–D section

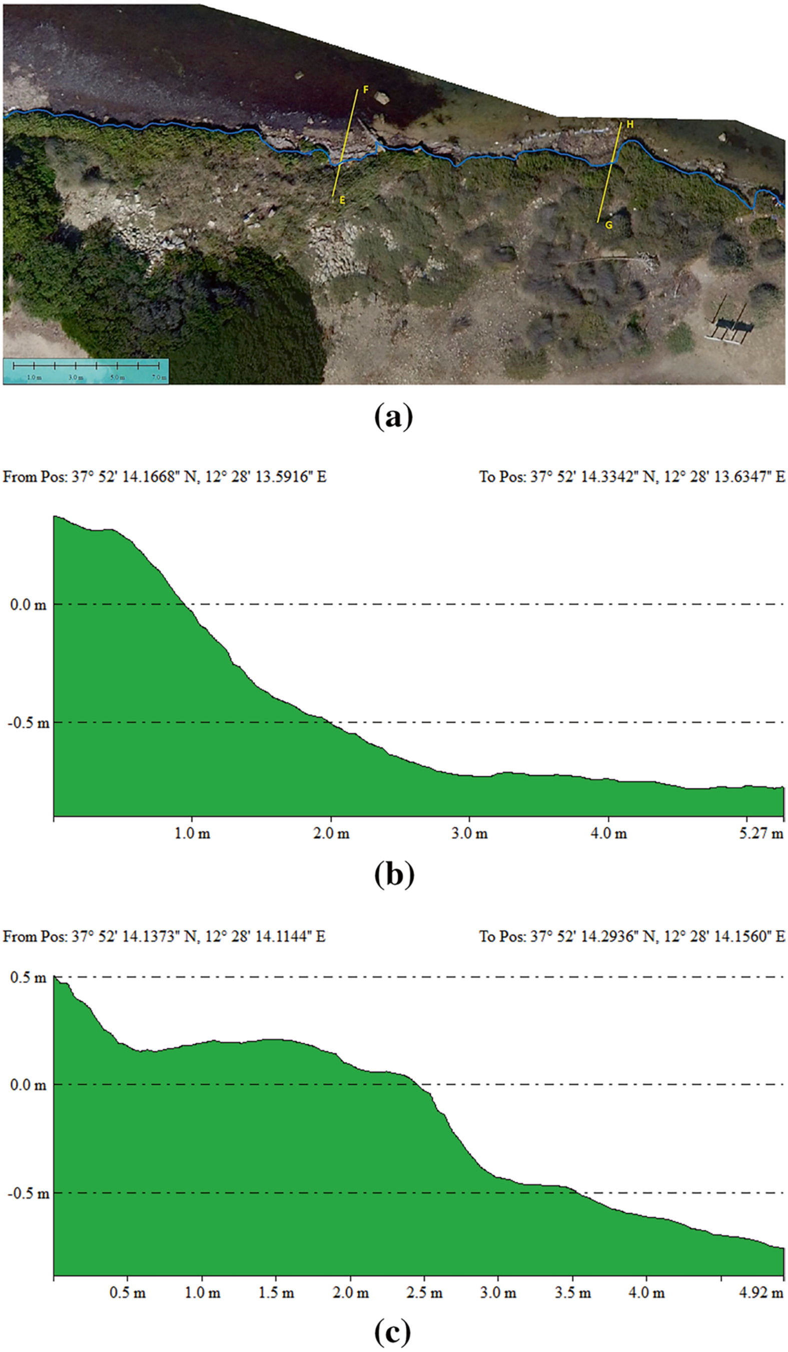


Fig. 16.9 Topographic sections in the North-West area of Motya (in cyan, the current coastline): (**a**) location of the sections; (**b**) the E–F section; (**c**) the G–H section

16.5 Monitoring, Detection, and Reconstruction of Archaeological Monuments

The monitoring action necessary to assess the conservation status of the coastal and submarine archaeological structures facing the coast consisted in the creation, management, and storage of constant and regular detail measurements through the use of three methodologies:

1. 3D scans of extreme detail with application of high-resolution photogrammetry.
2. Aerial photos from variable altitude taken from UAV.
3. Instrumental topographical surveys on the ground with Total Station, Laser Scanner and GPS.

Combining such three techniques the team has obtained a constant monitoring of the action of degradation of archaeological structures and has, at the same time, recorded the progress or regress of the coastline in different periods of the year.

To achieve this, advanced tools have been used to quickly and accurately scan archaeological features, creating models that are constantly updated as excavation progresses. These models are essential for developing 3D reconstructions that can serve as the foundation for virtual tours, museum exhibits, three-dimensional printing, and more. Effective cultural heritage management today requires a solid knowledge base to ensure better planning of conservation and restoration efforts, enabling continuous monitoring of changes over time and even anticipating potential catastrophic or unexpected events.

In the case of the archaeological site of Motya, digital technologies play a crucial role in safeguarding and monitoring its structures. They streamline documentation processes and significantly enhance the quality of the resulting records.

In particular, the applications mentioned above have produced:

- state of the art and maps of degradation: detailed state of the art and precise maps of degradation to design a restoration and restoration intervention or to monitor over time the outcome of the intervention on the artifact.
- structures and details: thanks to the acquisition speed and accuracy even at considerable distances, the most complex and delicate structures and products can be fully documented.
- database for documentation purposes: the status, degradation, structures, and details are stored in a database that always allows the reconstruction of complex artifacts and the use by users thanks to virtual navigation.
- 2D returns and 3D models: from the detected 3D data 2D tables can be extracted such as plants, elevations, sections, or three-dimensional models for reconstruction or subsequent restructuring.
- orthophoto: thanks to a high-resolution camera you can texturize a 3D model and get an orthophoto plane.

In addition to the use of laser scanner technology, the integrated application of aerospace and drone technologies is now a very effective tool for monitoring and remote sensing on a large scale of the archaeological heritage of Motya.

Among these new application technologies, also available for the cultural heritage sector, we highlight the increasingly widespread use of platforms and data derived from sensors and satellite services of the latest generation and, especially in recent years, increasingly also from "proximity monitoring" carried out with the use of the so-called UAV or RPA (Remote Piloting Aircraft).

These drones can record high resolution images with the most classic photogrammetric instrumentation or collect data with many other types of new generation sensors (e.g., thermal, infrared, multispectral/hyperspectral sensors etc.) capable of capturing, based on specific and increasingly refined needs, data of different nature through increasingly sophisticated and miniaturized systems. The main advantage of this new generation of tools is also inherent in being able to obtain data of extreme detail with processing times and costs significantly reduced compared to the most traditional surveying/monitoring techniques. And in fact, the increasing use of drones is encouraging, in parallel, the development of application software for the processing of data obtained through techniques of "remote sensing and close-range digital photogrammetry" (Cardenal et al., 2008; Liu & Huang, 2016) increasingly sophisticated, advanced and, at the same time, usable and low cost.

Therefore, in the specific case of the remains of the ancient settlement of Motya have been programmed with the support of technological applications, some monitoring actions aimed at obtaining predictive models and virtual restoration interventions through modelling and three-dimensional reconstructions.

We are implementing the site platform that manages a geographic information system (GIS) where high-resolution satellite images are merged, themes related to geomorphology, changes in the coastline, hydrogeological aspects, as well as the overlapping of cadenced 3D models, the result of detailed surveys of archaeological areas. The recording of this data in a dynamic platform allows the development of coastal vulnerability models whose purpose is to formulate and prioritize certain archaeological risk management strategies.

Among the monitoring actions undertaken on the island of Motya, the one that calculates the impact of coastal erosion on archaeological structures was particularly effective. Coastal erosion of Motya archaeological evidence such as the perimeter walls or entrance gates or even the architecture of Khoton has long been a problem for archaeologists seeking to understand maritime interactions in the past. A new model has therefore been applied, using the ARCGIS software to collect diversified data related to erosion processes over time of risk areas, with the hope that it can be expanded and adapted according to the degrees of evidence destruction. Despite recent theoretical and methodological advances in coastal archaeology, ongoing erosion remains a serious problem for both conservation and interpretation of coastal sites.

To classify the severity of coastal erosion in 10-m segments, the research team utilized the Digital Shoreline Analysis System (DSAS), an ARCGIS toolbar designed for detailed analysis of diachronic shoreline changes. This classification process involves comparing the positions of digitized historical coastlines through the creation of perpendicular transects spaced at 20-m intervals. The system generates a table quantifying the net movement of the waterline along each transect, allowing for precise measurements of coastal changes.

For the site of Motya, with particular attention to areas considered most at risk—such as Khoton, the Tophet, and the North Gate sector—we based our analysis on the digitized survey conducted in 2016 in collaboration with Leica Geosystems LG (Switzerland) and Aibotix GmbH (Germany). Our focus was on documenting the current coastline. This analysis combined aerial photographs taken during two periods of the year (March and September) with a detailed survey using a total station, achieving a precision of 0.5 mm.

The digital survey operations conducted along the coastline of Motya aimed to identify any variations since the 2016 survey, which provided an accurate baseline of the coastline's position and offered predictions for future retreat. Through a combination of detailed digital surveys and drone-acquired aerial photographs, we identified noticeable changes in the coastline.

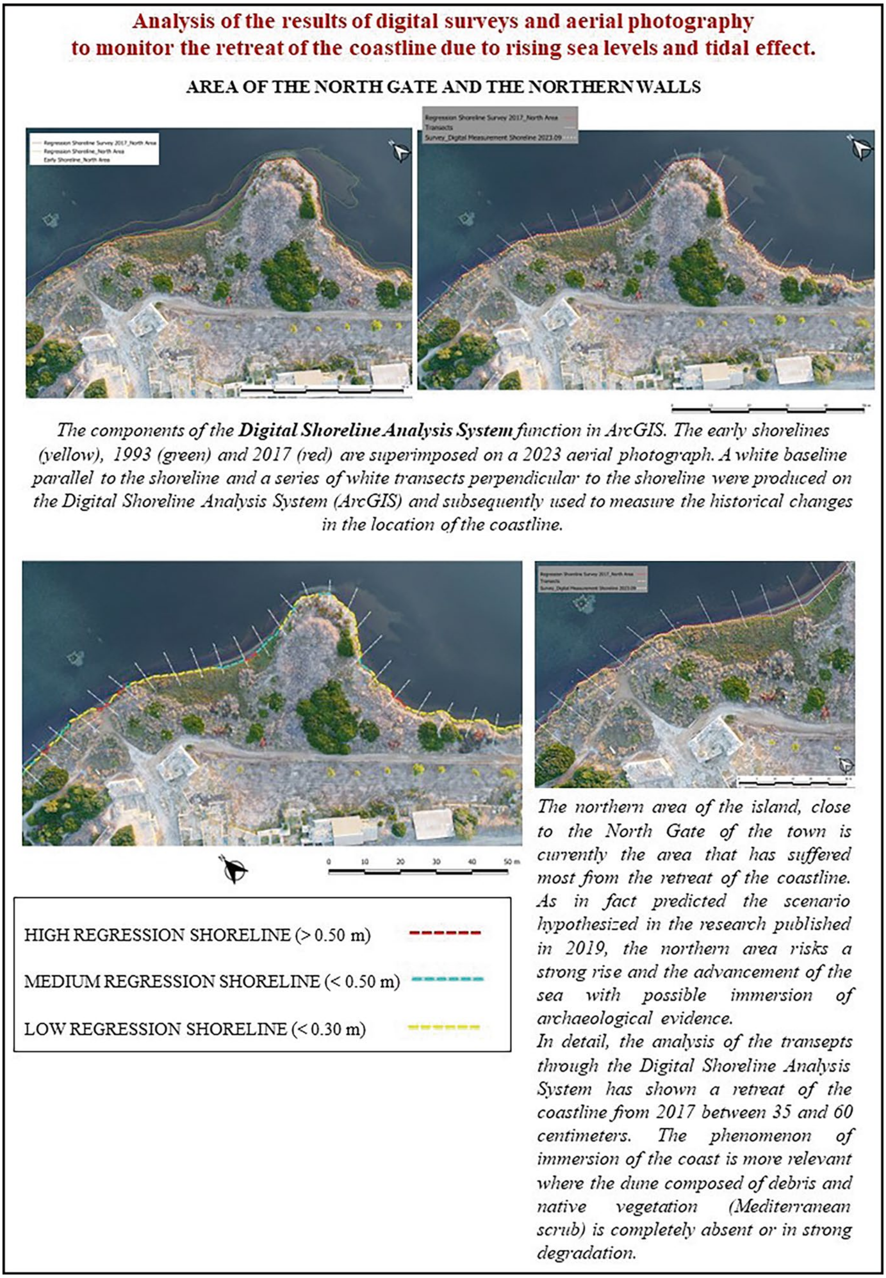
The surveys, carried out in two sample areas and superimposed onto aerial images, revealed a quantifiable coastal retreat. In the Khoton area, the retreat ranged from 25 to 55 centimetres, while in the area near the North Gate, it ranged from 35 to 60 centimetres (Figs. 16.10 and 16.11).

In contrast, the archaeological area of the Tophet appears to have experienced less significant coastal retreat. This relative stability is likely due to protection provided by a dune with dense vegetation on the northwest side, which partially mitigates wave action. Digital surveys recorded a retreat ranging from only 10 to 20 cm in this area. However, the Tophet's archaeological deposits are heavily affected by wind erosion, which seasonally exposes portions of archaeological layers and artifacts. The same wind erosion is evident on the surfaces of the stelae scattered across the Tophet and on the large boulders forming the walls in the northern area. The artifacts exhibit smoothed surfaces, chamfered edges, and cracks caused by wind action (Fig. 16.12).

16.6 Management Plan and Mitigation Actions

The Management Plan of an archaeological site as Motya should include monitoring activities facing the climate threaten and establishing measures to reduce their impact.

It is all the same essential to identify a procedure which could establish a gradation of priorities on risks and corresponding interventions to be carried out, ensuring an early warning system and mitigation strategies to be adopted regularly in addition to the operational protocol to reduce vulnerability and loss.



Analysis of the results of digital surveys and aerial photography
to monitor the retreat of the coastline due to rising sea levels and tidal effect.

AREA OF THE NORTH GATE AND THE NORTHERN WALLS

The components of the ***Digital Shoreline Analysis System*** *function in ArcGIS. The early shorelines (yellow), 1993 (green) and 2017 (red) are superimposed on a 2023 aerial photograph. A white baseline parallel to the shoreline and a series of white transects perpendicular to the shoreline were produced on the Digital Shoreline Analysis System (ArcGIS) and subsequently used to measure the historical changes in the location of the coastline.*

HIGH REGRESSION SHORELINE (> 0.50 m) 🟥

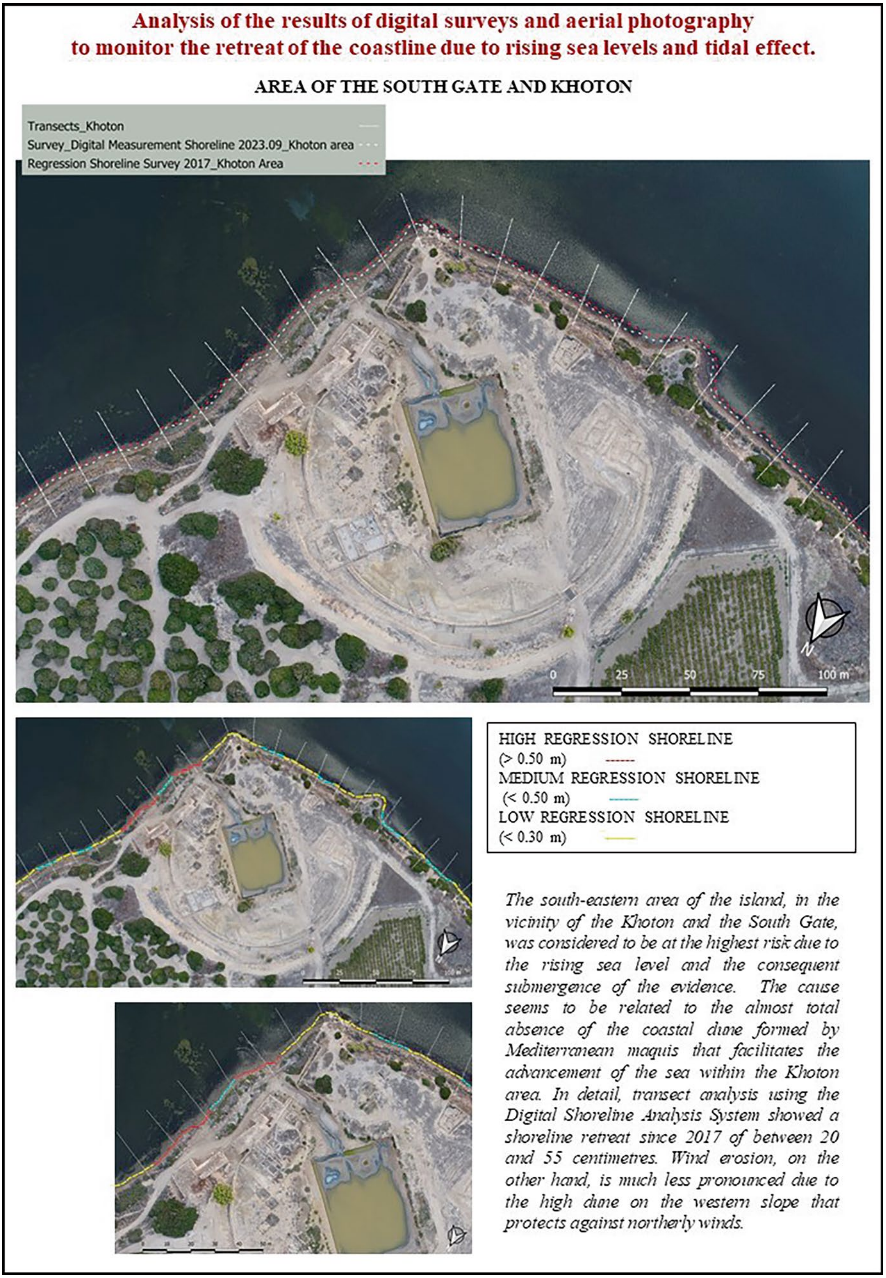
MEDIUM REGRESSION SHORELINE (< 0.50 m) 🟦

LOW REGRESSION SHORELINE (< 0.30 m) 🟨

The northern area of the island, close to the North Gate of the town is currently the area that has suffered most from the retreat of the coastline. As in fact predicted the scenario hypothesized in the research published in 2019, the northern area risks a strong rise and the advancement of the sea with possible immersion of archaeological evidence.

In detail, the analysis of the transepts through the Digital Shoreline Analysis System has shown a retreat of the coastline from 2017 between 35 and 60 centimeters. The phenomenon of immersion of the coast is more relevant where the dune composed of debris and native vegetation (Mediterranean scrub) is completely absent or in strong degradation.

Fig. 16.10 Marine regression data sheet in the northern area



Analysis of the results of digital surveys and aerial photography to monitor the retreat of the coastline due to rising sea levels and tidal effect.

AREA OF THE SOUTH GATE AND KHOTON

HIGH REGRESSION SHORELINE (> 0.50 m)
MEDIUM REGRESSION SHORELINE (< 0.50 m)
LOW REGRESSION SHORELINE (< 0.30 m)

The south-eastern area of the island, in the vicinity of the Khoton and the South Gate, was considered to be at the highest risk due to the rising sea level and the consequent submergence of the evidence. The cause seems to be related to the almost total absence of the coastal dune formed by Mediterranean maquis that facilitates the advancement of the sea within the Khoton area. In detail, transect analysis using the Digital Shoreline Analysis System showed a shoreline retreat since 2017 of between 20 and 55 centimetres. Wind erosion, on the other hand, is much less pronounced due to the high dune on the western slope that protects against northerly winds.

Fig. 16.11 Marine regression data sheet in the Khoton area

The north-western area of the island, close to the Tofet burial site and the associated stretch of wall, is currently the area that shows a low degree of shoreline retreat. The reason may be related to the presence of the high coastal dune formed by Mediterranean shrubs that hold back the advancing tides from the south, protecting the coastline.
In detail, the analysis of transects using the Digital Shoreline Analysis System showed a shoreline retreat since 2017 of between 15 and 30 centimetres. In contrast, wind erosion is very pronounced due to winds from the north and has caused the exposure of archaeological deposits and surface damage to the evidence.

Fig. 16.12 Marine regression data sheet in the Tofet area

16.6.1 Environmental Measures to Protect Coastal Sites: Natural Engineering

From this point of view, the approach historically used in Italy, the use of rigid works facing the sea, usually considered as the only possible solution for the defence of the coasts, should be overcome, as they cause adverse environmental and landscape effects, often unpredictably altering local coastal dynamics which directly affect monuments like harbours, temples, settlements and necropolis facing the sea.

It is essential, following the principles of integrated management, to adopt a holistic approach that encompasses not only coastal protection but also the conservation and restoration of natural habitats. Coastal dunes and *Posidonia oceanica* meadows, for instance, play a critical role in naturally mitigating erosive phenomena. In this context, protected areas act as catalysts and managers of innovative solutions within parks and nature reserves. These solutions, tested locally, can later serve as transferable examples of sustainable development. This is especially the case of Motya and the Marsala Lagoon, where Posidonia is endemic and represent a real natural resource.

Coastal dunes, beyond their ecological significance, are crucial for mitigating coastal risks such as erosion and flooding. At Motya they are present all around the island over the edge of the emerging limestone marl bedrock. The Intergovernmental Panel on Climate Change (IPCC) has identified dunes as resilient components of sandy coastal zones, alongside coral reefs, brackish wetlands, and mangrove forests. Dunes function as “sedimentary reservoirs”, supplying sand to the adjacent beach during periods of deficit. Additionally, their elevated morphology acts as a barrier against marine flooding, protecting inland vegetation from salt spray caused by wave action.

As transition ecosystems, coastal dunes and the typical Motyan coastal ridges are highly sensitive and vulnerable, requiring specialized restoration techniques and protection installation that traditional engineering cannot adequately address. However, these unique ecosystems, with their distinct pedological characteristics, are well-suited to environmental restoration methods grounded in naturalistic engineering. This discipline focuses on reconstructing or initiating semi-natural ecosystems, creating habitats that support plant and animal species while seamlessly integrating interventions into the surrounding natural landscape. Naturalistic engineering is the transversal discipline that promotes the use of native plants in combination with inert materials for anti-erosive, stabilizing and consolidation purposes.

A set of possible naturalistic engineering techniques can be implemented in Motya:

- renaturation techniques aimed at creating environments suitable for plant and/or animal species or communities.
- live plants, or parts thereof, as building materials, alone or in combination with other materials.

- materials, whether inert, infrastructure and other measures to provide conditions favourable to the life of animal species.

With naturalistic engineering it is possible to intervene to protect and restore the limestone marl ridge and the connected dunes system or intervene to rebuild it where it was destroyed (Fig. 16.13).

It is important, first, to identify the plant species suitable for regret and calculate for each species the number of seedlings needed. The most used species is the *Ammophila littoralis* or the *Calamagrostis arenaria* possibly accompanied in a second phase by the herbaceous or shrubby species of embryonic dunes (*Cakile maritima*, *Juniperus* spp., *Tamarix* spp., etc.) locally more suitable. The practice of sprinkling the dunes with the beached remains of Posidonia and other beached sea grasses also gave good results, since they are natural materials that are widely available on site and that quickly decompose without leaving any traces or requiring resetting work.

Obviously, in addition to the action of restoring the vegetation typical of the dunes there are some interventions that aim to protect the coastline such as windbreak barriers that may consist of wooden slats or twigs, or structures in jute mesh or reeds fibre, or basal barriers in wicker and screens checkerboard windbreak, more suitable for the conditions of erosion by the waves. These structures also have the function of encouraging the deposition of wind sand and the consequent creation of a dune deposit. The vegetation then finds the favourable conditions for its development evolving and progressively providing for the growth and stabilization of the deposit. With time, the palisades cover themselves with sand, rot and disappear, leaving the dune with a natural appearance already from the sixth to seventh year.

In one case, in front of the Tophet a defensive artificial dune with a path on top was realized with soil resulting from excavation, extending the natural bank of five metres (Fig. 16.14), while all around the island reeds (*Arundo donax* L.) were planted to protect the edge of the natural ridge from wind erosion (Fig. 16.15).

Fig. 16.13 Patterns of Mediterranean scrub (*garrigue*) replanting and dune development

Fig. 16.14 On the right, the barrier made to protect the Tophet of Motya reinforced with reeds

Fig. 16.15 Motya: reeds barrier on the edge of the coastal ridge, Area C, towards south

16.6.2 Other Protection Actions

Excavation at Motya have exposed walls, floors, mosaics, and wall paintings to sudden changes in environmental conditions, bringing them from centuries of protection underground to vulnerability against wind, rain, sea salts, pollution, and destructive forces from plants, animals, and human activity. This exposure inevitably leads to material degradation, despite varying processes.

The archaeological remains uncovered during years of research on the Island of Motya must be considered within the broader landscape, which is intrinsically tied to the life of the ancient settlement. This unique landscape, shaped by its natural and coastal environment, requires any protective intervention to be carefully integrated into the island's context while respecting environmental constraints.

Following the guidelines of the Central Institute of Restoration (ICR), risk factors can be divided into natural phenomena (seismic activity, hydrogeological instability, climate change) and anthropogenic causes (pollution, urban encroachment, vandalism, tourism). Effective protection must address these risks while ensuring the preservation of fragile structures like walls and floor coverings. Increasingly, roofing systems are being used as passive protection for archaeological remains, not only to shield them but also to enhance their accessibility and integration into site museums.

Roofs, shelters, and protective structures, however, must be carefully designed. Poorly planned coverings can distort the original character of the site, replacing its historical context with the new structure. At Motya, where wind, sea erosion, and tidal fluctuations pose significant threats, protective casings are often more effective than traditional canopies. These casings create enclosed spaces with technological components like supports, infill, and coverings. Fully enclosed casings allow for continuous monitoring of artifacts, but their high construction and maintenance costs often necessitate intermediate solutions. A set of shelters has been experimented over the House of Mosaics, with good results. While others were set up in the northern areas of the site.

Perimeter shielding made with reeds filters strong winds, block heavy rain, and allow controlled airflow. This creates an optimal environment by preventing mold, parasitic vegetation, and rising humidity, which is particularly suited for Motya's windy and coastal conditions. While these systems provide technical protection, they can also isolate artifacts from their original spatial context, transforming the site into an artificial container rather than an integrated landscape. A more thoughtful design can balance preservation with maintaining the historical and spatial relationships of the site.

Transparent envelopes are particularly valuable, as they reconnect the protected interior with the surrounding landscape, reflecting the relationship between the ancient site and its environment. Despite changes over time, the landscape retains elements of the original setting, making it vital to harmonize protective structures with the island's natural and archaeological heritage.

Conservation efforts on Motya have respected its unique Mediterranean coastal and naturalistic character. Architectural interventions were blend into the context, preserving both the archaeological remains and the surrounding environment. Protecting archaeological sites also involves interpreting and modifying them through architecture that respects their ancient memory, requiring thoughtful and discreet solutions.

16.6.3 Virtual Restoration

One promising solution for preserving and presenting archaeological heritage is "virtual restoration". Photogrammetry and laser scanning technologies allow for realistic reconstructions with high visual impact. In cases of long-term degradation or inaccessible areas, virtual restoration offers an alternative, particularly for fragile or damaged evidence.

A notable example of this approach is the "Virtual Hierapolis" project in Phrygia, which digitally restored and reconstructed monumental complexes of the Hellenistic-Roman and Byzantine city (Limoncelli & Scardozzi, 2013). Similarly, 3D printing of archaeological remains or scaled models can enhance museum displays, improving accessibility and understanding for visitors. At Motya, this approach was implemented in the local museum.

All these techniques and technologies applied to the archaeological heritage of the Island of Motya in Sicily have refrained erosion protecting the site and its invaluable monuments from climate change.

References

Andreou, G. M. (2018). Monitoring the impact of coastal erosion on archaeological sites: The Cyprus Ancient Shoreline Project. *Antiquity, 92,* 361, e4, 1–6.

Antonioli, F., Presti, V. L., Rovere, A., Ferranti, L., Anzidei, M., Furlani, S., Mastronuzzi, G., Orru, P. E., Scicchitano, G., Sannino, G., Spampinato, C. R., Pagliarulo, R., Deiana, G., De Sabata, E., Sanso, P., Vacchi, M., & Vecchio, A. (2015). Tidal notches in Mediterranean Sea: A comprehensive analysis. *Q Science Reviews, 119*, 66–84.

Antonioli, F., Anzidei, M., Amorosi, A., Presti, V. L., Mastronuzzi, G., Deiana, G., De Falco, G., Fontana, A., Fontolan, G., Lisco, S., Marsico, A., Moretti, M., Orrù, P. E., Sannino, G. M., Serpelloni, E., & Vecchio, A. (2017). Sea-level rise and potential drowning of the Italian Coastal Plains: Flooding risk scenarios for 2100. *Quaternary Science Reviews, 158*, 29–43.

Anzidei, M., Bosman, A., Carluccio, R., Casalbore, D., D'Ajello Caracciolo, F., Esposito, A., Nicolosi, I., Pietrantonio, G., Vecchio, A., Carmisciano, C., Chiappini, M., Chiocci, F. L., Muccini, F., & Vincenzo, S. (2017). Flooding scenarios due to land subsidence and sea-level rise: A case study for Lipari Island (Italy). *Terra Nova, 29*(1), 44–51.

Barradas Gutierrez, R. (2018). Mapping Mediterranean origins in 3D. *Reporter, 84*, 33–37.

Behringer, W. A. (2009). *Cultural history of climate*. Polity Press.

Bruun, P. (1962). Sea-level rise as a cause of shoreline erosion. *Journal of Waterways Harb Division, 88*, 117–130.

Bruun, P. (1983). Review of conditions for uses of the Bruun rule of erosion. *Coastal Engineering, 7*, 77–89.

Cardenal, J., Mata, E., Perez-Garcia, J. L., Delgado, J., Hernandez, M. A., Gonzalez, A., & Diaz-de-Teran, J. R. (2008). Close range digital photogrammetry techniques applied to landslides monitoring. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Vol. XXXVII. Part B8. Beijing 2008.

Di Rita, F., Fletcher, W., Aranbarri, J., Margaritelli, G., Lirer, F., & Magri, D. (2018). Holocene Forest dynamics in central and western Mediterranean: Periodicity, spatio-temporal patterns and climate influence. *Scientific Reports, 8*.

Domen, F., Fiederling, M., Lo Porto, A., Oliveri, F., Peukert, D., Pflederer, T., Reitz, J., Schaffeld, R., Toti, M. P. (2023). Prime evidenze di strutture portuali fenicie sul versante orientale di Mozia. In R. La Rocca (a cura di), *Atti del VI Convegno Nazionale di Archeologia Subacquea, 10–12 ottobre 2019 Palazzo Ciampoli—Taormina, Palermo* (pp. 271–279).

Drake, B. L. (2012). The influence of climatic change on the Late Bronze Age collapse and the Greek dark ages. *Journal of Archaeological Science, 39*, 1862–1870c.

Ferranti, L., Antonioli, F., Amorosi, A., Dai Prà, G., Mastronuzzi, G., Mauz, B., Monaco, C., Orrù, P., Pappalardo, M., Radtke, U., Renda, P., Romano, P., Sansò, P., & Verrubbi, V. (2006). Elevation of the last interglacial highstand in Sicily (Italy): A benchmark of coastal tectonics. *Quaternary International, 145, 146*, 30e54.

Furlani, S., Antonioli, F., Biolchi, S., Gambin, T., Gauci, R., Presti, V. L., Anzidei, M., Devoto, S., Palombo, M., & Sulli, A. (2013). Holocene Sea level change in Malta. *Quaternary International, 288*, 146–157.

Kaniewski, D., Paulissen, E., Campo, E., Weiss, H., Otto, T., Bretschneider, J., & Van Lerberghe, K. (2010). Late second-early fist millennium BC abrupt climate changes in coastal Syria and their possible significance for the history of the Eastern Mediterranean. *Quaternary Research, 74*, 207–215.

Lambeck, K., & Purcell, A. (2005). Sea-level change in the Mediterranean Sea since the LGM: Model predictions for tectonically stable areas. *Quaternary Science Reviews, 24*, 1969e1988.

Lambeck, K., Antonioli, F., Anzidei, M., Ferranti, L., Leoni, G., Scicchitano, G., & Silenzi, S. (2011). Sea level change along the Italian coast during the Holocene and projections for the future. *Quaternary International, 232*(1–2), 250–257.

Limoncelli, M., & Scardozzi, G. (2013). Dalla Cartografia Archeologica Digitale Al Restauro Virtuale: Recenti Casi Di Studio A Hierapolis Di Frigia. *Archeologia e Calcolatori, 24*, 75–99.

Liu, W.-C., & Huang, W.-C. (2016). Close range digital photogrammetry applied to topography and landslide measurements. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, XLI-B5*, 875–880. https://doi.org/10.5194/isprs-archives-XLI-B5-875-2016

Margaritelli, G., Cacho, I., Catala, A., Barra, M., Bellucci, L. G., Lubritto, C., Rettori, R., & Lirer, F. (2020). Persistent warm Mediterranean surface waters during the Roman period. *Scientific Reports, 10*, 10431.

Mayewski, P., Rohling, E., Curt Stager, J., Karlén, W., Maasch, K., Meeker, L., & Steig, E. (2004). Holocene climate variability. *Quaternary Research, 62*, 243–255.

Nigro, L. (2014). An absolute iron age chronology of the Levant and the Mediterranean. In L. Nigro (Ed.), *Overcoming catastrophes. Essays on disastrous agents characterization and resilience strategies in pre-classical southern Levant (Rome «La Sapienza» studies on the archaeology of Palestine and Transjordan, 11), Rome* (pp. 261–269). [ISBN 9788898154081; ISSN 1826-9206] https://bit.ly/35kVvJi

Nigro, L. (2018). La Sapienza a Mozia 2010-2016: il primo insediamento fenicio, l'area sacra di Baal e Astarte, il Tofet, la necropoli, l'abitato, i nuovi scavi alle mura – una sintesi. M. Guirguis (a cura di), *From The Mediterranean To The Atlantic: People, Goods And Ideas Between East And West. Proceedings of the 8th International Congress of Phoenician and Punic Studies, Vol. II (Folia Phoenicia 2), Pisa - Roma* (pp. 253–277). [ISBN 9788862279680; ISSN 2532-6384] [https://doi.org/10.19272/201813201038] https://bit.ly/32ChLN8

Nigro, L. (2023). Sull'urbanistica di Mozia fenicia e punica. R. Brancato (Ed.), *Città e territorio nel Mediterraneo antico. Studi offerti ad Edoardo Tortorici (Cronache Monografie), Roma* (pp. 127–138).

Nisi, M. F., Antonioli, F., Dai Pra, G., Leoni, G., & Silenzi, S. (2003). Coastal deformation between the Versilia and the Garigliano Plains (Italy) since the last interglacial stage. *Journal of Quaternary Science, 18*(8), 709e721.

Ravanelli, R., Riguzzi, F., Anzidei, M., Vecchio, A., Nigro, L., Spagnoli, F., & Crespi, M. (2019). Sea level rise scenario for 2100 A.D. for the archaeological site of Motya. *Rendiconti Lincei: Scienze Fisiche e Naturali, 30*, 747–757.

Sammari, C., Koutitonsky, V. G., & Moussa, M. (2006). Sea level variability and tidal resonance in the Gulf of Gabes, Tunisia. *Continental Shelf Research, 26*(3), 338–350.

Schmiedt, G., Caputo, M., Conta, G., Guidi, F., Pellegrini, M., & Pieri, L. (1972). *Il livello antico del Mar Tirreno: testimonianze dei resti archeologici*. Leo S, Olschki.

Shaw, B. D. (1981). Climate, environment, and history: The case of Roman North Africa. In T. M. L. Wigley, M. Ingram, & G. Farmer (Eds.), *climate and history: Studies in past climates and their impact on man* (pp. 379–403). Cambridge University Press.

Weiss, B. (1982). The decline of the Late Bronze Age civilization as a possible response to climate change. *Climatic Change, 4*, 173–198.

Zolitschka, B., Behre, K. E., & Schneider, J. (2003). Human and climate impact on the environmental as derived from colluvial, fluvial and lacustrine archives-examples from the Bronze Age to the migration period, Germany. *Quaternary Science Reviews, 22*, 81–100.

Part IV

Restoration and Sustainable Strategies for Heritage Preservation Against Risks and Climate Change

Chapter 17
Recovery of Terraced Landscapes as a Distinctive Sign of Land Culture and Protection from Hydrogeological Risk

Alessandro Sardella, Sara Carallo, Fabiana Di Ciaccio, Emeri Farinetti, Fabrizio Terenzio Gizzi, Carla Masetti, Antonio Minervino Amodio, Erica Isabella Parisi, and Alessandra Bonazza

Abstract Terraced landscapes are ancient agricultural systems that demonstrate human skill and respect for the environment. They are often found in challenging terrains and utilize techniques to safeguard biodiversity and prevent erosion. However, climate change threatens these landscapes, increasing the risk of extreme weather events. To protect these valuable systems, efforts are being made to preserve traditional knowledge, such as dry-stone wall construction, which is now recognized as a UNESCO Intangible Cultural Heritage. This paper examines three specific regions to develop strategies for the restoration and sustainable management of terraced landscapes, focusing on techniques to mitigate impacts of climate change and preserve cultural heritage.

Keywords Terraced landscape · Climate change · Dry stone walls · Historical landscapes · Aeolian archipelago · Lamole Valley · Lucretili mountains · Hydrogeological risk

---

A. Sardella · A. Bonazza
National Research Council, Institute of Atmospheric Science and Climate, Bologna, Italy
e-mail: a.sardella@isac.cnr.it; a.bonazza@isac.cnr.it

S. Carallo · E. Farinetti · C. Masetti
Department of Humanities Rome, Roma Tre University, Rome, Italy
e-mail: sara.carallo@uniroma3.it; emeri.farinetti@uniroma3.it; carla.masetti@uniroma3.it

F. Di Ciaccio · E. I. Parisi
Department of Civil and Environmental Engineering, University of Florence, Florence, Italy
e-mail: fabiana.diciaccio@unifi.it; ericaisabella.parisi@unifi.it

F. T. Gizzi · A. M. Amodio (✉)
National Research Council, Institute of Heritage Science, Potenza, Italy
e-mail: fabrizioterenzio.gizzi@cnr.it; antonio.minervinoamodio@cnr.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_17

17.1 Introduction

Generally located in inhospitable land, terraced landscapes represent an ancient agricultural and ecological system created by the adaptability and inventiveness of the human kind since ancient times. They express a long and intimate relationship between peoples and their natural environment and reflect specific techniques of land use that guarantee and sustain biodiversity development and safeguarding of the landscape towards hydrogeological risks. Spread all around the world, traditional terracing shows common techniques of farming, utilizing dry stone walls to realize the terraces.

It is widely demonstrated that in recent decades, changes in climate have caused impacts on natural and human systems and are expected to increase in the future. Moreover, climate change is contributing towards increased intensity and frequency of hydro-meteorological events, such as heavy rainfall, wind-storm, heat waves and droughts (IPCC, 2023). Landscape is consequently put at risk not only by impending disasters, but very often also by emergency and post disaster recovery actions with consequently jeopardization and even global loss of biodiversity, as highlighted by the Convention on Biological Diversity (CBD)[1] and the United Nation Convention to Combat Desertification (UNCCD).[2]

The regeneration and protection of the terraced landscape is therefore extremely important, since it triggers a chain process of conservation of socio-cultural aspects distinctive of the way of life of the local community, as well as of protection of the surrounding environment (i.e. preventing landslides and floods, combating desertification and erosion). In particular, the awareness of the pivotal role played by the knowledge of the traditional construction technique of dry-stone walls motivated its inclusion in the UNESCO's Intangible Cultural Heritage list in 2018 (UNESCO, 2018b).

This contribution feeds into WP4 "Restoration and sustainable strategies for Heritage preservation against risks and climate change" of the project PNRR CHANGES by providing the state of progress of interdisciplinary activities addressed to the protection of terraced landscape performed by the University of Florence, University of Roma Tre, and two Institutes of the National Research Council of Italy (1 - Institute of Atmospheric Sciences and Climate; 2 - Institute of Heritage Science).

Specifically, we here illustrate the methodology applied and the preliminary results obtained so far on three Italian case studies representative of terraced landscape selected in the framework of the project:

- Aeolian Archipelago, Sicily.
- Lamole Valley, Tuscany.
- The Natural Regional Park of Lucretili Mountains, Lazio.

---

[1] https://www.cbd.int/doc/legal/cbd-en.pdf

[2] http://www.unccd.int/en/Pages/default.aspx

17.2 The Aeolian Archipelago and Its Terraced Landscape

Located in the Southern Tyrrhenian Sea at the North of Sicily, the Aeolian Archipelago consists of seven main Islands (Lipari, Vulcano, Filicudi, Alicudi, Salina, Stromboli and Panarea) and its landscape is the result of volcanic activity over 250,000 years.

The historical terraced landscape of the Aeolian Islands reflects the environmental and geological characteristics of the territory and is fully integrated with the natural landscape. The predominant material used for the construction of the dry-stone walls that delimit the agricultural terraces, *lenze* in local dialect, is the volcanic stone obtained from the solidified lavas (Fig. 17.1). The natural color of the stones and their biological cover generally give a homogeneous appearance that gives uniformity to the landscape.

The Aeolian Archipelago is a particularly fragile ecosystem. Located in the Mediterranean Sea, a hot spot of climate change, it is increasingly affected by drought and heavy rainfall. Catastrophic floods and increasingly prolonged drought periods are the main "water" challenges facing the islands of the archipelago, where current water management practices may not be robust enough to cope with the impacts of climate change. Among the various consequences of these catastrophic

Fig. 17.1 Picture illustrating characteristic dry-stone walls of one terraced area in the island of Panarea (Photo by Alessandro Sardella)

events can be the increase in soil erosion, which in a terraced landscape can be considerable.

Densely inhabited and cultivated until the mid-1900s, the Aeolian Islands are among the smaller islands of Sicily, those with the highest percentage of terraces abandoned (90%) (Barbera et al., 2009). Alicudi, Filicudi, Salina and Panarea are almost entirely terraced, while Lipari presents a random distribution of terraces and Vulcano is characterized by their total absence due to the last eruption in 1888–1890, which determined the abandonment of large parts of cultivated terraces.

In general, the state of conservation of dry-stone walls is good in still cultivated areas where maintenance is constant. In the case of abandoned land, on the other hand, conservation is very variable, ranging from occasional or extended collapses to areas in good structural condition, but characterized by degradation due to colonization by spontaneous vegetation causing structural problems in dry stone walls that are already in poor stability. Animals grazing and the effect of the increasing frequency of summer fires and heavy rainfall are undoubtedly additional factors of damage, as well as the implementation of inadequate interventions of maintenance. As a result, the landscape is degrading gradually. Soil erosion is decreasing in some areas that have been abandoned totally and allowed to revert to nature (Camera et al., 2018). Soil erosion in such cases is more gradual than on recently abandoned or badly maintained land, as seen in other terraced (Brandolini et al., 2017) and non-terraced locations (Nasta et al., 2017) around the Mediterranean Region.

The present contribution is addressed to: (i) an increase understanding of the potential impacts of extreme hydrometeorological events (heavy rain, flooding and drought) on the terraced landscape of the Aeolian Islands in climate change conditions by performing an hazard analysis at regional scale of the likelihood of increase/decrease of climate induced extreme events including fires linked to prolonged drought periods; (ii) understand and quantify soil erosion and deposition at a local scale for Panarea, making use of an empirical model.

17.2.1 Methodological Approach

The two sections of this work are as follows (Fig. 17.2): (i) developing risk maps for the entire Aeolian islands archipelago to study the effects and evaluate the vulnerability associated with heavy rainfall and flood events; (ii) using the Unit Stream Power Erosion and Deposition (USPED) model to evaluate soil erosion on Panarea Island.

The investigation of future projections of hazards at territorial level covering the Aeolian Archipelago is performed by applying the Risk Mapping Tool for Cultural Heritage Protection (WGT). This platform, implemented within the Interreg Central Europe projects ProteCHt2save and STRENCH and currently under further development in the framework of the Interreg Central Europe project INACO, aims to support private and public authorities in the safeguarding of cultural heritage in Europe and in the Mediterranean Basin from climate induced events (https://www.

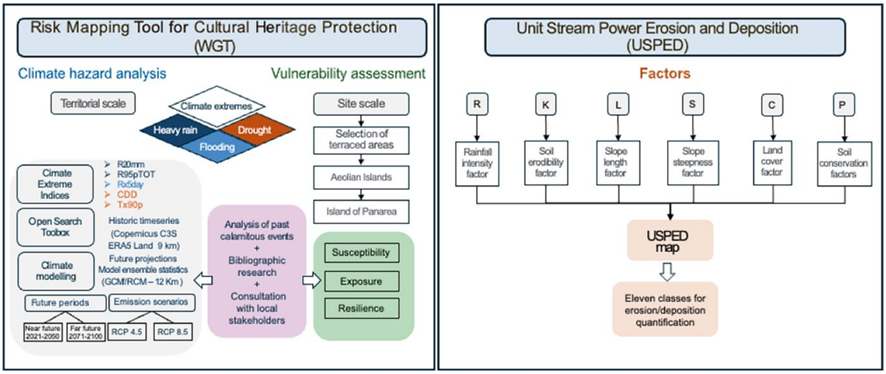


Fig. 17.2 Overview of the applied methodological approaches illustrating the two sections of the work: on the left, the procedure for the risk assessment by climate mapping and vulnerability ranking associated with heavy rainfall and flood events; on the right, the application of the Unit Stream Power Erosion and Deposition (USPED) model to evaluate soil erosion

protecht2save-wgt.eu.). First of all, among the climate variables and climate extreme standard indices defined by the Expert Team on Climate Change Detection Indices (ETCCDI) and available in the WGT, the following ones are selected and used: R20mm (very heavy precipitation days), R95pTOT (precipitation due to extremely wet days), Rx5day (highest 5-day precipitation amount), CDD (consecutive wet days) and Tx90p (extremely warm days). The selected indices are widely employed for the elaboration of future climate projections at global and regional level (Bonazza et al., 2021). The "Climate Modelling" tool of the WGT was then used for elaborating climate hazard maps covering the areas under investigation (Aeolian Archipelago). The WGT can provide maps developed by using 12 different combinations of 6 forcing global models (GCM) driving 5 regional models (RCM) under two emission scenarios: RCP4.5 (stabilization scenario) and RCP 8.5 (high pathway scenario), outlined in the AR5 Intergovernmental Panel on Climate Change (IPCC) assessment report (Sardella et al., 2020; IPCC, 2013). Maps of the minimum, mean, and maximum values of the model ensembles are also available.

For the current study, maps of future changes in R20mm, Rx5day, R95pTOT, CDD and Tx90p are investigated (~12 km resolution). The maps show the differences between the periods 2021–2050 and 1976–2005 (near future projection) and between the periods 2071–2100 and 1976–2005 (far future projection), under both RCP 4.5 and 8.5 scenarios.

The island of Panarea was selected to analyze how soil erosion affects an abandoned terraced landscape. The average soil loss (A) was calculated by the 2-dimensional USPED erosion-deposition model using the structure of the empirical Revised Universal Soil Loss Equation (RUSLE). Modelling was carried out based on the assumption that erosion and deposition predominantly depend on the sediment transport capacity of surface runoff, in contrast to the 1-dimensional RUSLE model (Mitasova et al., 1996). In particular, the formula that allows to estimate the annual soil loss is:

$$A = R \cdot K \cdot LS \cdot C \cdot P$$

where A is the annual average soil loss (Mg ha^{-1} $year^{-1}$), R is the rainfall intensity factor (MJ mm h^{-1} ha^{-1} $year^{-1}$), K is the soil erodibility factor (Mg h MJ^{-1} mm^{-1}), L is the slope length factor (dimensionless), S is the slope steepness factor (dimensionless). C is the land cover factor (dimensionless) and P is the soil conservation or prevention practice factors (dimensionless).

The R factor was computed using the empirical equation developed by Capolongo et al. (2008), which was previously utilized in Gioia et al. (2021). The K factor was estimated using a conventional Wischmeier erosion plot (Renard et al., 1997). The formula present in Minervino Amodio et al. (2023) was used to evaluate the K-factor.

The LS factor was generated using the same workflow present in Gioia et al. (2021). The C factor, which shows how crops and management practices affect soil erosion rates, was computed taking advance of literature data (Wischmeier & Smith, 1978; Renard & Foster, 1983). The resulting three land-use types were given C values based on the literature. Considering there are no noteworthy supporting practices in the research domain, the P factor's value is regarded as 1. Table 17.1 describes the types of data, the acquisition periods and the sources used for the different factors.

For the application of the USPED model we fixed the R-factor and K-factor in the following way. The R-factor was based on the use of rainfall data from the station on the island of Salina, located about 20 km from the island of Panarea. This choice was made considering that the Salina station was the only active rainfall gauge with a time series of at least 10 years. Regarding the K-factor, the features of the geological map described in Table 17.1 was used, which was merged to obtain a lithology map (as described and already used by Gioia et al., 2021 and Minervino Amodio et al., 2023).

Table 17.1 Table summarizes required and acquired data to compute the average soil loss (A) calculated by the USPED model

	Data	Period	Source
R-factor	Daily precipitation	2014–2023	SIAS—Servizio Informativo Agrometeorologico Siciliano
K-factor	Lithological data	1999	Geological map of the island of Panarea and Basiluzzo (Aeolian Islands) by Calanchi et al. (1999)
LS-factor	2 metres Lidar data	2012–2013	Geoportale Regione Siciliana
C-factor	Land uses data	2018	Corine Land Cover Dataset

17.2.2 Results and Discussion

17.2.2.1 Future Projections of Climate Hazards Impacting the Aeolian Islands

The complete set of maps of future changes of R20mm (very heavy precipitation days), R95pTOT (precipitation due to extremely wet days), and Rx5day (highest 5-day precipitation amount), produced with the model ensemble statistics (minimum, mean, and maximum) in the near (2021–2050) and far future (2071–2100) under RCP 4.5 (stabilization scenario) and RCP 8.5 (high pathway scenario), were analyzed and the outcomes are reported in Table 17.2. The maps illustrated in Fig. 17.3 represent an example of the maps obtained by using the Maps toolbox of the Risk Mapping Tool for Cultural Heritage Protection.

17.2.2.2 USPED Model

The rainfall intensity factor (R factor) calculated for the Panarea Island using daily rainfall data is 949 MJ mm ha^{-1} h^{-1} $year^{-1}$. The land use and management factor (C factor) (Fig. 17.4a) ranges from 0 to a maximum of 0.025, here using the CLC classes the following values were assigned: 0 for class 523; 0.001 for class 112; 0.01 for class 332; 0.025 for class 323.

Table 17.2 Data acquired from the future (near and far) projections hazard maps of 5 climate extreme indices: R20mm, Rx5day, R95pTOT, CDD and Tx90p

Index (measurement)	Projection	Ensmin RCP4.5	Ensmin RCP8.5	Ensmean RCP4.5	Ensmean RCP8.5	Ensmax RCP4.5	Ensmax RCP8.5
R20mm (days)	Near future	−2/−1	−2/−1	−1/0	0/1	1/2	2/3
	Far future	−1/0	−1/0	0/1	0/1	2/3	3/4
Rx5day	Near future	−14/−12	−15/−13	−3/−1	−2/0	10/12	12/14
	Far future	−12/−10	−13/−11	0/2	0/2	10/12	20/22
R95pTOT (mm)	Near future	−40/−30	−40/−30	0/10	0/10	40/50	40/50
	Far future	−40/−30	−40/−30	10/20	20/30	50/60	70/80
CDD (days)	Near future	−7/−6	−6/−5	0/2	2/4	10/12	13/15
	Far future	−7/−6	0/2	3/5	13/15	13/15	16/18
TX90p (%)	Near future	0/2	4/6	8/10	10/12	30/32	40/42
	Far future	10/12	38/40	28/30	40/42	48/50	78/80

In the table the minimum, mean and maximum variations of the indexes in relation to RCPs 4.5 and 8.5 are reported

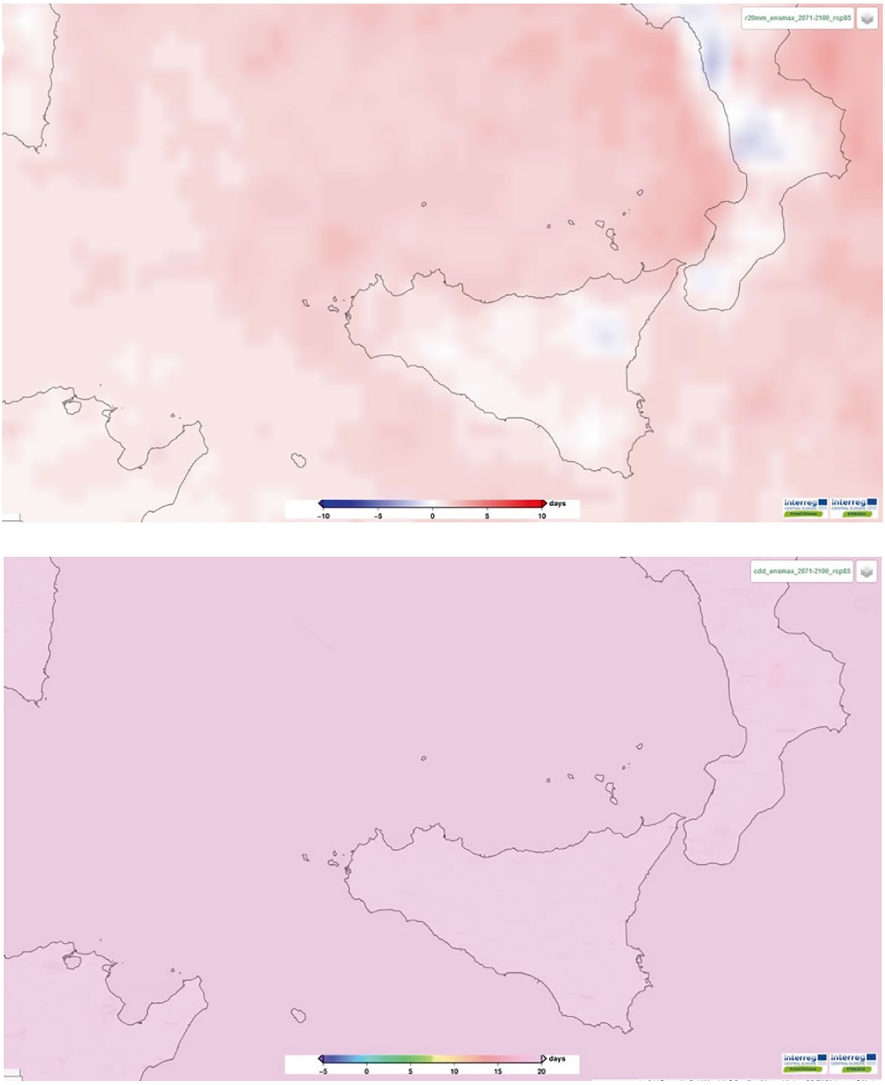


Fig. 17.3 Maps showing the climate projection simulation (ensemble maximum "ENSMAX") of the indices R20mm (top) and CDD (bottom) for the far future (2071–2100) under RCP 8.5. Focus Area: Southern Italy and Aeolian Islands (~12 km resolution)

The soil erodibility factor (K-factor, Fig. 17.4b) was derived from the lithological information of the geological map (Calanchi et al., 1999) and it shows a range between 0 and 0.06. A value of 0 was attributed to the presence of the urban area, while a value of 0.06 was attributed to unstable areas prone to erosion, such as landslide areas and debris fan deposits. The map of slope length and steepness factor (LS factor, Fig. 17.4c) shows values between 0 and 1462. High value of the LS

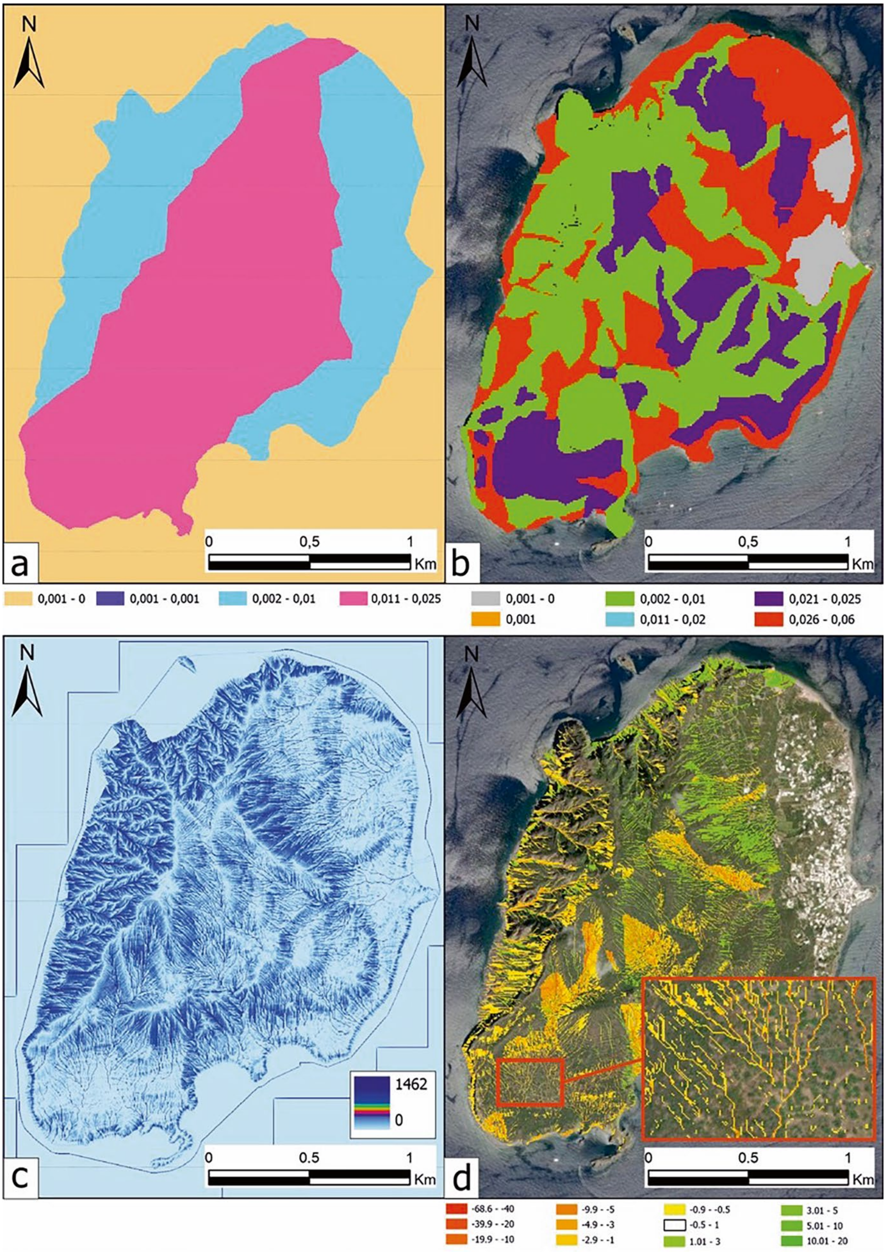


Fig. 17.4 Factors considered for building the USPED model (**a**: C factor; **b**: K-factor; **c**: LS factor) and model output (**d**: A values) (see text)

factor can be found in the north-western part of the island, where the particular topographic conditions have not allowed man to build terraced areas for the farming activities; in fact this area is mostly characterized by landslides, and linear erosion.

By combining all the factors, we obtained the results of the USPED model, as Fig. 17.4d shows. In the figure, each pixel was categorised using the 11 erosion/deposition classes listed below:

- Extreme erosion (<−40 Mg ha^{-1} year $^{-1}$)
- High erosion (−40/−20 Mg ha^{-1} year^{-1})
- Moderate erosion (−20/−10 Mg ha^{-1} year^{-1})
- Low erosion (−10/−5 Mg ha^{-1} year^{-1})
- Very low erosion (−5/−2 Mg ha^{-1} year^{-1})
- Stable (−2/2 Mg ha^{-1} year^{-1})
- Very low deposition (2/5 Mg ha^{-1} year^{-1})
- Low deposition (5/10 Mg ha^{-1} year^{-1})
- Moderate deposition (10/20 Mg ha^{-1} year^{-1})
- High deposition (20/40 Mg ha^{-1} year^{-1})
- Extreme deposition (>40 Mg ha^{-1} year^{-1})

Both erosion and deposition areas emerge from the processing, but stable areas clearly prevail. Furthermore, making a focus on an area with high density of terraces (red rectangle in Fig. 17.4d), it can be seen how the erosion/deposition.

The distribution of classes in the USPED model (Fig. 17.5) shows that most of the analyzed area is stable (about 96%), while the area in erosion is about 2% and the area characterized by deposition is 1.9%. This small difference between erosion/deposition translates into 1.25 ha in favor of erosion, probably this net loss of material is due to the north-west area of the island characterized by large linear incisions and landslides that remove material depositing it directly into the sea.

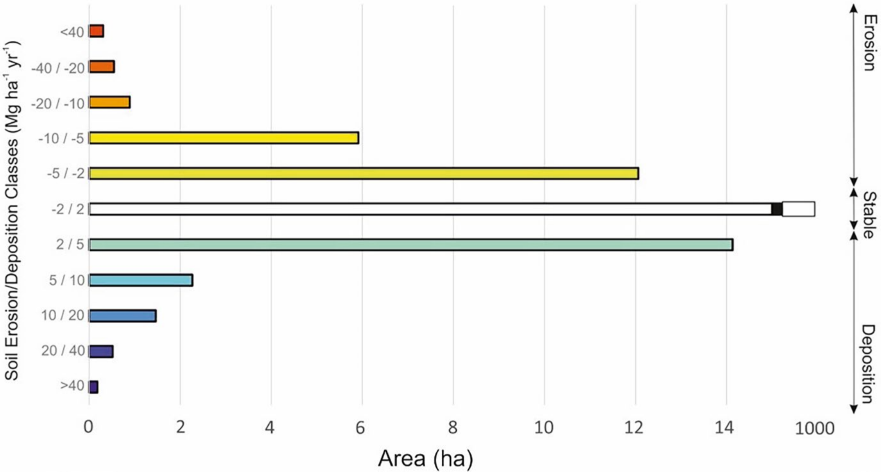


Fig. 17.5 Histograms show the USPED model's area distribution

17.2.3 Future Work

As a further step the analysis of historic time series of climate extreme indices suitable for investigating past climate extreme events on the area will be conducted by using the "Open search Tool Box" of the WGT which allows the exploration of selected climate indices recomputed following the full time series products of Copernicus C3S ERA5 Land (~9 km resolution, from 1981), Copernicus C3S ERA5 (~31 km resolution, from 1981), and NASA GPM IMERG (~10 km resolution, from 2000). Parallelly, an analysis of the past calamitous events affecting the area will be conducted based on bibliographic research, data available in the literature and consultation with local stakeholders, with the objective of collecting information on the areal distribution of the episode, the impacts and recovery or preventive measures put in place by local authorities.

Further investigations will be devoted at improving the USPED model by making use of more refined input spatial data, such as knowledge of soil characteristics (e.g., typology, thickness) and their use at a more detailed scale. This will allow us to define in a more detailed way those terraced areas where erosion rates are higher, and which therefore no longer play the role of risk mitigation. The results will be useful in defining priority areas for intervention and restoration of dry-stone walls.

17.3 The Terraced Landscape of the Lamole Valley (Chianti)

17.3.1 Description of the Study Area

The landscape of Lamole (see Fig. 17.6) is a product of centuries of human adaptation to its high-hill environment, situated at a medium altitude of around 600 m above sea level. Communities in this region have long transformed the natural terrain to make it suitable for agriculture. Historical records show settlements in Lamole dating back to the Etruscan period, and by the medieval era, its steep slopes were utilized to build dry-stone terraces. These terraces not only levelled the land for farming but also created a unique microclimate that enhanced crop quality and yield. Over time, these terraces became a distinctive feature of Lamole's agricultural landscape, contributing to its productivity and its cultural and historical heritage (Ministerial Decree, 2018).

Agriculture has always been fundamental to Lamole's economy, with diverse crops forming a distinctive mosaic of terraced landscapes. The area has largely maintained traditional practices, focusing on the mixed cultivation of vines, olive trees, and other crops. Efforts by local farmers, such as Fattoria di Lamole, have restored and preserved traditional terraces, counteracting trends in the wider Chianti region where many terraces have been destroyed to accommodate industrial-scale farming. These efforts earned Lamole recognition in 2018 when it was added to the National Register of Historic Rural Landscapes by the Italian Ministry of

Fig. 17.6 The Lamole Valley, point cloud from the airborne survey of 2020

Agricultural, Food, and Forestry Policies (Ministerial Decree, 2018). Its terraced vineyards were later acknowledged also as heroic and historical vineyards in 2020 (Inter-ministerial Decree, 2020).

Terraces and dry-stone walls in Lamole provide a wide range of environmental benefits, including managing water runoff, preventing soil erosion, enhancing soil fertility and productivity, improving food security, promoting agrobiodiversity, and addressing climate change impacts. When maintained, terraces mitigate natural hazards such as landslides and floods (Agnoletti et al., 2023). However, many terraces have deteriorated due to abandonment and insufficient maintenance, leading to increased hydrogeological risks like erosion and slope instability. The lack of unified regulations on terrace recovery, inadequate education in dry-stone wall construction, and insufficient economic incentives for farmers contribute to this decline. Recent efforts aim to recover and preserve the knowledge of this practice, the art of dry-stone walling, recognized by UNESCO as intangible cultural heritage, to safeguard traditional viticulture techniques and ensure the enduring cultural and historical significance of the region (UNESCO, 2018a).

In recent years, Lamole has become a hub for research integrating historic preservation with modern scientific methodologies to enhance agricultural practices (Preti et al., 2013, 2018; Tarolli et al., 2014; Agnoletti et al., 2015; Tucci et al., 2019; Parisi & Tyc, 2021, Tyc et al., 2022). Since 2016, collaboration with Fattoria di Lamole has expanded access to several vineyards, enabling long-term monitoring of terraced vineyards like Grospoli and Le Stinche (see Table 17.3). This has facilitated continuous spatial and temporal data collection to better understand terrace dynamics.

In the context of broader framework of the research conducted in Lamole, the focus during the CHANGES project has been primarily the accurate assessment of temperature from thermal imaging and its role in terraced vineyards dynamics on a multi-temporal and multi-spatial scale. In fact, the study of traditional

Table 17.3 Detailed information about the vineyards considered in the Lamole case study area

Area of study	Terraced Vineyards of Lamole (Greve in Chianti, Florence, Italy)	
Scale of reference	Territory and landscape	
Location	Lamole Valley	
Owner	Fattoria di Lamole, property of Paolo Socci	
Vineyard	Grospoli II	Le Stinche
Geographic coordinates	43°32′32″N 11°21′37″E	43°31′49”N 11°21′27″E
Type of terracing	Terraces with dry-stone walls and soil embarkments	Terraced portion with soil embarkments
Vineyard exposure	E-O	O-E
Years of monitoring	2017, 2019, 2020, 2022, 2024	2022
Vineyards' terraced area	~1.3 ha	~1.9 ha
Vine variety	Sangioveto 100%	Sauvignon blanc 50% Chardonnay 50%
Cultivation method	The vines are cultivated by the traditional "alberello" method	

agro-hydraulic systems, such as terraces, has been performed on different scales, from the entire valley (airborne survey) to the single vineyards (UAV-based survey), to the single vine or dry-stone wall (ground-based measurements) to understand how mitigation strategies for climate change affect the quality and characteristic of the wine production despite the environmental shifts. In this context, geo-spatial technologies provide a shared substrate for different disciplines in terms of spatial data and thematic information for documenting the geometry, for modelling and simulation of hydrogeological phenomena and for monitoring through time and space the evolution in terms of geometry and thermal behaviour of such complex systems to ensure that this ancient landscape remains resilient and productive facing the challenges of a changing climate.

17.3.2 Methodological Approach

A key aspect of the research is the use of geospatial technologies to collect high-resolution spatial and temporal data, combining both aerial and ground-based data. Unmanned Aerial Vehicles (UAVs) equipped with visible (VIS) and Thermal Infrared (TIR) sensors are used as advanced thermal monitoring techniques to create 3D models of the morphology and thematic maps of the thermal behavior of the selected vineyards. The UAV photogrammetry, in conjunction with ground-based thermal imaging, allows for precise spatial reconstructions and detailed monitoring of temperature fluctuations at the local vineyard scale on different time spans (from daily variation to multi-year monitoring).

This study focuses on monitoring vineyard temperature using advanced tools to enhance vine health, optimize grape ripening, and support sustainable water use.

Technologies such as thermal imaging and infrared sensors help assessing temperature variations, detect water stress, and design smart irrigation strategies. By analyzing temperature fluctuations due to evapotranspiration and stomatal activity, farmers can better allocate water resources, leading to healthier vines and higher-quality grapes. Another important consideration, where monitoring temperature variations plays a crucial role, is the increasing use of terracing as an adaptation strategy to climate change and rising temperatures, allowing for the effective utilization of steep slopes and facilitating the shift of vine cultivation to higher latitudes and altitudes.

The research utilizes a structured approach for data collection and analysis:

1. Thermal Imaging and Temperature Estimation: Precise temperature estimation via thermal imaging requires attention to parameters such as emissivity, reflected temperature, and ambient conditions like relative humidity and temperature. By refining field data collection methods, the study aims to track vineyard daily temperature behavior over multiple years and compare patterns across various vineyards.
2. Sensor Selection and UAV Integration: After testing different sensor-platform setups for data acquisition, the DJI Matrice 300 RTK UAV and the Zenmuse H20T thermal sensor have been selected as the optimal combination for geospatial imaging and thermal data collection.
3. Ground-Based Control Network: To validate drone-collected temperatures, a ground-based control network has been set up using contact sensors like thermocouples, providing essential reference data (ground-truth) for validation, calibration, and accuracy enhancement.
4. Combined Ground and Aerial Measurements: Thermal data was captured from both ground and UAV-mounted sensors, allowing cross-validation. Ground-based cameras provided high-resolution data for single vines or sections, while UAVs delivered thermal maps of entire vineyards, to visualize temperature variation throughout the day.
5. Enhanced Data Collection Techniques: Improvements in data collection were made by using high-resolution contact sensors and onsite weather stations, ensuring higher accuracy in measuring environmental conditions like ambient temperature and relative humidity.
6. Periodic Thermal Surveys: Regular thermal surveys monitored daily and yearly temperature variations across different vineyards, evaluating the thermal behavior of various vineyard layouts, terrains, and altitudes, crucial for design and management.
7. UAV-Based Photogrammetry for Thermal Mapping: UAV photogrammetry enabled the creation of detailed thermal maps (orthomosaics) for vineyards, capturing temperature distribution and daily effects such as shadowing and differing responses from materials like stones, soil and vegetation.
8. Geometric Validation and Calibration: Increasing the geometric accuracy of UAV-based 3D thermal maps obtained from photogrammetry through

procedures such as partial camera pre-calibration, aimed at producing more spatially reliable 3D representations of vineyard terrains.

9. Radiometric Validation and Calibration: Validating the accuracy of thermal data by analyzing the sensitivity of temperature measurements to influencing parameters (e.g., emissivity, ambient conditions) and verifying their reliability for precise temperature readings.
10. Controlled and Real-World Testing: Tests in controlled and real environments validated the accuracy of the geometric and radiometric data, ensuring method reliability under diverse conditions.

17.3.3 Results and Discussion

The mentioned methodology allowed to obtain thematic maps for each vineyard representing the thermal distribution of temperature. This is possible thanks to a 3D reconstruction by using photogrammetry and by a radiometric conversion of the thermal data to obtain temperature values for each pixel.

The results of two selected vineyards are reported in Figs. 17.7 and 17.8, where the visual information related to the temperature distribution allowed to identify different thermal behaviors, induced by the sun position and by the different characteristics of the materials along the day (e.g. dry-stone walls).

This method allows for high temporal and spatial resolution mapping and monitoring of selected vineyards, to identify specific process affecting plant yield, growth and health.

Furthermore, it is possible to analyze the radiometric data to produce GIS-based statistical information for each terrace extracting the temperature values trend acquired for each terrace, at selected distances, to identify micro-variation within the vineyard area, like dominant influence of solar exposure and shadowing on temperature fluctuations, which provided a foundation for further research.

These outputs may be used for the design of specific management and mitigation strategies although it is necessary to assess their reliability from both the geometric and radiometric point of view.

For this reason, the latest research focused on these topics:

- preliminary analysis on the effects of GNSS measurements on the geometric self-camera calibration and how they affect the obtained photogrammetric 3d models (Parisi et al., 2022).
- preliminary analysis on the precision and accuracy of absolute temperature values obtained from thermal imaging radiometric conversion in different contexts (Parisi et al., 2024, publication in progress).

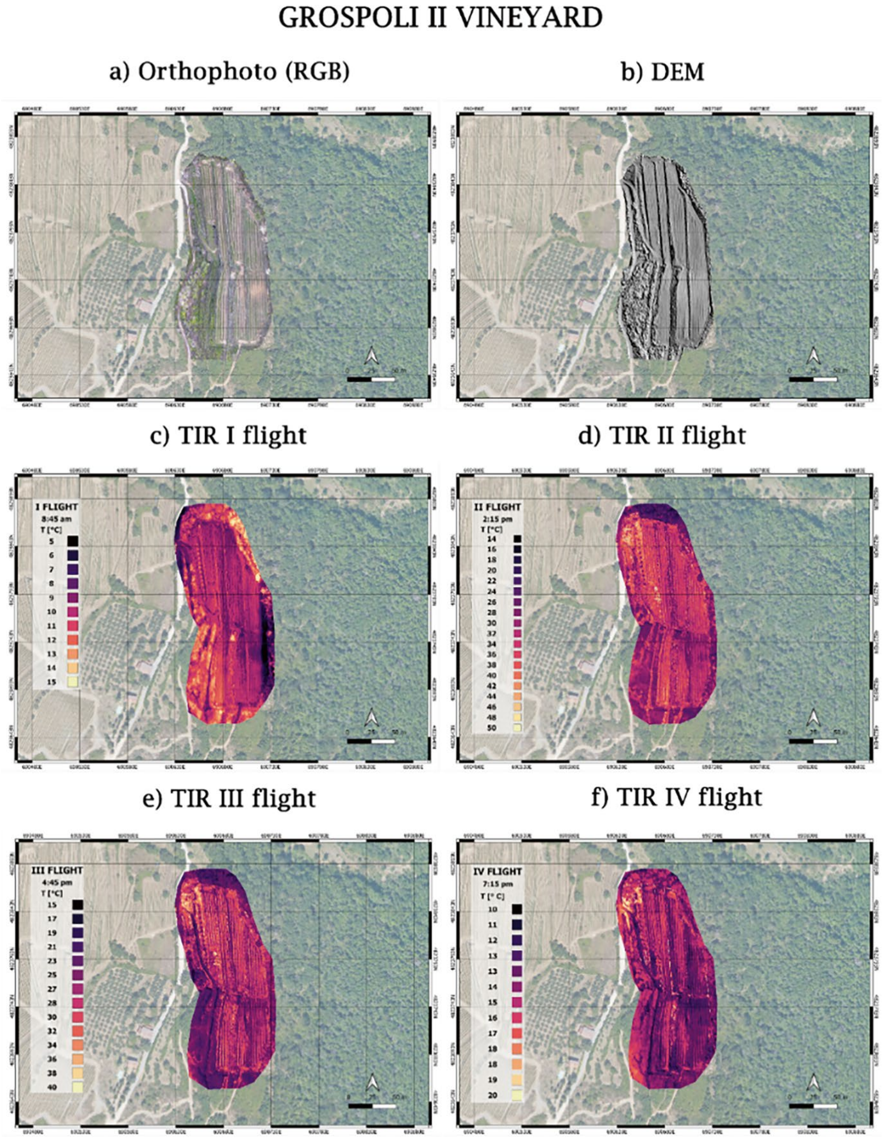


Fig. 17.7 Grospoli II vineyard: geospatial morphological data (orthophoto and digital elevation model) and thematic information (thermal orthomosaics) for spatial and temporal monitoring of the thermal behaviour with visual information and absolute temperature values

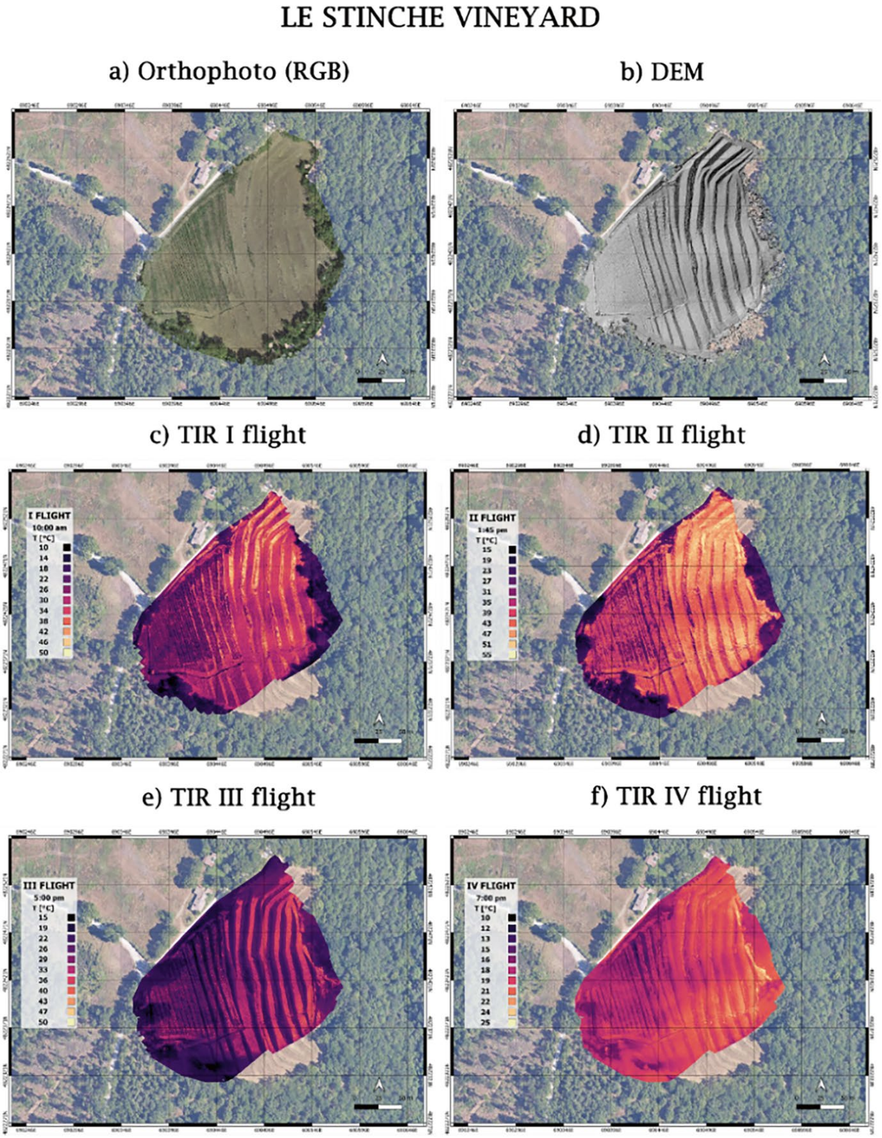


Fig. 17.8 "Le Stinche" vineyard: geospatial morphological data (orthophoto and digital elevation model) and thematic information (thermal orthomosaics) for spatial and temporal monitoring of the thermal behaviour with visual information and absolute temperature values

17.3.4 Future Works

Future work will explore customized methodologies for assessing the impact of terracing as traditional agro-hydraulic systems. These studies will consider the multidimensional benefits and challenges of terracing, particularly its role in enhancing climate resilience. Emphasis will be placed on evaluating terracing from various perspectives, integrating environmental, agricultural, and socio-economic factors to inform adaptation strategies that respond to shifting climate patterns.

Efforts will include the development of robust and reliable methodologies for monitoring intra- and inter-specific parameters of terraced vineyards. By using advanced geospatial techniques, future research will aim to improve the qualitative and quantitative measurement of key factors such as temperature. This approach will facilitate a deeper understanding of microclimatic variations and the overall health of vineyard ecosystems, supporting targeted management and optimization practices.

The research will also prioritize collaboration with experts within the Spoke 7 of the CHANGES project. This interdisciplinary approach will contribute to the creation of shared practices and strategies that ensure the long-term preservation of terraced landscapes. By leveraging diverse expertise, future work will develop best practices and workflows aimed at balancing productivity with conservation, thereby safeguarding the cultural and environmental value of terraced vineyards.

17.4 The Terraced Landscape of the Lucretili Mountains

17.4.1 The Research Group

The research group is affiliated with the Department of Humanities at Roma Tre University and is composed of an interdisciplinary team that combines the expertise of geographers (Carla Masetti and Sara Carallo) and landscape archaeologists (Emeri Farinetti), with the support of specialists from other disciplines (geomorphologists, plant ecologists, and experts in geotechnologies).

This integrated and multidisciplinary approach allows for the study of terracing from multiple perspectives, ensuring a critical, comprehensive, and in-depth analysis. The study of interactions between humans and the environment, traceable over time through phases of territorialization and the identification of cognitive and material sediments, has been fundamental in fully understanding the transformation of these structures in the long term.

The employed methodology is based on a detailed “regressive reading” of the territory, aimed at reconstructing the historical stratification process of these structures. Key steps include a critical analysis of geo-historical sources preserved in archives. These investigations are followed by field surveys, which involved direct and participatory observations, as well as the collection of oral sources.

* Although the work can be attributed to a common discussion and project, it should be specified that the following paragraphs are assigned as follows: Carla Masetti is responsible for the sections “Research Group” and “Study Area”; Emeri Farinetti for the sections “Methodological Framework” and “Terraced Slopes”; Sara Carallo for the section “Some Preliminary Results of the Participatory Investigations” and “Best Practices”. The “Conclusions” are the result of joint collaboration. The archaeological investigations and participatory archaeology activities are conducted as part of the MoLuLaP (Monti Lucretili Landscape Project), a comprehensive archaeological project active in the study area of the Monti Lucretili (Bernardi & Farinetti, 2023; Bernardi et al., 2024). Analyses of soil samples for micromorphological and paleobotanical analyses are currently underway, thanks to collaboration with teams of international specialists.

17.4.2 The Theoretical-Methodological Framework

Through a bottom-up approach (multidisciplinary, multiscale, and diachronic), the research also involved the participation of local communities and aimed to investigate the level of social perception regarding the significance and characteristics of the landscape heritage under study, as well as the degree of awareness of the environmental risks to which the historical landscape is subjected.

The aim is to identify traces of material culture related to terraced areas and to promote participatory protection of the cultural heritage of the local community, encouraging forms of active participation and citizen science (Calandra, 2018; Burini & Ghisalberti, 2020; Masetti, 2019; Masetti & Spadafora, 2024). The dialogues initiated with the communities, in the form of participatory workshops or one-on-one meetings, aim to stimulate and revive local historical memory, promote co-production of knowledge, and foster greater territorial awareness and sense of place among the communities (Becattini, 2015; Farinetti, 2020, 2021).

The research aims to move beyond the point-focused logic of merely preserving individual monuments or contexts, instead promoting the protection of a widespread heritage, of which the rural landscape is a testament (Carallo & De Pasquale, 2018; Farinetti, 2012, 2021).

The fieldwork and integrated methodology will generate content for the creation of a community map (Baratti, 2012; Burini, 2016). This cartography will reflect the community’s self-perception and its landscape, presenting itself as a dynamic product, just like the landscape itself. Participatory workshops, organized in collaboration between academics, experts, and community members, provide the ideal setting to promote the shared creation of spatial and geo-historical content through real-time digital cartography. This encourages engagement and awareness, making the map a visual form of shared knowledge and increasing territorial consciousness (Belotti et al., 2024).

17.4.3 The Study Area

The Lucretili Mountains are located in the Lazio region, northeast of Tivoli, and extend between the Metropolitan City of Rome and the province of Rieti. This mountain range, composed primarily of limestone, runs in a northeast/southwest direction, situated to the left of the Tiber River, between the Sabine Mountains and the Rieti plain to the east, and the Aniene River valley and the Tiburtini Mountains to the south.

The area is extremely diverse, characterized by a predominantly mountainous environment typical of the Apennines, consisting mainly of narrow and steep mountain gorges, plateaus, and a lesser presence of low-gradient areas, interspersed with hilly and flat regions (De Angelis, 1995; Bernardi et al., 2024).

The Lucretili Mountains are part of the Regional Natural Park of the Lucretili Mountains, a protected area established by Regional Law No. 41 on June 26, 1989, to preserve local flora and fauna, as well as to promote awareness, environmental education, and recreational activities (Fig. 17.9).

The area features a great variety and richness of landscapes and biodiversity, including oak and beech forests, meadows, and limestone formations, such as the karst depressions of the “Pratone” on Monte Gennaro and “Prato Favale”. These locations have been engaged in transhumant pastoralism for millennia.

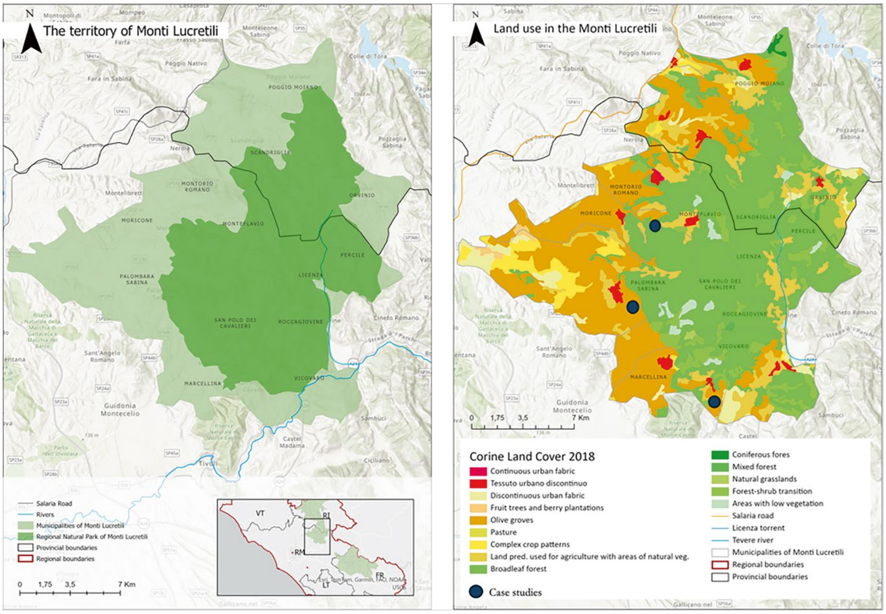


Fig. 17.9 Left: The territory of the Lucretili Mountains. Right: Corine Land Cover of Lucretili Mountains and case studies marked with black dots. Authors Sara Carallo and Francesco Atanasio Carolei

17.4.4 The Terraced Slopes

The most significant material signs of the relationship between local communities and the environment are represented by the terraced olive groves, which remain a distinctive feature of the Monti Lucretili landscape (Fig. 17.9). This practice has left evident tangible and intangible traces in the memory of the populations, as well as in the archaeological heritage and local toponyms, constituting a substantial immaterial wealth of great cultural value (Scaramellini & Trischitta, 2006; Agnoletti, 2011).

The terraced slopes, supported by dry stone walls, are largely disused today. These rural structures, locally known as "macère," are made from small-sized stone materials, primarily erratic or waste stones collected from the surrounding area. They are usually of limited height and, in addition to supporting terraces, are still used to delineate spaces and organize the land and resources available to local communities. They can define property boundaries, agricultural areas, enclosures for livestock, or paths. One example is the "cese" (as they are called in the local dialect), which are semi-circular enclosures designed to keep wild or domestic animals out of agricultural areas, thus protecting the crops (Bernardi & Farinetti, 2023) (Fig. 17.10).

In the study area, various types of structures can be found, constructed using different building techniques. Together with the diversity of the land, these create very distinct landscapes, ranging from terraced areas to flat steps extending over several

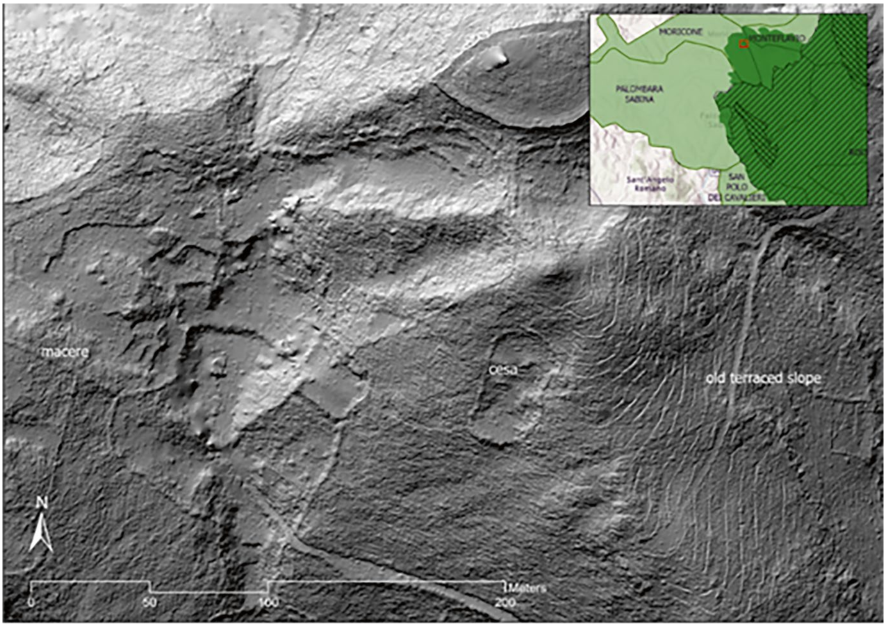


Fig. 17.10 LIDAR survey with a drone of the old, terraced area south of Monteflavio (south slope of Monte Calvario), now covered by forest vegetation. Author Federico Fasson

dozen meters (organized in altitudinal bands with pure row crops) to steep slopes with small crescent-shaped steps, where each plant is surrounded by a dry-stone wall.

The origins, chronologies, and functions of these terraces are still a topic of debate. The MoLuLaP archaeological project, following recent research lines, is conducting excavation tests and diagnostic sampling on "macère" that serve as terraces. The aim is to establish relative chronologies for these structures and to analyse soil sliding and accumulation processes. The periods of most intensive economic exploitation may have seen an increase in dry stone terraces on the slopes for agricultural and/or pastoral purposes, such as during the Roman Republic (third to first centuries BC) along the river valleys, or in the medieval period and the sixteenth to seventeenth centuries in the more inland areas (Bernardi, 2021; De Coste, 2024). The nineteenth century experienced intensive use of the mountainous land (with charcoal production, livestock farming, and the cultivation of fruit trees an olives), a trend that ultimately led to abandonment following the depopulation of these areas in the post-World War II period.

In the 1930s, deforestation efforts, followed by the construction of road infrastructures and land subdivision in the 1970s, led to significant damage and deterioration, and in some cases even the destruction of numerous dry-stone walls, particularly those located in the foothill areas (Parco dei Monti Lucretili, 2018). The risks associated with climate change for these structures are high, primarily due to the acceleration of karst processes, erosion, and landslides, likely resulting from intense rainfall events interspersed with long periods of elevated temperatures.

These selected zones are characterized by a rich archaeological heritage of significant historical and cultural interest, each telling different stories. In some areas, the terraces are now unused, while in others they continue to be actively used, representing a continuation of traditional agricultural practices and cultivation techniques (Fig. 17.10). These regions also showcase a variety of terracing types, as evidenced by the available historical cartography, which documents the evolution of the agricultural landscape over the centuries.

17.4.5 Some Preliminary Results of the Participatory Investigations

The bottom-up approach of the research, as we have seen, places the citizen at the centre of the process of data collection and interpretation, collectively represented by the local community and individually involved in the scientific dialogue of the ongoing research, even as a direct contributor of informational content. An online survey is being conducted via Google Forms to assess the social perception of anthropogenic environmental risk in the Monti Lucretili.

The survey, conducted through the administration of questionnaires, targets local residents and potential stakeholders. The questions focus on residents' awareness of the vulnerability of the landscape in their area, the impact of climate change on tangible and intangible cultural heritage, and their willingness to adopt direct measures to improve resilience.

The initial results of the ongoing survey reveal a significant natural degradation, exacerbated by the increasing depopulation that has led to the abandonment of lands and the loss of knowledge and skills related to traditional rural and agro-pastoral activities. This phenomenon is reflected in the instability of dry-stone walls, with widespread collapses, and could soon cause damage related to hydrogeological instability, triggering erosive processes and landslide phenomena that affect not only the mountain slopes but also the valley floor, already compromised by the climate crisis (ISPRA, 2021).

The main causes of environmental risk identified by the local population include both natural causes (fires, landslides, floods, and invasive vegetation) and anthropogenic origins (negligent management, abandonment, lack of maintenance, demographic decline and aging, loss of traditional knowledge, reforestation, and loss of agricultural land). In addition, there are the evident effects of climate change.

This investigation reveals clear evidence of an enhanced perception of risk among the populations of the Monti Lucretili. The majority of respondents express concern, accompanied by a sense of helplessness, along with a desire to deepen their understanding and feel more involved in efforts to address these risks. The collected responses also highlight significant awareness of the environmental and anthropogenic risks affecting the territory and the recognition of a strong link between exposure to risks and climate change. Furthermore, it is noteworthy that the vast majority of questionnaire participants report that they have been living a sustainable lifestyle for some time.

Understanding and knowledge of the population's perception of risk are of significant importance for effective management of dangerous situations and environmental threats. While quantitative analyses provide objective and measurable data, the social perception of risk reflects the emotions, fears, and concerns of the community. This perception can vary greatly among different social groups and influence their interaction with the territory and their reactions to risk events, both before and after such events (Wickes et al., 2015). A positive perception of the territory can motivate people to actively engage in its protection and enhancement, promoting sustainable behaviours and responsible management practices. Conversely, a negative or distorted perception of the territory can lead to choices that are harmful to the environment and the community (Geipel & Cesa Bianchi, 1980).

17.4.6 Best Practices

Thus, the ongoing investigation in the territory of the Monti Lucretili has revealed needs expressed by the local inhabitants themselves. Among the actions considered most urgent are the necessity to oversee and safeguard the rural territory, maintain riparian areas, and protect cultural heritage, ancient crafts, and local knowledge (of which, it should be noted, the dry-stone structures are an expression). The majority of participants in the meetings and interviews believe that it is essential to involve citizens in formulating strategies for the mitigation and prevention of environmental risks, while also expressing confidence in the work of experts in the field.

Regarding the monitoring of environmental and cultural heritage, many participants in the questionnaire and the participatory labs emphasize the lack of controls and sanctions as a critical point. Proposals include initiatives such as raising awareness starting from preschool, organizing conferences and events with industry experts, and paying particular attention to maintenance. The working group has initiated several initiatives in this direction. Among these, the involvement of schools in creating mental maps and community maps aimed at promoting territorial awareness and participatory inventorying of historical and cultural heritage. A documentary is also planned that will narrate the terraced landscape of the Monti Lucretili and its evolution over time, highlighting the connection between the environment, history, and local communities. The documentary will also showcase academic activities and field research conducted by the working group as part of the CHANGES project. Additionally, the 16th Seminar on Historical and Cartographic Studies "From the Map to GIS," which will take place in November 2024. Focused on "Settlement Systems, Spatial Analysis, and Local Knowledge: Interdisciplinary Pathways and Perspectives in Participatory Research", the seminar will provide an important opportunity for debate and reflection on best practices in participatory action research and citizen science.

Lastly, a workshop dedicated to the construction of dry-stone walls is scheduled for 2025, which will involve students, local skilled workers, qualified artisans, institutions, and local communities, thus promoting an intergenerational exchange of skills and knowledge.

17.4.7 Conclusions

The relationship between humans and the environment, as well as that between human communities and cultural heritage, can become sustainable and long-lasting if it is based on the values and identity memory of the community. When communities are aware of their heritage, they become capable of recognizing and enhancing their resources, better defining their needs and appreciating the value of the landscape. This approach generates responsible actions and greater care for the territory, along with openness and a high level of hospitality. Visitors or "temporary citizens," such as hikers, are also encouraged to actively participate and care for the place, enhancing commitment and sensitivity towards the preservation of heritage. In this context, rural dry-stone structures, such as the "macère", become tangible symbols of a cultural heritage to be preserved, not only for their historical value but also for their role in protecting the territory from environmental and anthropic threats.

References

Agnoletti, M., Santoro, A., Fiore, B., Piras, F., Romano, F., & Bazzurro, A. (2023). *Agricultural heritage systems in Europe, Asia, Africa, Central and South America*. Springer.

Agnoletti, M., Conti, L., Frezza, L., Monti, M., & Santoro, A. (2015). Features analysis of dry-stone walls of Tuscany (Italy). *Sustainability, 7*(10), 13887–13903.

Agnoletti, M. (2011). *Paesaggi rurali storici per un catalogo nazionale*. Laterza.

Baratti, F. (2012). *Ecomusei, paesaggi e comunità. Esperienze, progetti e ricerche nel Salento: Esperienze, progetti e ricerche nel Salento*. Franco Angeli.

Barbera, G., Culotta, S., Rossi-Doria, I., Ruhl, J., & Rossi Doria, B. (2009). *I paesaggi a Terrazze in Sicilia: metodologie per l'analisi, la tutela e la valorizzazione, Collana di Studi e dell'Agenzia Regionale per la Protezione dell'Ambiente V. 7*. Regione Sicilia.

Becattini, G. (2015). *La coscienza dei luoghi. Il territorio come soggetto corale*. Donzelli.

Belotti, S., Burini F., & Ghisalberti A. (2024). L'Università tra ricerca e co-progettazione: l'applicazione del modello a Tripla Elica allargata ai Gruppi di Azione Locale. *Geography Notebooks, 7(2)*. https://doi.org/10.7358/gn-2024-002-belo

Bernardi, M., Farinetti, E., & Santangeli Valenzani, R. (2024). *Archeologia nei Monti Lucretili. Nuove ricerche e prospettive di indagine in un paesaggio montano del Lazio* (Vol. 3160). BAR International Series.

Bernardi, M., & Farinetti, E. (2023). Monti Lucretili landscape project. Surveying an upland landscape around the Montefalco castle (2020–2022). *The Journal of Fasti Online, 20*, 1–24.

Bernardi, M. (2021). *L'incastellamento nei Monti Lucretili. Dinamiche insediative e paesaggio rurale tra alto e basso medioevo*. BAR.

Bonazza, A., Sardella, A., Kaiser, A., Cacciotti, R., De Nuntiis, P., Hanus, C., Maxwell, I., Drdácký, T., & Drdácký, M. (2021). Safeguarding cultural heritage from climate change related hydro-meteorological hazards in Central Europe. *International Journal of Disaster Risk Reduction, 63*, 102455. https://doi.org/10.1016/j.ijdrr.2021.102455

Brandolini, P., Cevasco, A., Capolongo, D., Pepe, G., Lovergine, F., & Del Monte, M. (2017). Response of terraced slopes to a very intense rainfall event and relationships with land abandonment: A case study from cinque Terre (Italy). *Land Degradation & Development*. https://doi.org/10.1002/ldr.2672

Burini, F., & Ghisalberti, A. (2020). Cartografia digitale tra partecipazione e rigenerazione urbana. In E. Boria (a cura di), *Gnosis* (n. 1, pp. 185–193).

Burini, F. (2016). *Cartografia partecipativa. Mapping per la governance ambientale e urbana*. FrancoAngeli.

Calanchi, N., Tranne, C. A., Lucchini, F., & Rossi, P. L. (1999). *Geological map of the Island of Panarea and Basiluzzo (Aeolian Islands)*. Repositories DST UniPI.

Calandra, L. (2018). "Il territorio dei miei sogni". Idee di turismo sostenibile tra ricerca e partecipazione nel territorio del Parco Nazionale del Gran Sasso Monti della Laga. *Documenti Geografici, 2*, 45–74.

Camera, C., Djuma, H., Bruggeman, A., Zoumides, C., Eliades, M., Charalambous, K., Abate, D., & Faka, M. (2018). Quantifying the effectiveness of mountain terraces on soil erosion protection with sediment traps and dry-stone wall laser scans. *Catena, 171*, 251–264, ISSN 0341-8162. https://doi.org/10.1016/j.catena.2018.07.017

Capolongo, D., Diodato, N., Mannaerts, C. M., Piccarreta, M., & Strobl, R. O. (2008). Analyzing temporal changes in climate erosivity using a simplified rainfall erosivity model in Basilicata (southern Italy). *Journal of Hydrology, 356*, 119–130.

Carallo, S., & De Pasquale, G. (2018). *AgriCulture. Tutela e valorizzazione del patrimonio rurale nel Lazio*. Roma TrE-Press.

De Angelis, G. (1995). *Monti Lucretili. Parco Regionale Naturale. Invito alla lettura del territorio*. Parco Regionale del Monti Lucretili.

De Coste. (2024). Per una lettura diacronica dell'insediamento nell'area dei Monti Lucretili. *Bernardi-Farinetti-Santangeli Valenzani*, 85–100.

Farinetti, E. (2012). *I paesaggi in archeologia: analisi....*

Farinetti, E. (2021). Exploring the interface between landscape archaeology and contemporary society. Back to community(-ies). *Journal of Public Archaeology Archeostorie* (on-line journal). https://archeostoriejpa.eu/2021_3a/

Farinetti, E. (2020). Voce 'Spazio'. *Atlante della Cultura Treccani*. Accessed July 30, 2022, from https://www.treccani.it/magazine/atlante/cultura/Spazio.html

Geipel, R., & Cesa Bianchi, M. (1980). *Ricerca geografica e percezione dell'ambiente. Unicopli, Milano.*

Gioia, D., Amodio, A. M., Maggio, A., & Sabia, C. A. (2021). Impact of land use changes on the erosion processes of a degraded rural landscape: An analysis based on high-resolution DEMs, historical images, and soil erosion models. *Land, 10*, 673.

Inter-ministerial Decree. (2020). *Safeguard of heroic and historical vineyards*. Decree n. 6899 of June 30, 2020.

ISPRA. (2021). *Rapporto Dissesto idrogeologico in Italia: pericolosità e indicatori di rischio*.

IPCC. (2023). Climate change 2023: Synthesis report. In H. Lee & J. Romero (Eds.), *Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change; Core writing team* (pp. 35–115). IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647

IPCC. (2013). Climate change 2013: The physical science basis. In T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P. M., & Midgley (Eds.), *Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* (1535p). Cambridge University Press.

Masetti, C. (2019). Cartografía histórica y gobierno territorial...

Masetti, C., & Spadafora, G. (2024). *Digital humanities, patrimonio culturale e applicazioni geostoriche*. LabGeo Caraci.

Minervino Amodio, A., Gioia, D., Danese, M., Masini, N., & Sabia, C. A. (2023). Land-use change effects on soil erosion: The case of Roman "via Herculia" (southern Italy)—Combining historical maps, aerial images and soil erosion model. *Sustainability, 15*, 9479. https://doi.org/10.3390/su15129479

Ministerial Decree. (2018). *Registration of the Rural Historic Landscape of Lamole in the National Register of Rural Landscapes of Historical Interest*. Ministry of Agriculture, Food, and Forestry Policies. Decree n. 6415 of February 20, 2018.

Mitasova, H., Hofierka, J., Zlocha, M., & Iverson, L. R. (1996). Modelling topographic potential for erosion and deposition using GIS. *International Journal of Geographical Information Systems, 10*, 629–641.

Nasta, P., Palladino, M., Ursino, N., Saracino, A., Sommella, A., & Romano, N. (2017). Assessing long-term impact of land-use change on hydrological ecosystem functions in a Mediterranean upland agro-forestry catchment. *Science of the Total Environment, 605*, 1070–1082. https://doi.org/10.1016/j.scitotenv.2017.06.008

Parco dei Monti Lucretili. (2018). *Dossier di candidatura al Registro dei Paesaggi Rurali terrazzati "Oliveti a terrazze e lunette dei Monti Lucretili"*. Ente Parco Monti Lucretili.

Parisi, E. I., Di Ciaccio, F., Masiero, A., Guarnieri, A., & Tucci, G. (2024). *Validation and error characterization in UAV-based thermal mapping*. Publication in progress in the 2024 IEEE Workshop on Metrology for Agriculture and Forestry (MetroAgriFor).

Parisi, E. I., Masiero, A., Tucci, G., Cortesi, I., & Mugnai, F. (2022). Thermal camera geometric self-calibration supported by RTK measurements. In *2022 IEEE Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)* (pp. 249–254).

Parisi, E. I., & Tyc, J. (2021). Multi-scale and multi-domain approaches for cultural terraced landscapes. In *Proceedings of the joint international event 9th ARQUEOLÓGICA 2.0 & 3rd GEORES, Valencia (Spain)*. 26–28 April 2021 (pp. 317–324). Editorial Universitat Politècnica de València.

Preti, F., Errico, A., Caruso, M., Dani, A., & Guastini, E. (2018). Dry-stone wall terrace monitoring and modelling. *Land Degradation & Development, 29*(6), 1806–1818.

Preti, F., Tarolli, P., Dani, A., Calligaro, S., & Prosdocimi, M. (2013). LiDAR derived high resolution topography: The next challenge for the analysis of terraces stability and vineyard soil erosion. *Journal of Agricultural Engineering, 44*, 85–89.

Renard KG, Foster GR, Weesies GA, McCool DK, Yoder DC (1997) Predicting soil erosion by water: A guide to conservation planning with the revised universal soil loss equation (RUSLE); United States Government Printing Office:.

Renard, K. G., & Foster, G. R. (1983). *Soil conservation: Principles of erosion by water*. American Society of Agronomy.

Sardella, A., Palazzi, E., Von Hardenberg, J., Del Grande, C., De Nuntiis, P., Sabbioni, C., & Bonazza, A. (2020). Risk mapping for the sustainable protection of cultural heritage in extreme changing environments. *Atmosphere, 11*, 700. https://doi.org/10.3390/atmos11070700

Scaramellini, G., & Trischitta, D. (2006). Paesaggi terrazzati. *Geotema, 29*, Bologna.

Tarolli, P., Preti, F., & Romano, N. (2014). Terraced landscapes: From an old best practice to a potential hazard for soil degradation due to land abandonment. *Anthropocene, 6*, 10–25.

Tucci, G., Parisi, E. I., Castelli, G., Errico, A., Corongiu, M., Sona, G., & Preti, F. (2019). Multisensor UAV application for thermal analysis on a dry-stone terraced vineyard in rural Tuscany landscape. *ISPRS International Journal of Geo-Information, 8*(2), 87.

Tyc, J., Parisi, E. I., Tucci, G., Hensel, D. S., & Hensel, M. U. (2022). A data-integrated and performance-oriented parametric design process for terraced vineyards. *Journal of Digital Landscape Architecture, 7*, 504–521.

UNESCO. (2018a). *Art of dry stone walling, knowledge and techniques*. Available online: https://ich.unesco.org/en/RL/art-ofdry-stone-walling-knowledge-and-techniques-01393

UNESCO. (2018b). *Decision of the Intergovernmental Committee: 13.COM 10.B.10 for inscription on the Representative List of the Intangible Cultural Heritage of Humanity of "Art of dry-stone walling, knowledge and techniques"*.

Wickes, R., Zahnow, R., Taylor, M., & Piquero, A. R. (2015). Neighborhood Structure, Social Capital, and Community Resilience: Longitudinal Evidence from the 2011 Brisbane Flood Disaster*. *Social Science Quarterly, 96, 330–353.* https://doi.org/10.1111/ssqu.12144

Wischmeier, W. H., & Smith, D. D. (1978). *Predicting rainfall erosion losses: A guide to conservation planning*. USDA, 58p.

Chapter 18
Seismic Retrofitting of Architectural Heritage: Experimental Validation of New Technologies

G. de Felice and S. De Santis

Abstract The combination of the development of new materials for the structural upgrade of historical architectural heritage and full-scale experimentation is one of the keys to technological progress and the transfer from scientific research to engineering practice. In the field of seismic protection of architectural heritage, the possibility of reproducing full-scale constructions in the laboratory and subjecting them to shaking table simulations is an exceptional opportunity for research. This chapter presents two experimental campaigns aimed at evaluating the contribution of new systems for the seismic reinforcement of historic masonry buildings. The technologies under experimentation are: (i) reinforced plaster with fiberglass mesh (Composite Reinforced Mortar, CRM) applied to the outer face of masonry only; (ii) restoration of the transversal connection of fair-face stone walls using carbon fibre connectors; and (iii) seismic upgrade by a combined intervention of reinforced plaster with fiberglass mesh on the inside and repointing of the mortar joints of the outer face with stainless steel cords. The research took advantage of the cooperation with some Italian companies recognized among the most active in the field of technologies for cultural heritage and of the participation of the ENEA Casaccia Research Centre where the seismic simulations were carried out. The research had the financial support of the extended Changes partnership, spoke 7, as well as the contribution of research projects funded by the Lazio Region and the Civil Protection, but above all it was possible thanks to the passionate participation of the Structures research group of the Department of Civil, Computer and Aeronautical Engineering of Roma Tre University.

G. de Felice (✉) · S. De Santis
Department of Civil Engineering Computer Science and Aeronautical Technologies, Roma Tre University, Rome, Italy
e-mail: gianmarco.defelice@uniroma3.it; stefano.desantis@uniroma3.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_18

Keywords Seismic vulnerability · Historic masonry · Retrofitting · Shake table test · Central Italy earthquake · Composite reinforced mortar

18.1 Introduction

The European building stock is largely made up of ordinary masonry structures. These constructions were built based on empirical rules, the result of an ancient knowledge that goes by the name of rule of art, which in each place acquired its peculiar characteristics according to the availability of materials and the skills of the masons. Over time, they have undergone the transformations and modifications that use had required, with the creation of wall openings, replacement of floors, elevations and, in some cases, actual tampering. The numerous seismic events that have affected southern Europe have highlighted the vulnerabilities of these buildings, which, despite the variety of construction characteristics, are damaged in recurring ways that can be classified according to three modes of collapse in descending order of importance: (i) masonry disintegration, (ii) out of plane wall overturning, and (iii) diagonal cracking. In the first case, the masonry walls, weakened by the weight of elevations, complicit in imperfect construction and the progressive deterioration of mortar, collapse, disintegrating dramatically; the outer face, because of seismic actions, detaches from the masonry core, sometimes simply consisting of irregular rubble stones arranged to fill the inner wall space between the two external leaves. This is the most dangerous mode of collapse, found in poorly made rubble stone walls. In the second case, the perimeter walls, because of the earthquake oscillations and the lack of seismic restraining elements, detach from the rest of the wall body and collapse by out of plane overturning. Sometimes the mechanism involves the entire facade, whilst other times, only the top part, depending on the quality of the connections between the walls, the presence of ties that constrain their motion or of pushing roof trusses that favour it. The last mode of seismic damage is due to in-plane actions, which stress masonry in compression and bending and shear. The most stressed walls form the diaphragms resistant to seismic action, where severe shear cracks open, such that their capacity for even vertical loads is compromised (de Felice et al., 2017; Sorrentino et al., 2018; Vlachakis et al., 2020). The severe damage to masonry buildings and the numerous collapses that have occurred have provided a strong impetus for the development of new technologies and the use of new materials for post-earthquake repair and seismic risk mitigation of existing buildings.

In this panorama, the use of composite materials applied to masonry by means of inorganic matrices, mortars like those commonly used for plasters, has gradually taken hold in the last decade. These systems are called CRM (Composite Reinforced Mortar) or FRCM (Fabric Reinforced Cementitious Matrix). Thanks to the high strength of the fabrics, CRM and FRCM provide the masonry with the ability to resist tensile stress, limit the phenomena of disintegration and detachment of the stones of the face, counteract the onset of cracking and the triggering of collapse mechanisms with the consequent increase in out-of-plane bending capacity (Gattesco & Boem, 2017; De Santis et al., 2019) and shear strength in the plane of the wall (Gattesco et al., 2015). Their thickness is small, such that it does not produce a significant increase in masses and therefore does not change the dynamic response of the structure, with the possibility of being integrated in extraordinary maintenance works of facades. Systems referred to as CRM make use of precured FRP meshes, while those referred to as FRCM employ dry fabrics. CRM have a larger mesh spacing (30 ÷ 50 mm), FRCM a narrower spacing (6 ÷ 25 mm); the overall application thickness varies from 30 ÷ 50 mm for CRM systems to 8 ÷ 15 mm in FRCM systems (Gattesco & Boem, 2017). Thanks to the impregnation with epoxy resin, the meshes are durable in an alkaline environment, even when composed of glass fibers, and this allows application with lime-based structural mortars, with an overall benefit in terms of compatibility with the substrate and the possibility of applying traditional plasters on top. CRM systems require the insertion of connectors to ensure the connection between the reinforcement and the masonry substrate and a better response to disintegration phenomena. In FRCM systems, where the matrix is certified jointly with the reinforcing mesh and the qualification process includes FRCM-to-substrate bond tests, connectors can be omitted since it is the matrix that ensures the transfer of stresses between the mesh and the masonry.

The development of technologies for the upgrade of fair-faced stone masonry walls is more complex, since the aforementioned systems can be installed only on the inner face, but the vulnerability of the outer face remains, especially in the presence of irregular stones lacking adequate bearings or in the presence of decohesive mortars lacking the original bonding capacity (D'Ayala & Paganoni, 2011; Sorrentino et al., 2018; Vlachakis et al., 2020). For these walls, the primary objective to be achieved is to restore their monolithic response and prevent the ruinous collapse mechanisms by disintegration and leaf separation. Since the fair-face aspect needs to be preserved, it is necessary to develop less invasive, but equally effective, technologies to ensure the monolithicity of the masonry.

This chapter describes two experimental campaigns aimed at investigating the effectiveness of the technologies by prototyping full-scale masonry structures designed to reproduce existing building types as closely as possible and subjected to seismic simulations on a shaking table under a sequence of accelerograms with gradually increasing intensity until collapse.

The first experimental campaign deals with the use of CRM applied on the outer walls only. The experimentation was conducted on a structure made of tuff blocks and composed of a facade (with a window), two side walls (one of them with a door near the corner) and a sloping wooden roof. The prototype, not yet reinforced, was subjected to a seismic sequence until the onset of collapse kinematics and then repaired and reinforced with the CRM system called *Fibre Net RiStruttura*. The application was designed to minimize the impact of reinforcement by limiting it to the walls that had exhibited damage and to the outer surface only, leaving the interior side undisturbed, to simulate an intervention that would not require the evacuation of the building. The comparison of the seismic behaviour of the sample before and after the intervention shows how the damage progression and failure mode is modified, how the dynamic properties of the structure change both as a result of the progressive damage and as a consequence of the applied reinforcement, and allows to evaluate the effects of the seismic upgrade technology in terms of increased capacity in acceleration and displacement, with the consequent effects on the design criteria.

The second experimental campaign is related to the development of compatible low-impact technologies for the seismic upgrade of fair-face stone masonry walls. The experimentation involved three prototypes of full-scale irregular stone masonry walls, the first one unreinforced and the other two ones reinforced with the proposed technologies. In order to replicate the materials and stresses experienced by buildings in central Italy affected by the earthquake, the stones were recovered from the rubbles of a hamlet that collapsed with the seismic events, the mortar was reproduced based on samples collected in the area, and the walls were built according to the typical construction practice of the region and subjected to three recordings of the 2016–2017 seismic sequence. The first prototype was tested in the absence of reinforcement until collapse to reproduce the typical conditions of stone building in the Apennines, the other two prototypes were reinforced with two different technologies. The first one, already proposed in the past (Borri et al., 2014; Corradi et al., 2016), called *Fibre Net Reticola plus*, consists in the reinforced repointing of the mortar joints of the wall face by means of stainless-steel cords connected by means of threaded rods to the thermal insulating plaster reinforced with glass fibre mesh (CRM) on the inner side. The second technology, developed by the proponents, consists of the use of transverse connectors that connect the two wall leaves by blocking the stone elements of the outer face to the masonry body. In the present case, carbon fibre-reinforced polymer (CFRP) connectors were developed that were inserted by drilling into the stone elements of the external face without perforating the entire thickness of the wall, so as not to affect the inner surface. Both techniques are designed to counteract the separation of the two masonry faces and provide a constraint suitable to prevent the disintegration of the wall, while preserving the architectural features of the fair-face masonry.

18.2 Shaking Table Tests on a CRM-Reinforced Tuff Masonry Prototype

18.2.1 Prototype Characteristics and Experimental Setup

The prototype (Fig. 18.1) consists of a front wall 3.30 m wide and two side walls 2.55 m long (right and left). The walls are 3.41 m high and 0.25 m thick and were built with 370 mm 250 mm 110 mm tuff blocks with compressive strength of 6 N/mm^2 and Young's modulus of 1575 N/mm^2 and a premixed lime-based mortar. The self-weight of the masonry is 12.6 kN/m^3. The front wall has a window 1.45 m high and 0.80 m wide. The left wall has a door 2.20 m high and 0.80 m wide near the

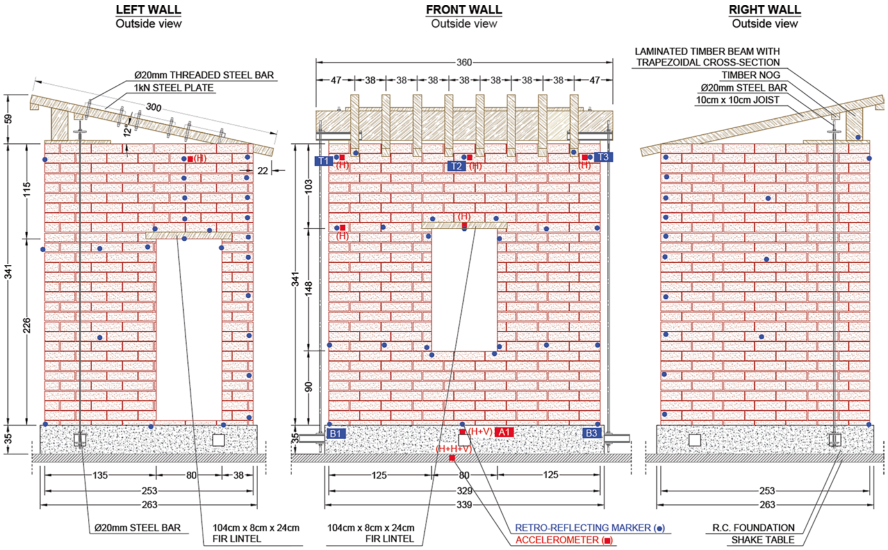


Fig. 18.1 Prototype characteristics and experimental setup

corner. The lintels of the holes are made of wood elements. The wall structure is covered by a 12° sloping roof consisting of eight 10 × 10 cm fir joists. On the back side, the rafters are simply supported by a timber beam. On the front side, the joists are embedded on the top of the wall. The wooden frames support 12 steel plates weighing 1 kN each, for an ultimate load of about 1.8 kN/m^2. The specimen was built on a reinforced concrete foundation, which was necessary to move the specimen and attach it to the shaking table. The total weight of the specimen is 135 kN.

The tests were carried out in Rome at the ENEA Casaccia Research Centre on a 4 m × 4 m shaking table with 6 degrees of freedom. Eight accelerometers were used to record accelerations (Fig. 18.1). A triaxial accelerometer was placed on the shaking table to record the three components. A biaxial accelerometer (named A1 in Fig. 18.1) was attached to the foundation to measure the vertical and horizontal components of the seismic input. Finally, five accelerometers were placed on the front wall and one on the left wall. A system called *3DVision*, capable of recording the displacement of 70 spherical reflective markers placed on the specimen by 9 digital near-infrared cameras, was used to acquire displacement data (Fig. 18.1).

18.2.2 Seismic Inputs

Considering the sensitivity of the seismic response to the input characteristics, to evaluate its effects, four natural accelerograms, recorded by the Italian National Accelerometric Network (RAN), were selected, namely MRN for Mirandola (2012 Emilia earthquake), NRC for Norcia (2016 Amatrice earthquake), NCR for Nocera

Umbra (1997 Umbria-Marche earthquake), and AQV for L'Aquila (2009 L'Aquila earthquake) (Table 18.1). The records were sorted according to their horizontal PGA and applied with a scaling factor (SF), starting from SF = 0.2. Before and after each set of four tests with the same SF, tests were performed with white noise input (WHN).

18.3 Reinforcement with CRM Technology

18.3.1 Seismic Improvement Criteria

The seismic reinforcement technology (Fig. 18.2) was designed to achieve the following objectives:

- counteracting the collapse mechanism of the unreinforced specimen and shifting the failure mode to other mechanisms associated with higher dissipation and seismic capacity, with emphasis on ensuring the connection between the walls at the corner;
- improve out-of-plane front wall flexural capacity and shear capacity;
- reinforce the arrangement of the wall, where there is a thrust of the roof beams on the masonry;
- reduce, as much as possible, the impact to building occupants induced by installation by working only from the outside and restricting the intervention to damaged walls only;
- ensure compatibility with the substrate by using natural hydraulic lime mortars;

Table 18.1 Accelerograms used in shaking table tests and nominal intensity measurements for SF = 1

			Event	PGA[b]	PGV[b]	PGD[b]	HI[c]
Signal	Site	Soil[a]	Date and time	H; V (g)	H; V (cm/s)	H; V (cm)	H; V (cm)
MRN	Mirandola (MO)	C	2012-05-20, 02:03	0.262; 0.303	29.9; 5.9	8.27; 1.87	101.3; 20.2
NRC	Norcia (PG)	B	2016-08-24, 01:36	0.374; 0.215	23.7; 11.6	6.62; 3.04	79.0; 34.8
NCR	Nocera umbra (PG)	E	1997-09-26, 09:40	0.502; 0.406	32.6; 21.2	2.61; 2.74	73.2; 55.6
AQV	L'Aquila (AQ)	B	2009-04-06, 01:32	0.657; 0.496	40.2; 12.4	6.79; 2.45	131.5; 41.2
WHN	White noise	–	–	0.050; 0.000	3.5; 0.0	0.40; 0.00	16.7; 0.0

[a] Soil type according to (EC8-1)

[b] PGA, PGV, PGD: acceleration, velocity and peak displacement

[c] HI: Housner's Intensity

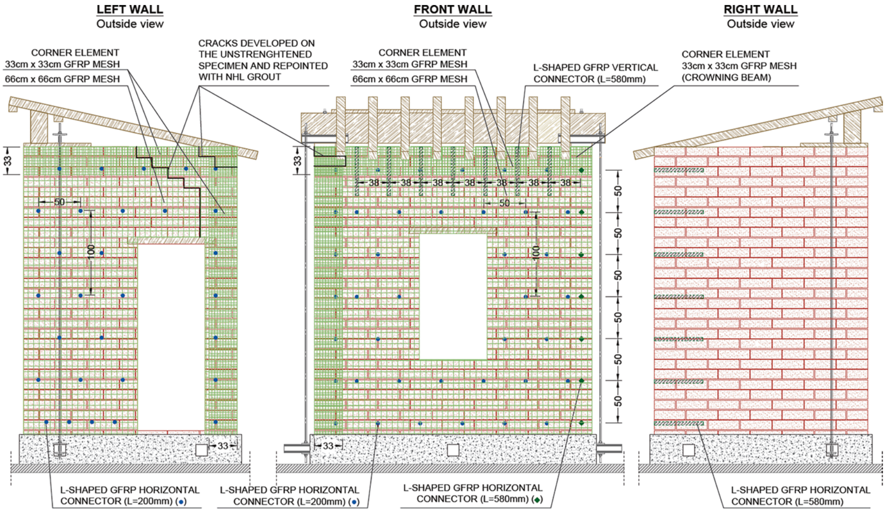


Fig. 18.2 Seismic reinforcement applied to the prototype

- ensure adequate durability of the mesh against the aggression of mortars (which are highly alkaline) and the environment;
- contain the time and cost of consolidation work through low-cost products and quick and easy installation operations.

18.3.2 Technologies and Materials

The reinforcement system, called Fibre Net RiStruttura, consists of the following elements:

- glass fiber-reinforced polymer (GFRP) mesh, composed of alkali-resistant glass fibers impregnated within an epoxy resin, with a fiber/resin weight ratio of 6.5:3.5, 66 mm spacing, and surface mass density of 420 g/m^2 (from data sheet-Fibre Net FBMESH66X66T96AR). Each fiber bundle has cross-sectional area 11.6 mm^2 (weft) and 8.9 mm^2 (warp), tensile strength 490 N/mm^2, ultimate strain 1.8% and tensile modulus of elasticity 25 kN/mm^2 (average values). Mesh is supplied in 2-m wide rolls and cut to size with bolt cutters on site;
- corner elements made of GFRP mesh, folded and then impregnated, consisting of two 330 mm long sides at a 90° angle;
- GFRP L-connectors with a cross section of 10 × 7 mm, short side 100 mm and long side 200 mm or 580 mm. The short connectors are grouted into the masonry and are part of the CRM system to ensure the connection of the web with the substrate. The long connectors were inserted in perforations at the two corners to improve the connection between orthogonal walls, and at the top of the façade

between the crowning beam and the masonry. Both connectors have tensile strength 443 N/mm^2, ultimate strain 1.7% and tensile elastic modulus 25 kN/mm^2 (average values);
- 33-mm spaced GFRP mesh handkerchiefs, measuring 150 mm × 150 mm;
- M10 premixed mortar with natural hydraulic lime used as the matrix of the CRM system;
- fast-curing, low-shrinkage vinylester resin for grouting connectors into masonry.

18.3.3 Methods of Application

Below is the sequence of seismic repair and strengthening work:

- Repair. The cracks were repaired with a fast-curing natural hydraulic lime (NHL) fluid-based mortar (Fig. 18.3);
- Preparation of the substrate. Drilling of the holes (7 horizontal holes of 12 mm section and 580 mm length on the right corner to ensure the connection with the cross wall, and 7 vertical holes on the masonry top to fix the roof joists; 50 holes of 12 mm section and 200 mm depth on the front wall (27 holes) and on the left wall (23 holes) for the affixing of the GFRP connectors of the CRM system in the number of 3/m^2). Subsequent fleshing of the mortar joints of the outer face in order to increase the roughness of the wall surface and improve the adhesion of the CRM;

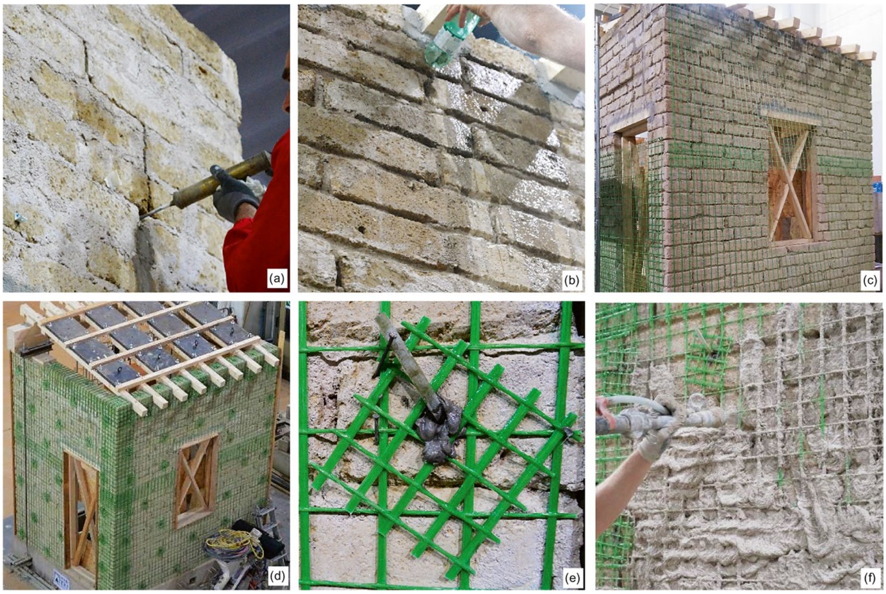


Fig. 18.3 Installation of the reinforcement

- Installation of GFRP mesh. GFRP mesh was placed on the front and left walls from above, taking care to ensure an overlap of at least 300 mm between different strips;
- laying the GFRP corner elements in the drilled holes;
- installation of GFRP L-connectors installed in the holes and injected with epoxy resin, after affixing a 33-mm mesh patch to thicken the GFRP mesh at the connectors;
- spray application of mortar to form the CRM system for a total thickness of about 30 mm. Note that the surface of the right wall was not covered by reinforced plaster.

18.4 Results of Seismic Simulations

18.4.1 Unreinforced Prototype: Damage Distribution and Collapse Mode

In the seismic sequence applied to the unreinforced prototype, the series of tests with SF = 0.2 and SF = 0.4 and three of the four inputs in the series with SF = 0.6 were completed, Prior to the NCR06 input, no damage had been detected on the prototype except for some small cracks along some mortar joints. With the NRC06 signal, a pass-through crack opened above the door lintel, which mainly developed along the mortar joints (Fig. 18.4). The width measured after the test was 15 mm. A smaller crack also appeared at the top of the facade, between the left corner and the first joist, while the rest of the prototype did not suffer any damage. The mode of rupture that occurred, consisting of a severe detachment lesion near the corner, is typical of unreinforced masonry structures and, in the present case, can be attributed to the presence of an opening near the corner that weakens the connection between the orthogonal walls and to the effect of the roof.

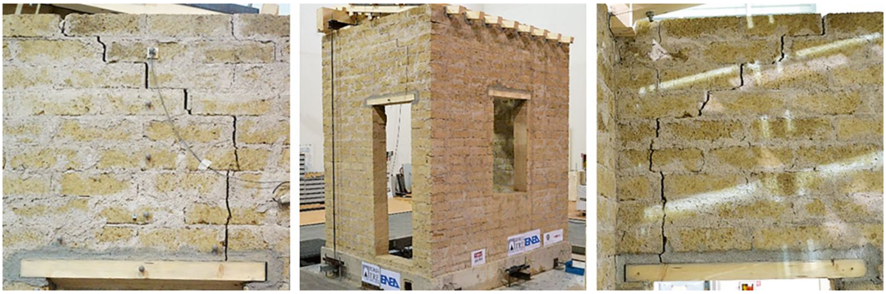


Fig. 18.4 Cracking mode of the unreinforced specimen following seismic input NRC06

18.4.2 Unreinforced Prototype: Capacity Curves and Dynamic Properties

The seismic response of the unreinforced prototype is depicted in terms of relative acceleration-displacement curves in Fig. 18.5, for each of the four accelerograms. The response (red lines) is nearly linear to rupture, with the only exception of the relative displacement on the left side under the NCR06 input, where the opening of the crack above the door lintel occurred, for a maximum acceleration at the base of 0.41 g.

Experimental Multi-Input/Multi-Output (MIMO) modal analysis (Phillips & Allemang, 2003) allowed estimating the main frequency of the prototype in the direction normal to the facade, as shown in Fig. 18.6, before and after reinforcement. As for the unreinforced specimen (red line), its initial frequency (undamaged state) was 7.5 ÷ 8 Hz and gradually decreased to 4.5 ÷ 5 Hz due to the accumulation

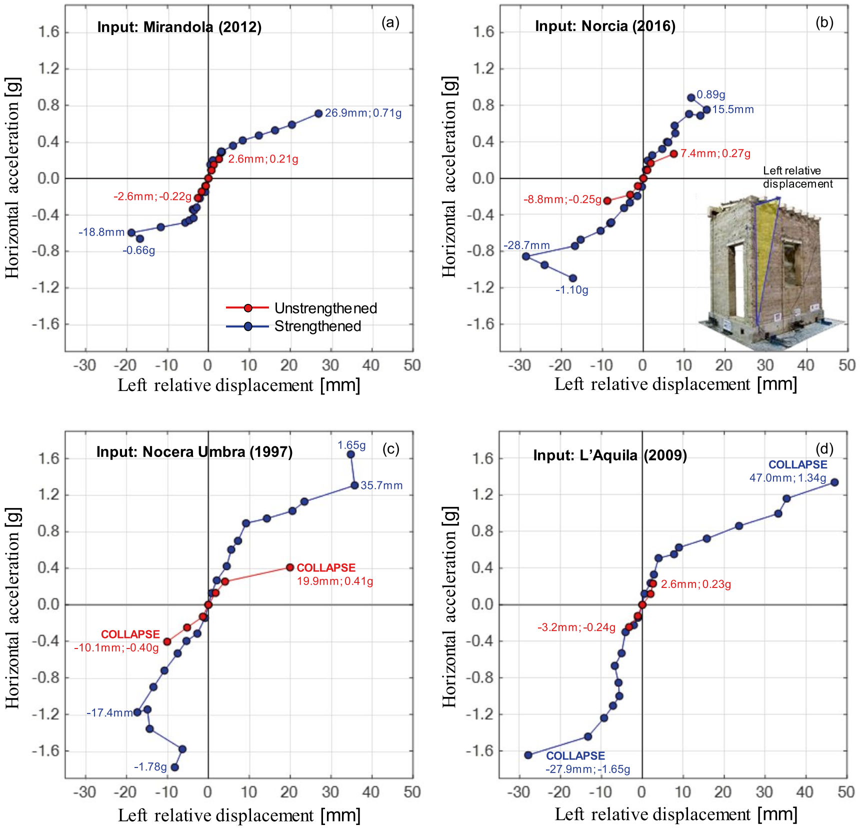


Fig. 18.5 Seismic capacity curves before and after reinforcement application: vertical bending

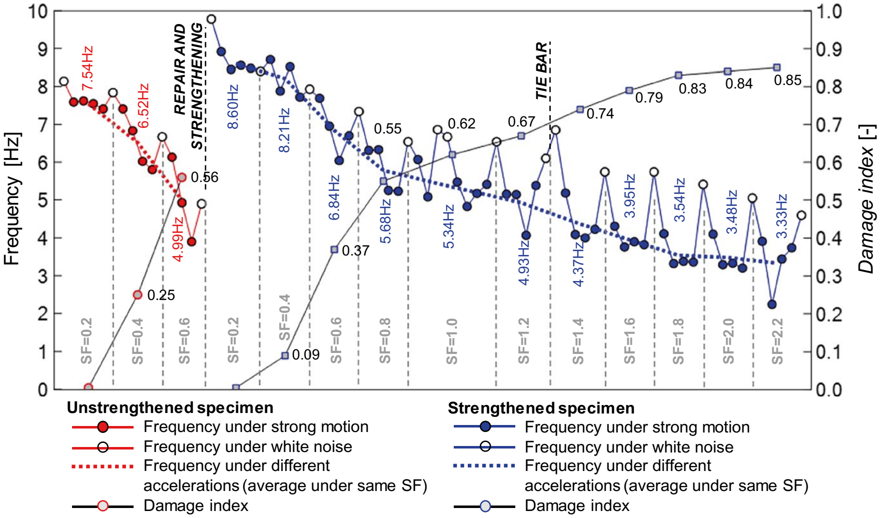


Fig. 18.6 Frequency of the prototype before and after reinforcement application and damage index

of damage. The white markers represent the WHN tests, for which a higher frequency was found than for the tests with strong motion input (red markers) due to the lower amplitude of displacements. The average value of the frequency obtained under different records was calculated for each set of strong motion tests with the same SF to account for the influence of the input on dynamic identification. The average frequency detected as the amplitude of seismic input increases is 7.54 Hz (SF = 0.2), 6.52 Hz (SF = 0.4), 4.99 Hz (SF = 0.6).

18.4.3 Damage and Collapse Mode

The reinforced prototype underwent a total of 46 seismic simulations and 15 white noise tests, which took 2 days. The tests performed in the previous session were repeated to compare the results before and after the seismic improvement intervention. In this case, no damage occurred in the series with SF = 0.2 and SF = 0.4, while an initial crack formed on the right wall (the unreinforced one), near the corner with the front wall, in the NCR06 simulation (a_{max} = 0.42 g). This crack gradually widened and extended. The first day of testing ended with NRC10. The cracking condition at the end of this testing session affected the right wall with diagonal cracks passing in a staircase pattern along the mortar joints (Fig. 18.7), while the front and left walls did not exhibit any damage. During the series of tests with SF = 1.2 (a_{max} = 0.90 g - NRC12), the cracks on the right wall further widened and extended, resulting in increased displacement of the upper right corner of the façade. Some cracks also formed on the inner side of the façade, mainly along the mortar joints. For the continuation of the seismic simulations, a steel bar was installed to tie the right lateral top of the facade to the transverse wall (Fig. 18.7a). The sequence of tests was then continued with SF = 1.4, 1.6 and 1.8. After AQV18, the further aggravation crack pattern on the right wall and the fall of two tuff blocks required tie tightening. Some cracks developed on the facade from the upper corners of the window toward the top corners of the wall, due to out-of-plane bending. The tuff blocks on the inner side of the facade also had cracks. Simulations were continued with SF = 2.0 and 2.2 until collapse.

The maximum acceleration recorded at the base was a_{max} = 1.78 g (NCR22). The nominal collapse condition was reached in the AQV22 sequence (a_{max} = 1.65 g) due to the failure of the left corner of the façade (Fig. 18.7): the GFRP mesh detached from the substrate and the corner element opened, compromising the connection with the side wall. On the other hand, the reinforcing meshes did not fail, nor were any breaks or sliding of the connectors from the masonry detected. The inner side of the facade was severely cracked (Fig. 18.7f), some of the tuff blocks having fallen

Fig. 18.7 Damage of the reinforced prototype after NCR22 (a_{max} = 1.78 g)

or detached (Fig. 18.7). On the right wall, pre-existing injuries had further aggravated (Fig. 18.7h). The crowning beam made of corner elements was not damaged, despite the severity of the seismic action, nor were cracks detected in the CRM plaster of the left wall, with the exception of a horizontal through lesion at the base of the wall, on the first mortar joint, with a strong sliding of the wall on the foundation of about 115 mm (Fig. 18.7) (note that no connectors were installed between the walls and the foundation).

18.4.4 Reinforced Prototype: Capacity Curves and Dynamic Properties

The response curves plotted in Fig. 18.5 show the increase in seismic capacity in terms of base acceleration and displacement. In terms of acceleration, the seismic repair and improvement work resulted in a 355% increase in capacity (a_{max} = 1.78 g vs. 0.41 g). The ultimate limit state condition was reached at the end of the test sequence with the records scaled by a factor of 220%. Also, it should be considered that the reinforced structure was subjected to a very long sequence of shaking table tests that caused progressive damage, so the maximum acceleration reached in the final stage may also underestimate the actual capacity. As for displacement, for most of the simulations, these were reversible, and only in the final stages of the experimental campaign crack opening and sliding of tuff blocks occurred locally. The increase in maximum displacement was more evident in horizontal out-of-plane bending (with a relative displacement dH = 50.1 mm vs. 5.8 mm, +762%, Fig. 18.8) than in vertical bending (dVL = 47.0 mm vs. 19.9 mm, +135%). The installation of the tie bar, as expected, drastically reduced the relative displacement on the right side.

In terms of frequency, the seismic repair and upgrade work resulted in an increase in frequency from 5 Hz (end of the first test session) to 8.5 ÷ 9 Hz, as a combined result of repairing the damage and installing the CRM (Fig. 18.8). The frequency of the structure after the application of the CRM, however, is only slightly higher than that of the undamaged prototype (7.5 ÷ 8 Hz), which allows to assert that the CRM system by itself does not produce a significant increase in the stiffness of the structure and does not induce a significant change in its dynamic properties. During seismic simulations of the reinforced prototype, damage developed more slowly than on the unreinforced specimen. The average frequency after the series of simulations with SF = 0.6 was 6.84 Hz for the reinforced prototype and 4.99 Hz for the unreinforced one. A damage level comparable to that at the end of the tests on the unreinforced structure was reached after the series with SF = 1.0 (f_{av} = 5.34 Hz), while the frequency after the entire sequence of simulations with SF = 2.2 was f_{av} = 3.33 Hz.

The deformed configurations of the prototype show that, in the similarity of the response, the CRM system gives the structure a box-like behaviour, with a

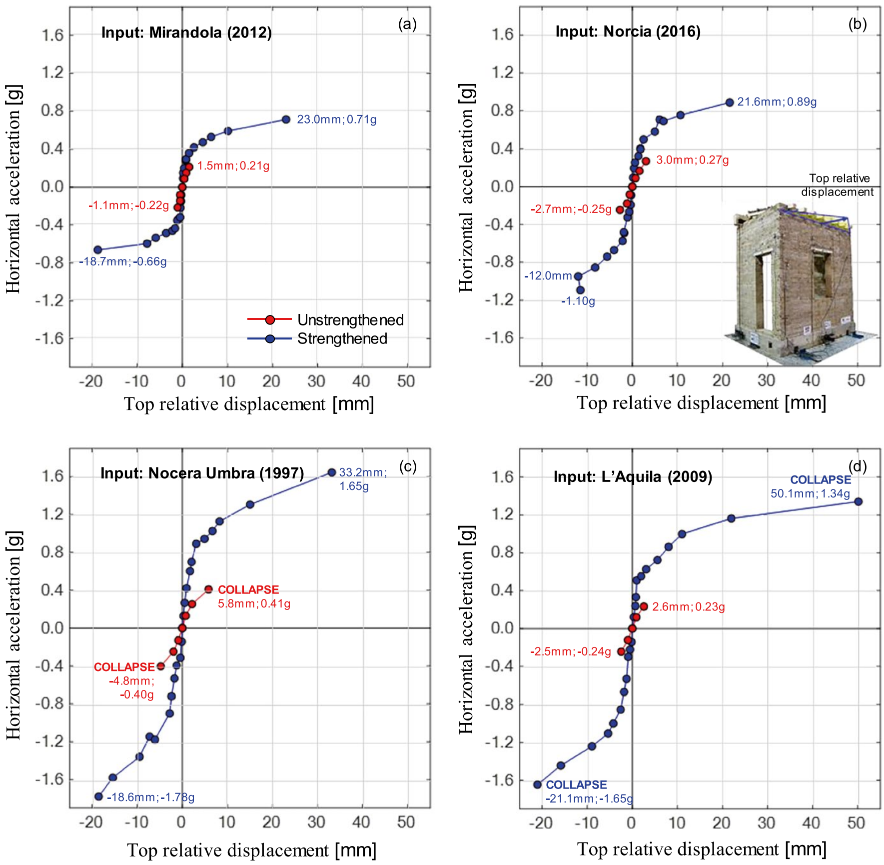


Fig. 18.8 Seismic capacity curves before and after the application of reinforcement: horizontal bending

significant reduction in out-of-plane displacements of the side walls and torsional rotation of the structure.

18.4.5 Summary of Experimental Results and Impact on Design

The experimentation conducted on a full-scale masonry prototype built with tuff blocks and consisting of three walls and a wooden roof and subjected to seismic simulations on a shaking table before and after the application of a reinforced plaster by means of Fibre Net RiStruttura CRM system allowed to verify and quantify the effectiveness of the CRM system for the seismic protection of existing structures as detailed below:

- the collapse mechanism of the unreinforced prototype (a local out-of-plane mechanism with the opening of a through crack near the corner between the façade and one of the side walls) was effectively counteracted by the CRM, partly due to the contribution of the angle meshes and GFRP L-connectors arranged at the angle and at the top;
- the application of the CRM system increased the seismic capacity of the structure by raising the acceleration at the base from 0.41 g to 0.89 g, shifting the collapse mode from the detachment of the facade to the shear failure of the wall without holes and not reinforced with CRM;
- further consolidation of the wall without reinforced plaster by installing a steel chain led to a further increase in the capacity of the retrofitted structure, up to a maximum acceleration at the base of 1.78 g (+335% compared to the unreinforced specimen);
- the application of the CRM system to the outer face only showed its full effectiveness in increasing the shear strength of the walls (by shifting the shear failure to the unreinforced solid wall instead of the one biased by the door but provided with reinforcement) and in inhibiting out-of-plane bending mechanisms, with a significant increase in the displacement capacity to horizontal bending;
- the application of the CRM system significantly increased the dissipation capacity of the structure due to matrix cracking and sliding of the reinforcing mesh, with no disconnection between reinforcement and masonry substrate, with the appearance of cracking on the outer plastered surface wide but diffuse and with the absence of significant cracks. Since this was an application to the outer face only, as seismic acceleration increased (for peak values greater than 1 g), cracking and crushing of the tuff blocks combined with the opening and creep of the mortar joints appeared on the inner surface without CRM, but without the detachment and collapse of the inner face.
- In relation to what was observed in the experiments, it can be concluded that:
- the CRM system represents a solution that can ensure seismic upgrade of existing structures, which can be integrated into extraordinary maintenance works of facades as a replacement for a traditional plaster, without significant increase in thickness and with the adoption of matrices based on hydraulic lime, with excellent durability performance thanks to the protection of reinforcement fabrics within an epoxy matrix, which can protect the reinforcement from the alkaline environment generated by the matrix or external agents;
- installation on the outer surface of walls only, which, in principle, does not require clearing the building (if reinforcement work can be limited to the perimeter walls) can be a feasible, low-cost, and systematic solution for seismic improvement work on existing masonry structures.

Of course, the experimental results obtained in the present experimental campaign cannot be generalized to different masonry types, especially irregular and multi-leaf masonry, where application to a single face may not be satisfactory in preventing the phenomena of wall disintegration. Likewise, the generalized application of the CRM system, in the absence of appropriate design of connection devices and structural details (shaped mesh elements at corners, FRP connectors, fabric grid spacing, and mechanical properties of the matrix) may not be fully effective without appropriate reference to the geometric and mechanical characteristics of the building structure.

Overall, the results of this experimental campaign show the great potential of the Fibre Net RiStruttura CRM system, which is a viable technology for combining effectiveness and sustainability in seismic upgrades of existing masonry structures.

18.5 Experimental Investigation on Fair-Face Stone Walls

18.5.1 Prototype Characteristics and Experimental Setup

The present experimental campaign stems from the dramatic seismic events in central Italy in 2016, which highlighted the great vulnerability of fair-face masonry constructions due to leaf separation and wall disintegration. It was therefore necessary to reproduce as faithfully as possible the construction practice of stone buildings in the Apennines, and therefore the design of the experiments started from a careful survey of the original masonry types. The prototypes to be tested on a shaking table were constructed with stones from buildings in a hamlet of Accumoli that collapsed as a result of the earthquake and with a lime mortar formulated to have the same characteristics (lime/sand ratio 1/9, maximum grain size 2 mm) as the samples collected in situ. The construction methods of the prototypes followed local practice with two separate leaves, a central core with smaller stone elements and voids, in the absence of headers. The walls were built on a reinforced concrete foundation beam. The wall top, which in the test setup is arranged in contrast to the rollers of a steel frame, was reinforced to prevent the occurrence of local damage phenomena with the same stones of the underlying masonry laid with premixed mortar based on hydraulic lime of good strength and a glass fibre reinforced polymer (GFRP) mesh embedded in each of the three bed joints. Three prototypes with the same geometric and mechanical characteristics were built: 500 mm thickness, not dissimilar to the average thickness found in the historic centres of Central Italy; 1630 mm width, sufficient to ensure the longitudinal stability of the prototypes; and 3730 mm height, in order to have a height/thickness ratio of about 7.5, similar to the existing buildings. To replicate the architectural features of historic villages, the front side of the walls was built of fair-face brickwork, while the back side finished with 30 mm thick plaster. A first prototype (named UR) was subjected to seismic simulation without reinforcement, while the other two samples were reinforced through new seismic protection technologies. The first technology, called CC, consists of the insertion of CFRP transverse connectors into the stone elements of the fair-face side; the second, called CR, consists of an FRP mesh-reinforced plaster called *Fibre Net ReStructure CRM* on the inner side, replacing the normal plaster, and the repointing of the mortar joints of the fair-face side with stainless steel cords, called *Fibre Net Reticola*.

18.5.2 Test Setup and Instrumentation

In order to stress the prototypes out of plane by vertical bending similarly to what has been done in (Derakhshan et al., 2013; Giaretton et al., 2017; De Santis et al., 2019), the test setup was realized by means of two braced steel frames rigidly connected to the shaking table at the sides of the wall (Fig. 18.9), which support two beams to which hard rubber rollers are attached, arranged in contrast with the front and rear faces of the prototype, so as to realize lateral constraint on the top of the wall. The rollers leave free the vertical displacement component and the rotation of the wall by constraining, albeit with some flexibility not unlike that offered by a roof slab, the top of the wall in the horizontal out-of-plane direction. Based on literature values, the roll stiffness can be estimated between 4000 and 7500 kN/m analogous to that of a wooden deck. The top load was applied by 15 steel plates attached to the top of the wall (Fig. 18.9). The tests were carried out at the ENEA Casaccia laboratory in Rome equipped with the shaking table previously described, and the deformation of the prototypes acquired through the 3DVision system (De Canio et al., 2016) employing 78 passive retro-reflective markers whose motion was detected by ten high-definition near-infrared digital cameras.

18.5.3 Seismic Inputs and Sequence of Tests

Three different stations and three different events were selected as seismic inputs, in three different regions, all part of the seismic sequence that devastated central Italy in 2016. Specifically, recordings from the National Accelerometer Network were selected at stations in Norcia, NRC (Aug. 24, 2016), Castelsantangelo sul Nera, CNE (Oct. 26, 2016), and Amatrice, AMT (Oct. 30, 2016). Both the horizontal

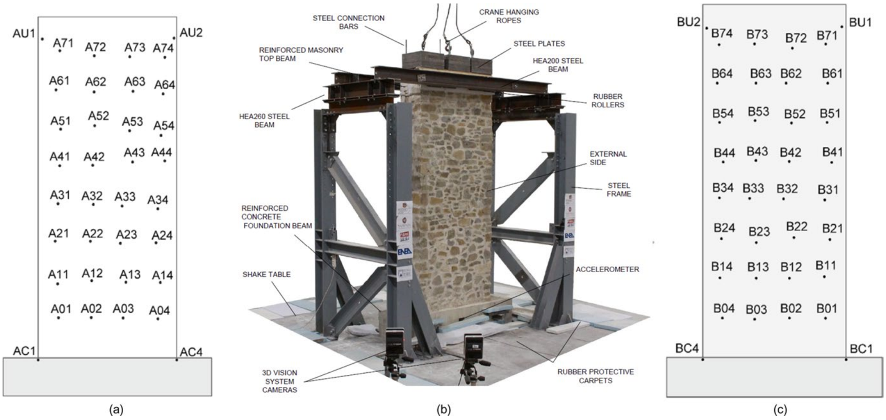


Fig. 18.9 Experimental setup

component (H) and the vertical component (V) were applied. Table 18.2 collects the intensity measurements of the seismic inputs (PGA, PGV, PGD and the Housner intensity—HI). The sequence of tests was designed by repeating the three records, in the order NRC, CNE, AMT after appropriately scaling the acceleration values with a progressively increasing scaling factor (SF), starting from 0.2 and proceeding by steps of 0.2. Before each test cycle with the same SF, a white noise (WHN) test was performed for dynamic identification, with nominal maximum acceleration of 0.05 g and duration of 120 s applied in the horizontal direction only.

18.6 Seismic Retrofitting Technologies of Fair-Faced Stone Walls

Two reinforcement technologies named CR and CC, respectively, were subjected to seismic simulation.

18.6.1 Retrofitting by Reinforced Plaster with Fiberglass Mesh and Joint Repointing with Stainless Steel Cords

The first reinforcement solution called CR and supplied by *Fibre* Net as the *Reticola Plus* system was born from the combination of a thermal insulating plaster reinforced with CRM glass fibre mesh (Gattesco & Boem, 2017; De Santis & de Felice, 2021) applied to the inner surface of the wall, and the repointing of the mortar joints in the fair-face side (Borri et al., 2014; Gattesco et al., 2015), connected by stainless

Table 18.2 Accelerograms used in shake table tests and nominal intensity measurements for SF = 1

			Event	PGA[b]	PGV[b]	PGD[b]	HI[c]
Signal	Site	Soil[a]	Date and time	H; V (g)	H; V (cm/s)	H; V (cm)	H; V (cm)
NRC	Norcia (PG)	B	2016-08-24, 01:36	0.360; 0.215	29.8; 11.6	5.32; 3.04	106.9; 34.9
CNE	Castelsantangelo sul Nera (MC)	C	2016-10-26, 19:18	0.537; 0.397	23.1; 19.6	2.73; 3.01	79.6; 44.7
AMT	Amatrice (RI)	B	2016-10-30, 6:40	0.532; 0.324	37.9; 31.4	6.02; 4.42	90.7; 69.4
WHN	White noise	–	–	0.050; 0.000	3.5; 0.0	0.40; 0.00	16.7; 0.0

[a] Soil type according to (EC8-1)

[b] PGA, PGV, PGD: acceleration, velocity and peak displacement

[c] HI: Housner's Intensity

steel transverse connectors arranged in the wall section (Corradi et al., 2016). The sequence of the installation phases is described below (Fig. 18.10):

- mortar injections. The wall was injected with NHL hydraulic lime-based grout by means of 4/m^2 drilled on the outer face;
- drilling of holes and installation of stainless-steel connectors. Prior removal of mortar from the joints of the fair-face (Fig. 18.10) and subsequent drilling of 24 holes (4/m^2) of 12 mm, starting from the bed joints for the entire thickness of the wall. Insertion of 8 mm threaded AISI316 stainless steel rods in each hole, fitted with a ring welded at the end on the external face;
- installation of cords consisting of 49 wires of AISI 316 stainless steel, nominal diameter of 3 mm, inserted into the mortar joints of the face side, following nearly vertical and horizontal joints to form a mesh of approximately 500 mm pitch;
- laying of GFRP mesh with 66 mm pitch on the inner face. A GFRP reinforcement with reduced 33 mm pitch and size 150 mm × 150 mm is applied at each connector for better load distribution;
- tightening the nuts of the connectors for tensioning the system consisting of stringing the cords arranged in the joints of the fair-face;
- repointing the joints of the fair-face veneer using premixed NHL mortar applied with a low-pressure nozzle. Stretching the joints ensures the adhesion of the

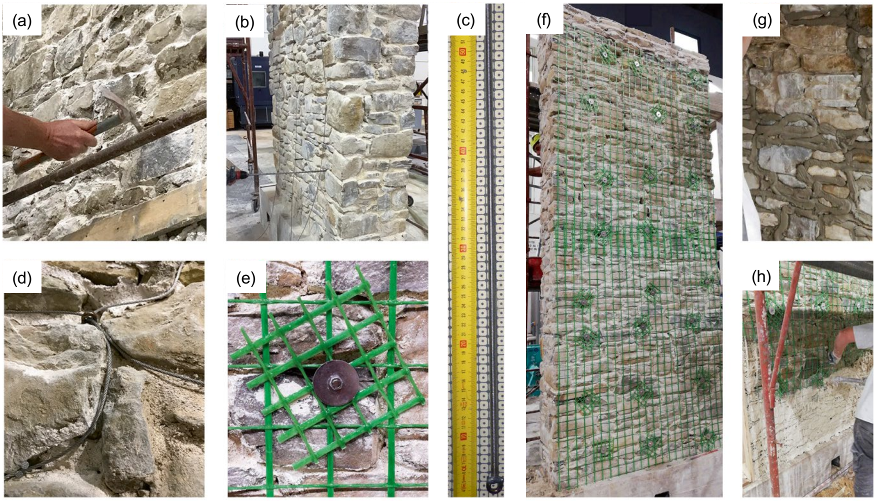


Fig. 18.10 Prototype reinforced with CR system. Work steps: removal of mortar from the joints of the exterior side (**a**); drilling for connector insertion (**b**); stainless steel connector detail (**c**); stainless steel cords placed in the mortar joints (**d**); GFRP mesh laid on the interior side (**e**); detail of connector anchorage on the GFRP mesh (**f**); repointing of the mortar joints of the exterior side with embedded steel strands (**g**); machine application of heat-insulating mortar on the GFRP mesh of the interior side (**h**)

strands to the masonry by concealing them from view, resulting in them being embedded in the mortar;

- application of thermal insulating mortar to the inner side. The GFRP mesh was already arranged on the inner side, and then the plaster consisting of premixed NHL mortar was applied by spray for a total thickness of about 30 mm. The formulation of the plaster was developed to provide fair thermal insulation without a significant reduction in mechanical properties.

18.6.2 Reinforcement by Carbon FRP Transverse Connectors

The second seismic improvement solution called CC involves the regeneration of stone masonry by injecting hydraulic lime-based binder mixtures and making CFRP connectors inserted by drilling into the stones of the fair-face with nearly horizontal lay. The main stages of the workmanship are as follows (Fig. 18.11):

- mortar injections. Twenty-four holes (4/m^2) were drilled in the mortar joints of the exposed wall (exterior side), 20 mm in diameter and 250 mm deep, to perform the binder mixture injections. After an initial flushing with water, NHL premixed mortar was injected, slowly moving the injection nozzle from the bottom of the hole, starting from the base of the wall to the top. The wet mortar, continuously stirred, was injected using a low-pressure hand pump. In total,

Fig. 18.11 Prototype reinforced with CC system. Reinforcement application steps

about 1.3kN of mixture corresponding to 15% of the wall volume and 12% of its weight was injected;

- drilling of holes for CFRP connectors. Thirty-nine holes (about 6/m^2) were drilled on the stone elements of the external face with a 12-mm-diameter percussion diamond drill, inclined 3–5° downward, with a length of 450 mm, so as not to affect the interior plastered surface;
- installation of CFRP connectors. The carbon FRP connectors (Fig. 18.11) are 6 mm in diameter and 420 mm in length and have a sandblasted outer surface to improve adhesion. They were inserted into the holes after pouring injection grout consisting of premixed mortar into the holes. Carbon was chosen for the fabrication of the connectors to reduce the cross-section of the connectors due to their high mechanical properties, ensuring their durability in the alkaline environment of the lime-based mortars. It was estimated during installation that at least 50% of the CFRP bars, after passing through the inner core of the wall, reached the stone elements of the inner face (the arrangement of which was hidden by the plaster), as required to make a transverse connection between the two faces, leaving the inner face undisturbed. Therefore, in principle, the reinforcement technology adopted does not require clearing the building during seismic improvement works. The holes on the fair-face side were sealed with grout to hide the connector heads.

The idea of intervening from the external side only for the seismic improvement of buildings, either through the application of composite meshes (see, among others, Stempniewski & Urban, 2014; Shabdin et al., 2018) or through transverse connectors (Walsh et al., 2015; Cascardi et al., 2020), is not new in the literature. In the present work the technology was designed for the direct anchoring of stone elements, as the true elements of vulnerability in the presence of decohesive and inconsistent mortar joints, and the effectiveness in terms of seismic improvement was assessed through dynamic tests replicating the real stress conditions of the wall subjected to seismic action.

18.7 Results of Shake Table Tests

18.7.1 Progression of Damage

The unreinforced prototype showed a major cracking framework already in the sequence of tests with SF = 0.6 to reach the collapse condition with the CNE08 simulation (CNE seismic input with SF = 0.8). Both reinforced walls, on the other hand, remained substantially elastic and damage-free until the test cycle with SF = 0.8. The first cracks appeared after AMT10, but significant cracks occurred only in the sequence of tests with SF = 1.2. The experimental results demonstrate the effectiveness of both reinforcement solutions, which would have allowed the stone wall to withstand all three seismic events referred to in the shaking table simulations substantially without damage. Below is a summary of the damage observed in the tests.

As for the wall named CC (reinforced with transverse carbon connectors), the first collapse occurs in simulation NRC14, with the detachment of a stone element below the top. In the following simulation (AMT14), more stone elements collapsed, both from the outer and inner sides, effectively separating the rubble wall from the upper crowning. There is to note that the rest of the structure showed no signs of masonry detachment or disintegration. Subsequently, two tests with higher SF (NRC16 and CNE16) were performed, during which the wall oscillated on the foundation, with additional stone elements falling from the top. The peak acceleration value recorded at the base of the wall during the AMT14 simulation was 1.03 g.

For the wall named CR (reinforced with *the Fibre Net Reticola plus* system), the first stone elements collapsed in the CNE14 simulation, resulting in the loosening of the steel strands and the subsequent disintegration of the wall during the next simulation (AMT14). In particular, the collapse affected the fair-face, which was no longer contained by the strand system present in the joints, while the inner face (reinforced with CRM) exhibited only limited damage. The peak acceleration recorded in the AMT14 simulation was 0.99 g.

Comparison of the experimental results shows an almost similar evolution of damage in the two walls reinforced with the CC and CR systems until the ultimate limit state conditions are reached. The main differences consist of less damage to the inner face of the CR prototype, due to the presence of the reinforced plaster, and less cracking of the wall section in the CC prototype, demonstrating the effectiveness of the connectors embedded in the stone elements.

18.7.2 Displacement Profiles

A quantitative assessment of the seismic performance of the walls is provided by the out-of-plane displacement profiles (Fig. 18.12) depicted for the same seismic input (CNE) at three different scaling factors (0.6, 0.8, and 1.4) for each of the three

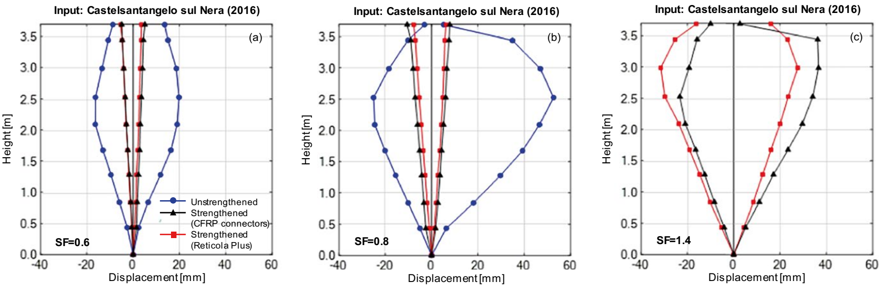


Fig. 18.12 Out-of-plane displacement profiles recorded in seismic simulations with CNE06 (**a**), CNE08 (**b**) and CNE14 (**c**)

prototypes, unreinforced UR and reinforced with the CC and CR systems. The profiles are shown at the instant of time when the average displacement of the seventh row of markers reaches the maximum value for both directions. The displacement profiles have an almost linear trend until the development of significant damage and the onset of the collapse mechanism by vertical bending and subsequent damage of the fair-face. As for the UR wall, the mechanism is activated for the CNE06 simulation (Fig. 18.12a), while the displacement reaches the peak value of 53 mm (external side with fair-face) and 25 mm (internal plastered side) in the CNE08 simulation, the last one before collapse (Fig. 18.12b). In the same simulations, the CC and CR walls still have elastic behaviour, with maximum displacements of 5 ÷ 10 mm at the top (Fig. 18.12b). Only for higher seismic inputs the reinforced prototypes also exhibit vertical bending behaviour with maximum displacements of 36 mm (23 mm interior side) and 28 mm (32 mm interior side) in the CC and CR prototypes, respectively, in the CNE14 simulation (Fig. 18.12c).

18.7.3 Separation of Wall Leaves

While the collapse of the UR wall was caused by the separation between the masonry leaves and the consequent disintegration of the fair-face masonry on the outer side, both reinforced walls showed a far higher capacity. The relative displacement between the corresponding markers arranged on the opposite faces of the prototype provides a measure of the separation between the two leaves as illustrated in Fig. 18.13 where the relative displacements between markers A41-B41 and A61-B61 (left side), and A44-B44 and A64-B64 (right side) are depicted.

An overall representation of the separation between the faces during the seismic simulations is shown in Fig. 18.13. The results demonstrate the effectiveness of CFRP connectors, combined with masonry regeneration injections (CC system), in preventing wall disintegration, even for high levels of seismic input (Fig. 18.13b).

The same was true for the *Reticola plus* (CR) system, where the relative A64-B64 displacement reached 4 mm only with the AMT12 signal, and then reached 21 mm with the NRC14 signal, only when the loosening of the steel cords had compromised the effectiveness of the system.

18.7.4 Dynamic Characterization and Seismic Capacity Assessment

The response in terms of base acceleration and out-of-plane displacement is shown in Fig. 18.14. For each seismic simulation, the maximum positive ($a_{h,max}$) and negative ($a_{h,min}$) value of the horizontal acceleration at the base of the wall is represented on the y-axis, as recorded by the accelerometer placed on the foundation as a

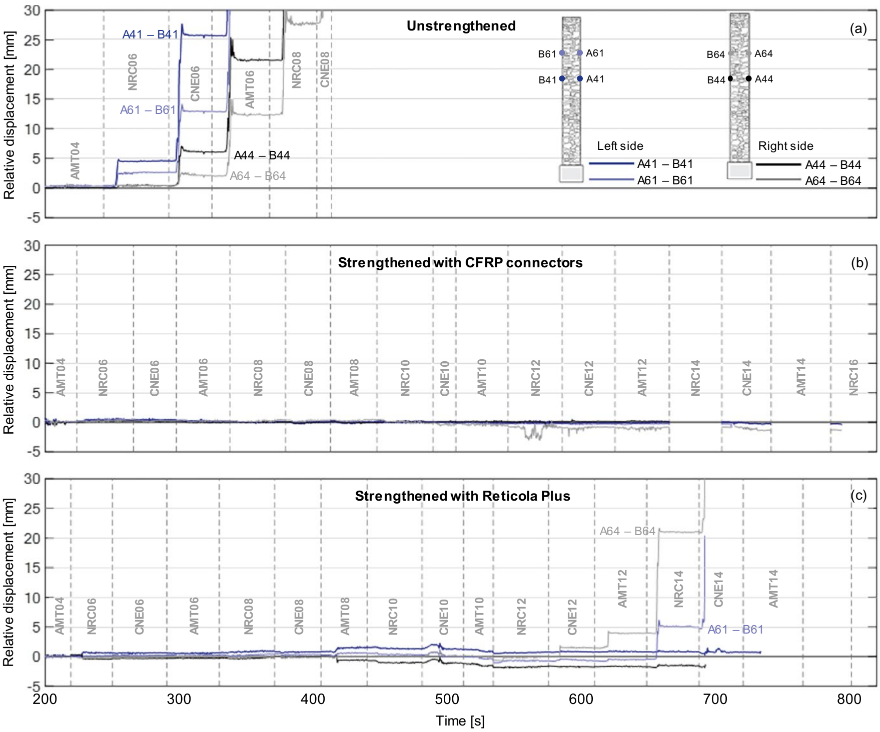


Fig. 18.13 Relative displacements between the two wall leaves UR (**a**), CC (**b**) and CR (**c**)

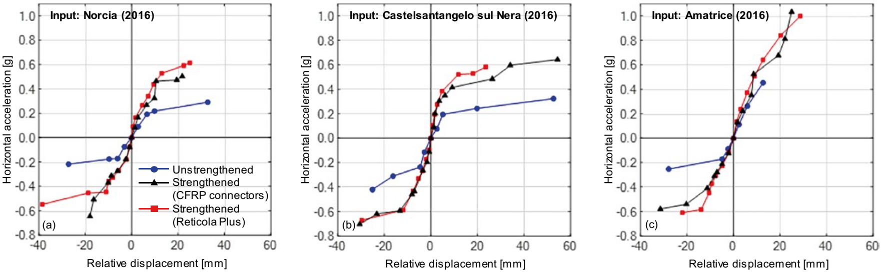


Fig. 18.14 Base accelerations and relative maximum out-of-plane displacements in the NRC (**a**), CNE (**b**) and AMT (**c**) simulations

function of the maximum displacement recorded (average value of the four markers in the seventh row) represented on the x-axis. Each graph compares the seismic response of the three walls (UR, CC, CR) in simulations with the same seismic input (NRC, CNE, and AMT) at different assigned scaling factors. The behaviour is nearly linear for low intensity inputs with subsequent stiffness reduction occurring at higher accelerations for CC and CR than for UR, consistent with the damage evolution described above. The maximum horizontal acceleration values recorded at the base of the three walls are 0.45 g for UR, 1.03 g for CC, 0.99 g for CR. Assuming the peak acceleration measurement as an indicator of the seismic capacity of the wall, the seismic improvement is 127% for the CC system and 120% for the CR system.

The out-of-plane frequency of the wall was calculated using a multi-input-multi-output (MIMO) approach (Phillips & Allemang, 2003), considering the four markers on the RC foundation for seismic input and the first 48 markers on the wall (third through eighth rows) for output. The resulting frequencies are shown in Fig. 18.15, together with the average value of the three simulations with the same scaling factor.

Both CC and CR reinforcement systems show an initial frequency of about 7 Hz, which gradually decreases to 4.5 Hz in tests with SF = 1.2, and a near-collapse frequency of about 3 Hz. The UR wall has a slightly lower frequency presumably induced by the different stiffness of the upper constraint, as well as the effect of masonry consolidation injections. By comparing the dynamic properties pre- and post-intervention, it can be concluded that the reinforcement systems effectively limited the progressive damage of the wall under repeated seismic excitations without significant increases in the stiffness of the structure.

18.7.5 Results Gained and Impact on Design

Test results demonstrated the effectiveness of both technologies for the seismic reinforcement of stone masonry walls. The considered systems make use of CFRP connectors installed from the outside by perforating the stone elements (CC wall),

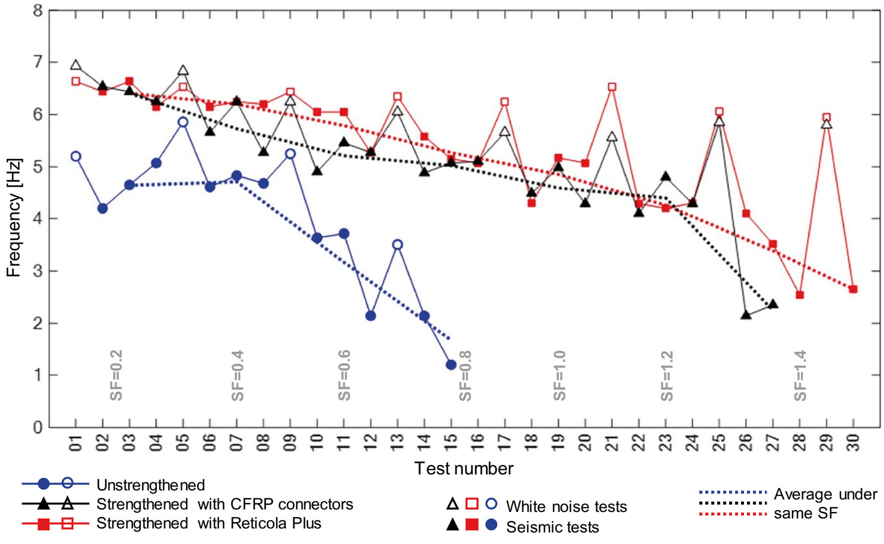


Fig. 18.15 Fundamental frequency of UR, CC and CR walls during shaking table test sequences

or of a stainless-steel cord mesh arranged in the mortar joints of the fair-face side and connected by means of transverse steel tie rods with a fiberglass mesh-reinforced plaster on the inner face (CR wall). Both interventions were associated with masonry consolidation by injection of natural hydraulic lime-based grout. It was possible to demonstrate how:

- the separation between the inner and outer faces of the masonry was effectively counteracted by the transverse connectors, so also the disintegration phenomena of the face stone masonry were counteracted either by the direct anchoring of the connectors to the stone elements (CC) or by the restraining action of the steel mesh in the mortar joints (CR);
- the progressive damage of the wall under repeated seismic inputs was considerably reduced;
- the application of the reinforcement systems did not result in a significant change in the wall stiffness, as the tests provided a 20% increase in frequency overall, due to both the mortar injections and the modification of the test setup with stiffening of the top constraint;
- the accelerations recorded at the base of the walls at the first crack increased from 0.22 g (unreinforced) to 0.59 g (+168%, CC) and 0.58 g (+163%, CR);
- the failure modes of the reinforced prototypes consisted of the fall of the stone elements of the fair-face side immediately below the crowning beam (CC) or with the disintegration of the fair-face as a result of the loosening of the stainless-steel strand mesh that occurred with the detachment of the stone elements from the mortar joints;
- displacement capacity (out-of-plane deflection) remained essentially unchanged, but for much higher values of seismic input;
- the peak acceleration of seismic input that induced the collapse of the prototype increased from 0.45 g to 1.03 g (+127%, CC) and 0.99 g (+120%, CR);
- the scaling factors (SF) achieved in the tests (SF = 1.4 at ultimate limit state conditions) showed that both reinforcement systems would ensure the ability to pass all three simulated seismic events without substantial damage.

Both seismic upgrade technologies have the merit of allowing the preservation of the existing masonry made of irregular stone with an external fair-face, thus without betraying one of the typical features of the historic villages of the Apennines. The materials used were designed to ensure compatibility with the masonry substrate (natural hydraulic lime-based mortar) and durability appropriate to a historic building (stainless steel cords or alkali-resistant meshes and connectors). Although the stone elements (collected from collapsed buildings) and the bedding mortar (formulated on the basis of the collected samples), as well as the seismic inputs used in the tests, were selected to represent the heritage affected by the 2016–2017 Central Italy earthquakes, the results of the present experimental campaign can be considered valid and applicable to stone masonry structures in many countries in Europe and around the world. Of course, an application in other contexts cannot disregard a detailed structural design aimed at defining, for example, the appropriate density of connectors, or identifying the arrangement and spacing of steel cords, based on the size of the stones, the mechanical properties and the state of preservation of the mortar, considering the thickness and masonry unit of the wall.

In conclusion, the experimental campaign shows how traditional and innovative materials can be usefully integrated for the preservation and conservation of the built heritage in seismic areas, even in the most vulnerable conditions of irregular stone masonry with fair-face, combining moderate structural effectiveness with limited impact of reinforcement technologies.

Acknowledgments The main thanks to ENEA—Casaccia Research Center and, in particular, to Engs. Gerardo De Canio and Ivan Roselli, without whom these experimental campaigns could not have been realized; thanks also to colleagues Domenico Liberatore, Luigi Sorrentino and Omar Al Shawa who participated in all phases of design and experimentation of the prototype masonry; thanks to the Accumoli and Amatrice inter-municipal operations office for allowing the collection of stones with which to build the prototypes, and thanks especially to our young colleagues Marialaura Malena, Marialuigia Sangirardi, Pietro Meriggi, Sara Fares, Rebecca Fugger, Francesca Gobbin, Vittorio Altomare, and Mario Lorello of Roma Tre research group for their constant, generous, and valuable support of research activities.

References

Borri, A., Castori, G., Corradi, M., & Sisti, R. (2014). Masonry wall panels with GFRP and steel-cord strengthening subjected to cyclic shear: An experimental study. *Construction and Building Materials, 56*, 63–73.

Cascardi, A., Leone, M., & Aiello, M. A. (2020). Transversal joining of multi-leaf masonry through different types of connector: Experimental and theoretical investigation. *Construction and Building Materials, 265*, 120733.

Corradi, M., Borri, A., Castori, G., & Sisti, R. (2016). The Reticulatus method for shear strengthening of fair-faced masonry. *Bulletin of Earthquake Engineering, 14*, 3547–3571.

D'Ayala, D. F., & Paganoni, S. (2011). Assessment and analysis of damage in L'Aquila historic city Centre after 6th April 2009. *Bulletin of Earthquake Engineering, 9*, 81–104.

De Canio, G., de Felice, G., De Santis, S., Giocoli, A., Mongelli, M., Paolacci, F., & Roselli, I. (2016). Passive 3D motion optical data in shaking table tests of a SRG-reinforced masonry wall. *Earthquakes and Structures, 10*, 53–71.

de Felice, G., De Santis, S., Lourenço, P. B., & Mendes, N. (2017). Methods and challenges for the seismic assessment of historic masonry structures. *International Journal of Architectural Heritage, 11*, 143–160.

De Santis, S., & de Felice, G. (2021). Shake table tests on a tuff masonry structure strengthened with composite reinforced mortar. *Composite Structures, 275*, 114508.

De Santis, S., De Canio, G., de Felice, G., Meriggi, P., & Roselli, I. (2019). Out-of-plane seismic retrofitting of masonry walls with textile reinforced mortar composites. *Bulletin of Earthquake Engineering, 17*, 6265–6300.

Derakhshan, H., Griffith, M. C., & Ingham, J. M. (2013). Airbag testing of multi-leaf unreinforced masonry walls subjected to one-way bending. *Engineering Structures, 57*, 512–522.

Gattesco, G., & Boem, I. (2017). Out-of-plane behavior of reinforced masonry walls: Experimental and numerical study. *Composites Part B, Engineering, 128*, 39–52.

Gattesco, N., Amadio, C., & Bedon, C. (2015). Experimental and numerical study on the shear behavior of stone masonry walls strengthened with GFRP reinforced mortar coating and steel-cord reinforced repointing. *Engineering Structures, 90*, 143–157.

Giaretton, M., Valluzzi, M. R., Mazzon, N., & Modena, C. (2017). Out of plane shake-table tests of strengthened multi-leaf stone masonry walls. *Bulletin of Earthquake Engineering, 15*, 4299–4317.

Phillips, A. W., & Allemang, R. J. (2003). An overview of MIMO-FRF excitation/averaging/processing techniques. *Journal of Sound and Vibration, 262*, 651–675.

Shabdin, M., Zargaran, M., & Attari, N. K. A. (2018). Experimental diagonal tension (shear) test of un-reinforced masonry (URM) walls strengthened with textile reinforced mortar (TRM). *Construction and Building Materials, 164*, 704–715.

Sorrentino, L., Cattari, S., Da Porto, F., Magenes, G., & Penna, A. (2018). Seismic behaviour of ordinary masonry buildings during the 2016 Central Italy earthquakes. *Bulletin of Earthquake Engineering, 17*, 5583–5607.

Stempniewski, L., & Urban, M. (2014). Shaking table tests of a full-scale two-storey pre-damaged natural stone building retrofitted with the multi-axial hybrid textile system "eq-grid". In *Geotechnical, Geological and Earthquake Engineering* (Vol. 26, pp. 155–169).

Vlachakis, G., Vlachaki, E., & Lourenço, P. B. (2020). Learning from failure: Damage and failure of masonry structures, after the 2017 Lesvos earthquake (Greece). *Engineering Failure Analysis, 117*, 104803. https://doi.org/10.1016/j.engfailanal.2020.104803

Walsh, K. Q., Dizhur, D. Y., Shafaei, J., Derakhshan, H., & Ingham, J. M. (2015). In situ out-of-plane testing of unreinforced masonry cavity walls in as-built and improved conditions. *Structure, 3*, 187–199.

Chapter 19
Application of Volatile Binders for the Securing of Artworks in Emergency Contexts

A. Cagnini, M. Bandiera, V. Amato, P. Belluzzo, S. Ciattini, L. Lisi, D. Petrocchi, C. Riminesi, and B. Salvadori

Abstract This chapter illustrates the potential of using volatile binding media (VBM) in emergency contexts to secure works of art through a temporary consolidation that allows either a safe transport or an in-situ restoration. VBM are substances with adhesive and cohesive properties that at room temperature are solid, passing directly to the aeriform state by sublimation. They are requested to ensure adequate consolidation, to leave the composition, morphology, or structure of the object unaffected, and to be completely reversible. Cyclododecane (CDD) was extensively used in past decades, but, due to its recent limited availability, the identification of an alternative VBM is a challenging task. In this work, experimental activity focuses on characterizing the properties of either already known molecules (such as menthol) or less investigated materials (such as menthyl lactate). The application of VBM (melted or dissolved in solvents) on several substrates (wood, plaster, terracotta…) was explored to evaluate different parameters. These results will be useful to select the most adequate application protocol in different emergency contexts. Preliminary results of the use of the selected VBM on a wooden sculpture recovered after the 2016 earthquake are reported. Biocide activity of menthol, as a further property to secure artworks, was also studied.

Keywords Consolidation · In-situ · Conservation · Restoration · Adhesive

---

A. Cagnini (✉) · M. Bandiera · V. Amato · P. Belluzzo · L. Lisi · D. Petrocchi
Opificio delle Pietre Dure, Firenze, Scientific Laboratory, Florence, Italy
e-mail: andrea.cagnini@cultura.gov.it; paolo.belluzzo@cultura.gov.it; lorenzo.lisi@edu.unifi.it

S. Ciattini
CRIST, Service Center of Crystallografic Structure, UNIFI, Sesto Fiorentino, Florence, Italy
e-mail: samuele.ciattini@unifi.it

C. Riminesi · B. Salvadori
CNR, Sesto Fiorentino, Florence, Italy
e-mail: cristiano.riminesi@cnr.it; barbara.salvadori@cnr.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_19

19.1 Introduction

The increase of natural disasters in Europe and especially in Italy, due to the impact of climate changes and anthropic activity, in last years has driven the scientific community to develop suitable tools to intervene in securing works of art in emergency scenarios. One of the most critical interventions that conservators deal with in this field is the temporary consolidation, aimed to stop deterioration of the objects that underwent decohesion, fractures and loss of fragments, for example due to impacts during earthquakes or floods. Temporary consolidation involves the use of a material that can counteract decohesion to allow restoration activities or to ensure the safe transport of the artwork. The material must be also highly reversible, meaning that once the consolidation is no longer required, it can be removed, without leaving residues within or on the surface of the object, by using methods that do not damage the artwork. The consolidant must assure that no alteration of the substrate material and no modifications of the structure occur, during its solidification within the substrate. It must be also, easy to apply and to be found in the market. In 1995, the work of Hangleiter et al. (1995) suggested the use of Volatile Binding Media (VBM) in restoration and conservation fields. These materials share some properties: binding ability, sublimation at room temperature, no or low polarity and hydrophobicity (Hangleiter et al., 1995; Rozeik, 2018; Rowe, 2018). For these reasons, in the last decades, they were extensively tested as temporary consolidants. The most popular VBM for application on cultural artworks was cyclododecane (CDD), no longer manufactured since 2017 but recently back on the market at major suppliers of restoration products. It was used not only as temporary consolidant, but also as adhesive and, by itself or mixed with other materials, to form protective layers. Another application has been the formation of hydrophobic layers to avoid any interaction of the substrate with water (Rozeik, 2018). To find a substitute and expand the range of usable materials, in the last years several research was performed on other molecules, such as menthol and camphene to define their properties, and even though menthol seems to be a good candidate to be used, many doubts still survive, as reported later in this text.

To evaluate substances as possible VBM for cultural heritage, many different aspects must be investigated. The sublimation rate is of crucial importance to select the most suitable VBM to apply to specific situations, because it indicates how long it keeps its consolidating properties or simply remains in the object. The sublimation rate is affected by several factors: temperature, ventilation, humidity, the chemical composition and the structure of the substrate (Rozeik, 2018). Moreover, it is also to be taken into consideration the effect of the exposure surface: since sublimation is a transition phase in which the molecules leave their solid phase and are dispersed in the environment in gaseous form, it is easy to understand how the larger the surface in contact with the environment, the greater the quantity of molecules that can simultaneously pass from solid to gaseous state (Cagna & Riggiardi, 2008). This is why also the application methods are important: VBM can be applied melted, dissolved in solvent or sprayed (Rowe, 2018; Borgioli et al., 2009; Papini et al., 2018). Each method exhibits advantages and disadvantages, which are determined by climatic factors (temperature and ventilation), in addition to the nature of the solvent and the amount of VBM melted.

Aim of this work is the selection of effective VBM to be used in an emergency situation to ensure the artworks during their transportation and restoration, and the identification of other molecules suitable to be applied as temporary consolidants. This might enlarge the list of substances that can substitute the CDD and provide a larger group of molecules with different characteristics to be applied in different scenarios.

In this work the VBM widely mentioned in literature (menthol, cyclododecanol, cyclododecanone, camphene), as well as less studied molecules (menthyl lactate) were selected and tested to better understand their properties and to identify the most suitable and versatile. CDD was used as reference owing to its wide use and the vast literature about it. The investigation, still in progress, focuses on the evaluation of different features such as sublimation kinetic on different substrate (wood, terracotta, wood with gypsum and glue, as well as plaster) the penetration capability, the hydrophobic properties, the consolidation activity and the possible production of damages within the structure. The VBM will be tested by two distinct applications (melted and in solution). Moreover, preliminary tests to evaluate the biocide activity of menthol will be performed. Finally, the selected VBM are tested on an artwork recovered from an emergency context.

19.2 VBM Properties and Their Main Applications

Cyclododecane (CDD) is a cyclic hydrocarbon ($C_{12}H_{24}$) that melts between 58° and 61 °C, it is soluble in non-polar solvents, hence it is a hydrophobic material (Stein et al., 2000). Since its introduction in conservation and restoration fields (Hangleiter et al., 1995), many applications on different objects were reported: polychrome and stone artworks (Barberà et al., 2008), mural paintings (Hensick et al., 2018), fossils (Brown and Davidson 2010; Langdon et al., 2018), ceramic objects (Caspi and Kaplan 2001), paper and textile artworks (Kasiulyte & Garšviene, 2018; Nichols & Mustalish, 2002).

Several studies in literature showed the use of cyclododecane in different ways: melted (Brown & Davidson, 2010; Caspi & Kaplan, 2001; De Clercq, 2021), as well as dissolved in n-cyclohexane or hexane (Borgioli et al., 2009; Caspi & Kaplan, 2001) or sprayed (Borgioli et al., 2009).

The properties of cyclododecane are obviously affected by the application methodology: when melted, it is very hard to apply because it has a short range of workability as it solidifies very fast. This can be dangerous for fragile objects: brush can remove unstable parts or create new fractures. To avoid this problem, restorers started to test a wax-melting stylus, originally used for the decoration of eggs in Ukraine, called *kistka* (Muñoz-Viñas et al., 2016; Rowe & Rozeik, 2008).

The application temperature is also a crucial parameter, due to the CDD limited workability temperature range, so it is preferred to be used at temperatures higher than 65 °C, allowing a slow crystallization and an increased penetration. Moreover, in the range between 65 and 80 °C it is possible to efficiently delimitate the diffusion of CDD on the surface of the substrate, but not at higher temperatures (Muñoz-Viñas et al., 2016).

CDD required to be used cautiously because it is reported that in some applications it was not very safe for the artwork (Muros & Hirx, 2004): when it is applied in solution on mural paintings, components of the substrate could be sensitive to the solvent. Moreover, the porosity of the substrate is also an important parameter: indeed, high porosity influences the mobility of the solution allowing an elevated penetration into the structure, while in materials with low porosity like mortars the mobility decreases. High penetration of CDD into the substrate structure might affect the sublimation rate, as it could decrease inside the pores. CDD seems nonetheless to be a good protective layer from humidity, when applied on water-sensitive areas, during restoration activities with the use of aqueous media (White, 2018; Brückle et al., 1999).

Menthol is a monoterpenic alcohol and has a lower melting temperature than CDD (41°–44 °C): it solidifies slower, and it can be applied easily with a brush. According to literature, it has a higher cohesive strength than other VBM (Han et al., 2014, 2015). The studies of Zhao et al. (2020) and Chen et al. (2020) showed the formation of internal stress due to the volumetric shrinkage of the menthol, affected by the amount and the temperature of melted menthol. These stresses anyway are weak and do not seem to be a risk for the stability of the artwork.

The presence of a hydroxylic group raises some doubts about its inert nature, making menthol less hydrophobic than CDD, and partially soluble in polar solvent including water; moreover, some authors suspected that -OH group exposes menthol to oxidation process, or that it can react with some materials of the substrate (Rozeik, 2018). This seems to be a crucial point: in fact, in painted wood, the acidity of wood support seems to facilitate the reaction of menthol producing menthone, which hampers the sublimation and fixes it on the surface (Thuer, 2011). On the other hand, Han et al. (2014) supported the inert nature of menthol, and stated that the scenario supposed by Thuer can occur just in an extreme hot and acidic environment, favouring the reaction between VBM and wood supports. Conversely, the same authors considered positive the partial solubility of menthol in polar solvents, as it can improve the penetration capability, especially in terracotta materials which generally contain high amount of water. This was observed by comparing the behaviour of CDD, and although menthol showed higher viscosity, its penetration level was the same, while expected to be less (Han et al., 2014).

Han et al. (2018) also suggested that water decreases the solidification rate, retaining the menthol liquid and allowing it to penetrate deeper. Moreover, the melting temperature also affects the penetration into the substrate: indeed, it increases at temperature higher than 42 °C as menthol solidifies more slowly. Solutions with menthol seemed to have a lower consolidation effect compared to the application of melted menthol (Zhang et al., 2022).

Menthol, as well as CDD, has also been applied as temporary adhesive in restoration procedures, and as a protective layer during cleaning activities (Bressan, 2021). An issue to point out is that large amounts of melted menthol are considered not safe for the environment and the user (Cagna & Riggiardi, 2008).

Camphene ($C_{10}H_6$) occurs naturally as essential oil or is industrially produced as intermediate product of molecular synthesis for compounds used to make perfumes. It has waxy consistence and melts between 48° and 52 °C. Its structure contains double bonds that makes it more sensitive to oxidation process. It is soluble in nonpolar solvent, and less soluble in polar solvent. It has been applied by melting methods, because through the solution the crystallization mechanism is hampered (Rozeik, 2018). Although it sublimates at room temperature, the need to add antioxidants to stabilize camphene, and its toxicity for the user, discouraged its use. Sadek et al. (2018) showed that camphene has a weak consolidation strength.

Menthyl lactate is produced from menthol, and shows similar properties, despite it shows some features that differentiate it from the latter. Due to its low vapor pressure, menthyl lactate sublimates slower, hence, it stays more time on the substrate surface and represents a lower risk for the user than menthol. Moreover, it has a low grade of crystallinity, which keeps it at liquid state for prolonged period (Yu et al., 2019). Menthyl lactate seems to have a low toxicity even though it is probably metabolized to menthol (Api et al., 2018).

Cyclododecanol ($C_{12}H_{24}O$) and cyclododecanone ($C_{12}H_{22}O$) have higher melting temperatures (79 °C and 62 °C, respectively) than the VBM mentioned above; however, this characteristic makes them good VBM to be applied on external surfaces of historical buildings exposed to high temperatures. It was observed that the chemical composition of the substrate affects the sublimation rate; however, they have been applied on the surface of archaeological/historical building, and not yet on more sensitive artworks, due to their high melting temperature and very low sublimation rate (Kotb et al., 2024).

19.3 Characterization of the VBM

The first part of this work focuses on the characterization of six volatile binding media (L-menthol: Carlo Erba reagents, impurities <0.3%, L-Menthyl lactate: Sigma-Aldrich, pur. 97%, Cyclododecane: CTS, pur. 98%; Cyclododecanol: TCI, pur. >98.0%, Cyclododecanone: TCI, pur. >99.0% and Camphene: Aldrich, pur. 95%). They were studied considering different parameters as the morphology of crystals after solidification, the sublimation rate and their hydrophobicity.

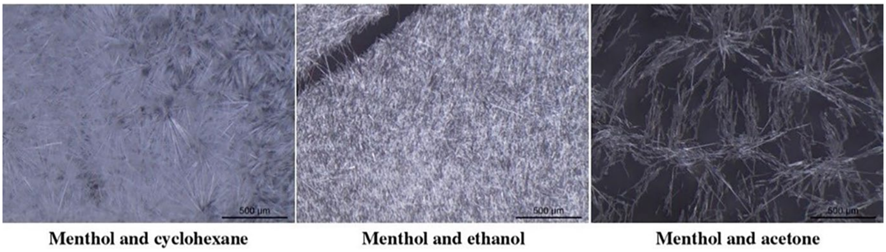


Fig. 19.1 Different morphology of three crystalline films formed using menthol solutions (in cyclohexane, ethanol and acetone) (magnification 6.3×)

19.3.1 Morphology of Crystals

The morphology of the VBM crystals after solidification or solvent evaporation is a very important aspect both for its influence on the consolidation efficacy and on possible harmful effects on the structure of the artwork. Morphology is directly dependent on the environmental conditions, and it is deeply affected by the application method.

Crystals were observed using a stereomicroscope Leica 205C in reflected LED source light, after the solidification of 10 mg of melted VBM and 50 μL of different saturated solutions poured on a non-porous glass support. The solutions were prepared using acetone (Carlo Erba reagents, pur. 99.8%), ethanol (Carlo Erba reagents, 99.8%) and cyclohexane (Titolchimica, pur. 99.5%).

Melted VBM usually produced a thicker and more compact layer. Moreover, based on the evaporation rate of each solvent, different crystalline films and crystal sizes were obtained (Fig. 19.1). It was noted that the application of VBM in cyclohexane solution produced a well delimited area (avoiding the spreading effect observed when using other solvents) and a thinner layer. Another common feature is that the smallest crystals were formed with acetone solutions, due to its higher evaporation rate. Camphene remains mainly fluid after evaporation of each solvent, avoiding the formation of crystalline films.

19.3.2 Sublimation Rate

The kinetic of sublimation of the six VBM has been studied using again two different methods of applications: by melting and using saturated solutions in different solvents.

In the first method, 10 mg of melted VBM were poured by *kistka* on a glass support. Measurements were recorded every 1000 s to monitor continuously the weight loss during 24 h by a balance (Mettler Toledo, model XRS105DU, resolution 0.01 mg, LABX software) in an environment with controlled humidity and temperature. Similarly, 50 μl of saturated solution were poured on the same glass support and the weight loss was monitored as mentioned above. The factors affecting sublimation rates are the amount of VBM and the characteristics of the layer formed on the glass. Concerning the solutions, the solvent vapor tension is one of the factors that influences the solidification of the VBM (hence the amount and the size of the VBM crystals), as well as the amount of VBM dissolved in the solvent (related to their solubility). By using cyclohexane or acetone generally thick layers are formed, while by using ethanol the solution spreads in a larger and thinner film which increases the sublimation rate.

Comparing the sublimation rate of the different melted VBM (Fig. 19.2), camphene is the fastest followed by menthol and CDD that have similar rates (0.25–0.22 mg/h respectively), while menthyl lactate and cyclododecanol are the slowest. Therefore, camphene cannot be considered as an effective consolidant because in a few hours it almost completely sublimated. The application by melting seems adequate for menthol, CDD and menthyl lactate. Even though menthyl lactate shows a lower rate than the other two VBM, it has a melting temperature very close to menthol while cyclododecanol melts around 80 °C, a temperature that can be considered harmful for the application on artworks.

As expected, the solutions sublimate faster than the melted VBM. In the first period of time, it is possible to observe the evaporation of the solvents, and then the sublimation of the VBM (the sublimation rate was calculated considering the last

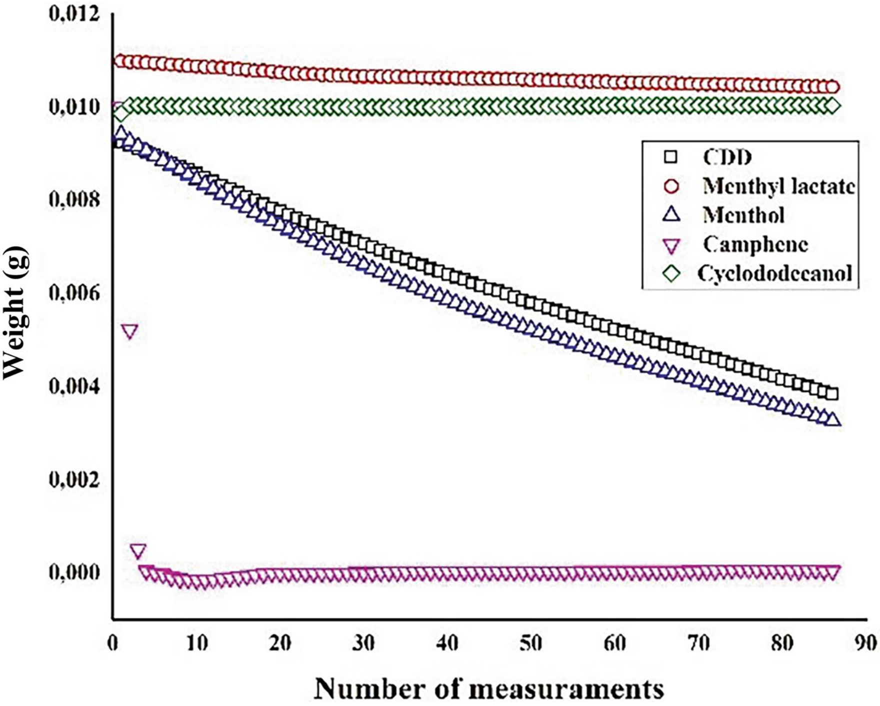
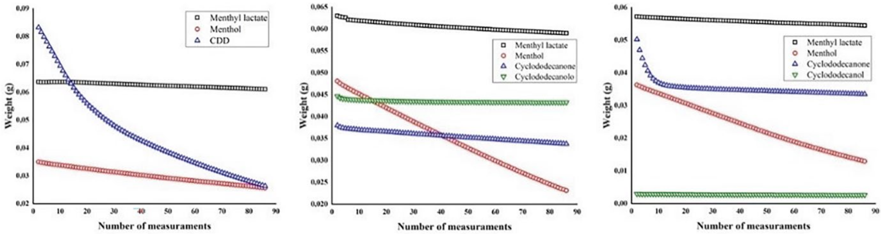


Fig. 19.2 Comparison of the sublimation rates of melted VBM



Solutions with cyclohexane **Solutions with ethanol** **Solutions with acetone**

Fig. 19.3 Sublimation rates of each VBM dissolved in cyclohexane, ethanol and acetone

Table 19.1 Sublimation rates (mg/h) of each VBM in different solutions ([a]very low sublimation rate)

VBM	Cyclohexane	Acetone	Ethanol
CDD	2.37	Not dissolved	Not dissolved
Menthol	0.40	0.97	1.04
Menthyl lactate	0.11	0.11	0.16
Cyclododecanone	Not dissolved	0.17	0.17
Cyclododecanol	Not dissolved	0.00[a]	0.06

step). They usually formed very thin film on the glass, and the high rate of evaporation does not give enough time for the crystal growth, thus favouring the formation of numerous very small crystals, that sublimate faster.

Ethanol solutions are generally faster than acetone and cyclohexane, as observed in all the solution applications (Fig. 19.3, Table 19.1). CDD in solution with cyclohexane is the fastest, while menthol and menthyl lactate are slower. It is interesting to note that cyclododecanone is faster than menthyl lactate, but due to its higher melting temperature (80 °C) it is less applicable in artworks.

19.3.3 Hydrophobicity

The degree of hydrophobicity of VBM is an important aspect to be investigated considering that artworks in emergency sites could often be in contact with water, in different forms. This property can be evaluated measuring the contact angle of VBM with water itself. Five cubes (1 × 1 × 1 cm) were prepared pouring the melted VBM into a silicon mould.[1] Then the faces of the so obtained cubes were polished to have parallel and smooth surfaces. Three measurements were carried out for each material, dropping 10 μl of milli-Q water on the surface. The image was acquired immediately after water release by measuring the static contact angle with water. A spherical and in some cases pseudo spherical fitting was made to calculate the contact angle.

---

[1] Camphene properties did not allow to make a suitable mock-up to perform the measurements.

Table 19.2 The values of the contact angle (CA) (mean with standard deviation)

VBM	CA (degree)
CDD	94.65 ± 1.89
Cyclododecanone	75.66 ± 3.73
Cyclododecanol	78.30 ± 7.11
Menthol	80.64 ± 10.24
Menthyl lactate	77.15 ± 2.22

The results (Table 19.2) show that CDD has the higher hydrophobicity, as expected, while menthyl lactate has the lowest. This parameter must be considered when VBM is applied on a substrate containing water.

19.4 Influence of Substrate Composition on Cyclododecane, Menthol and Menthyl Lactate Performance

The previous experimental work has been useful to check VBM potentiality and to select which ones were the most suitable to be applied on artworks in emergency scenarios: menthol and menthyl lactate were chosen to continue the test. CDD, as reference material, was also tested.

In this part, the VBM were applied directly on different materials (Carrara marble in form of micro grains) or on mock-ups simulating artworks (plaster, wood, a ground layer of glue and gypsum on wood, terracotta, and brick[2]) (Fig. 19.4) to test the VBM properties (penetration degree and surface resistance to compression[3]), and their interaction with the selected substrate (colour changes, sublimation kinetic and variation of porosity).

---

[2] Wood: fragments (2 × 1 × 1 cm) from a frame (poplar) with a biological attack (woodworms).

Terracotta specimens (irregular shape around 2 × 1 × 1 cm): a silty-sandy clay rich in carbonates with evidence of firing; petrographic composition: quartz, K-feldspar; plagioclase, pyroxene, flint, biotite.

Brick specimens: (2 × 1 × 1 cm) a silty-sandy clay rich in carbonates with evidence of firing; petrographic composition: quartz, feldspar, fragments of carbonate nature, granules rich in iron oxides; flint fragments, pyroxene, biotite flakes, fragments of intrusive igneous rocks with quartz, fragments of gabbroid igneous rock with plagioclase, fragments of extrusive magmatic rock with microcrystalline plagioclase.

Wood with ground layer (gypsum and glue) (2 × 1 × 1 cm): thickness of the wood support is 1.1 cm, while the glue and gypsum layer is 0.820 mm thick.

Carrara marble: powder with a wide range of grain sizes: the most part of grains has a diameter from 3 to 1 mm, and small fractions of grains showed dimension varying between 800 and 100 μm.

[3] The proposed method to evaluate the surface resistance is inspired to the Rockwell hardness test, this is standardized for the metallic materials (ASTM E18-22 standard test methods for Rockwell Hardness of metallic materials.

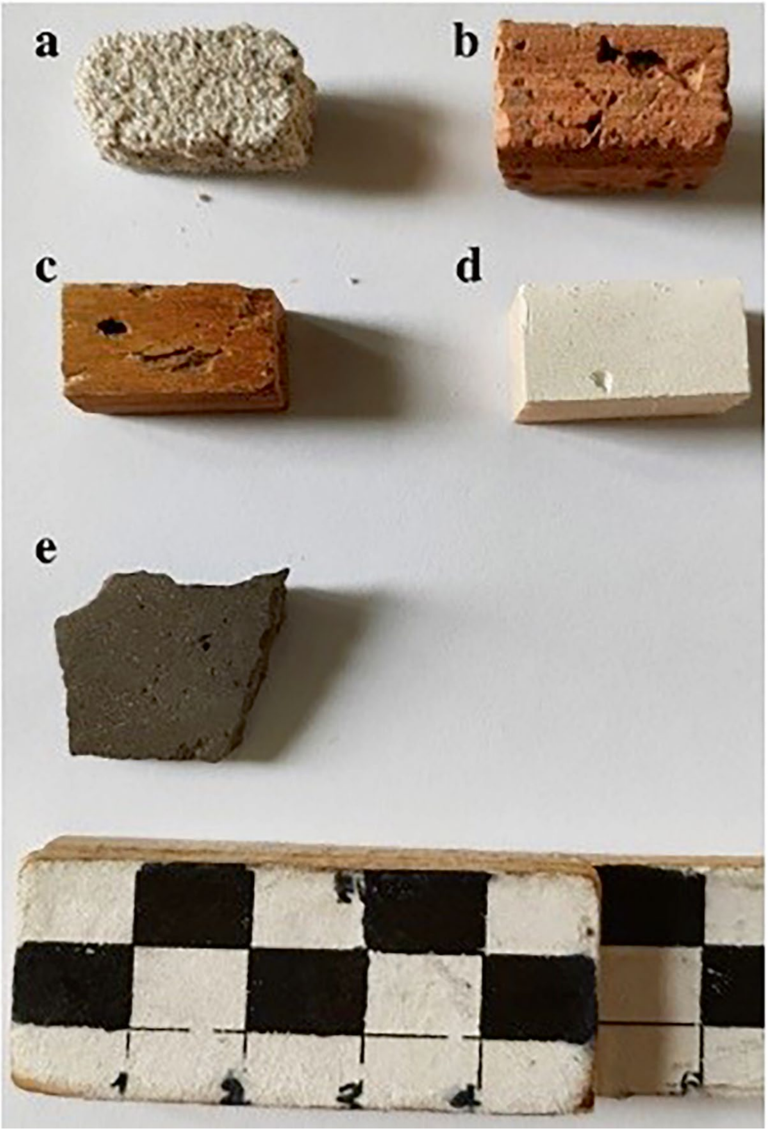


Fig. 19.4 The mock-ups used to study the properties of the VBM: (**a**) plaster; (**b**) brick; (**c**) wood; (**d**) ground of gypsum and glue on wood; (**e**) terracotta

19.4.1 Penetration Degree

One of the most important properties to be evaluated was the ability of the binder to penetrate into the object and to ensure a stable consolidation. This property has been evaluated by using common plastic 20 ml syringes cut at the bottom and closed with a compact layer of cotton. Afterwards, the volume of the syringe was filled with the substrate material (in this case, reported as example, by Carrara marble grains). For testing the penetration degree of different application methods, 1 g of each melted VBM, and 300 μl of each saturated solution were added into the syringes (Table 19.3).

Concerning the application by melting, menthol is the VBM that can penetrate more than the others. This can be explained by its slow crystallization rate; indeed, it takes more time to solidify and that's why it has a wider workability. On the contrary CDD penetrated just 0.5 cm, due to its faster crystallization: when it was poured, it solidified immediately on the surface forming a thick layer covering all the grains. Menthyl lactacte penetrated more than CDD and less than menthol, showing an intermediate behaviour.

Regarding the solutions, using cyclohexane as solvent, menthol again turned out to be the VBM that penetrates more. It is important to note that with menthol/acetone solution the consolidation power appeared extremely reduced: the solution crossed almost the entire length of the specimen but only few centimetres of marble grains were consolidated. Moreover, based on the evaporation rate of each solvent and the amount of VBM dissolved in the solution, the ability to consolidate decreased. Menthyl lactate seems to be the most suitable VBM showing good consolidation effect with all the three solvents (Fig. 19.5).

19.4.2 Compression Strength (Hardness)

Compression strength can be considered an index of consolidation power. To test this parameter 25 g of each VBM was put into a silicon mould and melted at 60 °C in an electric furnace. The same amount of material to be consolidated (in this example Carrara marble grains) was poured into the mould stirring the batch to homogenize the mixture and obtaining three cubes (2.5 × 2.5 × 5 cm). On each specimen five measurements using a Galileo mod DG 201 hardness tester were performed. The tests were performed with a load of 5 kg, and the ball indenter with $\frac{1}{8}$ inch diameter was used. The results of tests are in R (Rockwell units), and the mean and standard deviation were calculated (Table 19.4).

Following these preliminary results, that must be confirmed in a following part of this project, it was possible to observe that menthyl lactate exhibits the strong resistance at compression, which is slightly higher than using menthol. CDD

Table 19.3 The range of penetration depth (in cm) of each VBM using different application methods

VBM	Melted	Cyclohexane	Acetone	Ethanol
Menthol	3.5–4	1.8–2.7	Not consolidated	3.5
Menthyl lactate	1.5–2	1–2	3.5–4.5	3.5
CDD	~ 0.5	1.2–1.5	Not dissolved	Not dissolved

Melted Cyclohexane Acetone Ethanol

Fig. 19.5 The picture shows the consolidated grain of Carrara marble indicating the penetration depth of menthyl lactate in four application methods

Table 19.4 Indent value (Rockwell Units) of consolidated Carrara marble grains with different VBM

CDD	Menthol	Menthyl lactate
49.4 ± 7.1	88.2 ± 3.8	89.2 ± 4.2

showed a good resistance, however its values are lower than those showed by menthol and menthyl lactate.

19.4.3 Colorimetric Measurements

In order to evaluate whether the application of VBM affects the chromatic aspect of the substrate, colorimetric measurements were performed on the surface, comparing values before application and after sublimation of the different melted VBM. 1 g of VBM was melted and the mock-ups (Fig. 19.4) were kept in contact and left to absorb it.

The measurements were performed using a spectrophotometer Minolta CM 2006d (with a standard observer 10° and D65 light) on a circular area (diameter 6 mm). Each area was measured three times.

Using CDD and menthol, practically no colorimetric changes were recorded. On the contrary, the application of menthyl lactate seems to produce chromatic differences when applied on wood, brick and terracotta specimens, showing some decrease of a* and b* chromatic coordinates values. The presence of these chromatic alterations is still unclear and needs to be more investigated.

19.4.4 Sublimation Kinetic

The possible interaction between VBM and the substrate on which the substance is applied might influence the sublimation rate. In this experimental step VBM were applied on the previous mock-ups and the loss of weight was monitored using the same balance.

CDD, that has the lowest penetration capability, showed the highest sublimation rate in all the substrates. On the contrary, menthol and menthyl lactate are slower than CDD, due to their deeper penetration. Moreover, the different porosity of each substrate influenced the sublimation rate of menthol and menthyl lactate. Indeed, more porous substrates (such as wood) slowed down the sublimation of both VBM, while less porous substrates (such as glue and gypsum) showed opposite tendency. A peculiar effect was observed using menthyl lactate: in some cases, such as the application on wood and gypsum and glue, it seems to be more sensitive to humidity, as it is possible to observe in (Fig. 19.6). The graph exhibits initial increasing of weight that finds connection with the weak humidity variation recorded in the environment.

19.4.5 Porosity Alteration

The application of VBM in a mock-up dictates that their molecules penetrate in liquid form or in solution into the substrate through its porosity. In the following step, VBM crystalizes, and this could affect the internal structure of the material creating mechanical stress and producing alterations. To check the effects of VBM crystallization, the porosity of the mock-ups was measured using micro-computed tomography (μ-CT) analysis.[4]

The samples were analyzed/scanned before the application of the VBM and after their sublimation. The percentage of total porosity before the application and after the sublimation of the VBM was calculated to observe the possible production of changes/damages caused by the solidification of VBM within the substrate. The

---

[4] The samples were analyzed by collecting μ-CT data using Skyscan 1172 high-resolution microCT. This system has a sealed, microfocus tungsten X-ray tube with a 5 μm focal spot size. The X-ray was produced by exposing the anode to an electron beam at a range of 100 kV and 100 μA with 0.5 mm Al + Cu as primary filters. Each sample was placed on a pedestal between the X-ray tube source and the charge-coupled device detector. The 2D X-ray images were captured with a slice-to-slice rotation angle range of 0.2°. The spatial resolution of the images was kept at 5 μm in terms of pixel size. The 3D image of the object's internal structure was reconstructed using a modified Feldkamp algorithm for cone-beam acquisition geometry, realised in Nrecon v.1.6.3.3 software. The alignment and beam hardening corrections were made before starting the re-construction process. CTVox and CTVol programs were used for 3D visualisation, while CT-Analyser (CTan) software was used for the image clean up and measurements and to get the porosity measurements.

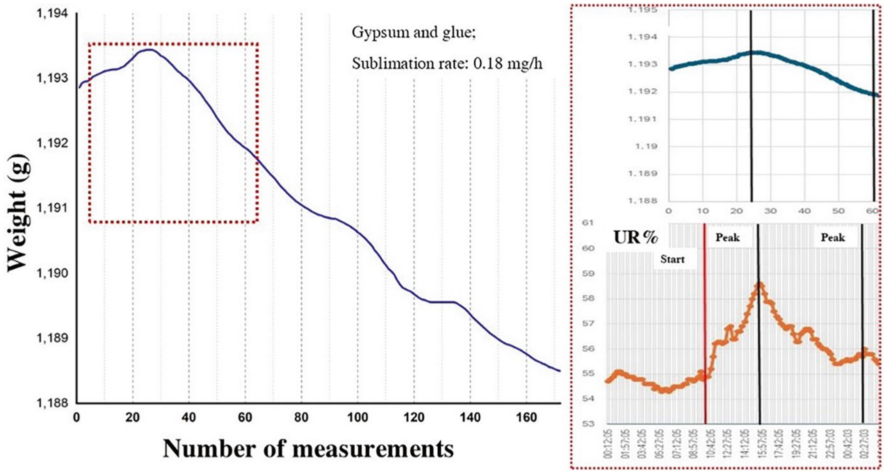


Fig. 19.6 The sublimation kinetic of menthyl lactate applied on the mock-up with a ground layer of gypsum and glue is reported. The fluctuation of weight is probably due to the humidity variation as showed in the right side

Table 19.5 Percentage of porosity in the plaster mock-up before the treatment and after sublimation

Menthol application method	Pre-treatment porosity (%)	Post sublimation porosity %
Melted	11.51	14.63
Solution (cyclohexane)	13.50	16.28

measurements are still in progress; in Table 19.5 some of the results are reported as examples.

The calculation of porosity showed its average increase in the internal structure of the plaster, suggesting that the crystallization of the VBM in both the applications (melted and dissolved in cyclohexane) creates some structural stresses. Further analyses have to be performed to measure the stability of the samples, determining whether the modification of the structural porosity affects the integrity of the objects (Zhao et al., 2020; Chen et al., 2020).

19.4.6 Preliminary Conclusions

Even though this project is still in progress and the results reported in this paper must be considered preliminary, the comparison between the different VBM allowed to better observe their properties on non-porous and porous materials. The obtained data shall be helpful in understanding which of the VBM is more suitable to be used in specific substrates. They clearly showed different sublimation rates and distinct crystallization forms, that make some of them (such as menthol and menthyl lactate) suitable in emergency situations, when it is important to obtain a thick protective and waterproof crystalline film in order to secure artworks and transfer them to restoration laboratories. Camphene seems to be not suitable due to its fast sublimation rate, while cyclododecanol and cyclododecanone could be used for a long-term consolidation.

Although the data obtained on non-porous materials are encouraging, the application in real case requires more caution. The sublimation rate resulted to be affected by the porosity of the substrate, especially the VBM that penetrate deeper. Furthermore, menthyl lactate showed to be sensitive to the variation of humidity contents.

Within the structure, the crystallization of the VBM seems to cause stress and the confirmation whether these data represent a real risk for the stability of the artworks is needed. On the other hand, VBM showed good waterproof and consolidation properties that make them valid products for a fast consolidation.

19.5 The Case Study: The Wooden Crucifix by Giovanni Teutonico in the Santo Chiodo Storage Unit

Menthol and menthyl lactate seem, at this point of the research, a valid alternative to CDD and they have been effectively tested to safe and transport a wooden crucifix, heavily damaged in 2016 by an earthquake and stored at the Santo Chiodo storage unit.

19.5.1 Description of the Artwork

The polychrome wooden crucifix, sculpted in 1494 by Giovanni Teutonico, until the violent earthquake on October 30, 2016, was positioned in the Chapel of the Crucifix above the first altar in the left nave of the co-cathedral dedicated to Santa Maria Argentea in Norcia (PG) (Fig. 19.7). The statue represents a crucified Christ before His death, conforming to specific formal canons that make it a convergence between International Gothic, with its expressionism and details, and Italian Renaissance style (Carvatori, 2016).

All-round full size carved (174 × 174 cm), the crucifix is made of several elements of linden wood, assembled with hide glue and wooden pegs. The body was carved from a single trunk, whose pith core has been removed through a rectangular opening made at the rear, which was closed with a board. The arms were inserted into the shoulder cavities, locked in position with two rectangular pegs. Legs and feet, as well as the left elbow, showed similar joints. The head, connected to the body by four pegs, was inclined by placing a wedge between it and the shoulders, and has an internal cavity, accessible through a rectangular opening on the top and

Fig. 19.7 Giovanni Teutonico, 1494, crucifix, polychrome carved wood, 174 × 174 cm, Santa Maria Argentea—Norcia (PG), image before the earthquake (©Archidiocesi di Spoleto-Norcia)

closed originally by a removable dowel. This cavity contained an articulated mechanism to move the tongue, visible between the dental arches. The carving was prepared with plaster and glue, then a very thin layer of white lead primer was applied, followed by a layer of protein glue. The paint layer probably had a protein binder and pigments such as white lead, vermilion, ochre and charcoal black. In addition to the mechanism of the movable tongue several elements contributed to the realism and drama of the work: the veins under the skin, obtained by a network of vegetable fibre cords arranged over the entire preparation; the strands of hair made with iron wires and vegetable fibres; copper wires for eyelashes and beard. The sculpture was completed by a crown of thorns made of two fiber ropes, plastered and painted, in which wooden carved thorns were inserted.

On October 30, 2016, a 6.5 magnitude earthquake, with epicenter between Norcia and Preci, caused the collapse of the roof and the facade of the church. This event caused the detachment of the crucifix from its cross and its crash onto the floor. The violent impact and the fall of the architectural elements heavily damaged the artwork. The entire sculpture stayed covered by ruins until its recovery, which took place between February 14 and 16, 2018, when it was moved to the Santo Chiodo storage unit. During this long period, the intense exposure to atmospheric agents worsened the conservative condition of the crucifix.

19.5.2 State of Conservation

The state of conservation of the artwork was investigated both with autoptic observations and analytical measurements.

The violent impact on the floor and the falling of the church roof and walls on the artwork caused severe structural damage and fragmented it into several parts, with deformations of wood fibers (Fig. 19.8). In addition, the preparatory and paint layers were damaged, with widespread scratches, abrasions, losses, deformations and cleavage from the wooden substrate. Furthermore, a large part of the surface got covered by concretions of debris and various deposited materials.

The characterization of constituent materials was performed on three fragments coming from the artwork (Table 19.6). Each sample was embedded in polyester resin to obtain cross-sections, polished with abrasive paper, and studied by optical microscopy (visible and UV light) by means of a Zeiss Axioplan optical microscope (equipped with lens from 5× to 50×) (Figs. 19.9 and 19.10). Scanning electron

Fig. 19.8 Parts of the crucifix at the Santo Chiodo Storage unit

Table 19.6 List of samples

Sample	Origin
Sample A	Erratic whitish fragment, probably from skin
Sample B	Red fragment, from blood on quadriceps
Sample C	Blue fragment, from a vein on an arm

microscopy was performed on the cross sections with an EVO® MA25 Zeiss microscope[5] (Fig. 19.11).

In the three samples common features can be highlighted: a ground layer, based on gypsum and animal glue with silicatic compounds; the presence of porosity and cracks that point out the alteration of the ground layer and the loss of cohesion. Over the ground a white-yellowish layer rich of lead white and containing silicates with iron, 10 μm thick, with a white UV fluorescence, and a thin (5 μm) organic layer, probably to be interpreted as animal binding media are present. At the top of the stratigraphy, we can see a painted layer (containing vermillion in the red fragment) of variable thickness (from 20 to 70 μm).

19.5.3 Application of Temporary Consolidants

The sculpture was placed at the Santo Chiodo storage unit in Spoleto (PG) to manage the first recovery operations on the artefact and to set up its safe transport towards the Opificio delle Pietre Dure in Florence. The study and execution of these activities were the focus of a research carried out by the team Opificio delle Pietre Dure (Dr. Sara Bassi, Dr. Renata Pintus, and Dr. Riccardo Gennaioli) involved in Spoke 6 of this project (History, conservation and restoration of cultural heritage), in collaboration with Dr. Vincenzo Amato, who completed a PhD on this case study at the University of Florence with the scientific and technical support of the Opificio.

Experiments to set up a suitable methodology to secure the preparatory and paint layers and avoid further loss of original material were performed. It was decided to consolidate preparation and paint by applying volatile binders, opting for a temporary solution that would prevent further aggregation of debris on the surface and would allow a safer handling of the artwork. Menthol and menthyl lactate, both melted and in solution of cyclohexane, ethanol and acetone were first applied on the fragment corresponding to the right leg of the crucifix (Fig. 19.12).

---

[5] The cross-sections were carbon-coated for SEM analysis, performed in high-vacuum conditions using 20 kV voltage. Elemental analysis was carried out with the energy dispersive probe X-MAX 80 mm^2 (Oxford, UK). AZTEC® software version 4.0 was used for image acquisition and processing.

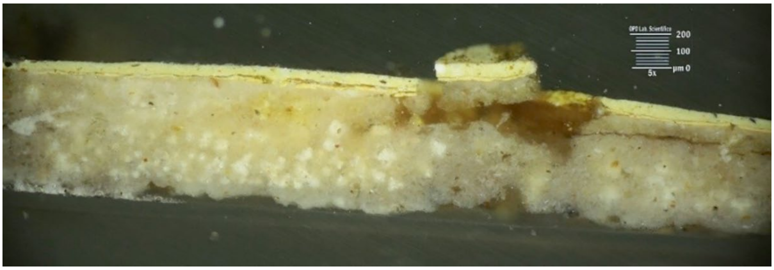


Fig. 19.9 Optical microscopy image of the cross section of fragment A, visible light, 5×

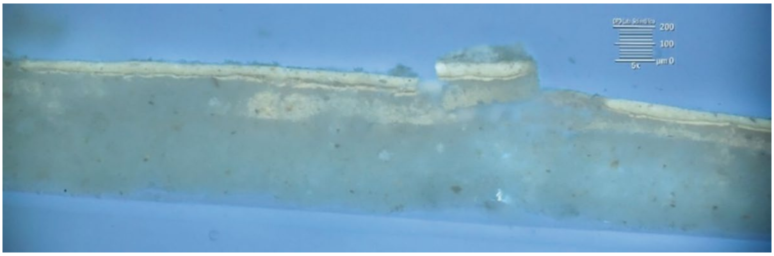


Fig. 19.10 Optical microscopy image of the cross section of fragment A, UV light, 5×

Due to the severity of cleavages, the solutions of volatile binders were incapable of quickly crystallizing and forming compact films that would consolidate the paint layers and, at the same time, fill the space between them and the underlying wood. Attempts to apply the same mixtures to areas previously treated did not give good results, as the addition of solvent caused the dissolution of the crystalline film already formed. Instead, the melted volatile binders formed compact and resistant crystalline films, suitable for the required consolidation. Furthermore, their low viscosity allows easy syringe conveyance to the preparation level, as well as between it and the wooden substrate, even in difficult to reach areas. Consecutive applications of melted volatile binders allow crystals stratification to fill the empty space under the cleavages. Both menthol and menthyl lactate have provided excellent performance, having comparable consolidating capabilities. In this case, menthyl lactate was selected for its lower sublimation rate (which provided longer-lasting effect), its non-hazardousness and less pungent smell, useful for a large-scale application, although it is always recommended to work near an aspiration and/or ventilation system. The results of the temporarily consolidation and transport of the crucifix will be published soon.

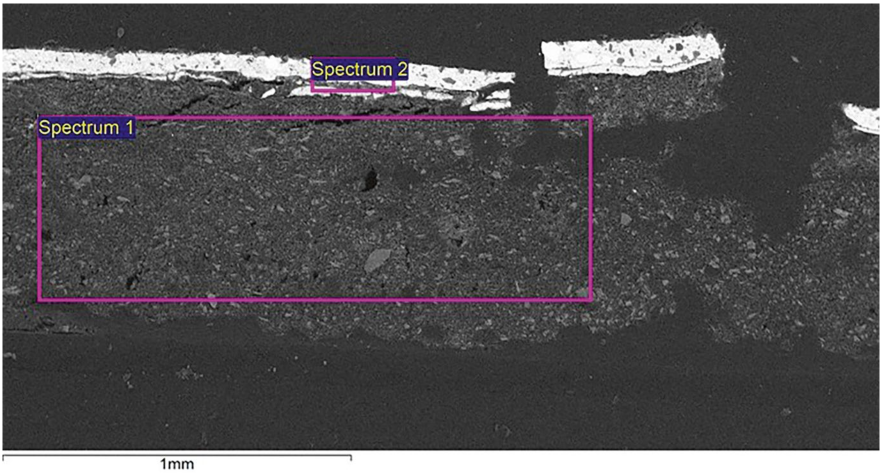


Fig. 19.11 Scanning electron microscopy image of the cross section of fragment A

Fig. 19.12 Area on the right leg of the crucifix, before (left) and after (right) consolidation with menthol

19.6 Preliminary Results on Menthol Biocide Activity

In emergency scenarios, the priority is ensuring the structural stability of artworks, however the preventing potential threats from biological agents is also crucial. As part of this project, the potential biocidal effects of menthol were also explored. Various studies in literature highlight the antimicrobial activity of mint essential oil and menthol (Kamatou et al., 2013).

Preliminary in vitro tests were conducted to evaluate the antimicrobial activity of menthol against a strain of *Penicillium* isolated from an active biological attack. Culture plates using Plate Count Agar (PCA) as the growth medium were prepared and one piece (around 1 cm^2) of mycelium was transplanted. The study was designed with three experimental setups: control plates, plates with a 1 cm diameter paper disc soaked in melted menthol and plates containing a crystal of menthol (around 0.5 g). The culture plates were then incubated at 30 °C for 1 month, with microbial growth monitored every 7 days. At the end of the month, all control plates exhibited significant mycelial growth, while no fungal growth was observed on any of the plates treated with menthol, whether in melted form or as crystals. This clearly show the potentiality of menthol as a biocide that will be investigated in further studies.

Acknowledgments We kindly acknowledge Dr. Edoardo Tartaglia and the CCHT-IIT, at Ca′ Foscari in Venice, for the measurements of contact angle.

References

Api, A. M., et al. (2018). RIFM fragrance ingredient safety assessment, l-menthyl lactate, CAS Registry Number 59259-38-0. *Food and Chemical Toxicology, 115*, 561–571.

Barberà, X. M., Uden, A. V., Kröner, S., Bazán, M. M., Carbó, M. T. D., & de la Cruz Cañizares, J. (2008). The study of cyclododecane as a temporary barrier in the molding of stone sculptures and ornaments. In *Arché: Publicación del instituto universitario de restauración del patrimonio de la UPV - Núm. 3*, 179–184.

Borgioli, L., Boschetti, E., & Splendore, A. (2009). Preconsolidare e velinare: l'opzione ciclododecano. *Kermes, 73*, 67–73. (Nardini editore).

Bressan, A. (2021). *Spada in ferro ed elmo in bronzo di periodo ellenistico dalla tomba 52 della necropoli di Santa Maria Cardetola, Crecchio (CH)*. Microscavo, intervento conservativo e nuove proposte di consolidamento dei materiali organici residui, Master degree thesis, Opificio delle Pietre Dure.

Brown, M., & Davidson, A. (2010). The use of cyclododecane to protect delicate fossils during transportation. *Journal of Vertebrate Paleontology, 30*(1), 300–303.

Brückle, J., Thornton, K. N., & Strickler, G. (1999). Cyclododecane: Technical note on some uses in paper and objects conservation. *Journal of the American Institute for Conservation, 38*(2), 162–175.

Cagna, M., & Riggiardi, D. (2008). Il controllo dei tempi di sublimazione del ciclododecano utilizzato come fissativo temporaneo, In: Cesmar7, ed. Colore e Conservazione, L'attenzione alle superfici pittoriche: materiali e metodi per il consolidamento e metodi scientifici per valutarne l'efficacia, Casa Editrice Il Prato, Padova, pp. 91–98.

Carvatori, S. (2016). *Giovanni Teutonico Scultura lignea tedesca nell'Italia del secondo Quattrocento*, Aguaplano, Perugia.

Caspi, S., & Kaplan, E. (2001). Dilemmas in transporting unstable ceramics: A look at cyclododecane. *The American Institute for Conservation of Historic & Artistic Works*, 115–135.

Chen, X., Xu, Y., Chen, M., Huang, X., Luo, H., & Song, Y. (2020). Studies of internal stress induced by solidification of menthol melt as temporary consolidant in archaeological excavations using resistance strain gauge method. *Heritage Science*.

De Clercq, C. (2021). *Contribution Title Cyclododecane as protection for water-sensitive polychromy during water bath desalination of limestone sculptures: The case study of a* *mid-15th-century wall-mounted memorial from the Burgundian Netherlands, in Transcending Boundaries: Integrated Approaches to Conservation, ICOM-CC 19th Triennial Conference Preprints*, Beijing, 17–21 May.

Han, X., Rong, B., Huang, X., Zhou, T., Luo, H., & Wang, C. (2014). The use of menthol as temporary consolidant in the excavation of qin Shihuang's terracotta army. *Archaeometry, 56*(6), 1041–1053.

Han, X., Huang, X., & Zhang, B. (2015). Morphological studies of menthol as a temporary consolidant for urgent conservation in archaeological field. *Journal of Cultural Heritage, 18*, 271–278.

Han, X., Huang, B. J., & Zhang. (2018). Laboratory research into the use of menthol as a temporary consolidant for conservation on archaeological excavations. *Archaeometry, 60*(6), 1334–1345.

Hangleiter, H. M., Jägers, E., & Jägers, E. (1995). Flüchtige Bindemittel—Teil 1: Anwendungen, Teil 2: Materialien und Materialeigenschaften. *Zeitschrift für Kunsttechnologie und Konservierung, 9*(2), 385–392.

Hensick, T., Sigel, A., Lie, H., Khandekar, N., Smith, K., Bewer, F., Chang, A., Orsini, L., & Mysak, E. (2018). Protection and relocation of frescoes during construction at the Harvard Art Museums. In C. Rozeik (Ed.), *Subliming surfaces: Volatile binding media in heritage conservation* (pp. 141–152). University of Cambridge Museums.

Kamatou, G. P. P., Vermak, I., Viljoen, A. M., & Lawrence, B. M. (2013). Menthol: A simple monoterpene with remarkable biological properties. *Phytochemistry*. https://doi.org/10.1016/j.phytochem.2013.08.005

Kasiulyte, R., & Garšviene, S. (2018). Several case studies using CDD in paper and textile conservation at the Lithuanian Art Museum's Pranas Gudynas Restoration Centre. In C. Rozeik (Ed.), *Subliming surfaces: Volatile binding media in heritage conservation'* (pp. 91–93). University of Cambridge Museums.

Kotb, H. S., Saccani, A., Vallet, J.-M., & Franzoni, E. (2024). Preliminary assessment of new single and blended volatile binding media for temporary consolidation of cultural heritage. *Scientific Reports, 14*, 5115.

Langdon, K., Skinner, L., & Shugar, A. (2018). Archaeological block-lifting with volatile binding media: exploring alternatives to cyclododecane. In C. Rozeik (Ed.), *Subliming Surfaces: Volatile Binding Media in Heritage Conservation* (pp. 97–99). University of Cambridge Museums.

Muñoz-Viñas, S., Vivancos-Ramón, V., & Ruiz-Segura, P. (2016). The influence of temperature on the application of cyclododecane in paper conservation. *Restaurator. International Journal for the Preservation of Library and Archival Material, 37*(1), 29–48.

Muros, V., & Hirx, J. (2004). The use of cyclododecane as a temporary barrier for water-sensitive ink on archaeological ceramics during desalination. *Journal of the American Institute for Conservation, 43*(1), 75–89.

Nichols, K., & Mustalish, R. (2002). Cyclododecane in paper conservation discussion'. *The Book and Paper Group Annual, 21*, 81–84.

Papini, G., Borgioli, L., De Luca, D., Gui, M. O., & Modugno, F. (2018). Evaluation of the effects of cyclododecane on oil paintings. *International Journal of Conservation Science, 9*(1), 105–116.

Rowe, S. (2018). Second fiddle: A review of lesser-known volatile binding media in conservation. In C. Rozeik (Ed.), *Subliming surfaces: Volatile binding media in heritage conservation* (pp. 13–20). University of Cambridge Museums.

Rowe, S., & Rozeik, C. (2008). The uses of cyclododecane in conservation. *Reviews in Conservation, 9*, 17–31.

Rozeik, C. (2018). Volatile binding media: The first 20 years... and beyond. In C. Rozeik (Ed.), *Subliming Surfaces: Volatile Binding Media in Heritage Conservation* (pp. 1–12). University of Cambridge Museums.

Sadek, H., Berrie, B. H., & Weiss, R. G. (2018). Sublimable layers for protection of painted pottery during desalination. A comparative study, in. *Journal of the American Institute for Conservation, 57*(4), 189–202.

Stein, R., Kimmel, J., Marincola, M., & Klemm, F. (2000). Observations on Cyclododecane as a temporary Consolidant for Stone. *Journal of the American Institute for Conservation, 39*(3), 355–369.

Thuer, C. H. (2011). Scottish Renaissance Interiors: Facings and adhesives for size-tempera painted wood. *Historic Scotland Technical Paper, 11*, 96.

White, G. (2018). The use of cyclododecane as an adhesive for temporary facings in paper conservation. In C. Rozeik (Ed.), *Subliming surfaces: Volatile binding media in heritage conservation* (pp. 83–90). University of Cambridge Museums.

Yu, Y., Zhang, W., Han, X., Huang, X., Zhao, J., Ren, Q., & Luo, H. (2019). Menthol-based eutectic mixtures: Novel potential temporary consolidants for archaeological excavation applications. *Journal of Cultural Heritage, 39*, 103–109.

Zhang, W., Wang, X., Han, X., Meng, C., Huang, X., & Luo, H. (2022). Laboratory research of solvent-assisted menthol sols as temporary consolidants in Archaeological excavation applications. *Heritage Science, 10*(1), 74.

Zhao, Z. C., Song, Y. C., Huang, X., Soh, A. K., & Zhang, D. S. (2020). Study of solidification of menthol for the applications in temporary consolidation of cultural heritage. *Journal of Cultural Heritage, 44*, 83–89.

Part V
Green Materials and Methodologies for Conservation

Chapter 20
Mechanical Methods for Dry Cleaning

Paolo Belluzzo, Andrea Cagnini, Simone Di Virgilio, Nicola Ricotta, Alessandra Santagostino Barbone, and Cristina Scibè

Abstract Dry cleaning in the field of cultural heritage refers to the cleaning of historical artifacts (such as textiles, paintings, stone sculptures, and metals) without the use of water or liquid solutions. This approach is particularly suitable and affordable for fragile or water-sensitive materials where traditional wet cleaning could cause irreversible damage.

Keywords Dry-cleaning · Green materials · Sustainability · Custom-made erasers · Brass alloys · Conservation · Restoration

20.1 Mechanical Cleaning of Brass Alloys Using Erasers

Dry-cleaning methods are generally considered smoother than other cleaning methods for removing surface deposits and corrosion products from metals, which can be potentially damaging, promoting the alteration of the metal alloy or compromising the visibility of the surface information (Megahed & Abdelbar, 2018).

At the same time, original surface patinas should be preserved for their protectiveness, historical value and aesthetical features. For this reason, extreme care must be taken to avoid removing important trace evidence that may give clues to how the artifact was made, used and conserved (Turner-Walker, 2008).

The main drawback of a mechanical cleaning is the contact with the object to treat, that could suffer damage resulting in an optical or physical change of the surface. Moreover, the residues left by the cleaning tools, in the form of a spotty particulate or organic materials, may be subject to alteration in time, or promote an alteration of the surface itself (Daudin-Schotte et al., 2013). Cleaning always implies a balance between the efficiency of the treatment and the care of the object.

P. Belluzzo (✉) · A. Cagnini · S. Di Virgilio · N. Ricotta · A. Santagostino Barbone · C. Scibè
Opificio delle Pietre Dure, Firenze, Italy
e-mail: paolo.belluzzo@cultura.gov.it; andrea.cagnini@cultura.gov.it; crisci1@alum.us.es

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_20

The application of erasers in the dry-cleaning has been already tested on several materials: textile (Estabrook, 1989), paper (Pearlstein et al., 1982; Brokerhof et al., 2002), plaster (Daudin-Schotte, 2010; Brugioni, 2015), marble (Williams & Lauffenburger, 1996), photographs (Bernier, 1997) and plastics (Shashoua et al., 2011). The most comprehensive study was carried out at the Cultural Heritage Agency of the Netherlands to evaluate dry-cleaning materials in painting (Daudin-Schotte, 2010).

Following a previous pilot project on the dry-cleaning of tarnished silver alloy artworks by erasers (Basilissi et al., 2021), in this first part of the work, one-step cleaning procedure using commercial erasers, commonly used in the artistic, conservation and dental fields, has been attempted on brass alloy artworks.

Brass has been and is still used extensively in a wide range of objects, because of its relative cheapness compared to bronze and because of its excellent mechanical properties and corrosion resistance (Turner-Walker, 2008). However, it tends to oxidize (tarnishing) quickly when exposed to air.

The conservation environment plays a key role in the type of corrosion; indeed, outdoor objects suffer the presence of pollution and may present more complex corrosion than indoor objects (Turner-Walker, 2008). Therefore, the cleaning procedure cannot follow a general and straightforward approach, it needs to be evaluated case by case and area by area.

The control of the cleaning treatment is very difficult using traditional mechanical methods, as also those involving lasers. Conversely, the main advantage of using erasers is the complete control of the treatment. Indeed, it is a highly flexible method, because it is possible to always monitor the cleaning effect. Moreover, different areas, characterized by diverse corrosion levels, can be treated separately using the most appropriate eraser that can be selected according to the hardness or shape required. Finally, the effectiveness of the cleaning can be enhanced by adjusting the force applied and the duration of the intervention (Basilissi et al., 2021).

The present project aimed at setting up a sustainable mechanical dry-cleaning method suitable for the removal of corrosion and other surface deposits from brass and copper alloys objects, either indoor or outdoor. In this work, the procedure to evaluate the cleaning efficiency, as well as the potential changes of the surface properties and the presence of residues resulting by erasers use is reported.

The selected erasers were preliminarily analyzed by Optical Microscopy (OM),[1] in visible and ultraviolet light, by embedding small fragments in cross-section, Scanning Electron Microscopy associated with Energy Dispersive X-ray

---

[1] Zeiss Axioplan optical microscope equipped with objectives from 5× to 50× and having a halogen lamp and a UV LED lamp as illuminating sources.

Spectroscopy (SEM-EDS),[2] ATR-FTIR spectroscopy[3] and Raman spectroscopy,[4] to characterize the composition of raw materials (inorganic and organic components), check the correspondence with the one provided by producers and investigate the distribution of the abrasive powders in the matrix.

Two series of rectangular-shape brass mock-ups were prepared to test the erasers on different surfaces. The first one was made up by a naturally aged sheet of brass (67 wt% of copper and 33 wt% of zinc) characterized by two surfaces of reddish and greenish color respectively, resembling different alteration patterns. Copper oxides, oxalates and chlorides and copper/zinc/calcium sulfates were diffused on the reddish side while gypsum, copper oxalates and copper/zinc carboxylates, in addition to traces of a silicone rubber-based protective on the greenish one. On the first step, 25 erasers were tested to evaluate their cleaning performance and selected, based on visual observations, the most suitable ones to apply on the second set of mock-ups.

The second one was prepared from an untreated and non-aged brass sheet (65 wt% of copper and 35 wt% of zinc), to evaluate possible damage produced on the metallic surface by the nine erasers[5] previously selected (Fig. 20.1).

Color residue coming from the erasers was preliminarily tested on a white paper, and only two traces were left (E5 and E9).

The characterization of the metallic surface, before and after the cleaning treatment, has been conducted by different analytical techniques: stereomicroscope[6] and scanning electron microscope (in secondary electrons mode)[7] at different magnifications (50×, 300×, 600× and 1000×) to observe the morphological features such as scratches and abrasion marks; color,[8] gloss[9] and roughness[10] measurements to

---

[2] EVO® MA 25 Zeiss microscope. The sections were observed by electron backscattered detector (QBSD), once carbon coated (about 200 nm). The analysis of the elements was carried out with the Oxford EDS X-MAX 80 mm^2 probe.

[3] The samples were analyzed by Fourier Transform IR Spectrophotometer (FT-IR), using a THERMO NICOLET NEXUS™ device (OMNIC™ software), in ATR mode.

[4] The Raman analyses were carried out with a portable BWTek i-Raman Pro device equipped with a red laser (785 nm).

[5] E1: white Faber-Castell Perfection 7057 (polypropylene and calcium carbonate); E2: pink Faber-Castell Perfection 7057 (polypropylene and calcium carbonate); E3: Identoflex A8 (silicone and alumina); E4: Mealli (acrylic and carborundum); E5: Identoflex G8 (silicone and carborundum); E6: Identik CERDIA 32HPGF (polyurethane and diamond); E7: Identik ZIRDIA 32HPGF (polyurethane and diamond); E8: Identik DLTDIA 32HPGF (polyurethane and diamond); E9: Identik LLA 38HPGF (silicone and carborundum).

[6] Leica M205C microscope with magnifications up to 16x and having LED lights as an illuminating source (reflected light).

[7] EVO® MA 25 Zeiss microscope. The samples were observed as-is by secondary electron detectors (SED).

[8] Konica Minolta CM-26dG spectrocolorimeter.

[9] Glossmeter ARWE206085. Measuring angle: 20°. Measuring range: 0–200 GU.

[10] Mitutoyo Surftest SJ-210 roughness tester.

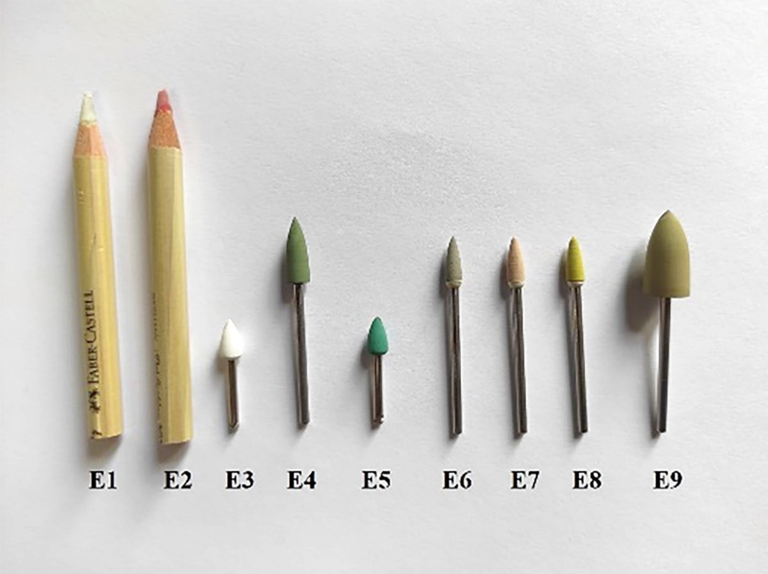


Fig. 20.1 Set of erasers selected after the first step and tested on mock-ups from the untreated and non-aged brass sheet

Table 20.1 Dry-cleaning test results on the second set of brass mock-ups (untreated and non-aged brass sheet)

ERASER	ERASER COLOR RESIDUAL	METAL RESIDUES ON THE ERASER	COLOR CHANGE	GLOSS CHANGE	ABRASION MARKS (SM)	ABRASION MARKS (SEM)	ROUGHNESS CHANGE	EVIDENCE OF RESIDUES (FT-IR)
E 1	V	X	V	X	X	X	X	V
E 2	V	V	X	V	V	V	V	V
E 3	V	V	X	V	V	V	V	V
E 4	V	X	X	V	X	X	X	V
E 5	X	X	V	V	X	X	X	V
E 6	V	X	X	V	X	X	V	V
E 7	V	X	V	V	X	X	V	V
E 8	V	X	V	X	X	X	X	V
E 9	X	X	V	V	X	X	X	V

V = test passed; X = test failed; SM = stereomicroscope; SEM = scanning electron microscope; FT-IR = Fourier-transform infrared spectroscopy

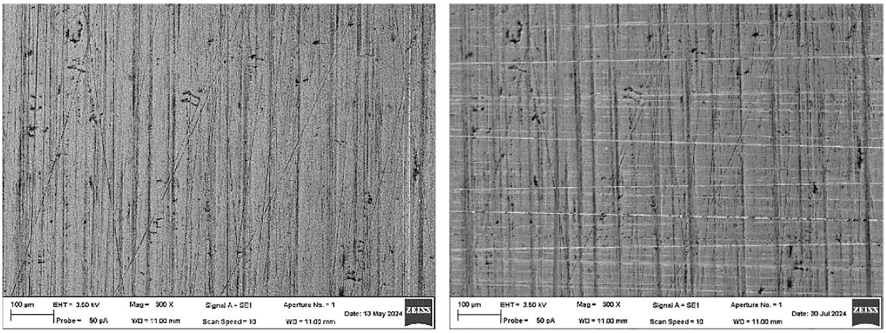


Fig. 20.2 SE Microphotographs at 3.5 kV, scale bar 100 µm: brass mock-up (untreated and non-aged) before the test (left) and after the test (right), where evident are abrasion marks after using eraser Faber-Castell Perfection 7057 (white tip)—E1

highlight optical and topographic modifications; FT-IR analysis (in REF EXT mode)[11] to detect the presence of eraser residues. The results are reported in Table 20.1.

Besides E2 and E3, all the other erasers resulted in severe modifications of the mock-ups surface (morphology and geometry) as attested by microscopic observations (Fig. 20.2) and roughness data. Conversely, color measurements did not show remarkable variations as well as gloss values, except in two cases (E1 and E8). None of the erasers left organic residues on the mock-ups surface. Metallic residues on top of the erasers after the cleaning treatment, evidence of an excessive abrasive power, were also not observed on two erasers (E2 and E3). According to the evaluation results, these last ones proved to be the most suitable tools in terms of efficiency and harmless.

Analytical characterization of commercial erasers revealed the presence of other substances not reported by producers; thus, their use could be potentially harmful for the objects. In connection with this issue, the production of custom-made erasers allows to refine and improve their composition, hardness, shape and size case by case, according to the areas to treat and the different thickness and degree of altered material to remove.

Therefore, further developments of the investigation will focus on testing the cleaning power of custom-made synthetic and natural erasers with different concentrations of abrasive powders, again on brass mock-ups. The selected commercial and custom-made erasers will be applied on natural brass patina to check their efficiency and to provide a low technological, portable and flexible cleaning method for an eco-friendly conservation of metal objects.

---

[11] Agilent handheld spectrometer with MicroLAb Mobile software.

References

Basilissi, G., Brini, A., Cagnini, A., Ortolani, C., & Barbone, A. S. (2021). Evaluation of a dry method using erasers for silver–copper alloy tarnish cleaning and comparison with traditional methods. *Journal of the American Institute for Conservation, 61*, 112–128.

Bernier, B. M. (1997). A study of poly(vinyl chloride) erasers used in the surface cleaning of photographs. *Topics in Photographic Preservation, 7*(2), 10–18.

Brokerhof, A. W., de Groot, S., Pedersoli, J. L., van Keulen, H., Reissland, B., & Ligterink, F. (2002). Dry cleaning: The effects of new Wishab Spezialschwamm and Spezialpulver on paper. *Papierrestaurierung, 3*(2), 13–19.

Brugioni, K. (2015). Eraser cleaning of gypsum plaster: Evaluating damage potential using reflectance transformation imaging. *Objects Specialty Group Postprints (American Institute for Conservation of Historic and Artistic Works. Objects Specialty Group), 22*, 205–224. https://resources.culturalheritage.org/wp-content/uploads/sites/8/2015/05/osg022-13.pdf

Daudin-Schotte, M. (2010). *Cultural heritage Agency of The Netherlands*, unpublished internal report from the 2006–2009 research project "application of dry cleaning methods on unvarnished modern paintings".

Daudin-Schotte, M., Bisschoff, M., Joosten, I., Van Keulen, H., & Van den Berg, K. J. (2013). "Dry-cleaning approaches for unvarnished paint surfaces". New Insights into the Cleaning of Paintings: Proceedings from the Cleaning 2010 International conference, Universidad Politecnica de Valencia and Museum Conservation Institute. In M. F. Mecklenburg, A. E. Charola, & R. J. Koestler (Eds.), *Smithsonian contributions to museum conservation* (pp. 209–219). Smithsonian Institution.

Estabrook, E. (1989). Considerations of the effect of erasers on cotton fabric. *Journal of the American Institute for Conservation, 28*(2), 79–96. https://doi.org/10.2307/3179482

Megahed, M. M., & Abdelbar, M. M. (2018). Characterization and treatment study of a handcraft brass trumpet from Dhamar Museum, Yemen. *Archeomatica, 3*, 36–41.

Pearlstein, E. J., Cabelli, D., King, A., & Indictor, N. (1982). Effects of eraser treatment on paper. *Journal of the American Institute for Conservation, 22*(1), 1–12.

Shashoua, Y., Segel, K., Van Oosten, T., Laganá, A., Keneghan, B., Barabant, G., Bollard, C., & Kuperholc, S. (2011). *Wiping away the dirt – A safe option for plastics?*. Paper presented at ICOM-CC 16th, Lisbon, Portugal. https://www.icom-cc-publications-online.org/1242/Wiping-away-the-dirt%2D%2Da-safe-option-for-plastics

Turner-Walker, G. (2008). *A practical guide to the care and conservation of metals*. Wang Show-Lai, Council for Cultural Affairs.

Williams, J., & Lauffenburger, J. (1996). Testing erasers used to clean marble surfaces. *Objects Specialty Group postprints (American Institute for Conservation of Historic and Artistic Works*. Objects Specialty *Group), 3*, 118–124. https://resources.culturalheritage.org/wp content/uploads/sites/8/2015/02/osg003-12.pdf

Chapter 21

Coping with Stone Biodeterioration Using Low Environmental Impact Materials and Methods

Filippo Edoardo Capasso, Federica Antonelli, Marco Bartolini, Marino Lavorgna, Elodia Spinelli, Silvia Licoccia, and Eleonora Gioventù

Abstract Stone monuments in archaeological contexts are particularly vulnerable to biodeterioration due to environmental exposure and the intrinsic properties of their materials. Biodeterioration occurs through the action of microorganisms and macroscopic organisms, whose effects are influenced by factors such as stone material type and environmental conditions. Traditional approaches to managing bio-

---

F. E. Capasso (✉)
Stone Materials Laboratory, Istituto Centrale per il Restauro, Rome, Italy

Department of Environmental Biology, Sapienza University of Rome, Rome, Italy
e-mail: filippoedoardo.capasso@uniroma1.it

F. Antonelli
Biology Laboratory, Istituto Centrale per il Restauro, Rome, Italy

Bio.Co.Ré. Lab, Scurcola Marsicana, Italy

M. Bartolini
Biology Laboratory, Istituto Centrale per il Restauro, Rome, Italy
e-mail: marco.bartolini@cultura.gov.it

M. Lavorgna
Istituto per i Polimeri, Compositi e Biomateriali, Consiglio Nazionale delle Ricerche, Portici, Naples, Italy
e-mail: marino.lavorgna@cnr.it

E. Spinelli · S. Licoccia
Istituto per i Polimeri, Compositi e Biomateriali, Consiglio Nazionale delle Ricerche, Portici, Naples, Italy

Department of Chemical Science and Technologies, University of Rome Tor Vergata, Rome, Italy
e-mail: licoccia@uniroma2.it

E. Gioventù
Stone Materials Laboratory, Istituto Centrale per il Restauro, Rome, Italy
e-mail: eleonora.gioventu@cultura.gov.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_21

logical growth often relied on chemical biocides but increasing environmental and regulatory concerns have led to a shift towards sustainable alternatives. Recent research has emphasized eco-friendly solutions, investigating essential oils (EOs) along with engineered mesoporous silica nanoparticles (MSNs) and halloysite nanotubes (HNTs) as effective carriers to enhance the stability and efficacy of natural biocides. This contribution addresses the critical challenge of managing biodeterioration on stone monuments exposed to external environments, emphasizing the necessity of a multidisciplinary approach. Indeed, synergistic methods that integrate indirect treatments, environmental monitoring, and selective use of biocides are critical for reducing environmental impact while preserving material integrity. Ongoing research aims to refine sustainable biocidal formulations and application methods, exploring hybrid models that combine biological, chemical, and physical interventions. By fostering such integrated conservation strategies, the field can balance heritage preservation with environmental sustainability, ensuring the longevity of outdoor stone artifacts.

Keywords Stone biodeterioration · Methodological approach · Green biocides · Sustainable conservation · Biotechnology

21.1 Introduction

Stone monuments exposed to external environments, particularly those located in archaeological context, are extremely vulnerable to natural deterioration due to the intrinsic properties of their materials. An important degradation factor in these contexts is attributable to the action of microorganisms and organisms that colonize the stones surfaces, creating different biocenoses depending on the context in which the artefact is preserved.

The management and control of biological growth, therefore, become crucial in balancing all the factors that concern the conservation and enhancement of stone materials exposed to external agents.

Biodeterioration occurs through the interaction between the constituent materials and the living organisms present in the surrounding environment. It is known that microbial (i.e., cyanobacteria, algae, fungi, and lichens) or macroscopic biodeteriogens (i.e., higher plants) can damage the substrate through chemical and physical mechanisms (Tiano, 2001). The effects of biodeterioration can vary significantly depending on the types of organisms involved, their growth modes (epilithic or endolithic) (Golubić et al., 2015), the type of stone material, its state of preservation, and environmental conditions (Pinna, 2021). Climate change influences the issue of biodeterioration as it alters the environmental conditions that affect biological growth (Sabbioni et al., 2009; Gómez-Bolea et al., 2012). Rising average temperatures, changes in humidity patterns and precipitation can create environments more conducive to the proliferation of degrading organisms or select microorganisms adapted to increasingly extreme environments (Smith et al., 2011). Climate change can also increase the frequency of extreme weather events, such as floods and droughts, which, in turn, affect the stability of archaeological materials (Wilhelm et al., 2017).

21.2 Between Practice and Scientific Research: Historical Approaches and New Directions

The approach to treating biodeteriorated stone monuments has evolved over time. In the past, and for a long time, the most common method was characterized by a non-intervention principle, stemming from the perception that other factors, such as the migration of soluble salts and the freeze-thaw cycle, were the primary causes of degradation, and the belief that biodeterioration was merely an aesthetic problem. This approach reflected a misunderstanding of the biodeterioration nature and its synergistic effect on other degradation processes, also influenced by a more romantic and decaying view of historical artifacts.

Since the 1970s, however, this approach has gradually given way, though not entirely, to a methodological dualism. For some time now, the biodeterioration of materials exposed to the outdoors has been addressed through two main strategies: direct and indirect treatments. Direct treatments work by removing or directly inhibiting degrading organisms present on materials and can be carried out using mechanical techniques, physical methods, or more frequently, chemical methods. The latter includes the use of biocides, chemical substances capable of devitalizing potential biodeteriogens, facilitating their removal, and slowing down recolonization processes (Favero-Longo et al., 2023).

Indirect treatments, on the other hand, focus on modifying environmental conditions to make the site less conducive to organism growth (Pinna, 2017). This can involve reducing humidity and temperature using covering systems, drainage, and dehumidification. Additionally, the use of physical barriers or protective coatings can prevent direct contact between organisms and materials, while still maintaining the aesthetic and functional integrity of the site (Romani et al., 2022). Consolidants and protective materials are also employed to prevent biodeterioration, although their selection must be carefully considered, as some may even promote biological growth if not properly formulated.

The current scenario, however, has changed, and these considerations are now accompanied by a cross-cutting need for sustainability, which has heightened concerns about the use of biocides in cultural heritage conservation, both for workers and the environment. In recent years, the enforcement of regulations concerning biocides (Directive 98/8/EC, 1998; Regulation (EU) No 528/2012), which govern the placing of products on the market to ensure a high level of protection for the environment and human health, has significantly reduced the number of active ingredients applicable in the restoration sector, eliminating the most effective ones due to their persistence and the consequent phenomenon of bioaccumulation in the environment.

For this reason, numerous researchers have focused their interest on eco-friendly products (Fidanza & Caneva, 2019). Materials synthesized from plants, marine organisms, microorganisms, and living microbial cells have been tested and experimented with. Physical and chemicals methods with low environmental impact have also been applied (Lo Schiavo et al., 2020).

Thus, there is a vast array of products available for disinfection treatments on colonized stone surfaces. However, it is important to remember that, in the face of this wide range, it is always necessary to verify the actual effectiveness of the compounds against the complex biocenoses that form on outdoor-exposed artifacts, and to ensure there is no interference between these often-experimental products and the constituent materials of the artwork (Casanova Municchia et al., 2023).

Regarding the evaluation of the biocidal efficacy of these new products, the study of available literature reveals a lack of shared laboratory methodologies and techniques. The use of different methodologies and equipment makes it complex, if not impossible, to compare the results obtained, thereby limiting the usability of the data produced. One aspect considered in this research project is the study of techniques and technologies that are effective in assessing the vitality of microorganisms that most frequently colonize outdoor-exposed artifacts. For this reason, tests are being conducted to identify a biochemical ATP extraction and quantification procedure applicable to bacteria, cyanobacteria, algae, and fungi, and to evaluate the applicability of instruments that quantify the chlorophyll present in photosynthetic microorganisms or their photosynthetic activity.

21.3 Strategies for an Environmentally Low-Impact Approach

On account of this, what are the sustainable prospects for this sector, considering the extensive availability of materials, tools, and techniques for the analysis and restoration of stone materials in outdoor environments? Research conducted so far has primarily focused on comparative studies between the performance of traditional chemical biocides and the more recent products developed by scientific research. Often, if not almost always, synthetic chemical biocides have proven to be more effective or more decisive, particularly because of their broad-spectrum action, unlike other natural solutions, which act more selectively (Mascalchi et al., 2020; Santo et al., 2023). Other aspects have also been shown to be more advantageous: ease of application, surface persistence, durability of the treatment, and product availability. Consequently, when measured in these terms, the performance of the new generation of products will always be at a disadvantage.

As part of this research project, in-situ tests were conducted to evaluate sustainable materials comparatively, with the aim of better understanding their potential and limitations. Preliminary trials were carried out on stone surfaces colonized by cyanobacteria, algae, and fungi at the Appia Antica Archaeological Park. The tests compared the biocidal effect of two essential oils (EOs) (cinnamon bark and oregano), two essential oil-based products (Biotersus and Essenzio), and three chemical biocides commonly used in the conservation of stone artifacts (Biotin R1+R2, NewDes50, and Preventol RI50) applied with a brush. This experimentation also marked the first phase of developing an analytical procedure to verify the effectiveness of biocides against the microorganisms constituting the microbial biocenoses responsible for alterations, based on chlorophyll fluorescence analysis and ATP quantification through biochemical tests. The results showed a higher efficacy of synthetic biocides compared to EOs-based products when applied by brush. Chemical biocides exhibited superior biocidal activity, exceeding 99.5% with a single application, whereas cinnamon oil and Essenzio required two applications to achieve the same level of efficacy (Antonelli et al., 2024).

The result, however, could be related to the reduced action time due to the high volatility of essential oils. Therefore, the continuation of the study will focus on developing application methods for essential oils that enhance their efficacy, making them a viable alternative to synthetic chemical biocides. Nanotechnology has proven to be a useful tool to address these existing barriers, enhancing EOs stability and efficacy. In this regard, nanocarriers can protect EOs from external factors, such as UV or thermal induced degradation, overcome EOs solubility limits, finely regulate the kinetic release and inhibit their rapid sublimation. Among the most employed nanoparticles, Mesoporous Silica Nanoparticles (MSNs) and Halloysite Nanotubes (HNTs) are widely used as inorganic carriers, while Zein Nanoparticles as protein-based organic ones. MSNs are usually synthetized by a modified Stober process, exploiting the hydrolysis and condensation of silica precursors and the use of surfactant as template. It is possible to synthesize different MSNs with a tunable porous structure and controlled particle size (Olivieri et al., 2021). Furthermore, it has been observed that the encapsulation of essential oils into meso-porous silica nanoparticles enhance EOs antimicrobial effect, compared to the use in their free form (Weisany et al., 2022; Bravo Cadena et al., 2018).

HNTs are a natural porous filler with a tubular structure. Loaded Halloysite exhibits an excellent retarding capacity in Essential Oil vaporization. In fact, research reports that the release by sublimation of thyme oil from HNTs was sustained for more than 3 weeks (Lee et al., 2017).

Loaded nanoparticles exhibit a low sublimation kinetic of EOs, whereas regardless of the nanocarriers used, their release in water seems to be unaffected by the embedding in the nanocarriers. To overcome this limitation and minimize the leaching of essential oils by water (i.e., rain) by enhancing their long-lasting effectiveness, capping systems can be designed and built around the nanoparticles in order to tailor the kinetic of oil release. This activity is very challenging, and different approaches have been explored.

Tannic Acid has been used to cover the nanoparticles surface. Its abundant phenolic hydroxyl groups can interact with metal ions (including Fe3+ and Zn2+) by forming coordination complexes. These complexes were shown to slow down the release as well as promoting the pH-sensitive one (Yao et al., 2016).

MSN covered by polymeric coating represents a valid strategy too. For instance, sodium alginate polymer, modified with Ca^{2+} ion, could be covalently bonded to the surface of aminated MSN, which could block the mesopores of MSN and effectively prevent the drug early release (Li et al., 2019).

The effectiveness of the proposed approach has been validated through in-vitro tests, which have demonstrated the efficacy of engineered nanoparticles in slowing down the release of thyme oil and enhancing its biocidal effect against algae. Ongoing activities aim to further develop these smart systems by loading EOs into MSNs and HNTs, using suitable mixtures of essential oils with other biocidal compounds such as selected Ionic Liquids (such as imidazolium based ILs with 16 o 18 carbon atoms), and implementing appropriate capping/release mechanisms to exploit these systems for in-situ treatment in real-world applications.

Anyway, the issue undoubtedly remains that, when measured the performance of traditional chemical biocides and the more recent products, the latter will always be at a disadvantage. Therefore, how can this operative issue be overcome, considering the growing demand for improved ecological characteristics of materials?

A fundamental step is to distinguish between the concepts of disinfection and inhibition, and consequently between restoration and maintenance. Disinfection and subsequent removal of biomass is a phase often necessary in the context of restoration interventions to allow further conservative operations. However, beyond this phase that we can define as “curative” it is appropriate, when possible, to implement synergistic strategies for the prevention and control of bio growth, the aforementioned indirect methods, which can limit the use of biocides over time, allowing the reduction of environmental impact. Furthermore, it should be considered that it is not always necessary to eliminate biological colonization, especially with regard to lichen encrustations, since in some cases their presence can protect stone surfaces, reducing erosion and moderating the exchange of humidity with the environment (Wang et al., 2023; Cao et al., 2023). Therefore, it is crucial to conduct a comprehensive and detailed analysis to ascertain whether the microorganisms present on stone surfaces truly alter the chemical composition or physical properties of the materials. In addition to this, the influence of abiotic factors, such as weathering and pollution, which contribute significantly to the degradation process, must be thoroughly considered. This approach enables a deeper understanding of the relative importance of biological activity within the broader framework of stone material deterioration. By doing so, we will reach a more targeted, precise, and informed conservation interventions, therefore sustainable.

Thus, today, disinfection takes on a more complex significance, requiring a multidisciplinary approach and a nuanced response. It is no longer sufficient to simply apply chemical agents to eliminate biological threats but is essential to ensure that interventions are not only effective in addressing immediate biological risks but are also mindful of long-term material preservation. Since biological degradation is an ongoing process which cannot be stopped with a single product, even with a chemical one, it must be monitored and inhibited. Maintenance is therefore fundamental in the conservation dynamics of an artwork displayed outdoors. With this awareness, the numerous green research that are coming onto the scene become relevant. Especially when these are combined with methodologies using new-generation physical or mechanical methods, based on systems that minimize electrical and water resources. The future should focus on hybrid and integrated models, designed to advance and provide solutions that promote sustainability, from resource and service management to the prevention of issues related to an unbalanced distribution of interventions and materials.

To implement this vision, a synergistic and integrated methodology must be adopted, combining rigorous study, continuous monitoring, direct interventions, and ongoing maintenance. Such an approach ensures that the impact on the surface of the works themselves is minimized, preserving their integrity while extending their lifespan. This dynamic process represents the true essence of sustainability in conservation, facilitating the harmonious coexistence of preservation efforts and environmental responsibility.

References

Antonelli, F., Iovine, S., Sacco Perasso, C., Macro, N., Gioventù, E., Capasso, F. E., & Bartolini, M. (2024). Essential oils and essential oil-based products compared to chemical biocides against microbial patinas on stone cultural heritage. *Coatings, 14*, 1546.

Bravo Cadena, M., Preston, G. M., Van der Hoorn, R. A. L., et al. (2018). Species-specific antimicrobial activity of essential oils and enhancement by encapsulation in mesoporous silica nanoparticles. *Industrial Crops and Products, 122*, 582–590.

Cao, Y., Bowker, M. A., Delgado-Baquerizo, M., & Xiao, B. (2023). Biocrusts protect the Great Wall of China from erosion. *Science Advances, 9*, eadk5892.

Casanova Municchia, A., Fidanza, M. R., & Caneva, G. (2023). Advances in testing the interference of biocides on stone materials: A comparative analysis and guidelines for a standardised approach. *Journal of Cultural Heritage, 64*, 23–41.

Directive 98/8/EC of the European Parliament and of the Council of 16 February 1998 concerning the placing of biocidal products on the market.

Favero-Longo, S. E., Matteucci, E., Voyron, S., et al. (2023). Lithobiontic recolonization following cleaning and preservative treatments on the rock engravings of Valle Camonica, Italy: A 54-months monitoring. *Science Total Environment, 901*, 165885.

Fidanza, M. R., & Caneva, G. (2019). Natural biocides for the conservation of stone cultural heritage: A review. *Journal of Cultural Heritage, 38*, 271–286.

Golubić, S., Pietrini, A., & Ricci, S. (2015). Euendolithic activity of the cyanobacterium Chroococcus lithophilus Erc. in biodeterioration of the pyramid of Caius Cestius, Rome, Italy. *International Biodeterioration & Biodegradation, 100*, 7–16.

Gómez-Bolea, A., Llop, E., Ariño, X., et al. (2012). Mapping the impact of climate change on biomass accumulation on stone. *Journal of Cultural Heritage, 13*, 254–258.

Lee, M. H., Seo, H. S., & Park, H. J. (2017). Thyme oil encapsulated in halloysite nanotubes for antimicrobial packaging system. *Journal of Food Science, 82*, 922–932.

Li, X., Wang, Z., & Xia, H. (2019). Ultrasound reversible response nanocarrier based on sodium alginate modified mesoporous silica nanoparticles. *Frontiers in Chemistry, 7*, 59.

Lo Schiavo, S., De Leo, F., & Urzì, C. (2020). Present and future perspectives for biocides and antifouling products for stone-built cultural heritage: Ionic liquids as a challenging alternative. *Applied Sciences, 10*, 6568.

Mascalchi, M., Orsini, C., Pinna, D., et al. (2020). Assessment of different methods for the removal of biofilms and lichens on gravestones of the English Cemetery in Florence. *International Biodeterioration and Biodegradation, 154*, 105041.

Olivieri, F., Castaldo, R., Cocca, M., et al. (2021). Mesoporous silica nanoparticles as carriers of active agents for smart anticorrosive organic coatings: A critical review. *Nanoscale, 13*, 9091–9111.

Pinna, D. (2017). *Coping with biological growth on stone heritage objects: Methods, products, applications, and perspectives*. Taylor and Francis.

Pinna, D. (2021). Microbial growth and its effects on inorganic heritage materials. In *Microorganisms in the deterioration and preservation of cultural heritage* (pp. 3–35). Springer International Publishing.

Regulation (EU) No 528/2012 of the European Parliament and of the Council of 22 May 2012 concerning the making available on the market and use of biocidal products.

Romani, M., Warscheid, T., Nicole, L., et al. (2022). Current and future chemical treatments to fight biodeterioration of outdoor building materials and associated biofilms: Moving away from ecotoxic and towards efficient, sustainable solutions. *Science Total Environment, 802*, 149846.

Sabbioni, C., Cassar, M., & Brimblecombe, P. (2009). Vulnerability of cultural heritage to climate change. *Pollution Atmosphérique, 203*, 285–298.

Santo, A. P., Agostini, B., Cuzman, O. A., et al. (2023). Essential oils to contrast biodeterioration of the external marble of Florence Cathedral. *Science Total Environment, 877*, 162913.

Smith, B. J., McCabe, S., McAllister, D., et al. (2011). A commentary on climate change, stone decay dynamics and the "greening" of natural stone buildings: New perspectives on "deep wetting". *Environmental Earth Sciences, 63*, 1691–1700.

Tiano, P. (2001). Biodegradation of cultural heritage: Decay mechanisms and control methods. In *The proceedings of the ARIADNE 9 WS*. Institute of Theoretical and Applied Mechanics of the Academy of Sciences of the Czech Republic. Institute of Theoretical and Applied Mechanics of the Academy of Sciences of the Czech Republic, Prague, pp. 1–37.

Wang, T., Guo, Q., Pei, Q., et al. (2023). Destruction or protection? Experimental studies on the mechanism of biological soil crusts on the surfaces of earthen sites. *Catena, 227*, 107096.

Weisany, W., Samadi, S., Tahir, N. A., razzak, et al. (2022). Nano-encapsulated with mesoporous silica enhanced the antifungal activity of essential oil against Botrytis cinerea (Helotiales; Sclerotiniaceae) and Colletotrichum nymphaeae (Glomerellales; Glomerellaceae). *Physiological and Molecular Plant Pathology, 122*, 101902.

Wilhelm, K., Viles, H., Winter, E., et al. (2017). Catastrophic limestone decay at the central sanctuary of Iupiter Dolichenus at Dülük Baba Tepesi in southern Turkey: Causes and implications for future conservation. *Conservation and Management of Archaeological Sites, 19*, 3–29.

Yao, X., Zheng, X., Zhang, J., & Cai, K. (2016). Oxidation-induced surface deposition of tannic acid: Towards molecular gates on porous nanocarriers for acid-responsive drug delivery. *RSC Advances, 6*, 76473–76481.

Chapter 22
Nanostructured Hybrid Systems for the Consolidation of Earthen Materials

Rodorico Giorgi, Emma Lena Huecker, Rachel Camerini, Eleonora Gioventù, and Francesca Stefanelli

Abstract This chapter addresses the consolidation of silicate-based building materials such as adobe, mud brick, mosaic soil, cob, and others, by exploring the pozzolanic reaction between silica and calcium hydroxide nanoparticles, which may favor the in-situ formation of calcium silicate hydrate (CSH). The contribution reports on the characterization of the investigated systems and their application on mud-brick mock-up samples to demonstrate the consolidation effect. A significant case-study, where a floor mosaic soil required consolidation, is also reported. The comparison with other traditional products used to this purpose clearly show the potential impact of this new formulation.

Keywords Consolidation · Nanocomposites · Nanolime · Nanosilica hybrids · Pozzolanic reaction

22.1 Introduction

During the last decades, the development of nanostructured and composite materials has revolutionized the field of cultural heritage conservation. In the present work, they are applied to the treatment of some of the most widespread building materials in human history: adobe, mud brick, mosaic soil, cob, and others.

These earthen materials are highly sensitive towards moisture and wind erosion, which makes it even more crucial to develop novel consolidation techniques.

Recent research (Camerini et al., 2019) demonstrated the in-situ formation of calcium silicate hydrate (CSH)—the key phase responsible for cement's

---

R. Giorgi (✉) · E. L. Huecker · R. Camerini
Department of Chemistry, University of Florence, Sesto Fiorentino, Italy
e-mail: rodorico.giorgi@unifi.it; emma@huecker.de; camerini@csgi.unifi.it

E. Gioventù · F. Stefanelli
Istituto Centrale per il Restauro (ICR), Rome, Italy
e-mail: eleonora.gioventu@cultura.gov.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_22

durability—when applying ternary systems consisting of calcium hydroxide nanoparticles (nanolime), silica nanoparticles, and hydroxypropyl cellulose (HPC) onto the surface of porous earthen substrates, like adobe. CSH in-situ formation represents a significant step forward the development of alternative consolidation techniques for the preservation of historic earthen buildings.

In the framework of the CHANGES program, the original formulation has been optimized to achieve enhanced dispersion stability and a more manageable application.

FT-IR and XRD techniques have revealed the outline of the transformation process, confirming the presence of CSH in the suspended phase, i.e., in wet conditions, and after few weeks after application within the porosities of treated surfaces. SEM images further illustrated the morphological features of the different reaction products.

One of the studied ternary formulations was selected and applied to model mud bricks. XRD analysis was employed to verify the formation of the new binding phase on the treated surfaces. The optical and mechanical properties before and after the treatment were then assessed by peeling tests, water absorption tests, and colorimetric analyses.

The diffusion process in porous materials plays a fundamental role in the achievement of successful consolidation. Generally, when a liquid meets a porous surface, there are two main competing processes. Firstly, the absorption by the pores of the solid via capillary penetration takes place, favoring a homogenous consolidation through the layers, from the uppers to the inners. This phenomenon is assimilable to the capillary flow conditions in tubes and is influenced by the fluid properties such as its viscosity. Secondly, the evaporation of the solvent may limit penetration, thus impeding the mass transport to the inner layers and resulting in the precipitation of the composite on the upper layers. Moreover, water participates in the hydration reaction to give CSH, therefore its presence in the pores is required. Kinetic studies are hence fundamental to support experimental evidences and reach the balance conditions for proper applications in different environments (Camerini et al., 2022).

22.2 Calcium Silicate Hydrate Formation

CSH describes a number of amorphous and poorly crystalline structures with the general formula $xCaO \cdot SiO_2 \cdot yH_2O$, with varying stoichiometry. Depending on the calcium/silicon ratio, the structure of CSH gel phases can resemble the crystalline structure of jennite or tobermorite minerals (Merlino et al., 2001). Since CSH is the main binding phase that is responsible for the mechanical properties of cementitious materials (Alizadeh et al., 2011; Nonat, 2004), its involvement in novel efficient consolidants is of crucial interest.

The formation of CSH can occur in various ways. The common reactions taking place in Portland cement involve the hydration of tri- and di- calcium silicates:

$2\ (3CaO{\cdot}SiO_2) + 7\ H_2O \rightarrow 3CaO{\cdot}2SiO_2{\cdot}4H_2O + 3\ Ca(OH)_2$
$2\ (2CaO{\cdot}SiO_2) + 5\ H_2O \rightarrow 3CaO{\cdot}2SiO_2{\cdot}4H_2O + Ca(OH)_2$

CSH can also be obtained through the reaction of finely dispersed siliceous (or aluminous) materials with calcium hydroxide, in the presence of water, forming compounds with cementitious properties via the pozzolanic reaction, which also occurs in Portland cements between the hydration by-product $Ca(OH)_2$ and additional pozzolans (fine siliceous compounds with hydraulic properties).

The proposed hybrid composite exploits the alkaline activation of silica nanoparticles with nanolime (reactants) in water, mediated by the presence of HPC, here acting as viscosity-modifier and water-release regulator during hydration. The nano-size of the reagents aims at bursting their reactivity by maximizing surface area, hence increasing the reaction rate and obtaining higher yield of calcium silicate hydrate.

In a study by Daniele et al. that employed nanolime, silica fume and a surfactant, CSH could be detected already after 7 days with a complete consumption of calcium hydroxide by 28 days (Daniele et al., 2013). However, for consolidation purposes, it is preferable to avoid the use of surfactants because they could remain entrapped into the substrate after solvent evaporation and modify its surface properties.

A more compatible approach was proposed by Camerini et al. (2022) for the in-situ production of CSH from the application of a hybrid formulation containing nanolime, nanosilica and HPC on earthen materials, obtaining significant improvements in the surface cohesion without altering the optical properties of the substrate. The first step of the reaction involves the dissolution of calcium hydroxide in water, which increases the pH, so that released hydroxide ions can break the silica network exposing silanol groups. In a second step, calcium cations bridge the depolymerized silica, forming the typical sheet structure of CSH (Grangeon et al., 2013). In humid air conditions and in the presence of atmospheric CO_2, CSH is produced along with $CaCO_3$, which forms at a lower rate as the partial pressure of carbon dioxide in the air is low (~ 0.4 mbar). While the inner silica is reached and cleaved by diffusion of dissolved $Ca(OH)_2$, the latter is partially converted into $CaCO_3$ during air-drying of the sample, with minor contribution to the strengthening of the earthen material.

In light of these results, further investigations have been carried out to propose alternative formulations prepared varying the silica source, maintaining or enhancing dispersion stability and easiness of application.

22.3 Characterization of Ternary Nanocomposite

FT-IR analysis was employed to gather insights on the different reaction steps and rates of CSH formation in aqueous media or in humid environment, evaluating the influence in various types of silica nanoparticles.

Figure 22.1 shows spectra collected on powders from adobe samples, before and after treatment, at different time intervals. The treatment was performed on the

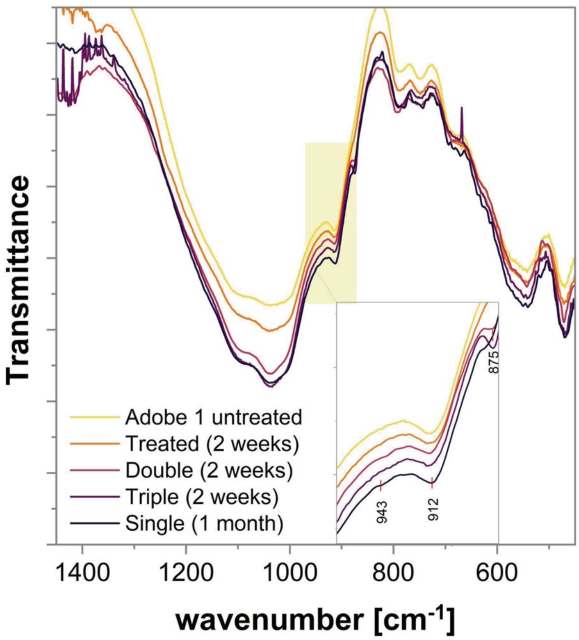


Fig. 22.1 FT-IR spectrum of untreated and treated adobe (single, double and triple treatment) using Ternary B, with inlet of the wavenumber interval of 970 to 870 cm^{-1} with marked silanols and carbonate peak

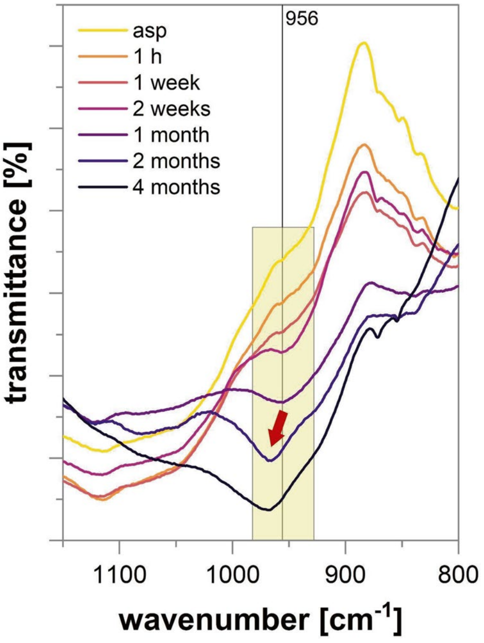


Fig. 22.2 Overlaid spectra of the Ternary A (prepared with Levasil CC503) in suspension, dried and measured at different times from preparation, up to four months. The vertical line marks the peak assigned to the silanols, within the wavenumber interval from 1150 to 800 cm^{-1}, normalized with respect to the HPC signal

ternary formulation prepared with Nanosilica B (described below), applying the same amount of product in single or multiple steps onto the adobe samples. The stretching vibration of Si–O of silanol groups is associated with the peak at around 950 cm^{-1}, thus the signal here overlaps with the intense band of the silica originally found in adobe. However, a small signal is found at 943 cm^{-1} after 2 weeks from double treatment and after 1 month from single treatment. Calcium carbonate is also present, as confirmed by the signals at 875 cm^{-1}.

Figures 22.2 and 22.3 show the FT-IR spectra of the ternary over time, prepared with different silica sources: Nanosilica A, which identifies the commercial product Levasil CC503 (Nouryon, Netherlands), an opaque suspension of silica spheres, with a diameter of around 34 nm, stabilized via silanol surface modifications, and Nanosilica B, namely Levasil CS30-716 P, which has not surface modifications and presents a smaller average diameter of the particles, around 17 nm. The two ternaries will be hereinafter indicated as Ternary A and Ternary B, respectively. Two significant aspects emerge. First, Ternary B produces a faster intensification of the peak at 956 cm^{-1} than Ternary A, where the conversion of siloxane groups into silanol groups occurs over months. This could be explained considering the surface modification on the particles of Nanosilica A, whose presence avoids aggregation due to steric hindrance but also attenuate reactivity. Secondly, a peak shift from 956 to 967 cm^{-1} in later stages of the hydration process is found in both systems, showing that silanol groups—where the silicon is bound in a 3D-tetrahedral environment, converts into CSH, where the Si–O bonds are configured in a 2D-chain. So, the shift towards higher wavenumbers shows a lower contribution of the tetrahedral

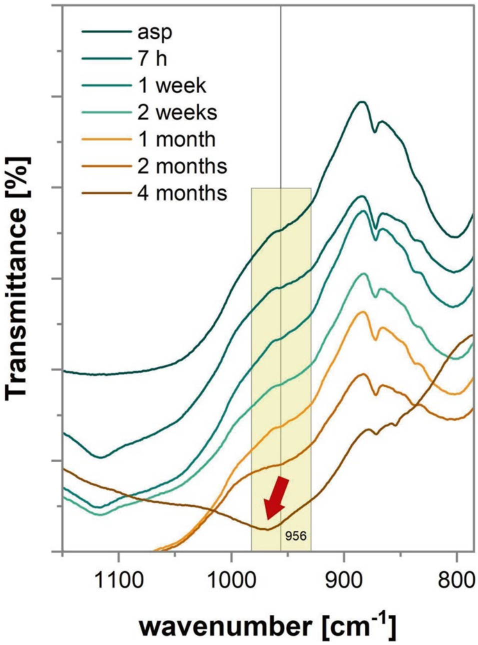


Fig. 22.3 Overlaid spectra of the Ternary B (prepared with Levasil CS30 716 P) in suspension, dried and measured at different times from preparation, up to four months. The vertical line marks the peak assigned to the silanols, within the wavenumber interval from 1150 to 800 cm^{-1}, normalized with respect to the HPC signal

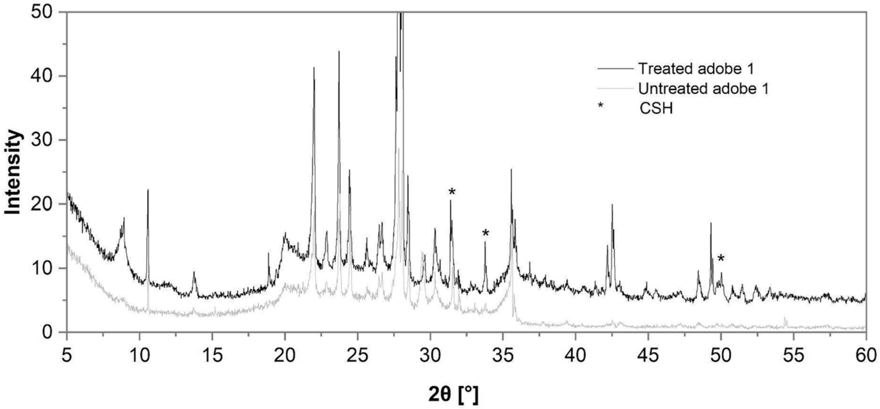


Fig. 22.4 XRD spectra of powders collected from the surface of adobe mock-ups: the gray spectrum indicates untreated adobe and the black spectrum indicates the adobe treated with Ternary B applied in triple step. CSH signals are marked with an asterisk

silica, which is produced by the initial depolymerization reaction of the silicates, and a higher contribution of the chain configuration found in tobermorite, a natural CSH phase (Yu et al., 1999). This phenomenon is found when both nanosilica types are used, confirming that CSH formation eventually occurs in both cases.

X-ray diffraction (XRD) analysis was employed to support the evidences of CSH formation on adobe gathered with FT-IR analysis. The comparison of XRD patterns of powders collected from adobe samples before treatment and after treatment with Ternary B (Fig. 22.4) shows that peaks at 31.5, 33 and 50, assigned to CSH phases, are present in the latter. According to the literature, calcium silicate hydrate minerals tobermorite and jennite have diffraction patterns with maxima in the 28–33 region and at 50.7, with peak's morphology depending on the degree of order of the phases. It has to be noted that when the formulation sets in the pores of adobe, the original silica component of adobe takes part in the process along with silica nanoparticles, modifying Ca/Si ratio (Maddalena et al., 2019; Tajuelo Rodriguez et al., 2017).

22.4 Evaluation of Consolidation Effect on Floor Mosaic Soils

During the restoration of the detached Roman floor mosaic from Montescaglioso (Italy), which was the subject of a degree thesis from F. Stefanelli[1], performed at the Istituto Centrale per il Restauro, it was possible to carry out some tests to evaluate the effectiveness of these new formulations.

---

[1] F. Stefanelli, *Il Mosaico staccato di Montescaglioso. Studio, conservazione e restauro della stratigrafia originale,* Thesis (a.a. 2022–2023).

The detached mosaic has the peculiarity of fully preserving its original stratigraphy; therefore, the study focused on preparatory layers, particularly the one composed of clay elements embedded in the original soil (Fig. 22.5). Diagnostic campaign[2] carried out on the soil showed that it is mainly composed of silicates with very low percentages of calcium carbonate. To preserve the stratigraphy of original materials and, consequently, guarantee the conservation of the mosaic, it was decided to consolidate the earthy sediment. This provided the opportunity to conduct a comparative laboratory study on different consolidating products with some currently available on the market.

The employed products have to show compatibility with the sediment, do not alter its optical properties, and provide an efficient and durable consolidation effect.

In the experimental phase, the newly formulated hybrid system (indicated as T-CSH) was tested and compared with a common silica-based product, namely ethyl silicate (RC 70). Given the presence of HPC in the ternary, a third treatment was also performed using sole Klucel G (commercial product entirely based on hydroxypropyl cellulose) at the same percentage present in the hybrid system, allowing to define its influence during the consolidation process.

The application tests were performed on laboratory mock-ups resembling the composition of the earth of the Montescaglioso mosaic. The samples were prepared using soil gathered in Montescaglioso (20%), quartz sand (0.10–0.35 mm, 75%), micronized calcium carbonate (2%), purified clay (3%) and water (20%). The homogeneous mixture thus obtained was distributed inside polypropylene moulds of 5 × 5 × 2 cm^3 (Fig. 22.6).

Due to the mosaic characteristics, the consolidating products selected were applied using a syringe with a needle, from the surface of the specimen.

Fig. 22.5 Bottom view of the Montescaglioso mosaic, with clay elements embedded in the original raw earth

---

[2] XRF, XRD, Differential Thermal Analysis (DTA), Thermal Gravimetric Analysis (TGA) and mineralogical microscope by chemist Dr. Michele Macchiarola CNR-ISSMC in Faenza (Italy).

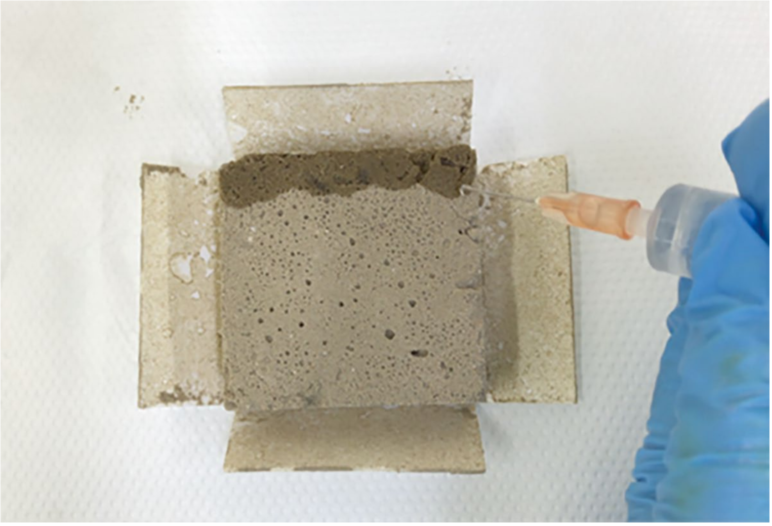


Fig. 22.6 Surface consolidation of laboratory mock-ups via syringe application

Table 22.1 Colour variations obtained by colorimetry after application of different consolidants

Colorimetry	
Consolidating product	ΔE*
T-CSH	1.96
RC-70	4.79
Klucel G	1.73

Table 22.2 Peeling resistance of the consolidated and untreated specimen surfaces

Peeling test	
Consolidating product	Peeling resistance (g/cm^2)
T-CSH	0.02
RC-70	0.03
Klucel G	0.07
None (untreated)	0.44

The test phase included: collection of colorimetric data (BS EN 15886:2010) before and after consolidation specimens with ΔE determination, in order to detect undesired chromatic alteration; Scotch Tape Test (or Peeling test) (Drdácký & Slížková, 2013) to assess the restoration of surface cohesion; measurement of water absorption by contact sponges (BS EN Standard 17655:2023). The results are reported as average of multiple measurements.

Colorimetric analyses show that each product cause a light colour saturation of the consolidated material (Table 22.1), but only ethyl silicate exceeds the acceptance threshold value of 3. Peeling test (Table 22.2) demonstrates a good surface consolidation action by the hydrated calcium-silicate formulation, much more effective than *Klucel G* alone. The results obtained with contact sponges (Table 22.3)

Table 22.3 Average amount of water capillary sorption of treated and untreated specimens

After sorption test	
Consolidating product	Water sorption (g/cm^2)
T-CSH	0.70
RC-70	0.18
Klucel G	0.58
None (untreated)	0.71

show a maintenance of the same absorption levels as the untreated sample for the hydrated calcium-silicate formulation and Klucel G, unlike ethyl silicate which significantly modified the surface characteristics.

In conclusion, T-CSH appears to be a very promising product, even if optimization is under continuous process, as different case studies has to be separately considered. The presence of HPC confers viscosity to the hybrid system, acting as stabilizing agent, but also possibly limiting the penetration of the suspension if pores are not interconnected and average pore dimension is low. A possible decrease of the hydroxypropyl cellulose amount, without affecting the consolidation ability, is an option.

References

Alizadeh, R., Beaudoin, J. J., & Raki, L. (2011). Mechanical properties of calcium silicate hydrates. *Materials and Structures, 44*, 13–28.

BS EN 15886:2010. Conservation of cultural property – Test Methods – Colour measurement of surfaces.

BS EN Standard 17655:2023. Conservation of cultural heritage – Determination of water absorption by contact sponge method.

Camerini, R., Chelazzi, D., Giorgi, R., & Baglioni, P. (2019). Hybrid nano-composites for the consolidation of earthen masonry. *Journal of Colloid and Interface Science, 539*, 504–515.

Camerini, R., Poggi, G., Ridi, F., & Baglioni, P. (2022). The kinetic of calcium silicate hydrate formation from silica and calcium hydroxide nanoparticles. *Journal of Colloid and Interface Science, 605*, 33–43.

Daniele, V., Taglieri, G., & Gregori, A. (2013). Synthesis of Ca(OH)2 nanoparticles aqueous suspensions and interaction with silica fume. *Advanced Materials Research, 629*, 482–487.

Drdácký, M., & Slížková, Z. (2013). Enhanced affordable methods for assessing material characteristics and consolidation effects on stone and mortar. *Journal of Geophysics and Engineering, 10*(6), 064005.

Grangeon, S., Claret, F., Linard, Y., & Chiaberge, C. (2013). X-ray diffraction: a powerful tool to probe and understand the structure of nanocrystalline calcium silicate hydrates. *Acta Crystallographica Section B: Structural Science, Crystal Engineering and Materials, 69*(Pt 5), 465–473.

Maddalena, R., Li, K., Chater, A. P., Michalik, S., & Hamilton, A. (2019). Direct synthesis of a solid calcium-silicate-hydrate (C-S-H). *Construction and Building Materials, 223*, 554–565.

Merlino, S., Bonaccorsi, E., & Armbruster, T. (2001). The real structure of tobermorite 11A: Normal and anomalous forms, OD character and polytypic modifications. *European Journal of Mineralogy, 13*(3), 577–590.

Nonat, A. (2004). The structure and stoichiometry of C-S-H. *Cement and Concrete Research, 34*(9), 1521–1528.

Tajuelo Rodriguez, E., Garbev, K., Merz, D., Black, L., & Richardson, G. I. (2017). Thermal stability of C-S-H phases and applicability of Richardson and Groves' and Richardson C-(A)-S-H(I) models to synthetic C-S-H. *Cement and Concrete Research, 93*, 45–56.

Yu, P., Kirkpatrick, R. J., Poe, B., McMillan, P. F., & Cong, X. (1999). Structure of Calcium Silicate Hydrate (C-S-H): Near-, Mid-, and Far-Infrared Spectroscopy. *Journal of the American Ceramic Society, 82*(3), 742–748.

Chapter 23
Novel "Green" Polymers, Gels and Composites for Cultural Heritage Preservation

Damiano Bandelli, Federico Olivieri, Giuseppe Cesare Lama, Gennaro Gentile, Marino Lavorgna, and David Chelazzi

Abstract Novel "green" materials are crucial in cultural heritage (CH) preservation since they allow time- and cost-effective interventions and avoid risks related to the use of toxic compounds. To this purpose, the physico-chemical properties of the new materials must be tailored to the tasks they must address. This chapter discusses some of the latest advanced materials for CH conservation, e.g. "green" polymers/olygomers and composites to formulate gels and coatings, tuning their physico-chemical properties to achieve optimal cleaning or protection of works of art. In particular, recent findings in the formulation of hydrogels and organogels for cleaning tasks, and coatings for the protection of metals against corrosion, are discussed, and new aspects are highlighted in the research of these materials. Gels with controlled hydrophilicity/hydrophobicity and tortuosity, and coatings with active response to corrosion, are illustrated to show the large applicative potential of sustainable materials in CH conservation.

Keywords Sustainable materials · Hydrogels · Organogels · Composites · Coatings · Cleaning · Protection · Cultural heritage preservation

---

D. Bandelli · D. Chelazzi (✉)
Dipartimento di Chimica, Università di Firenze, Sesto Fiorentino, Italy
e-mail: damiano.bandelli@unifi.it; david.chelazzi@unifi.it

F. Olivieri · G. Gentile
Istituto per i Polimeri, Compositi e Biomateriali, Consiglio Nazionale delle Ricerche, Pozzuoli, Naples, Italy
e-mail: federico.olivieri@cnr.it; gennaro.gentile@cnr.it

G. C. Lama · M. Lavorgna
Istituto per i Polimeri, Compositi e Biomateriali, Consiglio Nazionale delle Ricerche, Portici, Naples, Italy
e-mail: giuseppecesare.lama@cnr.it; marino.lavorgna@cnr.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_23

23.1 "Green" Oligomers as Gels/Coatings Precursors

Nowadays, the development of novel materials and tools in cultural heritage (CH) preservation represents a central requirement for enhancing intervention practices, reducing restorative time and avoiding risks related to the use of toxic compounds (Bandelli et al., 2024b, c). Despite the easiness of this concept, the material's design requires a strict translation from the type of restorative task required, to its desired physico-chemical properties. It follows that, given the multitude of materials, surface morphologies and degree of ageing found on CH objects, the research of "sustainable" and "smarter" advanced tools for counteracting degradation represent an ambitious, multidisciplinary field of study.

In the last decades, a vast library of systems based on polymers and oligomers, such as gels, hybrid materials, nanostructured fluids, protective coatings and polymeric films have been developed for CH preservation aims, enabling the cleaning, the consolidation and the protection (e.g. active coatings) of organic and inorganic (Casini et al., 2023; Bandelli et al., 2024b, c). If, on one hand, the use of polymers in, and beyond, CH goals rely on the high availability, low price and ease of application, on the other hand, most polymers employed in CH practices are obtained from non-renewable petrochemical resources. Given the growing significance of sustainability, renewability and zero-impact concepts in national and international policies, such as the European Green Deal, the research of alternatives to non-renewable materials is the main goal of CH scientists. Besides, the production of "green" polymeric systems should be carried out employing a diverse feedstock base, enabling optimum energy consumption, and employing benign solvents in all the steps of the material's production (Cheng et al., 2015; Casini et al., 2023).

However, the development and use of new materials represent a delicate task, since it is based on a careful evaluation of synthetic design, structure-property relationship of the materials, and the activity of the final systems. As a result, a vast library of features should be considered and tailored to access the desired effect, resulting in time-consuming practices if traditional "try and error" approaches are employed.

To this aim, the determination of a short list of desired features can be beneficial to speed up material's development. In particular, the knowledge of polymer hydrophilic lipophilic balance (HLB) is pivotal to tune parameters such as degradation and biodegradation, swelling capability, and processability. HLB calculation rely on counting single contributions connected to the compound's chemical identities, i.e. the methylene groups content and the types and contents of hydrophilic moieties, resulting in an optimum estimation for small molecules (Guo et al., 2006). Representing macromolecules able to rearrange in solution, polymers feature dynamics that are not only related to chemical composition but are strictly connected to the balance between polymer-solvent and polymer-polymer interactions, making HLB calculation a complex operation. In this regard, the octanol/water partition coefficient in its logarithm form (logP) is commonly employed to gain insights on the HLB of small molecules and amphiphilic polymers and oligomers.

Experimentally, logP can be obtained by means of different approaches such as the shake-flask method, chromatography, and nuclear magnetic resonance analyses, relying on the partition of the target compound in water or octanol phases (Harris & Logan, 2014). It follows that logP estimation depends on the solubility in water and octanol of the target compound, hindering such estimation for macromolecules that are not soluble in the two phases.

Aiming to comply with "green" metrics, a new protocol of logP estimation was developed employing a library of degradable oligoesters obtained via the reaction of selected dicarboxylic acids, i.e. sebacic, adipic, and succinic acid, and diols, 1,6-hexanediol and 1,4-butanediol, without the addition of any solvent or catalyst (Bandelli et al., 2024b, c). Such reactants can be produced avoiding the use of petrochemical resources and, according to the European Chemical Agency, are employed in fertilizers, cleaning products and pharmaceuticals. The final oligoester species (Ox) were analysed by means of size exclusion chromatography (SEC) in tetrahydrofuran mobile phase with a system equipped with multi-angle light scattering, viscometer and refractive index detector to access reliable molar mass estimation by means of both light scattering analysis and universal calibration approaches. Overall, both methodologies resulted in a similar molar mass estimation of ~3 kg mol^{-1} for all the Ox, while moderate to high dispersity index, above 1.36, were detected. In principle, having similar molar mass, the oligoesters differed in the chemical composition impaired from the use of different diols/diacids reactants. As a result, an increase of the parameter α of Mark-Houwink, calculated from SEC data, corresponding to a transition from compact to elongated structures in tetrahydrofuran, was detected increasing the calculated logP (clogP) of the oligoesters' repetition unit.

Aiming to gain insights on the dynamics of the Ox samples in a list of solvents with a broad range of logP, diffusion order spectroscopy nuclear magnetic resonance (DOSY NMR) analyses were performed in selected deuterated solvents, namely acetone, tetrahydrofuran, dichloromethane, chloroform, benzene and toluene at 25 °C. DOSY NMR analysis of the oligoesters enabled the estimation of their diffusion coefficient, that was translated to the hydrodynamic radius (R_h) by applying the Stokes-Einstein equation (Eq. 23.1).

$$R_h = \frac{k_b T}{6\pi\eta D} \tag{23.1}$$

where kb is the Boltzmann constant, T is the absolute temperature, η is the solvent viscosity at a given temperature and pressure, and D is the diffusion coefficient.

Independently on the sample analysed, the evolution of R_h over the solvent logP featured a pattern resembling a peak function, revealing that the Ox species featured a maximum R_h with solvents such as dichloromethane and chloroform (Fig. 23.1).

In principle, the capability of a solvent to dissolve a target macromolecule depends on the increase of polymer-solvent interactions, and the condition of highest solvation gives an indirect estimation of their logP. As expected, such estimation

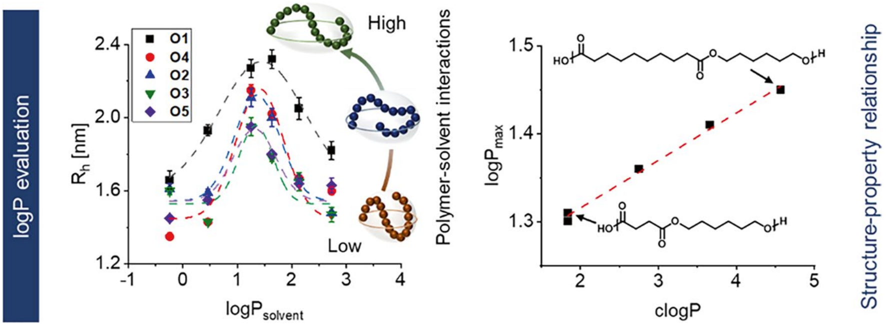


Fig. 23.1 Insights on the logP evaluation protocol. Left. Evolution of hydrodynamic radius over solvent's logP and fitting curves. Right. Evolution of the estimated logP from DOSY NMR analysis over repetition unit's logP. Reproduced with permissions from D. Bandelli et al., *Chem. Sci.* 2024, *15*, 2443–2455 (Bandelli et al., 2024b, c)

resulted in a linear logP increase over the clogP of the oligoesters' repetition unit, similarly to the trend depicted for the parameter *a* of Mark-Houwink (Fig. 23.1). Moreover, also bulk properties such as melting and crystallization temperature, and their degree of crystallinity linearly correlated with clogP increase, resulting in a strict structure-property relationship.

Overall, the library of "green" oligoesters featured similar molar mass, but different chemical composition, logP, and thermal properties, making them ideal candidates for the development of new materials such as coatings and gels for applications in cultural heritage practices and beyond.

In principle, the tailoring of polymeric features such as logP, degree of crystallinity, and glass temperature, are beneficial to tune its hydrolysis behaviour, a major parameter if degradable polymers are employed as coatings. In fact, the increase of such features reduces bulk permeability, due to a slower diffusion in the polymer bulk of water and hydrolysis reactants.

23.2 Composite Coatings for the Protection of Artworks

Traditionally, polyolefins such as polymethacrylates and polyacrylates are employed in coatings formulation for CH goals, resulting in the preparation of protecting layers (Bandelli et al., 2024b, c). Despite their use, such polymers can undergo degradative processes, resulting in the formation of patinas that should be removed to retrieve the original surface appearance. As an alternative, sustainable polymeric coatings have been developed from renewable biopolymers such as cellulose, pectin and chitosan (Caruso et al., 2023). Despite their use in CH practices, only few polymers employed in coatings have been extensively characterize with respect to their features, making the evaluation of structure-property relationship of outmost importance for further material's improvement.

In addition to the polymeric matrix, the development of sustainable and smart composites that, used as coatings, protect metal surfaces from corrosion by combining stimuli-responsive as well as superhydrophobic nanoparticles offers a promising solution for artworks long-term protection. This multifunctional approach addresses not only corrosion protection but also provides anti-biofouling and self-cleaning benefits (Piscitelli et al., 2019). An alternative strategy to protective coatings realized by embedding free active agents, such as corrosion inhibitors, within the polymeric matrix consists in approaches based on the loading of active agents into nanocarriers followed by the effective dispersion of the nanocarrier/active agent system in composite coatings. This strategy offers several advantages in the design of effective smart coatings:

(a) Due to their porosity, nanocarriers are potentially able to load high amounts of different active agents (i.e. anticorrosive and antifouling agents), allowing to overcome their solubility limit when used in polymeric coatings (Tundisi et al., 2023);
(b) Embedding active agents in the coatings through nanocarriers, also active agents that are not miscible with the coatings matrices can be used;
(c) Engineered nanocarriers/active agents systems can be designed, able to tailoring their release in selected conditions (stimuli-responsive release) (Bakhshian Nik et al., 2020);
(d) Nanocarriers protect the active agents from environmental degradation, such as UV-induced corrosion inhibitors degradation (Salzano de Luna et al., 2018);
(e) Enhancing nanocarriers dispersion and interfacial interactions with the coating matrix, also functional and structural properties of the coatings (e.g. mechanical, adhesion, indentation) can be improved.

Amongst different nanocarriers, mesoporous silica nanoparticles (MSNs) stand out for the relevant properties, including high surface area, chemical stability, low reactivity and good compatibility with several matrices (Olivieri et al., 2021a, b). More in detail, when MSNs are employed as nanocontainers of active species in coatings, both the loading of active agents and possibly their stimuli-responsive release must be properly designed and optimized. The release of inhibitor from MSNs can be modulated by taking account the inhibitor dimension and surface chemistry of MSN porous structure (Castaldo et al., 2020). More effectively, suitable capping/release mechanisms have to be designed to promote the release of the actives in selected conditions, ideally in presence of aggressive species for the substrate to be protected or soon after degradation phenomena start: capping/release mechanisms can be based on the application of external polymers or oligomer layers able to prevent the release of the agents, on the formation of coordination complexes in the external layer of the nanocarrier/active ingredient system (Xie et al., 2021), or by creating grafting the actives on the nanocarriers by reversible covalent bonds (Olivieri et al., 2023).

Recently, a highly effective capping/release system for the controlled release of a widely used anticorrosion agent, namely 1,2,3-benzotriazole (BTA), has been developed (Fig. 23.2, left) (Olivieri et al., 2021a, b). The capping system is realized by treating MSNs preloaded with BTA with a solution containing Ag(I) ions, that promotes the formation of a layer of BTA-Ag coordination complex around the loaded MSNs. This BTA-Ag complex has a pH-dependent stability, being soluble in acid (below 5) or basic conditions (above 8) while it is insoluble in neutral conditions. Thus, at neutral pH conditions, the capping system is stable and the release of BTA from the MSN nanocontainers is negligible. On the contrary, the BTA-Ag complex dissolves in acidic or basic conditions and BTA is released from MSN and diffuses into the coating matrix towards the metal substrate, creating a protective layer adsorbed on the metal surface to be protected.

However, when the BTA-Ag complex is solubilized and silver ions are released together with BTA, an active protective mechanism, due to the silver capability to sequestrate chloride ions and thus to delay the permeation of aggressive species toward the metal surface, is also effective (see Fig. 23.2, Left side).

The effectiveness of the MSN-BTA-Ag nanoparticles was validated in acrylic coatings applied on metals, demonstrating its superior protective effectiveness when the metal was aged by accelerated acid and basic corrosion tests. Activities are currently on going to develop further smart systems realized by loading onto MSN new bio-based anticorrosion agents, alternative to BTA, and suitable capping/release mechanisms and to exploit these systems in bio-derived and sustainable polymer coatings.

To further improve the protective performance of coatings, incorporating tailored superhydrophobic particles like Janus particles can be crucial. These particles are integrated into the coating and shield the underneath surfaces of artworks from harmful water interactions—whether from the environment or vandalism—by preventing any contact. Since most of developed sustainable coatings are water-based, the Janus particles must be dispersible in water while retaining their hydrophobicity. This is achieved by engineering nanoparticles with amphiphilic properties to improve dispersion in water-based coatings and hydrophobic properties to enhance surface protection (Fig. 23.2, Right side). Amongst different Janus nanoparticles used in protective coatings, silica based nanoparticles are gaining an even increasing interest for their effectiveness (Milian et al., 2023).

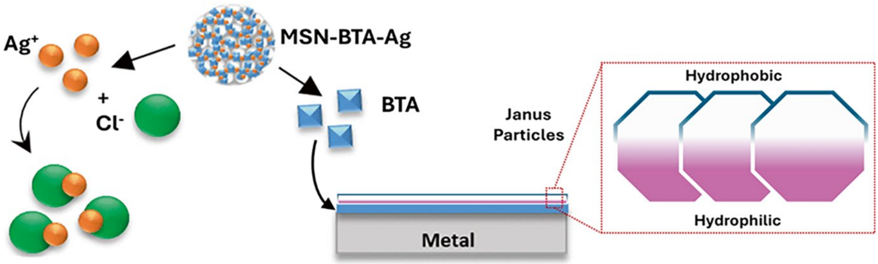


Fig. 23.2 (Left) Twofold anticorrosion mechanism of the developed MSN-BTA-Ag system for realization of active coatings; (Right) application of superhydrophobic nanoparticles for the realization of protective coatings

Combining the approaches above detailed, a very effective multifunctional coating can be designed, with a double layer structure: the inner layer in contact with the metal surface protects the metal surface with anticorrosion stimuli-responsive nanoparticles, while the outer superhydrophobic layer provides robust protection against water from environmental or intentional damage exploiting functional properties of Janus nanoparticles.

23.3 Gels for the Cleaning of Artworks

In addition to coatings, polymers and oligomers finds additional applications for CH practices as building blocks for gel development. Overall, polymeric gels represent some of the most advanced tools for cleaning practices, granting both optimum performances and controlled release of cleaning fluids on a surface of interest (Casini et al., 2023). Representing polymer-networks able of confining selected solvents or nanostructured fluids, gels can be obtained from polymers and monomers with different chemical identities and properties, resulting in hydrogels, i.e. capable of uptaking water solutions and dispersions, or organogels, i.e. capable of entrapping organic solvents (Bandelli et al., 2024b, c).

Traditionally, gels for CH practices are based on poly(acrylic acid) (PAA), polyacrylamide, poly(2-hydroxyethyl methacrylate) (pHEMA), polyvinylpyrrolidone (PVP), and poly(vinyl alcohol) (PVA), resulting in hydrogels and organogels with broad range of properties (Mastrangelo et al., 2020; Bandelli et al., 2024b, c). While such systems feature intriguing performance in CH practice there is still the need to design new gels capable to comply with “green” metrics, and, besides, to develop new protocol to estimate and to tune gel properties.

Representing gel systems capable of uptaking organic solvents, organogels enable the release of solvents that are traditionally employed in CH practices for the treatment of surfaces comprising pigments that are sensitive to water and, besides, to help the removal of unwanted organic layers such as coatings, and degraded patinas. Among the organogels employed in CH practices, systems based on the fully renewable and (bio)degradable castor oil (CO) are ideal candidates in CH practices, and can be obtained as polyurethanes (PU) without the use of solvents, employing reaction temperatures below 100 °C (Poggi et al., 2023). Such materials have been already employed for VOCs adsorption in the preventive conservation of museum enclosure but are in their infancy for remedial conservation aims and scope (Zuliani et al., 2022).

Representing a library of oligoesters with tailor made properties, such as logP, swelling behaviour in organic solvents and thermal properties, their use in CO organogels design can be beneficial to tune, and likely predict, the structure-property behaviour of the final materials. To this aim, a library of PU gels (Gx) was obtained from the reaction of CO, poly(hexamethylene diisocyanate) (pHDI), and Ox in a mass ratio of 72 to 18 to 10 in bulk at 80 °C (Bandelli et al., 2024b, c).

Already the study of the gelation process during the formation of PU a revealed that the use of Ox enabled a faster gelation time in comparison to the blank CO-PU system. Interestingly, the comparison between the gelation time over the clogP of Ox revealed that matching of Ox and pHDI clogP resulted in faster gelation. Moreover, DOSY NMR analysis of selected samples revealed that, at the beginning of the gelation process, Ox react faster with isocyanate in comparison to CO. Overall, both rheology and NMR analysis revealed that the gelation process is strictly correlated to the isocyanate reactivity, that is maximised when an additive matching the isocyanate hydrophobicity is employed. As a result, PU gelation in the presence of Ox determines the formation of Ox-enriched aggregates that facilitates the reaction with CO.

The final Gx polyurethanes featured micro- and nanoscale solid-like regions containing Ox species as depicted from small- and wide-angle X-ray scattering analyses, confirming the outcome of the reaction studies. The presence of oligoester aggregates resulted in a controlled variation of mechanical features at 25 °C as depicted from rheological analysis, resulting in an increase of both storage and loss modulus increasing oligoester's logP and, and consequently, Ox solid-like fractions.

Having accessed a new library of polyurethanes with tuned mechanical properties and featuring solid-like domains with well-defined HLB, solvent entrapment experiments were performed. As expected, the use of different oligoester additives with well-known logP in the PU design resulted in a controlled variation of the maximum of swelling behaviour. When solvents with lower logP in comparison with the oligoester additives, i.e. acetone and ethanol, were selected for swelling experiments, a linear decrease of the gel's maximum swelling was detected increasing the oligoester's additive logP (Fig. 23.3). Vice versa, the use of solvents with higher logP than the Ox species resulted in the opposite trend.

Insights on the process of solvent uptake were obtained from the Peppas-Salhin approach (Eq. 23.2), (Peppas & Sahlin, 1989) resulting in the estimation of the ratio between Case II transport, or material swelling, over Fickian transport, i.e. purely diffusive solvent transport in the PU matrix, R/F (Eq. 23.3).

$$\frac{m_t}{m_\infty} = k_F t^m + k_R t^{2m} \tag{23.2}$$

$$\frac{R}{F} = \frac{k_R}{k_F} t^m \tag{23.3}$$

where m_t is the mass of the PU-gel at time t, m_∞ is the maximum mass of the PU-gel obtained at the plateaux of swelling, k_F is the fickian constant, k_R is the Case II transport constant, and m is the purely Fickian diffusion exponent.

The results indicate that R/F followed the same trend depicted for the maximum swelling behaviour for solvents such as ethanol, acetone, methylethyl ketone, diethyl carbonate and p-xylene.

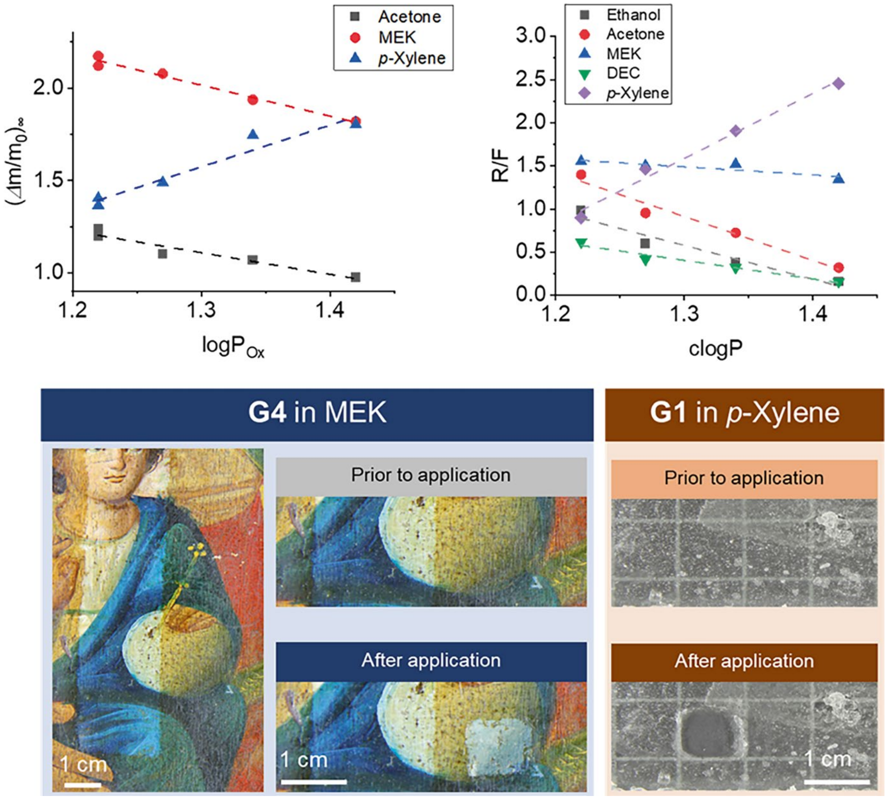


Fig. 23.3 Swelling behaviour and application of gels. Top left. Evolution of the maximum swelling capability over oligoester's logP ($\log P_{Ox}$). Top right. Evolution of R/F ratio obtained from Peppas Salhin equation (Eqs. 23.2 and 23.3) over $\log P_{Ox}$. Bottom. Cleaning tests using the CO-oligoester gels to remove varnish/coating from surfaces. The G4 gel was swollen in MEK and used to remove a polyhydroxy acid–based varnish from a painted wood panel. The G1 gel was swollen in p-xylene and used to remove beeswax from glass. The coated glass is lying on a slab with a grill that serves as spatial reference. Reproduced with permissions from D. Bandelli et al., *Chem. Sci.* **2024**, *15*, 2443–2455 and D. Bandelli et al., *Coll. Surf. A.* **2024**, *698, 134528* (Bandelli et al., 2024b, c)

The evaluation of the cleaning performances of PU-organogels was performed on ideal as well as real case study. In first instance, model mockups covered with wax (paraffin) or Paraloid B72 were treated with the Ox-based organogels that were previously swollen, up to doubling their mass, in p-xylene or acetone, respectively. The cleaning interventions resulted in a fast removal of both coatings in a fast, two applications of 10 min each, and controlled manner with minimum mechanical actions. At last, a byzantine icon case study covered with a degraded poly(hydroxy acids) varnish was treated with a selected gel swollen in methy lethyl ketone resulting in a prompt and effective varnish removal.

Overall, the development of new oligomeric species from renewable sources enabled the development of "green" castor oil polyurethanes with well-defined features, from structure, mechanical properties, and HLB behaviour. The tuning of such properties enabled the selective variation of solvent uptake mechanism and capability, making the new CO-PU materials ideal candidate for applications on surfaces exhibiting surface layers of hydrophobic varnish or organic degraded material.

Given the vast landscape of materials found in CH collections, cleaning practices based on gel do not solely aim for the removal of hydrophobic layers, but also on hydrophilic contaminants. In fact, already the accumulation of dust on CH objects results in the loss of the original surface appearance, requiring a prompt intervention. Nowadays, the use of PVA hydrogels represent the state-of-the-art materials for the removal of hydrophilic layers (Mastrangelo et al., 2020; Bandelli et al., 2024a). Such hydrogels exhibit optimal interfacial features, together with optimal micro- and nanostructural properties to carry out their function. To grant a uniform and fast cleaning action the porous PVA hydrogels must be able to embed cleaning fluids, allowing their diffusion at the interface and, at the same time, provide optimal roughness and adhesion. As a result, the structure-property of PVA hydrogels allow the applications of nanostructured fluids such as microemulsion, resulting in the removal of hydrophobic layers in substrates that are poorly sensible to water (Bandelli et al., 2024a). Recently, the role of gel's tortuosity, representing an evaluation of molecular diffusion in the gel matrix, has been introduced in the field of gels for cultural heritage preservation (Mastrangelo et al., 2024b). The tuning of such parameter has been obtained by means of varying the type of gel porogen, i.e. the additive that enables the formation of sponge-like interconnected cavity in the PVA cryogels, by varying its hydrophobicity (Mastrangelo et al., 2024a) Already the variation of the porogen structure, from linear to crosslinked, enabled the variation of mechanical properties, nanostructural features, and tortuosity of the final gels. Counterintuitively, the use of gel materials with high adaptivity in the removal of hydrophilic soil resulted in optimum performances when tortuosity increased, i.e. when molecular motions in the gel matrix were minimized, while gel adaptability on surfaces decreased. Overall, the study revealed that molecular motions of the solvent in the gel structure strongly impact the final applications, opening for additional development in the field of remedial conservation and beyond.

References

Bakhshian Nik, A., Zare, H., Razavi, S., Mohammadi, H., Torab Ahmadi, P., Yazdani, N., Bayandori, M., Rabiee, N., & Izadi Mobarakeh, J. (2020). Smart drug delivery: Capping strategies for mesoporous silica nanoparticles. *Microporous and Mesoporous Materials, 299*, 110115.

Bandelli, D., Casini, A., Guaragnone, T., Baglioni, M., Mastrangelo, R., Pensabene Buemi, L., Chelazzi, D., & Baglioni, P. (2024a). Tailoring the properties of poly(vinyl alcohol) "twin-chain" gels via sebacic acid decoration. *Journal of Colloid and Interface Science, 657*, 178–192.

Bandelli, D., Mastrangelo, R., Poggi, G., Chelazzi, D., & Baglioni, P. (2024b). New sustainable polymers and oligomers for cultural heritage conservation. *Chemical Science, 15*(7), 2443–2455.

Bandelli, D., Mastrangelo, R., Poggi, G., Chelazzi, D., & Baglioni, P. (2024c). Tailoring the properties of castor oil polyurethanes organogels with green oligoesters. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 698*, 134528.

Caruso, M. R., D'Agostino, G., Milioto, S., Cavallaro, G., & Lazzara, G. (2023). A review on biopolymer-based treatments for consolidation and surface protection of cultural heritage materials. *Journal of Materials Science, 58*(32), 12954–12975.

Casini, A., Chelazzi, D., & Baglioni, P. (2023). Advanced methodologies for the cleaning of works of art. *Science China Technological Sciences, 66*(8), 2162–2182.

Castaldo, R., de Luna, M. S., Siviello, C., Gentile, G., Lavorgna, M., Amendola, E., & Cocca, M. (2020). On the acid-responsive release of benzotriazole from engineered mesoporous silica nanoparticles for corrosion protection of metal surfaces. *Journal of Cultural Heritage, 44*, 317–324.

Cheng, H. N., Gross, R. A., & Smith, P. B. (2015). Green polymer chemistry: Some recent developments and examples. *Green Polymer Chemistry: Biobased Materials and Biocatalysis, American Chemical Society, 1192*, 1–13.

Guo, X., Rong, Z., & Ying, X. (2006). Calculation of hydrophile–lipophile balance for polyethoxylated surfactants by group contribution method. *Journal of Colloid and Interface Science, 298*(1), 441–450.

Harris, M. F., & Logan, J. L. (2014). Determination of log Kow values for four drugs. *Journal of Chemical Education, 91*(6), 915–918.

Mastrangelo, R., Chelazzi, D., Poggi, G., Fratini, E., Pensabene Buemi, L., Petruzzellis, M. L., & Baglioni, P. (2020). Twin-chain polymer hydrogels based on poly (vinyl alcohol) as new advanced tool for the cleaning of modern and contemporary art. *Proceedings of the National Academy of Sciences, 117*(13), 7011–7020.

Mastrangelo, R., Bandelli, D., Pensabene Buemi, L., & Baglioni, P. (2024a). "Twin chain" PVA Cryogels with controlled tortuosity as advanced materials for cleaning of works of art. *Advanced Functional Materials, 34*(41), 2404287.

Mastrangelo, R., Chelazzi, D., & Baglioni, P. (2024b). New horizons on advanced nanoscale materials for cultural heritage conservation. *Nanoscale Horizons, 9*(4), 566–579.

Milian, Y. E., Claros, M., Ushak, S., & Vallejos, S. (2023). Silica based Janus nanoparticles: Synthesis methods, characterization, and applications. *Applied Materials Today, 34*, 101901.

Olivieri, F., Castaldo, R., Cocca, M., Gentile, G., & Lavorgna, M. (2021a). Innovative silver-based capping system for mesoporous silica nanocarriers able to exploit a twofold anticorrosive mechanism in composite polymer coatings: Tailoring Benzotriazole release and capturing chloride ions. *ACS Applied Materials & Interfaces, 13*(40), 48141–48152.

Olivieri, F., Castaldo, R., Cocca, M., Gentile, G., & Lavorgna, M. (2021b). Mesoporous silica nanoparticles as carriers of active agents for smart anticorrosive organic coatings: A critical review. *Nanoscale, 13*(20), 9091–9111.

Olivieri, F., Scherillo, F., Castaldo, R., Cocca, M., Squillace, A., Gentile, G., & Lavorgna, M. (2023). Effectiveness of mesoporous silica nanoparticles functionalized with benzoyl chloride in pH-responsive anticorrosion polymer coatings. *ACS Applied Polymer Materials, 5*(8), 5917–5925.

Peppas, N. A., & Sahlin, J. J. (1989). A simple equation for the description of solute release. III. Coupling of diffusion and relaxation. *International Journal of Pharmaceutics, 57*(2), 169–172.

Piscitelli, F., Tescione, F., Mazzola, L., Bruno, G., & Lavorgna, M. (2019). On a simplified method to produce hydrophobic coatings for aeronautical applications. *Applied Surface Science, 472*, 71–81.

Poggi, G., Santan, H. D., Smets, J., Chelazzi, D., Noferini, D., Petruzzellis, M. L., Pensabene Buemi, L., Fratini, E., & Baglioni, P. (2023). Nanostructured bio-based castor oil organogels for the cleaning of artworks. *Journal of Colloid and Interface Science, 638*, 363–374.

Salzano de Luna, M., Buonocore, G. G., Giuliani, C., Messina, E., Di Carlo, G., Lavorgna, M., Ambrosio, L., & Ingo, G. M. (2018). Long-lasting efficacy of coatings for bronze artwork conservation: The key role of layered double hydroxide nanocarriers in protecting corrosion inhibitors from photodegradation. *Angewandte Chemie International Edition, 57*(25), 7380–7384.

Tundisi, L. L., Ataide, J. A., Costa, J. S. R., Coêlho, D. d. F., Liszbinski, R. B., Lopes, A. M., Oliveira-Nascimento, L., de Jesus, M. B., Jozala, A. F., Ehrhardt, C., & Mazzola, P. G. (2023). Nanotechnology as a tool to overcome macromolecules delivery issues. *Colloids and Surfaces B: Biointerfaces, 222*, 113043.

Xie, P., He, Y., Zhong, F., Zhang, C., Chen, C., Li, H., Liu, Y., Bai, Y., & Chen, J. (2021). Cu-BTA complexes coated layered double hydroxide for controlled release of corrosion inhibitors in dual self-healing waterborne epoxy coatings. *Progress in Organic Coatings, 153*, 106164.

Zuliani, A., Bandelli, D., Chelazzi, D., Giorgi, R., & Baglioni, P. (2022). Environmentally friendly ZnO/Castor oil polyurethane composites for the gas-phase adsorption of acetic acid. *Journal of Colloid and Interface Science, 614*, 451–459.

Chapter 24
Structural Reinforcement and Consolidating Treatment of Organic Materials

Marcella Ioele, Barbara Lavorini, Manuel Bucciarelli, Carolina Rigon, Antonella Di Giovanni, Patrizia Giacomazzi, Federica Antonelli, Elena Adanti, Giulia Galotta, Dsesiree Rossi, Maddalena Giuliano, and Maria Vera Quattrini

Abstract Conservation and restoration interventions must be implemented whenever the preservation of a cultural asset and its transmission to future generations, is deemed at risk. The causes and mechanisms by which cultural heritage undergoes progressive deterioration are numerous and complex, as are the restoration operations devised to address various issues and ensure their preservation. In light of the recent and growing need to identify solutions that are not only effective but also environmentally sustainable, promoting a gradual ecological transition in the field of cultural heritage, there is increasing interest in green materials and methods. Within this context, the ICR, is currently exploring the possibilities of bio-based solutions for consolidation purposes. The joint efforts of restoration and scientific laboratories is especially devoted to experimental campaigns started in order to test innovative environmentally friendly nanomaterials. As a part of these activities, ICR is recently focussing on the investigation of nanocellulose compounds for the consolidation and structural reinforcement of organic supports of cultural heritage, such as textile fibres, canvas, wood and paper. Nanocellulose, capable of obtaining good results without altering their main characteristics and chemical properties of cellulosic substrates, represents an attractive alternative to the use of synthetic polymers.

Keywords Nano-materials · Nano-cellulose · Canvas · Wood · Paper · Consolidation · Green chemistry

---

M. Ioele (✉) · B. Lavorini · M. Bucciarelli · C. Rigon · A. Di Giovanni · P. Giacomazzi · F. Antonelli · E. Adanti · G. Galotta · D. Rossi · M. Giuliano · M. V. Quattrini
Istituto Centrale per il Restauro (ICR), Rome, Italy
e-mail: marcella.ioele@cultura.gov.it; barbara.lavorini@cultura.gov.it; manuel.bucciarelli@uniroma1.it; carolina.rigon@uniroma1.it; antonella.digiovanni@cultura.gov.it; patrizia.giacomazzi@cultura.gov.it; fedantonelli@gmail.com; elena.adanti@gmail.com; giulia.galotta@cultura.gov.it; mariavera.quattrini@cultura.gov.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_24

24.1 Introduction

The Istituto Centrale per il Restauro (ICR), as a part of the wp5 activities of spoke 7, is conducting studies aimed at facing the challenging task of applying sustainable approaches for the structural reinforcement of works of art made of different organic materials (paper, wood, textile fibres, and fabrics). Solutions based on environmentally friendly materials and methods and their combinations have been considered to outline protocols and best practices for a correct application on Cultural Heritage, both in indoor and outdoor environments.

Organic materials used as paintings support (i.e., cellulosic textiles, wood or paper) due to their physical-chemical features are prone to degradation, therefore, it is essential to establish methods for their preservation (Fig. 24.1). The testing of new methods encompasses the evaluation of mechanical properties and the absence of negative effects on the original materials.

One of the most frequent interventions on organic supports is the consolidation of damaged textile fibres belonging to different types of artefacts, such as ancient garments, tapestries, archaeological fabrics, contemporary artworks and degraded canvas of paintings.

Consolidation treatments of textile fibres are usually poorly reversible, and the products currently used often alter the material's natural hygroscopicity and sometimes its colour, softness and flexibility; however, the degree of degradation makes it sometimes necessary to carry on this type of operation, and it is therefore fundamental to study and perform research on new products that do not significantly alter the appearance and characteristics of the constituent materials. Conservative

Fig. 24.1 Textile fibres in poor conservation conditions

solutions are clearly numerous and require to be specifically modulated for each case of study.

New generation nanomaterials of natural origin, particularly those derived from organic fibres (cellulose, fibroin, keratin, collagen), might represent a valid alternative to the use of synthetic polymers in repairing the damage occurred to the fibre by degradation, without altering its chemical composition. This type of approach, in addition to being respectful of the original material, is also eco-sustainable since these nanoproducts are obtained from natural substances.

24.2 Structural Reinforcement of Organic Supports with Nanocellulose

Nanocellulose has gained significant attention in recent years, due to its application in several important areas, including the conservation of Cultural Heritage. Based on production process, primarily determining its structure, dimensions and properties, nanocellulose can be classified into three categories: bacterial nanocellulose (BNC), cellulose nanofibres (CNF), cellulose nanocrystals (CNC) (Cataldi, 2015; Dreyfuss-Deseigne 2017; Völkel et al., 2017; Bergamonti et al., 2017; Neychyporchuk et al., 2018; Bridarolli et al., 2018a; Bridarolli et al., 2018b; Bridarolli, 2020; Bridarolli et al., 2020; Kolman et al., 2018; Böhme et al., 2020; Operamolla et al., 2021; Pradhan et al., 2022; Madsen et al., 2023).

Regardless of the type, nanocelluloses can be functionalized with groups capable of modulating some of their properties, such as hydrophilicity or resistance to biodegradation (Fig. 24.2).

For some years now, the ICR has been conducting studies on the efficacy of CNC, BNC and CNF for the structural reinforcement of wooden sculptures, archaeological wood, paper supports, canvas, and textile fibres in general. The research, which involved a series of tests on laboratory mock-ups and final application on the works of art, was carried out in the context of various SAF ICR master's degree thesis (Madeddu 2021; Sanfilippo 2022; Bucciarelli, 2022; Donati, 2023;

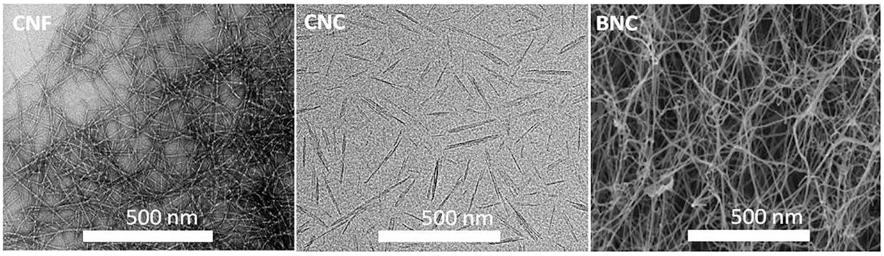


Fig. 24.2 Scanning electron microscope images of the structures of nanofibrillated cellulose (CNF), crystalline nanocellulose (CNC) and bacterial nanocellulose (BNC) (Thomas & Pottathara, 2020)

Rossi-Giuliano, 2024; Adanti, 2023), (Antonelli et al., 2020; Donati et al., 2023; Donati et al., 2024; Bucciarelli et al., 2024; Adanti et al., 2024) and is currently the subject of PhDs recently funded by CHANGES project.[1,2]

Concerning paintings on canvas, the consolidation of the textile support is of utmost significance, since it can allow to avoid or to defer over time a more invasive lining intervention. The intimate relationship of the canvas with the pictorial layers constitutes a determining element in the selection of the most suitable consolidating product and method to be used, for this reason the studies (Bucciarelli, 2022, Bucciarelli et al., 2024, Rossi-Giuliano, 2024) have been carried out through the production of a large number of mock-ups replicating the stratigraphy of ancient oil paintings on linen and hemp canvas (Fig. 24.3).

Performances of different types of nanocellulose have been compared with those of several other products, both of natural and synthetic origin, already in use for this kind of operation. Tensile tests, colorimetric and pH measurements were carried out before and after artificial ageing performed in climate chambers. The nanocellulose proved to be effective in improving the tensile strength of the canvas without changing substantially its natural hygroscopicity and appearance. After the experimental stage, the CNC was deemed to be the best one and so it was used to successfully treat the canvas supports of two seventeenth century Italian oil paintings (Fig. 24.4).

Further aspects about the use of CNC and its possible drawbacks are being addressed[1], to provide yet more insights regarding crucial aspects such as the penetration of the nanomaterial into the microstructure of the canvas, and its adhesion

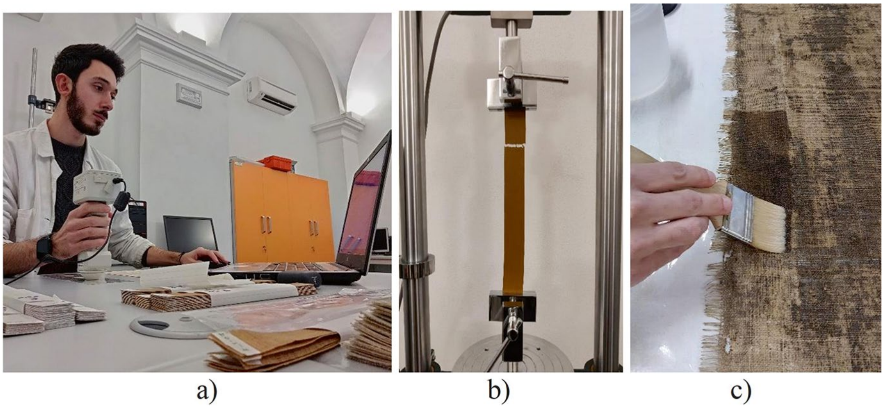

a) b) c)

Fig. 24.3 Colorimetric measurements performed on mock-ups treated with nanocellulose (**a**); tensile test performed on a mock-up treated with nanocellulose (**b**); application of CNC on the back of a painting (**c**)

---

[1] Manuel Bucciarelli, The use of nanocellulose for the conservation and restoration of paintings on canvas: proposal for the use of a biopolymer for a more sustainable restoration intervention, *National PhD in Heritage Science, 39° cycle, CV1*, in progress.

[2] Carolina Rigon, Application of innovative natural products and nano-materials for consolidation of degraded organic supports, *National PhD in Heritage Science, 39° cycle, CV1*, in progress.

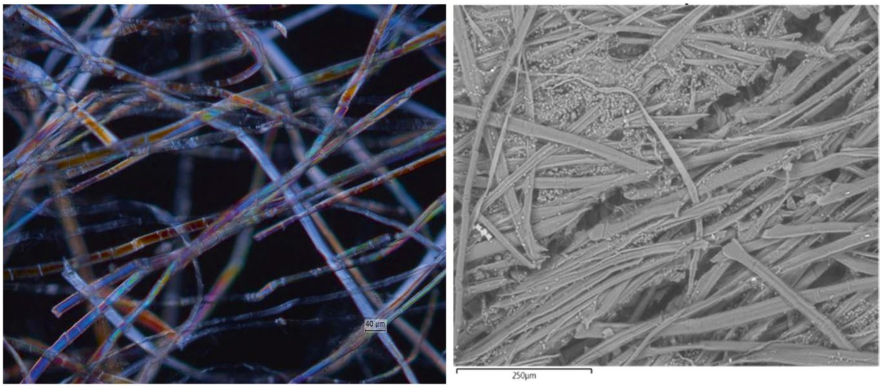
Fig. 24.4 Oil painting on canvas (unknown artist), after 1655, *The martyrdom of saint Barba*ra, from San Salvi deposit in Florence (**a**). Oil painting on canvas *The marriage of the Virgin* by Antonio Circignani, 1612, from Palazzo Petrucci deposit in Orvieto (**b**). The badly degraded canvases of the paintings were consolidated with CNC

towards the textile support. The possibility of reducing the amount of water applied to the canvas or dispersing CNC in non-polar solvents are also being addressed, in order to provide an answer to the main drawback of this material. Concurrently, new methodologies are being developed to temporarily seal the canvas to preserve it from unwanted impregnations during the reattaching of the flaking paint. This line of research is deeply connected to the previous one since it allows to maintain the textile support as unaltered as possible, operating on it in a fine-tuned way.

Another line of study[2] is focused on evaluating the potential of nanocellulose for structural reinforcement of cuts and rips on paper and for the consolidation of Japanese prints. Common paper consolidation practices, involving the use of small pieces of very thin paper applied on the back with adhesive products can affect paper transparency and this effect should be avoided when working on Japanese prints, being the transparency one of the main characteristics of these artefacts. For this purpose, tests are being performed by applying different types of nanocellulose, dispersed in water or in hydro-alcoholic solution, on test-samples realised by reproducing the artistic technique of Japanese prints (Fig. 24.5).

Japanese paper test-samples have been altered by reproducing manually rips and clean cuts by a scalpel blade. The effectiveness of nanocellulose in repairing cuts on cellulosic fibres has been monitored by scanning electron microscope (SEM) investigation (Fig. 24.6). Colorimetric analyses have been performed on untreated

Fig. 24.5 Application of CNC on test samples of Japanese paper realised by ukiyo-e print technique



a) b)

Fig. 24.6 Japanese paper for test samples. Optical microscope image under polarised transmitted light (**a**); BSE SEM image (**b**) samples and on treated ones before and after the ageing process to mainly evaluate any possible surface alteration but also to control the stability of the system over time.

24.3 Structural Reinforcement of Paleo-botanical Wood in an Outdoor Environment: The Dunarobba Fossil Forest

The Dunarobba Fossil Forest (DFF) came to light between the 1970s and 1980s, inside a clay quarry located in the Umbria region (Italy). It currently consists of approximately 50 trunks of gigantic conifers probably belonging to an extinct sequoia species, *Taxodioxylon gypsaceum* dated back to the plio-pleistocenic period (Fig. 24.7) (Biondi & Brugiapaglia, 1991; Martinetto et al., 2014). In that period a large part of Umbria was occupied by the lacustrine basin of Tiber. During their life, the trees were progressively covered by clay-silty sediments coming from the lake; this allowed their preservation in standing position thanks to the anoxic conditions created by deposits.

By now, the trunks are preserved in situ; they are partly excavated, emerging from the ground for some metres, and partly still buried in sediments. This position guarantees the presence of humidity in the internal part of trunks, linked to the water rising by capillarity from the subsoil along the trunk. Due to the rising temperatures imposed by climate change, in recent years the water gradient inside trunks is decreasing and a progressive loss of humidity, from the outside towards the central part of the trunks and from the base towards the apical end, has been registered. This

Fig. 24.7 Dunarobba *Fossil* Forest

condition is causing strong contractions of wood, with consequent deformations, orthogonal fracturing and material loss.

The experimental work has the aim of setting up a protocol for the in situ conservation of the trunks and the mitigation of the gradual drying of the exposed parts. In the first part of the study, products belonging to different classes (e.g., consolidating materials, adhesives, protective coatings, biocides and stucco) were selected and tested on wood specimens obtained from erratic fragments coming from the DFF (Fig. 24.8). Products to be tested were selected based on the criteria of minimum environmental impact and safety for the operator, without neglecting the conservation needs of the good itself (compatibility with the constituent material, chemical stability, reversibility and/or retractability, chromatic appearance etc.). To evaluate the ability of the products to withstand the stresses linked to outdoor exposure, tests were carried out involving the exposure to biological deteriogens, accelerated ageing cycles (light exposure, thermo-hygrometric variations), evaluation of dimensional stability, and vapour permeability.

Based on the laboratory test, products that had given the best results for each category were selected for a combined use and following the best application practices on one of the trunks of DFF (trunk n. 11 V, Fig. 24.9), selected in agreement with the *Superintendency of Archaeology, Fine Arts and Landscape* of Umbria region, as representative of the main conservation problems present on the site. At present, it has been possible to visually evaluate any changes occurred during the past year: the appearance of the surfaces has remained unchanged, with the exception of a powdery substance caused by the earthy deposits generated by its natural exposure. More in-depth investigations and further tests are planned in the near future.

Fig. 24.8 Test samples realised with Dunarobba ancient wood

Fig. 24.9 Trunk n. 11V

Acknowledgments The authors would like to thank Dr. Elena Roscini, from Superintendency of Archaeology, Fine Arts and Landscape of Umbria region, and Dr. Benedetto Pizzo, National Research Council of Italy-Institute of BioEconomy (IBE-CNR), for their collaboration in the frame of the experimentation on the Dunarobba Fossil Forest wood.

References

Adanti, E. (2023). *The case of Dunarobba fossil Forest: Conservative proposal for a trunk of the Pliocene in situ*. Master degree thesis (ICR).

Adanti, E., Galotta, G., Ioele, M., Roscini, E., Pizzo, B., Antonelli, F., Rigon, C., Conti, L., & Di Giovanni, A. (2024). Conservazione in situ di un tronco della Foresta Fossile di Dunarobba. Studio di materiali e metodi di intervento. *Atti del XXII Congresso Nazionale IGIIC—Lo Stato dell'Arte 22–17 - 19 ottobre 2024, Palazzo dei Capitani del Popolo,* Ascoli Piceno.

Antonelli, F., Galotta, G., Sidoti, G., Zikeli, F., Nisi, R., Davidde, B., & Romagnoli, M. (2020). Cellulose and lignin nano-scale consolidants for waterlogged archaeological wood. *Frontiers in Chemistry, 8*, 32.

Bergamonti, L., Graiff, C., Isca, C., Predieri, G., Lottici, P. P., Di Maggio, R., Palanti, R., Maistrello, L., & Montanari, M. (2017). Trattamenti sostenibili per la protezione e il consolidamento di legno e carta. *La chimica e l'industria*, *5*, 9–17. ISSN 2283-544X. https://doi.org/10.17374/CI.2017.99.5.9

Biondi, E., & Brugiapaglia, E. (1991). Taxodioxylon gypsaceum (Goppert) Krausel, nella foresta fossile di Dunarobba (Umbria, Italia centrale). *Flora Mediterranea*, 111–120.

Böhme, N., Anders, M., Reichelt, T., Schulmann, K., Bridarolli, A., & Chevalier, A. (2020). New treatments for canvas consolidation and conservation. *Heritage Science, 8*, 16. https://doi.org/10.1186/s40494-020-0362-y

Bridarolli, A. (2020). *Multiscale approach in the assessment of nanocellulose-based materials as consolidants for painting canvases*. Doctoral thesis (Ph.D), UCL (University College London).

Bridarolli, A., Odlyha, M., Nechyporchuk, O., Holmberg, K., Ruiz-Recasens, C., Bordes, R., & Bozec, L. (2018a). Evaluation of the adhesion and performance of natural consolidants for cotton canvas conservation. *ACS Applied Materials & Interfaces, 10*(39), 33652–33661. https://doi.org/10.1021/acsami.8b10727

Bridarolli, A., Nechyporchuk, O., Odlyha, M., Oriola, M., Bordes, R., Holmberg, K., Anders, M., Chevalier, A., & Bozec, L. (2018b). Nanocellulose-based materials for the reinforcement of modern canvas-supported paintings. *Studies in Conservation, 63*(Suppl 1), 332–334. https://doi.org/10.1080/00393630.2018.1475884

Bridarolli, A., Nualart-Torroja, A., Chevalier, A., Odlyha, M., & Bozec, L. (2020). Systematic mechanical assessment of consolidants for canvas reinforcement under controlled environment. *Heritage Science, 8*, 52. https://doi.org/10.1186/s40494-020-00396-x

Bucciarelli, M. (2022). *The consolidation of cellulosic textile supports: the potentiality of crystalline nanocellulose in the field of conservation: the case study of the oil painting on canvas from the Cortona area depicting the Martyrdom of a saint*. Master degree thesis (ICR).

Bucciarelli, M., Lavorini, B., Graiff, C., & Ioele, M. (2024). Il restauro di un dipinto a olio su tela di ambito cortonesco. L'impiego della nanocellulosa cristallina per il consolidamento dei supporti cellulosici. *Kermes*, 31–42.

Cataldi, A. (2015). A comparison between micro- and nanocellulose-filled composite adhesives for oil paintings restoration. *Nanocomposites*, 195–203.

Donati, S. (2023). *La Torre by Maria Lai, study and restoration of a complex multi-material work. research into products for twine consolidation and application of crystalline nanocellulose*. Master degree thesis (ICR).

Donati, S., Ioele, M., Rigon, C., Pitocco, M., Malintoppi, A., & Sacco Perasso, C. (2023). La Torre di Maria Lai (1971-2002); applicazione delle nanocellulose cristalline per il consolidamento dello spago di un'opera polimaterica complessa. *Atti del XI Congresso Nazionale IGIIC – Lo Stato dell'Arte 21, 19 - 21 ottobre 2023, Accademia di Belle Arti di Verona*.

Donati, S., Ioele, M., Rigon, C., Sacco Perasso, C., Torre, M., Pitocco, M., & Malintoppi, A. (2024). Study and application of crystalline nanocellulose for the consolidation of the polymaterial artwork "La Torre" (1971-2002) by Maria Lai. *IIC Lima Congress 23-27 Sept. 2024, Sustainable Solutions for Conservation: New Strategies for new times*.

Dreyfuss-Deseigne, R. (2017). Nanocellulose films in art conservation. *Journal of Paper Conservation, 18*(1), 18–29. https://doi.org/10.1080/18680860.2017.1334422

Kolman, K., Nechyporchuk, O., Persson, M., Holmberg, K., & Borde, R. (2018). Combined nanocellulose/nanosilica approach for multiscale consolidation of painting canvases. *ACS Applied Nano Materials, 1*, 2036–2040.

Madeddu, F. (2021). *The restoration of the wooden sculpture representing Saint Anthony of Padua from the Convent of Santa Maria di Loreto di Toro (CB)*. Experimental study of bioconsolidants for wood, *master degree thesis (ICR)*

Madsen, I. H., Odlyha, M., Andersen, C. K., Bridarolli, A., Corte-León, H., & Bozec, L. (2023). Nanomechanics of linen canvases treated with novel nanocellulose-based materials. In *Proceedings of ICOM-CC 20th Triennial Conference, Valencia, Spain*. https://www.icom-cc-publications-online.org/

Martinetto, E., Bertini, A., Basilici, G., Baldanza, A., Bizzarri, R., Cherin, M., Gentili, S., & Pontini M. R. (2014). The plants of record of the Dunarobba and Pietrafitta sites in the Plio-pleistocene Paleoenvironmental context of central Italy. *Alpine and Mediterranean Quaternary*, *27*, 29–72.

Neychyporchuk, O., Kolman, K., Bridarolli, A., Odlyha, M., Bozec, L., Oriola, M., Campo-Francés, G., Persson, M., Holmberg, K., & Bordes, R. (2018). On the potential of using nanocellulose for consolidation of painting canvases. *Carbohydrate Polymers, 194*, 161–169.

Operamolla, A., Mazzucca, C., Capodieci, L., Di Benedetto, F., Severini, L., Titubante, M., Martinelli, A., Castelvetro, V., & Micheli, L. (2021). Toward a reversible consolisation of paper material using cellulose nanocrystals. *ACS Applied Materials & Interfaces, 13*, 44972–44982.

Pradhan, D., Jaiswal, A. K., & Jaiswal, S. (2022). Emerging technologies for the production of nanocellulose from lignocellulosic biomass. *Carbohydrate Polymers, 285*(1), 119258.

Rossi, D., & Giuliano, M. (2024). *The Restoration of The wedding of the Virgin, by Antonio Circignani: new insights on the use of nanocellulose for the consolidation of textile supports*. Master's degree thesis (ICR).

Sanfilippo, S. (2022). *Restoration project of the polychrome wooden sculpture depicting Saint Anthony of Padua from the 17th century, located inside the Church of San Francesco d'Assisi in Sermoneta (LT)*. Experimentation of new eco-sustainable consolidation methods, master degree thesis (ICR).

Thomas, S., & Pottathara, Y. B. (2020). *Nanocellulose based composites for electronics* (p. 2). Elsevier. ISBN: 9780128223505.

Völkel, L., Ahn, K., Hähner, U., Gindl-Altmutter, W., & Potthast, A. (2017). Nano meets the sheet: Adhesive free application of nanocellulosic suspensions in paper conservation. *Heritage Science, 5*.

Chapter 25
Sustainable Conservation for Street-Art: Preliminary Research of a Green Coating and Monitoring of the Degradation of a Case Study

Chiara Cianci, Elisa Gualini, Serena Morrocchesi, and Rodorico Giorgi

Abstract This chapter addresses the challenges of conserving street art, focusing on a sustainable hybrid coating made of chitosan and nanosilica. This coating protects murals from environmental damage while preserving their visual appeal. Physico-chemical characterization confirms its strong protection, compatibility with various surfaces, and breathability. Studies on mock-ups and accelerated aging tests validate its durability and stability, making it a promising solution for the long-term preservation of contemporary murals. The chapter also presents data from monitoring a real case, proposing a potential application for this protective coating.

Keywords Chitosan hybrids · Green conservation · Protective coatings · Street-art · Sustainability

25.1 Street-Art and Its Conservation Challenges

Contemporary muralism is a widely accessible form of art that is increasingly visible in cities worldwide. It is known for its versatility and strong social and cultural significance, aiming to engage the public and make art accessible to everyone. This movement originated in the 1960s as Street-art, a rebellious and provocative form of expression aimed at defying societal norms and authority through illegal activities. Initially focused on protest and resistance, Street-art evolved by the 1980s to integrate social issues into urban landscapes, giving rise to Urban Art. This term emphasizes its connection to the city and contemporary art practices. Urban Art has become increasingly recognized as a legitimate form of art, distancing itself from the negative perceptions of vandalism.

C. Cianci · E. Gualini · S. Morrocchesi · R. Giorgi (✉)
Department of Chemistry, University of Florence, Sesto Fiorentino, Italy
e-mail: chiara.cianci@unifi.it; elisa.gualini@unifi.it; serena.morrocchesi@unifi.it; rodorico.giorgi@unifi.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_25

Despite its evolution, Urban Art has maintained its core purpose as a medium for political, ethical, and social commentary. Artists continue to use their work to convey important messages to the current generation, with the hope of preserving these ideas for future audiences. Urban Art not only enhances the aesthetic appeal of public spaces but also plays a role in the ethical and social rejuvenation of often overlooked or disadvantaged neighborhoods. These artworks have contributed to raising public awareness and promoting a deeper appreciation for both the themes and techniques employed by the artists (Rainer et al., 2003).

Urban Art's reliance on walls as a canvas ensures accessibility to a wide audience, continuing the tradition of outdoor murals that began in the early twentieth century. The growth of Street-art has led to large-scale murals, capturing the interest and support of local governments and private individuals. While efforts to preserve these works are increasing, challenges remain in ensuring their long-term survival.

Street-art presents significant challenges due to the absence of established conservation methods and the ephemeral nature of the artworks. It is crucial to collaborate with artists and actively engage in discussions about preservation methods, as they often overlook the long-term preservation of their pieces. Moreover, the constant evolution of artistic techniques and materials adds complexity to the selection of appropriate restoration methods, and ethical, legal, environmental, and economic challenges further complicate preservation efforts (Sawicki, 2022).

Street-art faces numerous forms of deterioration, including paint cracking, color fading, and detachment from the substrate. Key factors driving this decay include climate conditions, traffic, and wall orientation. Direct exposure to environmental elements like sunlight, fluctuating temperatures, humidity, water, and pollutants accelerates deterioration. Biological agents and vandalism further compromise the legibility and longevity of these artworks. These degradation processes often act synergistically, requiring further investigation to fully understand their impact.

The materials used in Street-art, their chemical composition, and their interaction with the atmosphere play a crucial role in defining effective conservation strategies. Unlike traditional wall paintings, Street-art is created with synthetic organic paints applied on various inorganic substrates, such as concrete, brick, and plaster. The wide range of materials, including spray cans, brushes, and rollers, allows artists to achieve unique aesthetic effects but also adds complexity to conservation efforts (Sanchez-Pons et al., 2015).

When the paint is not properly applied, issues such as poor adhesion, water infiltration, and cracking arise. Additionally, mechanical forces from rain or temperature changes can hasten the artwork's degradation. The synthetic compounds used in Street-art behave differently from those in traditional murals, making conventional conservation techniques insufficient. The variability in materials and the evolving nature of commercial paint formulations further complicate the development of conservation protocols. This highlights the need for specialized strategies to preserve Street-art's unique properties and ensure its longevity.

25.2 Green Protective Coatings for Street-Art

The ongoing deterioration of Street-art has prompted research into developing protective coatings that can safeguard these works from environmental damage. These coatings must be compatible with both the paint layers and the inorganic substrates typically found in urban environments. The coatings should also be optically transparent to preserve the aesthetic quality of the artwork, protect against moisture and UV light, and prevent chemical reactions with the painted surfaces. The challenge is to find coatings that can protect the murals without interfering with the breathability of the surface, which consists of both organic materials (such as paint) and inorganic ones (such as concrete or brick).

Sustainability is another important consideration. Conservators are increasingly turning to environmentally friendly materials like biopolymers. These materials, which include biodegradable substances like chitosan, offer a more sustainable approach to conservation (Pagnin et al., 2023).

Chitosan is a polysaccharide obtained through the partial deacetylation of chitin, the second most abundant biopolymer after cellulose. This material can be produced by the valorization of marine biomass, in particular, crustacean shell waste (Vidal et al., 2022). Moreover, this material possesses several properties that make it a promising candidate for use in protective coatings, including its biodegradability, film-forming ability, antimicrobial properties, and cost-effectiveness. Derived from chitin, a biopolymer found in crustacean shells, chitosan has been widely used in other conservation efforts, including in paper, wood, and stone preservation. However, it has limitations in terms of mechanical strength and compatibility with inorganic substrates, which can reduce its effectiveness as a protective material for Street-art.

To overcome these limitations, the possibility of combining chitosan with inorganic materials, such as nanosilica, to create hybrid coatings with enhanced properties was explored. Nanosilica is known for its high surface energy, strong mechanical strength, and stability, making it a valuable additive for improving the physical properties of protective coatings. It is also widely used in waterborne coatings to ensure compatibility with both organic paint films and inorganic substrates. Functionalized nanosilica, when combined with chitosan, can improve the coating's adhesion, flexibility, and durability, making it more suitable for the harsh outdoor conditions that Street-art is typically exposed to (Cao et al., 2023).

Our research was centered on developing and applying a hybrid coating made of chitosan and nanosilica specifically designed for the conservation of contemporary murals. We aimed to take advantage of chitosan's excellent film-forming ability, optical and antimicrobial properties, as well as its sustainability. We also investigated how silica can enhance the properties of chitosan films, especially its compatibility with paints and concrete substrates that characterize the Street-art production.

25.3 Testing and Evaluation of the Sustainable, Hybrid Protective and Consolidating Coating

The hybrid protective coating developed in this research has undergone an extensive series of tests to evaluate its effectiveness in preserving Street-art. These assessments aimed to ensure that the formulation protects artworks from environmental degradation, boosts the adhesion of the painted layer to the substrate, and preserves their visual appeal.

Key tests conducted included:

- Fourier Transform Infrared Spectroscopy (FTIR), to analyze the chemical composition and stability of the coating.
- Scanning Electron Microscopy (SEM), to analyze the morphology of the coating's surface, to assess its texture and structure at the microscopic level.
- Dynamic Light Scattering (DLS) and Zeta Potential Measurements, to measure the particle size and surface charge, ensuring that the hybrid solution remained stable during application.

The coating has also been tested for chemical stability, color and gloss variations, water vapor permeability, and hydrophobicity by assessing its effectiveness on spray-painted concrete mock-ups. The long-term stability of the coating has been evaluated through a protocol specifically designed for inducing photochemical, hydro-thermal, and thermal degradation. The goal of these tests was to ensure that the protective coating can withstand environmental stressors while maintaining the visual integrity of the artwork. The results so far suggest that the hybrid coating composed of chitosan and nanosilica offers a promising solution for the preservation of Street-art, providing both durability and compatibility with the complex substrates involved.

The hybrid organic-inorganic coating was obtained by dissolving chitosan powder in an acidic aqueous solution, using various precautions to obtain an optically transparent solution free of impurities. The pH was then adjusted close to neutrality to obtain a formulation that does not cause degradation processes on the substrate. The hybrid coating was obtained by adding an aqueous dispersion of silica nanoparticles—used as received by the producer—and the reciprocal concentrations of chitosan and nanosilica were adjusted for the characterization and the application on mock-ups.

Concrete mock-ups were prepared to replicate one of the most common Street-art substrates. A mixture of white concrete, sand, and water was used in the recommended ratio of 2:5:2, respectively. The paste was poured into wooden molds and left to dry for 2 weeks at room temperature. After curing, the mock-ups were spray-painted with white and blue acrylic paints, mimicking Street-art techniques. Once painted, the samples were left to set for another week before applying the protective coating.

To assess how the coating would hold up over time, three accelerated aging tests were performed, each lasting 200 days:

- Photo-Oxidative aging, by exposing the mock-ups to ultraviolet-visible (UV-vis) light in a climate-controlled box to simulate exposure to sunlight.
- Hydrothermal aging, by sealing the mock-ups in sealed vessels containing a solution that maintained 80% humidity at 60 °C, mimicking the effects of high humidity and temperature.
- Thermal aging, by placing the mock-ups in a dry oven at a constant temperature of 60 °C to simulate heat exposure over time.

25.4 Interactions of Chitosan and Nanosilica

The chitosan-nanosilica hybrid solution produced a transparent and colorless coating when applied to the mockups. A polymer-nanoparticles mass ratio of 1 is the most suitable composition for achieving a transparent solution and film.

The chemical structure of films made from the single components (chitosan and nanosilica) and the hybrid was studied using ATR-FTIR spectra. The hybrid film spectrum matches most absorption values of the single components, with some changes indicating hydrogen bonding between the components.

The analysis of the hybrid solution and its comparison with the analysis performed on the single components using DLS and zeta potential measurements revealed size distributions and surface charges. The hybrid solution has a broader size distribution and a higher positive charge than the chitosan solution due to the rearrangement of the biopolymer surrounding the silica particles, increasing the exposure of positive charges.

The surface morphology of the chitosan-based and hybrid films was observed by SEM analyses. The hybrid films show a compact, smooth, and homogeneous structure without defects. The silica nanoparticles are homogeneously distributed within the polymeric matrix.

Beyond characterizing the hybrid formulation, the study examined the properties and effectiveness of a chitosan-nanosilica coating on spray-painted concrete mock-ups.

The objective was to determine the potential of this sustainable formulation for protecting Street-art. The primary focus was to evaluate how well this coating serves as a protective layer and enhances paint adhesion to the surface. The goal was to ensure that they are artist-friendly materials capable of preserving the visual appeal and longevity of outdoor artworks.

The hybrid coating performance was evaluated according to different aspects:

Color changes. The impact of the coating on the visual appearance of the treated surfaces was assessed using colorimetric measurements to detect color changes. The ΔE parameter, indicating color variation, was used to measure these changes. The results revealed that the coating had a negligible effect on the color of the spray paints, as the ΔE value was below 3. This suggests that the application of the coating did not compromise the aesthetic appearance of the Street-art.

Adhesion and Consolidation. The Scotch tape test was used to evaluate the adhesion of the coating to the substrate and the consolidating effect of the formulation. The results indicated that the treated samples have improved adhesion and a reduction in the decohesion factor compared to untreated samples.

Interaction with Water. Tests conducted to analyze the interaction between the treated samples and water demonstrated that the coating does not compromise the substrate's breathability or its ability to absorb water by capillarity. Surface contact with water is slightly reduced due to the hydrophilicity of chitosan and nanosilica, but water vapor permeability remains largely unchanged. The coating does not cause further waterproofing of the substrate, which is important to maintain the breathability of the walls on which Street-art is created.

Long-Term Durability. As mentioned above, the durability of the hybrid coating and its protective action was evaluated through accelerated aging tests, simulating exposure to extreme environmental conditions. FTIR spectroscopy was used to monitor any changes in the molecular structure of the coating and revealed that the hybrid films show good resistance to photo-oxidative and thermal degradation, with no significant changes in molecular signals. However, hydrothermal aging caused some variations in signals attributed to N-H vibrations and amide II, likely due to the interaction of chitosan with moisture. The color changes of treated and aged samples were monitored and compared to untreated samples. The treated and aged samples showed low ΔE values, indicating effective protection compared to untreated samples, which experienced more pronounced color changes during artificial aging.

In conclusion, the chitosan-nanosilica hybrid films proved to be chemically stable and effective in protecting painted surfaces from environmental factors without significantly altering their aesthetic appearance. The results suggest that this formulation could be used to obtain new eco-friendly protective products for the conservation of Street-art, ensuring both durability and environmental sustainability.

25.5 The Evolution of a Mural: Research and Preservation of SKIM's "Anna Maria" Artwork

In the spring of 2023, Francesco Forconi, a Florentine Street artist known as SKIM, unveiled a mural commissioned by the municipality of Sesto Fiorentino to honor the partisan Anna Maria Enriques Agnoletti.

This vibrant work of art (Fig. 25.1) was painted on the south facade of the high school that bears her name, precisely where, just a few months earlier, vandalic graffiti with fascist messages had been found.

Spanning 290 square meters, the mural was executed on a substrate made of insulating thermal cladding and plaster. From the beginning, establishing a dialogue with the artist was crucial for gaining insights into his artistic technique. At the same

Fig. 25.1 "Anna Maria", mural painting by Skim, Sesto Fiorentino (Italy), 2023

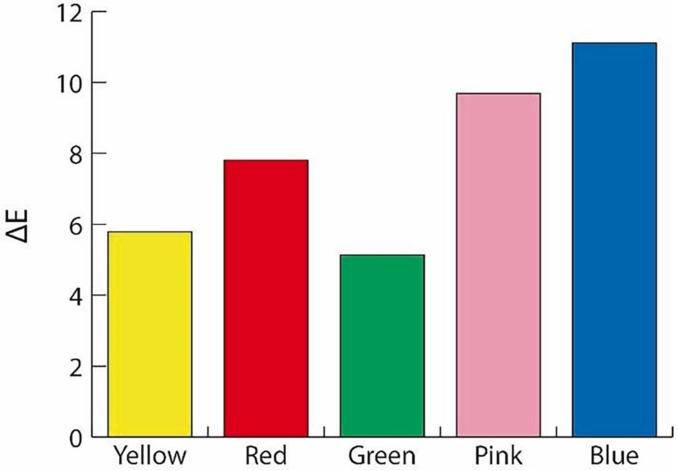


Fig. 25.2 Color variations of some spray-paints 1 year after the creation of the mural

time, the school showed great enthusiasm for our proposal to analyze, monitor, and study this colorful piece from its very first moments.

Our research has thus focused on the ongoing monitoring of the mural's conservation state over time. Analyses are still in progress, and the Fig. 25.2 illustrates the colorimetric variations of key colors in the artwork, 12 months after its completion.

A year after the creation of the painted mural, we have already identified various degradation patterns, including fading of the spray paint, substrate lifting that leads to cracking of the paint film, efflorescence, and the emergence of cracks likely caused by the thermo-mechanical stress of the underlying materials.

In addition to tracking the artwork's condition, our research has also explored the degradation processes through an accelerated aging protocol. By conducting artificial aging tests on mock-ups that closely replicate SKIM's artistic technique, we can not only effectively simulate the degradation observed a year and a half after the mural's creation but also reasonably predict how it will progress in the upcoming months and years. To accomplish this aim, we have designed a new kind of mock-up, which results more faithful to this specific case-study, and we have chemically characterized the spray paints employed by the artist.

Our primary hypothesis is that, once we identify an effective, realistic, and reproducible method for accelerated aging, we will be able to assess potential intervention strategies for preserving the artwork in advance.

This ongoing research and monitoring aim to not only preserve this specific mural artwork but also contribute to a deeper understanding of the complex degradation mechanisms that affect most contemporary painted murals. By developing an effective accelerated aging protocol and accurately characterizing the materials used, we can enhance our preservation strategies, ensuring that this artwork endures for future generations.

In conclusion, the preservation of Street-art, wish its unique materials and environmental challenges, requires specialized and sustainable conservation methods. The development of hybrid coatings, such as those combining chitosan and nanosilica, shows promise in protecting these artworks without compromising their visual integrity or the breathability of the surface. Ongoing research, testing, and collaboration with artists are essential to refining these methods and ensuring their long-term effectiveness. As urban art continues to evolve and inspire, conservation efforts must keep pace, safeguarding this vibrant form of cultural expression for future generations.

References

Cao, Y. J., Camaiti, M., Endrizzi, M., Forti, G., Vergani, E., & Forti, I. (2023). Enhanced consolidation efficacy and durability of highly porous calcareous building stones enabled by nanosilica-based treatments. *Science China Technological Sciences, 66*, 2197–2212.

Pagnin, L., Guarnieri, N., Izzo, F. C., Goidanich, S., & Toniolo, L. (2023). Protecting street art from outdoor environmental threats: What are the challenges? *Coatings, 13*.

Rainer, L., Paul, T. J., & Trust, G. (2003). The conservation of outdoor contemporary murals. *Conservation; The Getty Conservation Institute: Los Angeles, CA, USA, 8*, 4–9.

Sanchez-Pons, M., Shank, W., & Fuster-López, L.. (2015). *Conservation issues in modern and contemporary murals*.

Sawicki, T. (2022). The conservation of murals—A new trend in protecting works of art. *Acta Universitatis Lodziensis. Folia Philosophica. Ethica-Aesthetica-Practica*, 81–95.

Vidal, J. L., Jin, T., Lam, E., Kerton, F., & Moores, A. (2022). Blue is the new green: Valorization of crustacean waste. *Current Research in Green and Sustainable Chemistry, 5*, 100330.

Chapter 26
3D Printing for the Reintegration of Cultural Heritage Assets

Sonia Marfia, Elisabetta Monaldo, Davide Renzi, and Maurizio Ricci

Abstract Additive manufacturing (AM) allows production of highly complex, resource-efficient and high accuracy objects, without the need of moulds or other tools for shaping, based on a three-dimensional CAD model. Application of 3D printing in the field of cultural heritage restoration, is a promising approach to recreate artworks elements. The aim of this work is to evaluate the applicability of 3D printing technologies for the realization of structural/decorative elements that integrate gaps in the architectural heritage, in order to preserve and/or make it usable, while respecting the reversibility, durability and distinguishability of the materials. The main advantages of 3D printing over the use of traditional technologies are the possibility of reproducing elements of any geometry, even complex ones; the attractive weight—mechanical performance ratio, which is particularly important for historical buildings in seismic areas; the reduction in time required for the restoration work. In detail, a case study is herein considered. It refers to the reconstruction of the window cornices of the historical building Palazzo Orsini originally located in the central Italy. They are reproduced exploiting a particular 3D printing technique, i.e. the powder bed fusion. All the stages of this process are described and discussed. The idea is to use the faithful 3D reproductions of the cornices on the reconstructed building as they are lighter than the original ones, which could thus be preserved in a museum. The final aim of this project is the definition of an innovative design and production process for the realisation of decorative elements for the integration of architectural gaps necessary to recover an architectural asset.

Keywords 3D printed material · Powder bed fusion · Polyamide 12 · Experimental test · Cultural heritage · Asset reintegration

---

S. Marfia (✉) · E. Monaldo · D. Renzi · M. Ricci
Dipartimento di Ingegneria Civile, Informatica e delle Tecnologie Aeronautiche, Università degli Studi di Roma Tre, Rome, Italy
e-mail: sonia.marfia@uniroma3.it; elisabetta.monaldo@uniroma3.it; davide.renzi@uniroma3.it; maurizio.ricci@uniroma3.it

F. Di Ciaccio et al. (eds.), *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks*, https://doi.org/10.1007/978-3-032-12340-4_26

26.1 The Case Study of Palazzo Orsini

Palazzo Orsini was located in the heart of Amatrice's historic center, an Italian town in the province of Rieti in Lazio. The Palace was erected in the sixteenth century—perhaps by Alessandro Vitelli. The Palace has always been home to private and very wealthy families and it has been a strong identity symbol for the Amatrice's community. Following the earthquake of the central Italy in 2016, the palace, like the entire Amatrice's historic center, completely collapsed. Fortunately, the decorative elements, that characterized it, were collected and inventoried, by the Soprintendenza Archeologia, Belle Arti e Paesaggio for the metropolitan area of Rome and the Province of Rieti, inside a hangar located in the city of Rieti. Historical-documentary research on the Orsini Palace has produced no results. The only information on the characteristics of the artifact was found from Google Earth images prior to 2016. These images enabled the identification of the original arrangement of some decorative elements, currently deposited in the hangar, such as window cornices, which were then selected as case study (see Fig. 26.1). The same elements were then acquired with a laser scanning survey.

The survey was performed with the 3D scanner Artec Eva (https://www.artec3d.com/it). This 3D scanner is similar to a video camera which captures up to 16 frames per second and each frame is a 3D image. These frames are aligned automatically in real-time, thus the user immediately understands what he has already captured and which area of the object needs more attention. In this case the engraving of the lettering shown on the cornice and the moldings. The 3D scanner provides high resolution (up to 0.5 mm) and high accuracy (up to 0.1 mm). The procedure does not require a preliminar calibration phase or markers to be placed on the object before scanning.

The scan was then processed to produce the textured 3D digital model in.stl format by means of the dedicated software Artec studio 14. The resulting model was then used as a 3D printing prototype.

Fig. 26.1 Decorative elements of the Orsini Palace preserved in a hangar in Rieti

26.1.1 3D Printing with Powder Bed Fusion Technology

The powder bed fusion (PBF) is a type of AM process in which a laser based energy source selectively fuses polymer powder particles in a layer-by-layer process building up a three-dimensional structure (Bain, 2019). PBF process offers many advantages such as faster design to manufacturing cycle, high printing resolution, ability to print complex geometries without additional support, and inexpensive production of small numbers of parts.

One of the most remarkable characteristics of the PBF manufacturing process is that it is a support-free technology and can therefore print cantilevered or extremely complicated elements without needing to print extra parts to sustain the main object.

Currently, Polyamide 12 (PA12) is the most widely used powder material that accounts for more than 90% of polymeric PBF workpieces owing to the combination of easy processability, low cost, lightweight, and impact resistance. For these reasons, PA12 was selected as the material for the present research activity.

In the field of cultural heritage, the PBF printing technology allows to obtain replicas with an external appearance similar to the real original decorative or structural element and with satisfactory mechanical performance. For the research activity described here, reference was made to the HP 580 MultiJet Fusion 3D printer in use in the Laboratories of University of Pavia.

The HP 580 MultiJet Fusion 3D printer is a PBF additive manufacturing system, where the power source for melting the feedstock is an electric lamp. The virtual model (CAD or mesh) of the part to be manufactured is first sliced into layers, which are subsequently processed by the printing software to obtain all the necessary data to be sent to the 3D printer.

The software is HP 3D Build Manager and the file produced and sent to the printer is in an encrypted HP proprietary format. The starting material is a PA12 powder supplied by HP with an average particle size of 60 microns.

The process starts with the deployment of a 0.1 mm thick powder layer and continues with the printing head that selectively deposits a fusing agent in the internal part of the sections to be molten and a detailing agent at the interface between the sections and the surrounding powder.

Last, the electric lamp moves on the top of the layer transferring heat to the powder by thermal irradiation. All these sub-steps are repeated for each 0.1 mm thick layer until the part is completed. The fusing agent deposited in the internal part of the section increases the powder thermal conductivity, thus allowing for complete and fast melting inside the section to be built. The detailing agent deposited at the interface between the sections and the surrounding powder decreases the powder thermal conductivity allowing it to obtain enhanced dimensional accuracy at the section boundaries.

In order to evaluate the mechanical performance of PA12 3D printed elements, some experimental tensile tests were carried out. Regarding the specimen design for the tensile experimental tests, a rectangular shape was considered. Specimens of dimensions 250 mm × 30 mm × 2 mm were prepared.

The tensile tests were realized with an MTS machine and the experimental setup is reported in Fig. 26.2. A displacement control was applied with a quasi-static loading speed equal to 0.5 mm/min according to ASTMD638-14 (ASTM D638-14) and when the sample achieved the failure the test was stopped. The experimental test and set-up are similar to those described in (Alaimo et al., 2017; Monaldo et al., 2023). The results of the tensile tests are presented in the form of force-displacement curves in Fig. 26.3. The six specimens herein considered fail in the direction orthogonal to the applied displacement and the obtained force-displacement curves are homogeneous. The PA12 3D printed specimens prove to be a ductile material. The mechanical response is characterized by an initial linear phase followed by a pronounced nonlinear branch before failure. Moreover, a tensile stress measure can be obtained as the ratio between the registered force and the initial cross-sectional area of the specimen (i.e. 30 mm × 2 mm). A tensile strain measure can be derived as the ratio between the applied displacement and the free length. The latter is the length of the specimen free from the grips of the testing machine and assumes a value of 160 mm. In particular, the average maximum tensile stress is equal to 42.48 MPa and the average ultimate tensile strain is equal to 0.1868%. The obtained experimental results are in agreement with the other experimental results available in literature (Xu et al., 2023). In the next future, it is planned to investigate the mechanical response of the 3D printed material after being subjected to aging treatments. Such tests are necessary to understand the durability of 3D printed decorative elements with respect to external weathering conditions.

Fig. 26.2 Experimental set-up of tensile test

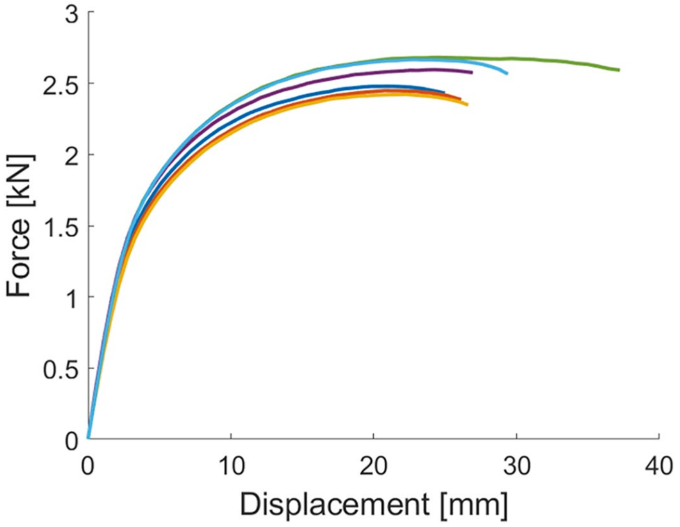


Fig. 26.3 Tensile test on PA12 3D printed samples: force-displacement curves

26.1.2 3D Printing of Decorative Elements

Given the size of the cornice selected as a case study, the model had to be subdivided into different modules to be printed separately and assembled at a later stage. The division into several modules is also necessary because the printing tray of the HP 580 MultiJet Fusion 3D printer here used has dimensions 248 × 190 mm while the only upper part of the cornice has dimensions 1640 × 174 mm.

The realization of the decorative elements selected as the case study was divided into two phases:

- first the entire cornice was printed on a small scale and mechanical joints between individual modules were used;
- then the upper part of the full-scale cornice was made by evaluating different types of surface finishes and joints between modules.

The geometric-dimensional design phase allowed the identification of the appropriate number of modules into which to subdivide the entire cornice. The first attempt to print a 3:1 scale cornice required subdivision into six modules. The evaluation of the division into modules also took into account the assembly strategy. Screws and bolts were used in this first phase. Each module was printed as a hollow geometry so as to reduce the overall weight of the object but also the time and cost of printing. The result is shown in Fig. 26.4. However, it was determined that bolted joints were not suitable for the printing materials used, as they could cause premature failure of the printed elements at the joints. Therefore, it was decided to opt for adhesive joints in subsequent prints. The use of adhesive also allows the joints to be as inconspicuous as possible when the element is finished.

Fig. 26.4 3D-printed cornice (3:1 scale) of Palazzo Orsini in Amatrice

Fig. 26.5 3D model created from the scanned data

In a second phase, a prototype of a full-scale cornice was made, also divided into different modules. In this phase, more attention was paid to reproducing the surface finishes of the element as best as possible. Then, from the digital model described in the first paragraph and shown in Fig. 26.5, the original texture of the cornice was integrated to capture colours and surface details. Finally, the model was partitioned into multiple modules and emptied to obtain a hollow geometry with a thickness of 3 mm. Specifically, the model was divided into six interlocking connectable pieces, and different joint surfaces were selected to evaluate visibility and effectiveness of different strategies. The final model consists of six individual modules. The latter choice makes it possible to greatly lighten the weight of the final element, reducing costs and printing time. The six parts were made in three separate printing sessions. Each module has dimensions 250 × 190 mm for a total size, when assembled, of 1640 × 174 mm.

After printing, the joints were glued and smoothed. Figures 26.6 and 26.7 shows the printed cornice highlighting different aspects. The three different shapes are shown in Fig. 26.6. The modules were connected with joint surfaces of different shape: linear, curved and adaptive. The adaptive joint surface follows the details of

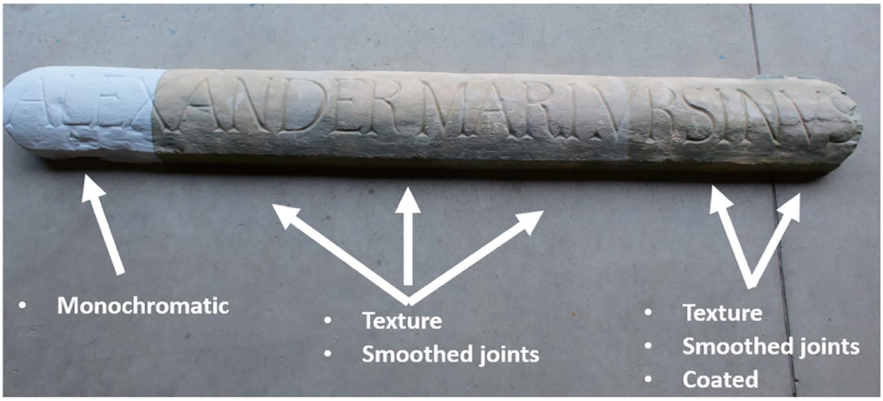


Fig. 26.6 Module assembly strategy considering different types of joint surface

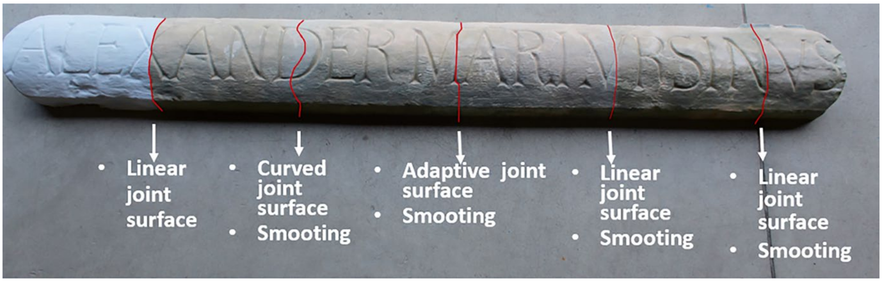


Fig. 26.7 Comparison of different textures and surface finishes

the inscription on the cornice, however, which is the most delicate part of the object. In cooperation with the restoration experts, the curvilinear line has been evaluated the best choice because, applying a little pressure, reduces, at least visually, the gap in the splice.

For each module a different texture was considered: monochrome, coloured and coated. The three textures are shown in Fig. 26.7. As final coating, a spray with protection against water, UV rays and environmental factors has been applied. In the smoothed joints, the glue was mixed with the colored powder. This technique was found very effective to hide joint and achieve uniform color.

In conclusion, it can be pointed out that the printing technology considered, and the material chosen resulted in a satisfactory final prototype both mechanically and aesthetically. Further studies will be devoted to investigate aspects of durability, connection to the existing or reconstructed structure, and further external finishing to meet aesthetic requirements.

References

Alaimo, G., Marconi, S., Costato, L., & Auricchio, F. (2017). Influence of meso-structure and chemical composition on FDM 3D-printed parts. *Composites Part B: Engineering, 113*, 371–380.

ASTM D638-14. Standard test method for tensile properties of plastics. ASTM international.

Bain, E. D. (2019). Polymer powder bed fusion additive manufacturing: Recent developments in materials, processes, and applications. *Polymer-Based Additive Manufacturing: Recent Developments*, 7–36.

Monaldo, E., Ricci, M., & Marfia, S. (2023). Mechanical properties of 3D printed polylactic acid elements: Experimental and numerical insights. *Mechanics of Materials, 177*, 104551.

Xu, Y., Quino, G., Ramakrishnan, K. R., & Pellegrino, A. (2023). Effects of build orientation and strain rate on the tensile-shear behaviour of polyamide-12 manufactured via laser powder bed fusion. *Materials & Design, 232*, 112162.