# A Multi-Scale Framework for Resilience-Enabling Interventions in Cultural Heritage Assets

H. S. Sousa, M. Santamaria-Ariza, J. C. Matos
*University of Minho, ISISE, ARISE, Department of Civil Engineering, Guimarães, Portugal*

I. Ingrosso, A. Largo
*Rina Consulting S.p.a., Lecce, Italy*

L. Urciuoli
*KTH Royal Institute of Technology, Sweden. MIT-Zaragoza Logistics Center, Spain*

ABSTRACT: The increasing frequency of extreme climatic events requires urgent planning, designing, and retrofitting of the built environment to adapt to evolving risks. In these efforts, cultural heritage assets need special attention due to their historical, cultural, economic, and social value to communities. This paper introduces a framework for resilience-enabling interventions in cultural heritage assets incorporating the United Nations Scorecard for assessing disaster resilience of cities. The scorecard addresses essential aspects such as governance and financial capacity, planning and disaster preparation, disaster response, and post-event recovery. The proposed multi-scale framework involves identifying and analyzing current and future risk scenarios for critical hazards. For the identified scenarios, the framework facilitates the assessment of the impacts of interventions on cultural heritage assets using performance indicators. An analysis of possible interventions for cultural heritage assets is conducted, recognizing their historical and cultural value and proposing targeted solutions that consider local geographic contexts, such as using traditional materials. Consequently, the proposed approach enables the comparison of plausible interventions to mitigate risks and enhance the resilience of cultural heritage assets and their urban or rural context.

## 1 INTRODUCTION

Cultural heritage (CH) assets embody unique historical and cultural values, requiring preservation approaches that respect their identity while addressing current challenges such as increasing threats from extreme climatic events, urbanization, and socio-economic changes. Unlike modern structures, CH assets deviate from standardized design codes, necessitating tailored interventions that align with their historical significance and structural uniqueness. ICOMOS (2003) presented a set of principles for the conservation and restoration of architectural heritage emphasizing a multidisciplinary approach that balances safety, durability, and minimal harm to heritage values. The use of reversible and minimally invasive techniques, compatibility of materials, and a deep understanding of cultural context are prioritized to safeguard CH authenticity.

To address the growing challenges of preserving CH assets, a resilience perspective is essential for designing interventions that enable them to withstand, adapt to, and recover from disruptions while maintaining their cultural significance. Existing frameworks, such as the United Nations Disaster Resilience Scorecard (UNDRR, 2022), provide tools for assessing resilience at an urban scale and verified that CH require a special analysis (addendum) for these assets, but still lack the specificity required at the element level for definition of management and intervention planning. Another resilience modeling framework was developed by Turksezer et al. (2022), designed to assess and enhance the resilience of historic bridges by integrating cultural, historical, and socio-technical aspects into resilience evaluations. The framework utilizes several resilience indicators to evaluate performance across subsystems, systems, and governance levels. It emphasizes the importance of preserving cultural and historical values alongside functional and structural performance. The framework is primarily targeted at evaluating overall resilience and the capacity of the system to withstand and recover from disturbances. However, it is also not specifically designed to assess the impact of different types of interventions on CH resilience.

This paper introduces a multi-scale framework for planning and evaluating resilience-enabling interventions for CH buildings. The framework proposes using Key Performance Indicators (KPIs) - reliability, robustness, resourcefulness, and recovery - and integrates the UNDRR Disaster Resilience Scorecard to evaluate intervention impacts across physical, environmental, social, and governance dimensions. The work was conducted within the MULTICLIMACT project (Grant Agreement No. 101123538) (Sousa et al., 2024).

## 2 KEY PERFORMANCE INDICATORS TO QUANTIFY RESILIENCE OF CH

Key Performance Indicators (KPIs) enable stakeholders to monitor changes in performance over time and evaluate the success of interventions, adaptation, and recovery efforts. Bruneau et al. (2003) proposed four KPIs that have been widely accepted to quantify the resilience of infrastructure systems, namely redundancy, robustness, resourcefulness, and rapidity of recovery. Redundancy refers to the ability of a structural system to redistribute loads and continue carrying them after one or more of its members reach their full capacity. Therefore, redundancy is strongly linked to reliability, a more general concept that relates to the ability of a structural system to meet a target performance level during its service life. In this sense, the resilience of CH can be broadly quantified by four KPIs: reliability, robustness, resourcefulness, and recovery.

### 2.1 *Reliability*

In the context of CH, reliability can be understood as the ability of physical structures, architecture, and other heritage elements to exist and maintain their integrity over time while withstanding external and internal impacts. Studies on reliability focus on factors contributing to failure probabilities and measures to mitigate risks. In the case of CH, these factors may include damage from the natural environment and the impact of human activities like vandalism or loss of knowledge and traditions. Reliability assessments for CH buildings are particularly challenging due to uncertainties in material properties, non-standardized structural configurations, and limited historical records of past interventions. Domański & Matysek (2020) highlighted the importance of applying probabilistic reliability assessment methods to CH buildings to account for their unique characteristics. Their framework combines destructive and non-destructive testing methods to evaluate parameters like compressive strength, material homogeneity, and load-bearing capacity, and proposes integrating correction factors for historical materials due to the variability in masonry properties and the complexities of heritage construction techniques. The study also discusses acceptable failure probabilities for CH buildings considering their socio-economic and cultural importance. For buildings subject to conservation protection, an acceptable probability of failure of $10^{-6}$ is proposed. This does not apply to CH buildings listed by UNESCO, which should be assessed individually. Other standards, such as the Probabilistic Model Code (JCSS, 2001), define acceptable failure probability depending on the failure consequences and the costs of intervention, i.e., the smaller the costs and the major the consequences, the smaller the acceptable failure probability will be.

### 2.2 *Robustness*

Robustness in CH refers to the ability of structures, systems, and communities to maintain functionality, integrity, and adaptability under various environmental, social, and economic challenges. Robustness ensures that heritage structures and practices are protected and can recover from adverse conditions while evolving to meet modern demands. This includes maintaining structural integrity through regular maintenance, adapting to climate change impacts, and recovering cultural practices and structures using traditional techniques and materials. Several factors influence CH robustness, such as physical resilience, legal frameworks, community engagement, and financial sustainability. Physical resilience involves ensuring the stability and durability of structures through maintenance and adaptation to climate conditions. Legal and policy frameworks provide protective legislation and international cooperation to safeguard heritage from vandalism or illegal development. Social adaptability highlights the importance of engaging communities in conservation efforts, and adapting heritage buildings for modern uses to ensure their relevance and sustainability. Financial sustainability is addressed through innovative funding models, such as public-private partnerships, ensuring the continuity of conservation efforts.

### 2.3 *Resourcefulness*

Resourcefulness, as a KPI for CH, assesses the capacity to effectively mobilize and manage resources to preserve cultural assets while responding to disruptions. It encompasses a multidimensional approach, addressing the availability of materials, labor, tools, and techniques necessary for resilience interventions alongside social, economic, and environmental considerations. This KPI emphasizes the integration of traditional and innovative practices, ensuring that interventions respect the historical and cultural significance of the assets while remaining adaptable to regulatory constraints and site-specific requirements. The factor-resource model proposed by Thomas & Ellis (2017) contextualizes resourcefulness by describing the transformation of various inputs into project outputs. Inputs include skilled and unskilled labor, materials, specialized equipment, tools, and information systems such as Heritage Building Information Modeling (HBIM) for efficient project management. Resourcefulness ensures that these elements are available in the right quantities and at the correct times to maintain the continuity and effectiveness of interventions. An essential aspect of resourcefulness in CH is the focus on traditional techniques and materials for restoring historic elements, i.e., skilled craftsmen are crucial, and materials must be carefully sourced to ensure compatibility with existing structures (Thomas & Ellis, 2017).

### 2.4 *Recovery*

Recovery as a KPI encompasses a set of strategies, tools, and processes designed to restore or maintain the normal functionality of CH following a disruptive event. Such as resourcefulness, this KPI depends heavily on the availability of resources, such as financial, technical, and human capital, and effective management strategies. Besides that, recovery is inherently linked to reliability and robustness, as it reflects the system's ability to withstand and regain its intended performance efficiently after disruptions. In recent years, Structural Health Monitoring (SHM) systems have become essential tools in supporting recovery efforts during and after disruptive events. Limongelli et al. (2019) underscored the advantages of SHM by showing how real-time data on structural behavior and damage can improve emergency management and inform recovery strategies. Their study highlighted SHM's role in minimizing functionality loss and enhancing resource allocation efficiency. For instance, SHM systems installed in Italian heritage structures post-earthquake provided critical insights into structural deformation and retrofitting performance, facilitating targeted interventions and efficient recovery processes.

## 3 FRAMEWORK FOR MULTI-SCALE EVALUATION OF RESILIENCE-ENABLING INTERVENTIONS IN CULTURAL HERITAGE ASSETS

The proposed framework for the multi-scale evaluation of resilience for interventions in CH buildings is presented in Figure 1. It begins with a comprehensive evaluation of the current condition of the CH building, considering its physical state, historical significance, and exposures. This initial assessment identifies vulnerabilities and provides a baseline for planning interventions. Following this, an initial list of possible interventions is generated, focusing on strategies aligning with the KPIs for quantifying resilience: robustness, reliability, resourcefulness, and recovery. Moreover, legal requirements and supply chain considerations are taken into account, ensuring that interventions are feasible within existing regulatory frameworks and that necessary materials, labor, and logistical support are available to implement them effectively. Each intervention is then analyzed for its potential impacts and performance at varying scales, from individual components to broader systems. Finally, interventions are classified based on their effectiveness in increasing resilience from a multidisciplinary perspective, based on the UNDRR resilience scorecard for CH (UNDRR, 2022).

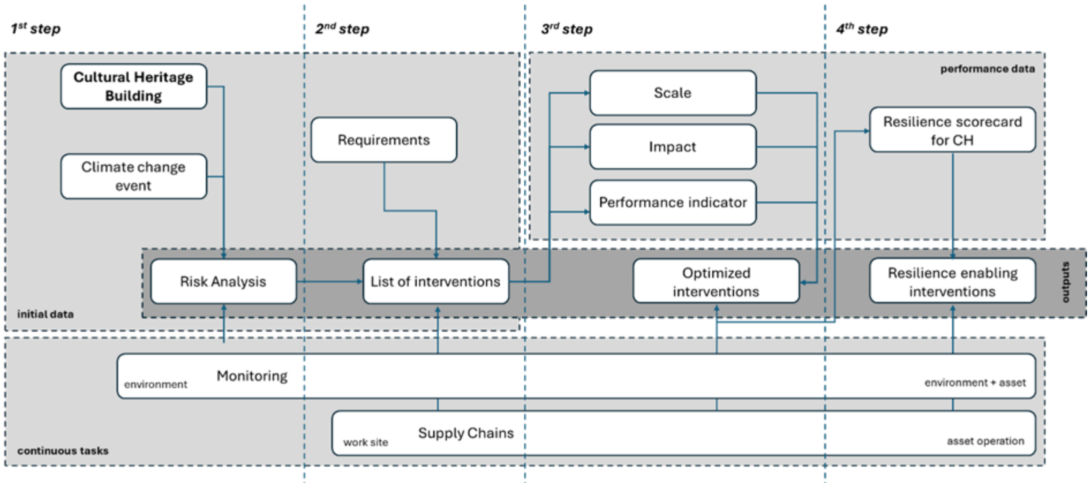

Figure 1. Framework for multi-scale evaluation of resilience-enabling interventions in CH buildings

## 4 RISK ASSESSMENT OF CULTURAL HERITAGE

The first step in the framework comprises the assessment of risks that threaten CH's value and integrity. These risks include sudden events like earthquakes and floods, gradual processes such as chemical deterioration, and factors exacerbated by climate change. Structured risk assessment methodologies are essential to address these challenges. The ABC Method proposed by Pedersoli Jr et al. (2016) offers a systematic framework for evaluating risks. It examines agents of deterioration, the building or site's susceptibility to these agents, and the consequences on the asset's value. By quantifying these components, the method facilitates the prioritization of interventions and informed decision-making.

Effective risk management requires a deep understanding of the agents of deterioration that threaten CH. Key agents include physical forces, water damage, pests, pollutants, and incorrect environmental conditions like temperature and humidity, which can vary based on the asset's characteristics and context. Challenges in managing these risks include limited resources, the complexity of heritage assets, and the impacts of climate change. However, emerging opportunities such as technological advancements in SHM and environmental sensors, collaborative approaches involving diverse stakeholders, and integrating risk management with sustainable development goals provide pathways to strengthen the resilience and preservation of CH. These efforts must be carefully tailored to the unique requirements of heritage structures, balancing innovation with respect for historical and cultural significance.

## 5 PLANNING AND DESIGNING RESILIENCE ENABLING INTERVENTIONS ON CULTURAL HERITAGE

The second step comprises the planning and designing of interventions to increase the resilience of CH structures. Table 1 presents a list of possible interventions categorized by the application phase with respect to the disturbance event: pre-, during, or post-event. It can be observed that SHM systems are suggested as possible interventions across the three event phases, as they inform decision-making by providing critical insights into the structural and environmental conditions of CH assets, enabling proactive maintenance, real-time emergency response, and post-event recovery (Limongelli et al., 2019). Moreover, Table 1 correlates each type of intervention with relevant disciplines, including social sciences (S), management/governance (Mg), economics (Eco), environmental (Env), and engineering (Eng), to assess which disciplines are more influenced by each intervention, and its impact scale. Similarly, the connection with the KPIs is also given to assess the impact of each intervention on the performance of CH assets.

Table 1. List of possible interventions in CH and its interaction with disciplines and KPIs

| Interventions | | Disciplines* | | | | | Impact scale** | KPI*** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase | Action | S | Mg | Eco | Env | Eng | | Rel | Rob | Res | Rec |
| Pre-event | Monitoring and sensing | | | | X | X | B, S | X | X | | |
| | Strengthening and reinforcement | | | | | X | B | X | X | | |
| | Protection and safeguard | | | | | X | B to R | X | X | X | |
| | Management restrictions | | X | X | | | B, S, R | | X | X | |
| | Maintenance plans | | X | | | | B, S, R | X | X | X | |
| | Social and community participation | X | X | | | | B, S, R | | X | | X |
| | Change on exposure/ vulnerability | | | | | X | B, S | X | X | | |
| | Adaptation measures | | | | X | X | B, S | X | X | | X |
| | Knowledge transfer and people awareness | X | X | X | | | S, R | | | X | X |
| Event | Emergency plans | X | X | X | | | B to R | | | X | X |
| | Early warning systems | X | X | | | | B to R | | | X | X |
| | Mitigation interventions | | | | | X | B, S | X | | | X |
| | Cleaning and demolition | X | | | X | X | B, S | | | X | X |
| Pos-event | Monitoring and sensing | | | | X | X | B, S | X | X | | |
| | Repair to prior performance | X | | | | X | B, S | X | X | | |
| | Strengthening and reinforcement | | | | | X | B | X | X | | |
| | Recovery management | X | X | X | | | B to R | | | | X |
| | Adaptation measures | | | | X | X | B, S | X | X | | X |

* S: social; Mg: management/governance; Eco: economics; Env: environmental; Eng: engineering; ** B: building, S: system, R: region; *** Rel: reliability; Rob: robustness; Res: resourcefulness; Rec: recovery.

In this step, it is also necessary to analyze whether the list of interventions complies with regulatory demands, material conservation, and societal integration. International frameworks, such as the World Heritage Convention, outline comprehensive processes for managing CH, including assessment, planning, preservation, conservation, restoration, and ongoing management (Wijesuriya, 2013). In addition, national standards like EN 16853:2017 provide specific guidelines for decision-making, planning, and implementation, ensuring interventions respect the heritage's significance while addressing practicalities such as resource availability and long-term resilience. A critical aspect of these preservation processes is the integration of supply chain considerations at every intervention stage. Materials and technologies are identified during decision-making, and contractors establish agreements with suppliers and logistics providers to ensure readiness for conservation tasks. The planning phase refines these requirements, estimating material volumes and aligning logistics strategies, such as inventory management and transport capacities, to meet project needs. Finally, in the implementation phase, supply chains mobilize to deliver materials accurately and on time, with robust monitoring and quality assurance systems. Accounting for supply chains also involves addressing risks and sustainability factors. External risks, such as weather disruptions or geopolitical issues, and internal risks, including capacity constraints and operational inefficiencies, can affect material flow and project timelines (Ho et al., 2015). Strategies to mitigate these risks include monitoring transport conditions, implementing contingency plans, and adopting lean versus resilience-based supply chain models depending on project needs. Additionally, sustainable practices, such as sourcing eco-friendly materials and utilizing local resources, are crucial to minimizing the environmental impact of interventions. By aligning supply chain operations with resilience objectives, CH preservation projects can achieve their goals effectively and sustainably.

## 6 MULTI-SCALE ANALYSIS OF INTERVENTION IMPACTS AND PERFORMANCE

The third step evaluates how the proposed interventions impact the assets and their surrounding contexts, considering urban and rural scales. For urban areas, impacts are commonly assessed using Quality of Life (QOL) indicators, as outlined in ISO 37120:2014, including public safety, environmental quality, transportation, and health. Interventions in dense urban settings often generate noise, air pollution, and transportation disruptions due to limited space availability and high population density. These impacts are evaluated to determine how well the interventions align with QOL objectives, ensuring that they enhance urban livability while preserving cultural and historical significance. By mapping construction-related impacts to broader QOL categories, as described in (Zou & Ergan, 2019), stakeholders can quantify changes in societal and environmental parameters, aiding in informed decision-making.

In rural contexts, the analysis shifts toward evaluating impacts on environmental components, local communities, and landscapes, as these areas often have lower population densities and different infrastructure networks (Du et al., 2019). Interventions in rural CH buildings can contribute to tourism and economic gains by revitalizing abandoned assets and promoting sustainable rural lifestyles. However, such actions must be balanced against potential adverse effects, such as overcrowding, loss of cultural identity, or environmental degradation of flora and fauna (Quintana et al., 2022). Using local labor and traditional materials can mitigate some of these impacts by reducing transportation demands and preserving the authenticity of the heritage.

In addition, this step assesses the effectiveness of resilience-enabling interventions through the KPIs described in Section 2. The impacts of the interventions are also measured from financial, economic, environmental, and social perspectives. The most appropriate interventions are selected based on the results to obtain more optimized solutions.

## 7 RESILIENCE EVALUATION OF INTERVENTIONS

In the last step, the set of optimized interventions is assessed through its impact on the resilience components given by the UNDRR's Disaster Resilience Scorecard for Cities, specifically tailored to CH buildings (UNDRR, 2022). This tool assesses resilience across physical, environmental, social, and governance dimensions, providing a practical framework for evaluating preparedness, identifying vulnerabilities, and guiding preservation efforts. The scorecard's objectives include evaluating the current state of resilience, highlighting weaknesses, prioritizing interventions, and monitoring progress over time. It emphasizes integrating local knowledge, traditional materials, and site-specific construction techniques into interventions to enhance the resilience and authenticity of CH assets. The scorecard structure encompasses 10 essential (E) components, such as organizing for disaster resilience, identifying current and future risk scenarios, strengthening financial and institutional capacities, and expediting recovery. It includes 44 questions scored on a scale from 0 to 3, where 0 indicates no preparation, and 3 represents comprehensive understanding and robust protective measures. Table 2 correlates these questions with the same relevant disciplines analyzed in Table 1, ensuring a multidisciplinary approach to resilience planning. This framework enables stakeholders to align interventions with their objectives by linking specific resilience aspects to their disciplinary impacts.

## 8 CONCLUSIONS

This study introduced a multi-scale framework for planning and evaluating resilience-enabling interventions for CH assets. The framework provides a structured approach to assessing the impacts of interventions across physical, environmental, social, and governance dimensions by integrating the United Nations Disaster Resilience Scorecard for Cities. KPIs such as reliability, robustness, resourcefulness, and recovery were proposed to quantify the resilience of interventions, enabling the identification and prioritization of strategies that address the unique complexities of CH. The study emphasized the use of traditional materials, the importance of engaging stakeholders, and the implementation of SHM systems to ensure the preservation of cultural identity and the adaptability of assets to evolving risks.

The framework also incorporates the analysis of the impacts of interventions at urban and rural scales, providing insights about how interventions contribute to improving quality of life, promoting sustainable rural tourism, and mitigating potential disruptions caused by climate change or human activities. Lastly, including multidisciplinary perspectives ensures a balanced approach to CH preservation, addressing technical, economic, and societal dimensions. While challenges such as data availability and accuracy in material properties, structural conditions, and historical documentation persist, this framework contributes to enhancing CH resilience, providing a foundation for future research and application to case studies.

Table 2. Disciplines considered for each scorecard question

| **Scorecard question** | | **Disciplines** | | | | | **Keywords / actions** |
|---|---|---|---|---|---|---|---|
| | | S | Mg | Eco | Env | Eng | |
| E1 | 1.1.1 | X | X | | | | Traditional community |
| | 1.1.2 | X | X | | | | Communities' participatory consultation |
| | 1.1.3 | X | X | X | | | Commercial activity |
| | 1.1.4 | X | | X | X | | Sustainable growth |
| | 1.1.5 | | | | | X | Traditional materials and construction techniques |
| | 1.2.1 | | X | X | | | Reduce disaster risk |
| E2 | 2.1.1 | | X | | | X | Exposure to hazards |
| | 2.1.2 | | X | X | | | Transient population |
| | 2.1.3 | | | | | X | Vulnerability, GIS |
| | 2.1.4 | X | X | | | | Intangible CH |
| | 2.2.1 | | X | X | | | Tourism as a risk driver |
| E3 | 3.1.1 | | | X | | | Financing and funding |
| | 3.2.1 | | X | X | | | Funding management |
| | 3.3.1 | | X | X | | | Insurance |
| | 3.4.1 | | X | X | | | Incentives |
| E4 | 4.1.1 | | X | | | X | % area of tangible CH |
| | 4.1.2 | | X | | | X | Proper uses |
| | 4.2.1 | | | | | X | Traditional design guidelines |
| | 4.2.2 | | | | | X | Strengthening |
| E5 | 5.1.1 | X | | | X | | Natural heritage |
| | 5.2.1 | X | X | | | | Traditional knowledge |
| E6 | 6.1.1 | X | X | X | | X | Skills, knowledge and experience |
| | 6.2.1 | X | | | | | Education promotion (schools) |
| | 6.2.2 | X | | | | | Education promotion (higher education) |
| | 6.3.1 | X | X | | | X | Data use and data sharing |
| | 6.4.1 | X | X | X | X | X | Knowledge exchange |
| E7 | 7.1.1 | X | X | | | | Community exchange |
| | 7.2.1 | X | | X | | | Business continuity plan |
| | 7.3.1 | X | X | | | | Communication plans |
| | 7.3.2 | X | X | | | | Population participation |
| E8 | 8.1.1 | | X | X | | | % CH hosting critical services |
| | 8.2.1 | | X | X | | X | Service availability, tourism |
| | 8.2.2 | | X | X | | X | Decrease of city revenue |
| | 8.3.1 | X | | | | X | Loss of worship places |
| E9 | 9.1.1 | X | X | | | X | Early warning by traditional knowledge |
| | 9.2.1 | | X | | | X | Emergency response plans |
| | 9.3.1 | | X | | | X | First responders' awareness |
| | 9.4.1 | X | X | | | X | Evacuation of transient population |
| | 9.5.1 | X | X | X | | X | Disaster relief supply needs |
| E10 | 10.1.1 | X | X | X | | | Post recovery plans |
| | 10.1.2 | X | X | | | | Post recovery plans inclusivity and participation |
| | 10.1.3 | X | X | X | | | Post recovery plans of surrounding areas |
| | 10.2.1 | X | | | | X | Traditional design guidelines for building back |
| | 10.2.2 | X | | | | X | Promotion of traditional materials and techniques |

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