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A Multi-Scale Resilience Framework for Cultural Heritage Preservation: Application to the Riga Central Market

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Cultural heritage structures represent distinctive historical and cultural values, requiring preservation approaches that safeguard their authenticity while addressing natural and anthropogenic hazards. To sustain their functionality and significance, it is essential to design interventions that enhance their ability to withstand, adapt to, and recover from disruptions. This study applies a multi-scale framework to assess resilience-enabling interventions for cultural heritage preservation. The framework integrates risk assessment, building-scale resilience assessment through four Key Performance Indicators (KPIs), namely reliability, robustness, resourcefulness, and recovery, and urban-scale assessment through the UNDRR Disaster Resilience Scorecard for Cities Cultural Heritage addendum. It is demonstrated through a case study of the Riga Central Market in Riga, Latvia, a UNESCO World Heritage site. The results identify heavy precipitation as the dominant climate-related hazard and show that the proposed building-scale interventions, based on strengthening, repair, and monitoring measures that comply with heritage preservation requirements, improve the current resilience, as measured by the KPIs. The urban-scale assessment reveals critical gaps in preparedness, coordination, response, and recovery capacity, and supports the definition of interventions related to emergency and recovery planning, risk-informed prioritization, and institutional organization and financing mechanisms. Overall, the findings highlight the value of combining building-scale and urban-scale perspectives to support more informed decisions for the long-term preservation and functioning of cultural heritage assets.

Keywords: Cultural heritage resilience; Risk assessment; Resilience indicators; Resourcefulness; Recovery

1. Introduction

Cultural heritage (CH) assets embody historical, cultural, social, and economic values that extend beyond their physical fabric. When damaged by hazardous events, the consequences may include not only repair costs, but also losses of evidential, historical, aesthetic, and communal value, as well as disruptions to the social and economic functions these assets support (Romão and Paupério, 2021). Resilience is therefore a relevant perspective for CH preservation, as interventions must reduce damage while safeguarding the continued functioning and significance of these assets.

Current approaches address this challenge from different perspectives. At the building scale, recent studies have proposed restoration and retrofitting strategies for CH buildings to improve structural resilience while preserving architectural authenticity (Formisano and Longobardi, 2025). At the urban scale, heritage resilience has been linked to urban planning, climate adaptation, disaster risk reduction, and wider social, cultural, economic, and environmental dimensions (Ripp et al., 2024). In this context, the UNDRR Disaster Resilience Scorecard for Cities Cultural Heritage Addendum provides a tool for assessing resilience through governance, preparedness, response, and recovery (UNDRR, 2022).

Despite these advances, important gaps remain. Building-scale studies mainly address heritage interventions from the perspective of structural vulnerability and safety (Formisano and Longobardi, 2025), whereas urban-scale studies and tools focus on the broader resilience of historic areas through planning, governance, and institutional coordination Therefore, urban-scale frameworks do not directly support the assessment and comparison of heritage-compatible interventions at the building scale, limiting coordinated resilience enhancement across scales for specific CH assets.

This paper presents a multi-scale framework to assess resilience-enabling interventions for CH preservation. Building on Sousa et al.(2025), it integrates risk assessment, building-scale resilience assessment through four KPIs, and urban-scale assessment through the UNDRR Disaster Resilience Scorecard for Cities Cultural Heritage Addendum (UNDRR, 2022). The framework is applied to the Riga Central Market, located in the Historic Centre of Riga, a UNESCO World Heritage Site and part of the MULTICLIMACT project, subject to heritage protection regulations(Kotovica et al., 2026).

2. Multi-scale Resilience Framework for CH assets

This study builds upon the multi-scale resilience framework proposed in Sousa et al.(2025). The framework comprises four steps: risk assessment; definition of building-scale interventions; resilience assessment using four KPIs—reliability, robustness, resourcefulness, and recovery; and identification of urban-scale interventions through the UNDRR Disaster Resilience Scorecard for Cities Cultural Heritage Addendum. Its application to the Riga Central Market and the Historic Centre of Riga is presented in Section 3.

3. Case study application: Riga Historic Centre and Riga Central Market

The Historic Centre of Riga, inscribed as a UNESCO World Heritage Site in 1997, includes the Riga Central Market (RCM), built between 1924 and 1930 and comprising five pavilions formed by repurposed steel structures with reinforced concrete (RC) and masonry elements (Fig. 1). Each pavilion consists of a high-volume hall with a basement extending beneath the entire structure. The basement floor is comprised of a RC slab supported on steel H-profile beams and masonry columns. Due to heritage protection regulations, any planned intervention must be non-invasive to preserve the building's architectural, historical, and cultural significance (Kotovica et al., 2026).

3.1. *Risk Assessment*

The most relevant climate hazards affecting the Riga Historic Centre are characterised using climate indicators acting as proxies for hazard processes. Following the methodological framework proposed in (CMCC Foundation, 2026), the selected indicators represent the intensity, frequency, and persistence of heat-related, heavy precipitation, and drought hazards. Table 1 summarises their projected variations for the period 2036–2065 (mid-century) under the Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 scenarios. The values were retrieved from the DATACLIME platform as part of the MULTICLIMACT project (CMCC Foundation, 2026).

The projected variations indicate intensification of climate-related hazards by mid-century. Heat-related indicators increase moderately under both emission scenarios, suggesting a higher likelihood of prolonged heat events. Heavy precipitation indicators show greater changes, with increases of

Fig. 1. General view of the Riga Central Market Dairy Pavilion. Source: (Peredistijs, 2024)

Table 1. Indicators for climate-related hazards at Riga

Hazard category	Climate indicator	RCP 4.5*	RCP 8.5*
Heat-related	Max. of daily max. temperature, TXx (°C)	3.9%	5.9%
	Max. 7-day average Tmax, TX7max (°C)	3.6%	5.9%
Heavy precipitation	Max. 1-day precipitation, RX1day (mm)	13%	14%
	Max. consecutive 5-day precipitation, RX5day (mm)	10%	13%
	10-year return period precipitation, TR10pr (mm)	16%	17%
	25-year return period precipitation, TR25pr (mm)	22%	19%
	100-year return period precipitation, TR100pr (mm)	50%	27%
Drought	SPEI-3 (dimensionless)	0%	1%
	SPEI-12 (dimensionless)	0%	1%

Note: * Projected variations for 2036–2065 relative to 1981–2010 for the emission scenario (CMCC Foundation, 2026).

up to 50% for the 100-year precipitation event, indicating increased flood risk. In contrast, drought-related indicators show negligible variation and are not expected to be a dominant hazard over the considered time horizon.

The impact severity of the climate-related hazards listed in Table 1 is assessed based on the building's current structural condition and the documented deterioration of its main load-bearing components. According to a recent technical inspection report (Peredistijs, 2024), the main ongoing degradation mechanism is prolonged moisture exposure in the basement, resulting from insufficient waterproofing, water infiltration, and persistently high relative humidity, combined with inadequate ventilation. The report identifies corrosion of reinforcement in the RC slab, corrosion of embedded steel beams, concrete delamination, and local section loss. Since corrosion in carbonated RC is influenced by temperature, moisture, and atmospheric CO_2, future changes in these climatic drivers may accelerate carbonation and related corrosion processes (Dimova et al., 2024). Intensified heavy precipitation may therefore increase moisture exposure in the basement structural system, accelerating corrosion and material degradation. Beyond structural implications, such deterioration may lead to the irreversible loss of historic material fabric and compromise the aesthetic integrity of visible elements through cracking and delamination (Romão and Paupério, 2021). Therefore, the overall impact severity associated with precipitation is assessed as major.

For heat-related hazards, thermal actions may induce expansion and contraction, potentially contributing to crack development or widening in masonry and RC elements. In the RCM, cracking has been observed in the lintel regions (Peredistijs, 2024), but it is attributed to differential movement rather than to thermal effects. Should elevated temperatures intensify such mechanisms, the resulting damage would likely remain localised and repairable, primarily affecting serviceability rather than structural safety. Surface cracking may also compromise the aesthetic integrity of masonry finishes, while elevated indoor temperatures may affect thermal comfort and operational conditions. Considering the absence of heat-induced material distress and the reversible nature of the damage, the overall impact severity associated with heat-related hazards is assessed as moderate.

For drought-related hazards, prolonged moisture deficits may induce soil shrinkage and differential settlement in structures founded on shrink–swell-susceptible soils, potentially leading to cracking and misalignment of structural elements. In the RCM, minor uneven foundation deformations have been reported (Peredistijs, 2024), but these are not attributed to drying phenomena, and no evidence of moisture-sensitive soil behaviour is documented. Therefore, drought-related effects are not expected to significantly affect structural safety or heritage value. Accordingly, the overall impact severity associated with drought is assessed as minor.

Figure 2 presents the qualitative risk matrix used in the assessment, combining the likelihood of a hazard increase relative to baseline climate conditions with the impact severity on structural performance and CH value. On this basis, heavy precipitation is classified in Risk Category I (very high), heat-related hazards in Risk Category III (moderate), and drought-related hazards in Risk Category IV (low), identifying heavy precipitation as the dominant future risk driver.

3.2. *Building-scale Interventions*

The building-scale interventions are defined based on the risk assessment, which identified ongoing moisture-induced deterioration of the basement structural system as a critical concern, potentially intensified by heavy precipitation. In parallel, an energy retrofit is planned for the Dairy pavilion within the MULTICLIMACT project, including the installation of a low-temperature underfloor heating system in the basement, followed by the construction of a new floor assembly (Kotovica et al., 2026). Within this context, the proposed interventions focus on increasing the structural resilience of the basement floor system, comprising the RC slab and supporting steel beams, in the face of existing deterioration and the additional demands introduced by the retrofit works. The following building-scale interventions (BI) are analysed for the RCM basement floor system (Santamaria et al., 2025; Urciuoli et al., 2025):

- **BI1:** Repair of the RC slab through replacement of deteriorated reinforcement, sealing of expansion joints, installation of shear connectors, and casting of a bonded concrete overlay to restore load-bearing capacity and improve durability.
- **BI2:** Repair of the RC slab through replacement of deteriorated reinforcement, application of corrosion-inhibiting treatments, installation of mechanical connectors, and casting of a new concrete overlay, combined with embedded corrosion sensors and data acquisition systems.
- **BI3:** Strengthening of selected steel beams with Carbon Fibre-Reinforced Polymer (CFRP) laminates combined with bonded fibre-optic (FBG) sensors for continuous strain monitoring, together with corrosion-monitoring sensors and data acquisition systems.

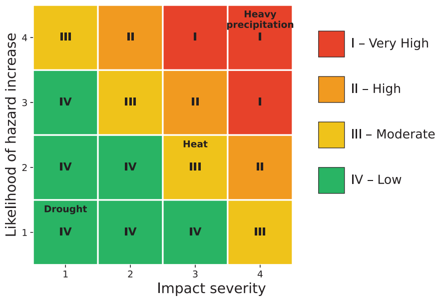

Fig. 2. Qualitative Risk Matrix for the Riga Central Market

All three BIs are compatible with heritage preservation principles, as they prioritize repair of existing components and compatibility with the original structural system. Moreover, BI2 and BI3 include monitoring as an optimized intervention strategy, since continuous information on corrosion and structural response supports early diagnosis and maintenance, helping reduce the need for more invasive future interventions.

3.3. *Resilience Assessment via Key Performance Indicators (KPIs)*

This section assesses the resilience of the basement floor system in its current condition and under the proposed interventions through the defined KPIs. These are expressed in four performance categories: 1-low, 2-moderate, 3-high, and 4-very high. When quantitative values are available, they are assigned to the corresponding category ranges; otherwise, classification is established qualitatively based on engineering judgment.

3.3.1. *Reliability*

Reliability is defined as the probability that a system will perform its intended function under specified conditions over a given reference period. For CH structures, acceptable reliability levels should reflect not only conventional safety requirements but also the consequences associated with the loss of historic value. The minimum reliability values specified in the Eurocode EN 1990 for the different consequence classes are used to define the categories adopted in this study. The bounds of these categories are expressed in terms of the reliability index, β, a dimensionless measure of structural safety that represents the distance, in standard deviation units, between the mean safety margin and the failure threshold. Higher values of β correspond to lower probabilities of failure. Accordingly, values below $\beta = 3.3$ are classified as low reliability, values in the range $3.3 \leq \beta < 3.8$ are classified as moderate, values in the range $3.8 \leq \beta < 4.3$ are classified as high reliability, while values equal to or greater than $\beta = 4.3$ are classified as very high reliability. The reliability of the RC basement slab under a deteriorated condition was evaluated by means of a probabilistic nonlinear finite element analysis considering permanent, live, and additional retrofit loads, accounting for uncertainties in material properties, geometry, and load effects (Santamaria et al., 2025). Under these conditions and for a reference period of 50 years, the analysis yielded a reliability index of $\beta = 2.36$, indicating a low reliability level. Regarding the proposed interventions, the reliability classifications assigned are based on qualitative engineering judgment. In this context, BI1 is classified as having high reliability because the bonded concrete overlay is expected to ensure the required load-bearing capacity of the RC slab under the additional retrofit demands. BI2 is also classified as high reliability because it includes repair and strengthening measures with similar structural effects, while the embedded corrosion sensors support operational reliability by enabling continuous tracking of deterioration and early diagnosis. BI3 is classified as very high reliability because CFRP laminates effectively increase the load-carrying capacity of the steel beams, while the FBG and corrosion-monitoring systems support operational reliability by continuously monitoring strain response and deterioration.

3.3.2. *Robustness*

Robustness can be understood as the ability of a system to limit the consequences of local damage and prevent them from developing into disproportionate losses. Robustness is assessed qualitatively based on engineering judgment by considering the extent to which moisture-induced damage may propagate beyond the initially affected components. The current condition is classified as low robustness, since deterioration has already extended to adjacent structural elements. BI1 provides moderate robustness, as repair and expansion joint sealing are expected to limit further moisture ingress and the propagation of damage. BI2 provides high robustness, since corrosion monitoring enables early detection and timely maintenance, thereby helping contain local deterioration. BI3 provides very high robustness, as continuous strain and corrosion monitoring offer the greatest capacity to detect early damage and prevent broader structural consequences.

3.3.3. *Resourcefulness*

In the context of CH renovation, resourcefulness can be understood as the ability to estimate, allocate, coordinate, and mobilise the resources required to carry out interventions under heritage preservation constraints. As discussed in Urciuoli et al.(2025), renovation projects depend on the coordinated availability and delivery of materials, equipment, tools, and skilled labour, often under limited suppliers, specialised craftsmanship, and regulatory constraints. These conditions require careful planning, procurement, and sequencing of activities, since delays in resource availability can directly affect project duration and create bottlenecks along the critical path. Urciuoli et al.(2025) proposed an operational framework that integrates supply chain operations with project management practices for CH renovation. Within this framework, resourcefulness can be interpreted as the system's ability to coordinate and mobilise the required resources while limiting bottlenecks and delays associated with supply chain constraints. Interventions are therefore considered more resourceful when the required resources are readily available and can be coordinated with limited disruption to the planned sequence of activities.

Based on this perspective, the current condition of the basement floor system is assessed qualitatively and classified as having low resourcefulness, as no active intervention strategy is in place to support the timely mobilisation and coordination of resources required to address the ongoing deterioration. The proposed interventions are also assessed qualitatively based on the expected availability and coordination of resources, as well as the sensitivity of the intervention schedule in correspondence to supply chain bottlenecks (see

(Urciuoli et al., 2025)). BI1 is classified as having moderate resourcefulness because its execution involves a sequence of labour- and equipment-intensive operations, including hydrodemolition, reinforcement cleaning, bar replacement, connector installation, overlay casting, and curing, which require careful sequencing and may create bottlenecks. BI2 is also classified as having moderate resourcefulness, as it combines extensive repair works, sensor embedment, and installation of data acquisition components, making the schedule sensitive to delays in sensor supply, rebars availability, and cabling and terminations. BI3 is classified as having high resourcefulness because, although it depends on specialised components and expertise, its nominal activity sequence is shorter than that of the other interventions, reducing coordination demands and the potential for schedule bottlenecks (Urciuoli et al., 2025).

3.3.4. *Recovery*

Recovery refers to the ability to restore functionality after a disturbance within an acceptable time frame. For CH structures, this concept extends beyond the reinstatement of structural performance to include the re-establishment of the asset's social, cultural, and economic functions (Limongelli et al., 2019). In this study, recovery is classified qualitatively based on the expected capacity to restore the functions of the CH asset within an acceptable timeframe, considering not only execution time but also the ability to detect and assess damage and to define the required intervention. In the RCM, recovery is linked to the continued use of the building as an active market and its role within the Historic Centre. Accordingly, interventions supported by monitoring systems are associated with higher recovery rates, as they enable earlier diagnosis and more timely intervention planning, thereby reducing disruption and supporting a faster return to normal operations. The estimated intervention durations, computed using the critical path method (CPM), were considered together with these aspects in the recovery classification (Urciuoli et al., 2025). From this perspective, the current condition of the basement floor system is classified as having low recovery, since no active intervention strategy is in place to address the ongoing deterioration. BI1 is classified as having moderate recovery, with an estimated duration of approximately 29 days. BI2 is also classified as having moderate recovery, despite its longer estimated duration of about 51.5 days, because the corrosion monitoring system supports more informed decisions and faster responses if further damage is detected. BI3 is classified as having high recovery, since its shorter estimated duration of 18 days reduces the interruption period, while the combined FBG and corrosion-monitoring systems further support rapid diagnosis and timely intervention.

3.4. *Urban-scale interventions: UNDRR scorecard for CH*

The UNDRR Disaster Resilience Scorecard for Cities Cultural Heritage Addendum (UNDRR, 2022) provides a structured method to assess urban-scale resilience for CH in the Historic Centre of Riga. It comprises 44 questions rated from 0 to 3, across ten Essentials (E). It emphasizes traditional knowledge, local construction practices, and materials to maintain authenticity while improving safety, and supports municipalities in establishing a baseline assessment, identifying vulnerabilities, prioritizing interventions, engaging stakeholders, and tracking progress. For the case study, the Riga Energy Agency (REA) interviewed different stakeholders to respond to the CH Resilience Scorecard (Santamaria et al., 2025). In this study, the results of the scorecard completed by the Riga city departments are presented (Fig. 4). The assessment yielded an overall score of 58 out of 132, corresponding to about 44% of the achievable score, indicating a low level of urban-scale resilience for CH in the Historic Centre of Riga. The lowest scores were obtained for E09 on disaster response and E10 on recovery and build back better, followed by E02 on risk scenarios, E03 on financial capacity, and E06 on institutional capacity. The main weaknesses lie in preparedness, institutional coordination, response capacity, and recovery planning. Accordingly, the following three urban-scale interventions (UI) are proposed:

- **UI1:** Development of an emergency response and post-event recovery plan for the Historic Centre of Riga that considers heritage peculiarities and prioritization, first responder training, evacuation of transient populations, culturally appropriate shelters and relief supplies, and post-disaster recovery and economic measures developed through inclusive consultations. The plan should also incorporate build-back-better principles by using traditional design guidelines, materials, and techniques. This UI mainly addresses E09 and E10.
- **UI2:** Development of a framework for the Historic Centre of Riga to identify and understand most probable risk scenarios through a complete database on exposure and vulnerability of tangible CH, considering possible changes over time related to urbanization, climate, tourism activity, and transient population. The framework should provide geographically based information with regular updates and support the assessment of critical infrastructure systems in relation to the identified risks. This UI mainly addresses E02 and E08.
- **UI3:** Establishment of a permanent mechanism within the city government for CH financing and funding, disaster resilience and adaptation incentives, and a shared database on disaster risk and resilience of CH, while promoting coordination with community organizations and related businesses. This UI addresses E03 and E06, while contributing to E01 and E07.

4. Results

Figure 3 presents the KPI-based resilience assessment for the current condition and the proposed building-scale interventions. The four KPI ratings are combined into a normalized composite resilience indicator, expressed as a percentage of the maximum attainable rating. The current condition reaches 25%, while BI1, BI2, and BI3 achieve 56%, 62%, and 88%, respectively. These results indicate a substantial increase in resilience for all the proposed interventions relative to the current condition. Among them, BI3 provides the highest overall improvement, driven by its very high reliability and robustness, and high resourcefulness and recovery. BI2 performs slightly better than BI1, mainly due to its greater robustness from integrating monitoring systems.

Figure 4 compares the baseline scorecard results with the expected improvements associated with the three proposed urban-scale interventions (UI). UI1 increases the score from 58 (44%) to 80 (61%), UI2 to 71 (54%), and UI3 to 75 (57%). UI1 provides the largest individual improvement, while UI2 and UI3 also contribute relevant gains in resilience. Since the three interventions address complementary aspects of urban-scale CH resilience, their joint implementation would raise the score to 110 out of 132 (83%), indicating a substantial improvement in the resilience profile of the Historic Centre of Riga.

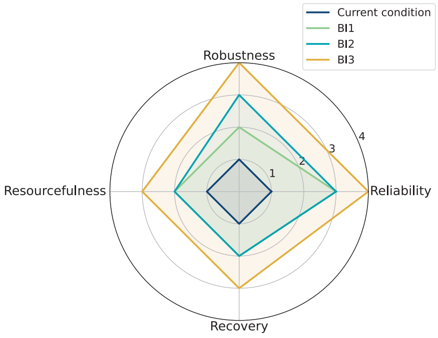

Fig. 3. Resilience Assessment of Building-scale Interventions (BI) via KPIs

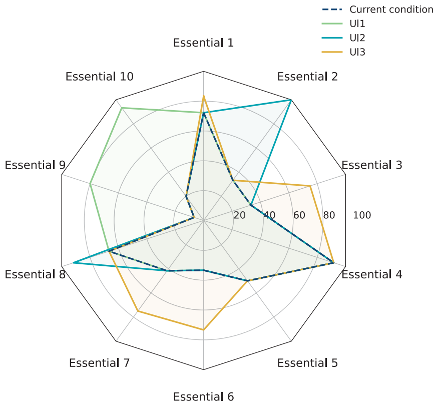

Fig. 4. Resilience Assessment of Urban-scale Interventions (UI) through the UNDRR Scorecard for CH

5. Conclusions

This study applied a multi-scale framework to support resilience-enhancing interventions for cultural heritage (CH) assets by linking building-scale and urban-scale assessments. For the Riga Central Market (RCM), the risk assessment identified heavy precipitation as the dominant climate-related hazard, due to the ongoing moisture-induced deterioration of the basement structural system and the potential acceleration of corrosion processes. On this basis, three building-scale interventions were defined and assessed through the proposed KPIs. All the interventions improved the current resilience condition, with the solution that combined steel beam strengthening with CFRP laminates and integrated monitoring systems delivering the highest overall performance. At the urban scale, the UNDRR scorecard assessment indicated a low baseline resilience level for CH in the Historic Centre of Riga, mainly reflecting weaknesses in preparedness, coordination, response, and recovery planning. The proposed urban-scale interventions significantly improved the score, and their combined implementation raised it from 58 to 110 out of 132. Overall, the results show that resilience-based CH preservation should account not only for structural safety, but also for intervention feasibility, operational constraints, governance capacity, and recovery.

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