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D8.6 – DEVELOPING RESILIENCE-ENABLING INTERVENTIONS IN CULTURAL HERITAGE BUILDINGS, URBAN AND RURAL CONTEXTS – APPLICATION TO A REAL DEMO

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MULTICLIMACT
D8.6 - DEVELOPING RESILIENCE-ENABLING INTERVENTIONS IN CULTURAL HERITAGE BUILDINGS, URBAN AND RURAL CONTEXTS - APPLICATION TO A REAL DEMO

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Abbreviations and Acronyms

ACRONYM	DESCRIPTION
CFRP	Carbon Fiber Reinforced Polymers
CH	Cultural Heritage
ICOMOS	International Council on Monuments and Sites
InSAR	Interferometric Synthetic Aperture Radar
DAQ	Data Acquisition System
FBG	Fiber Bragg Grating
FEM	Finite Element Modeling
FO	Fibre Optic
KPI	Key Performance Indicator
QoL	Quality of Life
SHM	Structural Health Monitoring
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNDRR	United Nations Office for Disaster Risk Reduction
WP	Work Package
CES	Cultural Heritage Engineering Strategies
GEM	Global Earthquake Model
PGA	Peak Ground Acceleration
RH	Relative Humidity
RCM	Riga Central Market
AAL	Average Annual Loss
SCC	Self-Compacting Concrete
NDT	Non-Destructive Testing
RC	Reinforced Concrete
PSI	Persistent Scatterer Interferometry
SBAS	Small Baseline Subset
QA	Quality Assurance
SF	Safety Factor

Executive Summary

This document constitutes a deliverable for MULTICLIMACT project, describing the outcomes of Task 8.6. This work presents the application of a multi-scale methodology for designing resilience-enabling interventions in cultural heritage (CH) buildings and their surrounding environments. The objective is to assess and implement strategies that enhance the resilience of CH assets while preserving their cultural and social value. The methodology integrates technical, social, economic, and environmental factors to quantify the impact of interventions, considering climate-specific hazards, urban and territorial constraints, and supply chain dependencies.

The methodology was applied to two case studies: Riga Central Market in Latvia and Tedingerbroek Polder in the Netherlands. For each site, a comprehensive analysis of hazards, vulnerabilities, and resilience performance was conducted. Key resilience indicators, namely reliability, robustness, resourcefulness, and recovery, were assessed to evaluate the effectiveness of different interventions. These interventions include structural reinforcement, monitoring solutions, and cultural heritage measures to preserve authenticity and cultural value, all contextualized within local constraints. Additionally, supply chain considerations were examined to ensure the feasibility of the proposed measures.

The final step of the methodology involved evaluating the proposed interventions using the UNDRR's Disaster Resilience Scorecard for Cities, specifically tailored for CH contexts. The selected interventions were then evaluated, ensuring their practical relevance and applicability. The findings contribute to advancing resilience planning for CH by providing a structured, multi-disciplinary approach to intervention assessment and decision-making. This work was carried out by a collaboration between partners of MULTICLIMACT, namely UMINHO, KTH, RINA-C, REA and TUDelft.

1. INTRODUCTION

Cultural Heritage (CH) buildings represent irreplaceable social, historical, and architectural values, yet they face increasing threats from climate change, urban development, and socio-economic transformations. These challenges necessitate integrated approaches to ensure that preservation efforts go beyond conventional conservation, embracing the concepts of resilience and risk-informed planning. In this context, the MULTICLIMACT project responds to this need by developing and applying tools that enable heritage assets and their surroundings to better withstand, adapt to, and recover from a wide range of hazards without compromising their cultural significance. One of these tools was contextualized in the Deliverable 2.6 of the project (Sousa, Ingrosso, and Urciuoli 2024) and consists of a multi-scale framework for planning and evaluating resilience-enabling interventions in CH buildings. The framework recognizes that traditional CH assets typically deviate from modern building standards and require tailored, multidisciplinary methodologies that account for their unique material, structural, and socio-cultural attributes.

The framework follows a four-step methodology as depicted in Figure 1. First, it begins with the comprehensive assessment of the CH asset's current condition, including its structural state, environmental exposures, historical relevance, and vulnerabilities. This step provides the foundation for identifying appropriate interventions that preserve the asset's authenticity while enhancing its resilience. In the second step, 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, labour, and logistical support are available to implement them effectively. The third step focuses on analysing the impacts of each intervention at multiple spatial scales, from individual building components to broader urban or rural contexts. This also includes the quantification of an intervention's contribution to resilience, and the technical, social, economic, and environmental impacts. Finally, the fourth step applies the UNDRR Disaster Resilience Scorecard for cultural heritage (UNDRR 2022), to classify the proposed interventions based on their effectiveness in increasing resilience from a governance and multidisciplinary perspective.

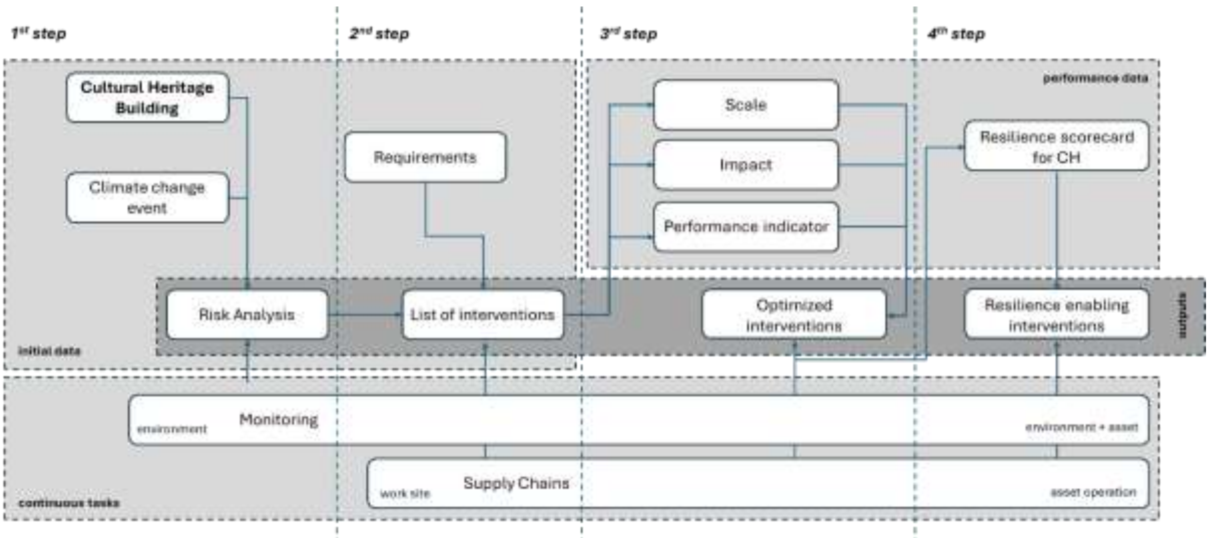


Figure 1. Proposed framework for multi-scale evaluation of resilience for interventions in cultural heritage buildings developed in Task 2.6 (Sousa, Ingrosso, and Urciuoli 2024)

This deliverable, D8.6 Developing resilience-enabling interventions in cultural heritage buildings, urban and rural contexts -- application to a real demo, reports on the implementation of the proposed multi-scale framework for designing resilience-enabling interventions in cultural heritage within Task 8.6 of the MULTICLIMACT project. The framework was applied to two demonstration sites: the Riga Central Market, a cultural heritage building in Latvia, and its urban surroundings, and the Dutch demonstration site in Tedingerbroek Polder near Den Haag, a historically significant landscape illustrating traditional Dutch water management practices, where a pumping station and an associated system of dikes along the Goo Wetering channel have played a central role in shaping local cultural and agricultural heritage. It should be noted that, due to a misalignment in the task description, TU Delft was not initially assigned effort for Task 8.6, and therefore the complete framework could not be applied to the Dutch demonstration. However, TU Delft contributed to selected activities, such as adapting parts of the methodology to the Dutch context and validating its applicability across distinct geographical, environmental, and cultural settings, ensuring that resilience and cultural heritage values were considered. As a result, the complete framework could not be applied to the Dutch demo. Nonetheless, some parts of the methodology were implemented with the objective of validating its applicability across distinct geographical, environmental, and cultural contexts. The results of this deliverable contribute to advancing resilience planning by enabling informed decision-making for designing, evaluating and prioritising interventions in cultural heritage contexts.

1.1. Objectives

The main objective of this deliverable is to translate the multi-scale approach for designing resilience-enabling interventions from Figure 1, into practical applications within the Latvian and Dutch demonstration sites. Therefore, this document provides a structured methodology for assessing hazards and identifying targeted resilience-enhancing measures, considering climate-specific risks, urban constraints, and territorial limitations. The integration of technical, social, economic, climatic, and cultural heritage factors allows for a comprehensive evaluation of the impact of different interventions, ensuring their feasibility, effectiveness, and compatibility with the preservation of the asset's historical and cultural significance in real-world conditions. Additionally, the deliverable aims to demonstrate how the supply chain framework from Task 2.2, contextualized in Task 8.2, can support the identification and selection of viable intervention strategies for the Latvian case study. Lastly, the deliverable showcases how discussions with stakeholders can align the proposed measures with local needs and priorities.

The primary target group for this deliverable includes policymakers, urban planners, heritage conservation specialists, engineers, and researchers involved in cultural heritage preservation and resilience planning. The methodology is demonstrated across two distinct CH contexts: the Riga Central Market, representing a single heritage building, and the Tedingerbroek Polder in the Netherlands, representing a cultural landscape, highlighting how the same resilience approach is flexible and applicable to both urban and rural heritage settings. Local and regional authorities, as well as stakeholders responsible for implementing resilience measures, can benefit from the insights and recommendations provided in this report, regardless of the type or scale of the heritage asset.

1.2. Contributions of partners

Task 8.6 was led by UMINHO in collaboration with RINA-C, KTH, REA and TUDelft. Table 1 depicts the main contributions from the project's partners in the development of deliverable D8.6.

Table 1: Contributions of Partners to D8.6

PARTNER SHORT NAME	CONTRIBUTIONS
UMINHO	Overall content to sections 1-8.
KTH	Overall content to section 4
RINA-C	Overall content to section 4
REA	Case study data for sections 2, 3 and contents to section 7
TUDelft	Case study data and contents to sections 2, 3, 4 and 5/layout

1.3. Interactions with other WPs and tasks

Task 8.6 builds upon the methodology developed in Task 2.6 for designing resilience-enabling interventions in CH buildings. In Task 8.6, this methodology is applied to real-world case studies, integrating social, economic, environmental, and technical considerations to assess and select optimal interventions. Moreover, the supply chain resilience methods developed in Task 2.2 and further contextualized in Task 8.2 provided crucial inputs for Task 8.6, particularly for the Latvian demo. These inputs help identify feasible intervention alternatives by ensuring robust and climate-proof supply chains that support resilience measures. Lastly, the outcomes of Task 8.6 will directly contribute to Task 11.4, where the resilience strategies developed and evaluated will be further validated with stakeholders and integrated into the CH context of Latvia. These interactions of Task 8.6 with other WPs and tasks are illustrated in

Figure 2.

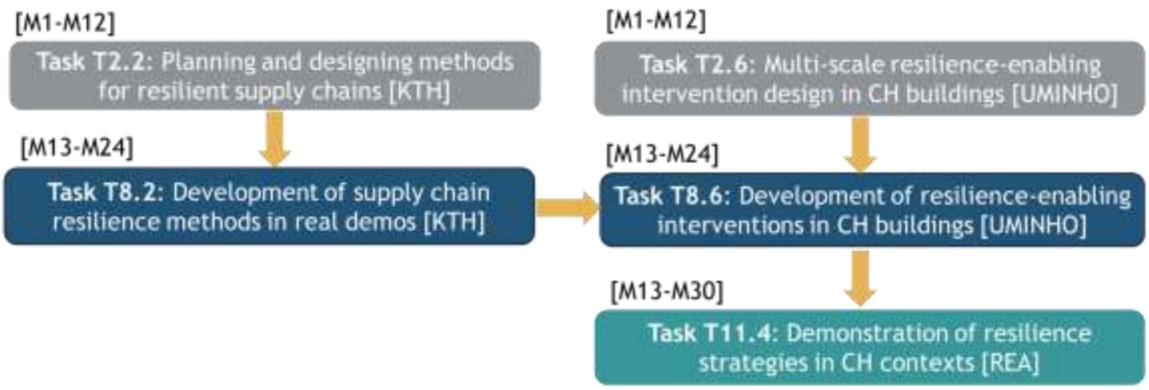


Figure 2. Interactions of Task 8.6 with other WPs and tasks

1.4. Structure of the deliverable

The deliverable is organized into eight main chapters. Chapter 1 introduces the main objectives of the work in Task 8.6 and the interactions with other tasks. Chapter 2 provides background on the demonstration sites and their cultural heritage significance. Chapter 3 presents the risk assessment of the cultural heritage sites, including hazard and vulnerability analyses for both case studies. Chapter 4 details the proposed resilience-enabling interventions, along with supply chain considerations and their multi-scale impacts. Chapter 5 outlines the key performance indicators used to quantify resilience, covering reliability, robustness, resourcefulness, and recovery. Chapter 6 evaluates the impacts of the interventions on quality of life (QoL) at urban or rural scale, as well as their economic, social and environmental impacts. Chapter 7 presents the evaluation of interventions using the UNDRR Disaster Resilience Scorecard for Cities, specifically tailored for CH contexts, with stakeholder engagement. Chapter 8 describes how the results of this deliverable will be applied in other WPs, and finally Chapter 9 summarizes the findings and conclusions.

2. GENERAL BACKGROUND OF THE DEMO SITES

2.1. Historic Centre of Riga and Riga Central Market (Latvia)

The Historic Centre of Riga, inscribed as a UNESCO World Heritage Site in 1997, embodies a rich architectural and urban fabric shaped by centuries of trade, cultural exchange, and geopolitical shifts. Established as a port city in 1201 along the banks of the River Daugava, Riga flourished as a key centre of the Hanseatic League, leaving an imprint of medieval urban planning that persists despite later reconstructions due to wars and fires. Its layered development is evident in the juxtaposition of well-preserved medieval structures, a 19th-century semi-circle of boulevards with a green belt, and former suburban quarters characterized by dense wooden architecture. The city's skyline, punctuated by church spires, reflects a harmonious relationship between built heritage and open spaces.

Figure 3 presents the boundaries of the Historic Centre of Riga and its protection zone per UNESCO World Heritage site (No. 852). A distinctive feature of the Historic Centre is its unparalleled concentration of Art Nouveau architecture, with over 300 buildings exemplifying this style. The early 20th-century transformation of Riga into a hub of architectural innovation contributed to its role as an influential cultural and educational centre in the Baltic region. The management of this heritage is supported by extensive legal frameworks, institutional collaboration, and heritage protection initiatives. Yet, maintaining authenticity remains a pressing concern due to factors such as the loss of original building materials, unsuitable restoration practices, and insufficient financial resources. Additionally, the relative proximity of the Riga Free Port transshipment zone to the Historic Centre poses a risk, as the transportation and reloading of hazardous and polluting substances through the area is considered a potential threat. Furthermore, the overall cohesion of the site remains susceptible to negative impacts from developments occurring both within its boundaries and in the surrounding buffer zone. These vulnerabilities highlight the ongoing need for strategic interventions to preserve Riga’s cultural heritage while accommodating contemporary urban demands (UNESCO 2024).

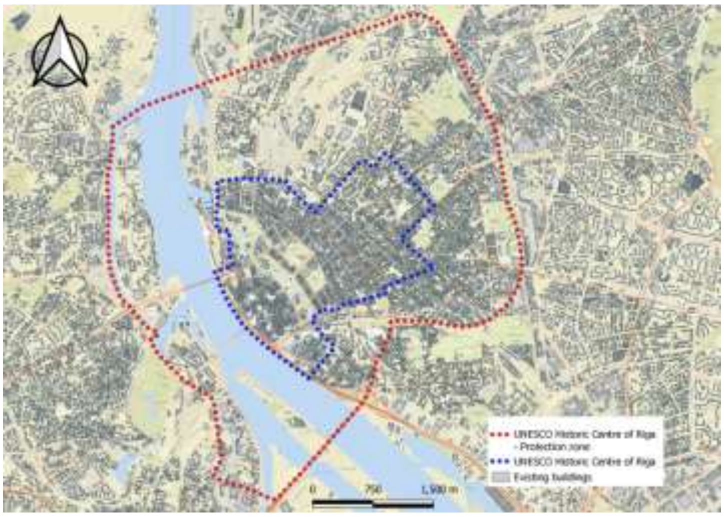
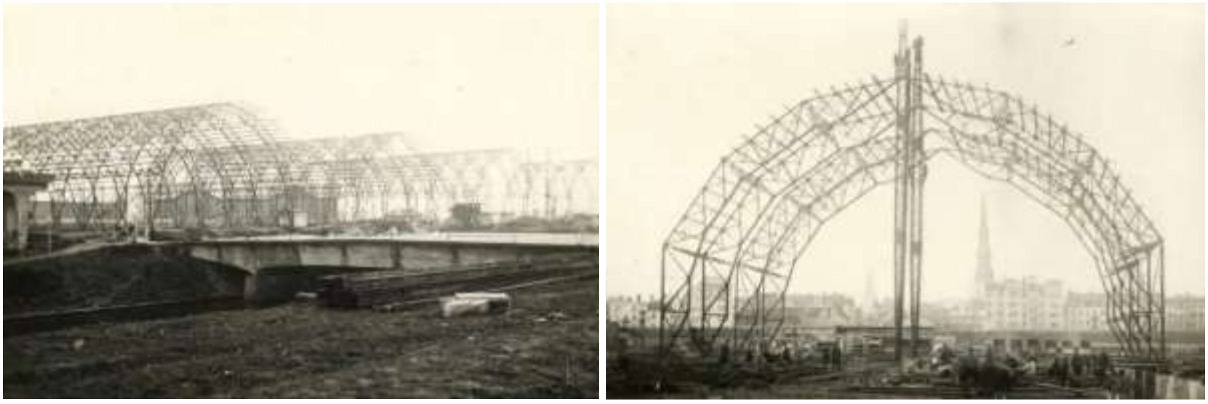


Figure 3. Historic Centre of Riga and its protection zone per UNESCO World Heritage (source of boundaries: https://georiga.eu)

The Riga Central Market stands as a significant landmark within the Historic Centre of Riga, reflecting the city's architectural innovation and commercial heritage. Constructed between 1924 and 1930, the market comprises five pavilions, showcasing Neoclassical and Art Deco design elements. Upon its opening on November 2, 1930, it was celebrated as the largest and most advanced marketplace in Europe, symbolizing Latvia's progress and modernity during the interwar period. In 1997 Riga Central Market area was added to the UNESCO World Heritage list as part of the Historic Centre of Riga.

The construction of the Riga Central Market was a remarkable feat of engineering and design. The project aimed to relocate the overcrowded and unsanitary Daugavmala Market to a modern facility that met contemporary hygienic and economic standards. The innovative approach involved repurposing metal frameworks from German Zeppelin hangars, which were dismantled and transported to Riga. Figure 4a depicts the dismantling of zeppelin hangars at Winode between 1924 and 1926. The original plan was to preserve them as they were. However, their height posed practical challenges for the intended market, particularly in terms of heating efficiency. To address this issue, the design team modified the structures by utilizing only the upper sections with vaulted frames. These elements were repurposed as structural trusses for the new market pavilions, which made it possible to cover a large space without additional supports (Neighborhood 2023). Figure 4b displays the erection of the metal frames for the Riga market pavilions in 1926.



a) b)

Figure 4. a) Dismantling of zeppelin hangars at Winode (1924-1926); b) Erection of metal frame for market pavilions in Riga, 1926 (source: Latvian State Historical Archive, (Neighborhood 2023))

The load-bearing walls of the market pavilions were built of reinforced concrete and masonry, as depicted in Figure 5. Each pavilion hall is 20.5 meters high and 35 meters wide, with a basement built under the entire hangar area. The basement slab, supported by the foundation structure and a grid of masonry columns (depicted in Figure 5b), is a cast reinforced concrete slab on steel beams (H-profile load-bearing beams, with concrete). For the construction of the five pavilions, 6 million bricks, 2,460 tonnes of iron and 60,000 barrels of cement were used (Neighborhood 2023).

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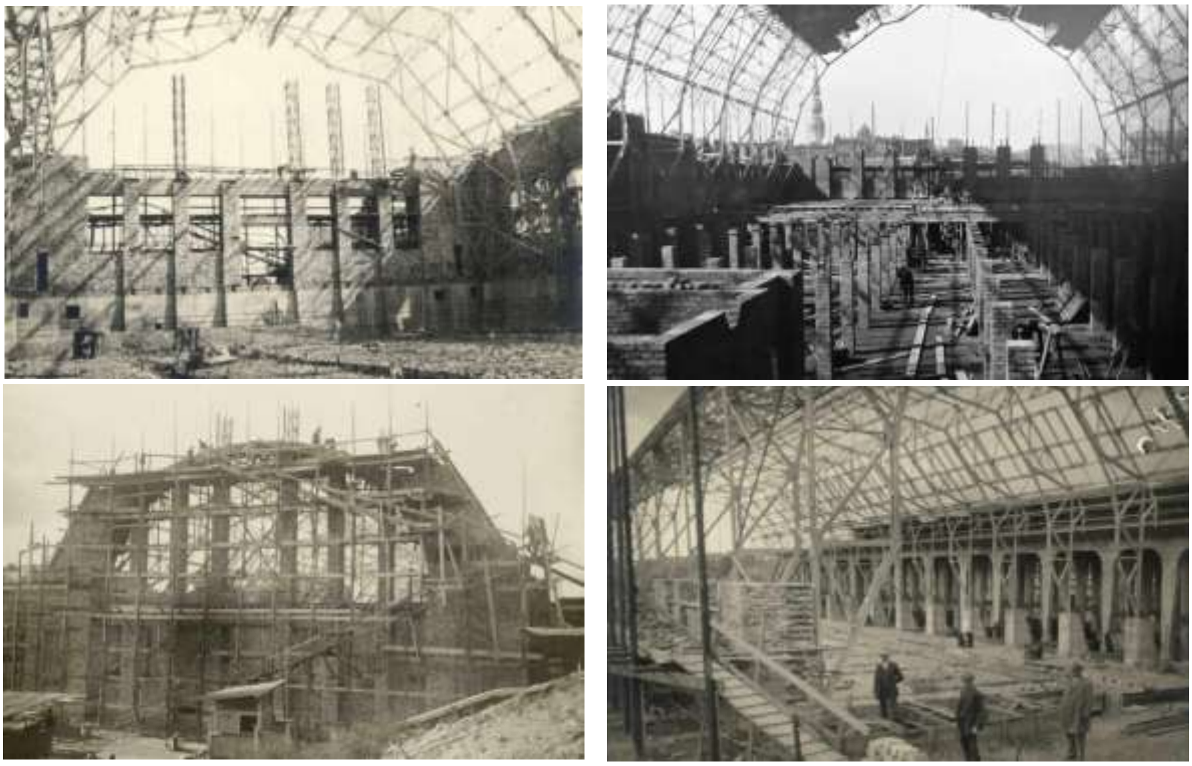

a) b)

Figure 5. a) Erection of market pavilions including brick side facades in 1928; b) Erection of the walls and roof of the pavilions (source: Latvian State Historical Archive, (Neighborhood 2023))

Nowadays, the Riga Central Market is not only one of the largest marketplaces in Eastern Europe, but also one of the most visited, with 80,000-100,000 people shopping there per day on average. This historic complex comprises heritage buildings with substantial energy demands, influenced by the region's northern climate, which experiences both harsh winters and hot summers. The market's large-scale premises, combined with specific heating and cooling requirements essential for market operations, such as food storage, further contribute to its high energy consumption. Figure 6 shows the five Central Market pavilions, where it can be seen that four of them are arranged in a row and one of them is parallel to the city canal. The Central Market Dairy Pavilion has been selected as the cultural heritage building to demonstrate the multi-scale approach for designing resilience-enabling interventions.

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Figure 6. Riga Central Market pavilions (source: (Neighborhood 2023))

The structure of the Dairy Pavilion includes a basement extending beneath the entire building and a single above-ground floor, with a stairwell in the central part of the building. Along the south facade (see Figure 7), a market square is situated, while a car park occupies the north facade. Additionally, a two-story structure is positioned between the Dairy Pavilion and an adjacent pavilion, establishing a connection between the inspected Dairy Pavilion and the neighboring Gastronomy Pavilion.

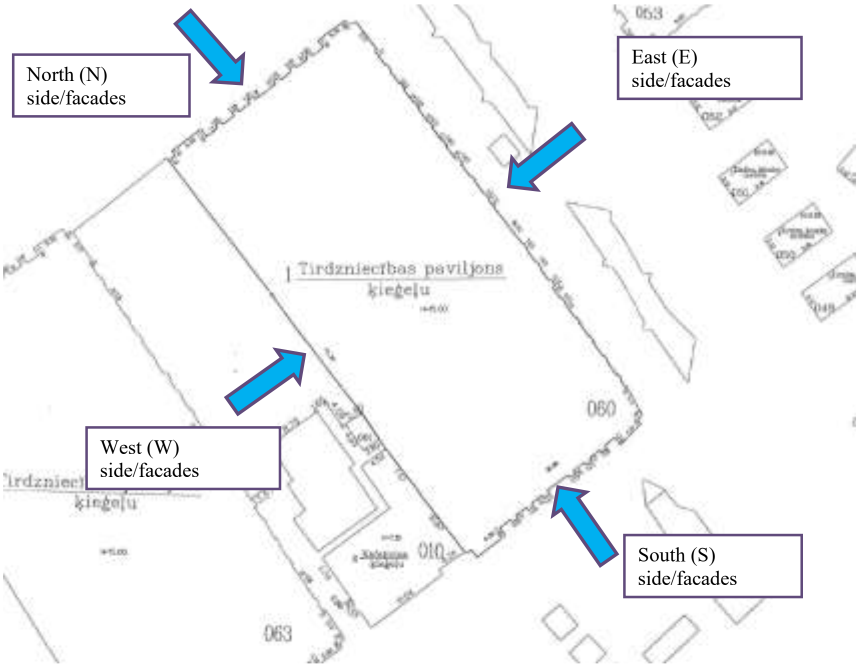

Figure 7. Location of the Dairy pavilion structure within the land plot

2.2. Tedingerbroekpolder Dike (Netherlands)

The Tedingerbroekpolder, located in South Holland, Netherlands, is a region of profound cultural and historical significance. Situated between the municipalities of Leidschendam, Nootdorp, Pijnacker, and Rijswijk, it is bordered by the Hoogheemraadschap van Rijnland to the north, the Polder van Nootdorp to the east, the Hoge- and Lage Broekpolder to the south, and the Leidsche Vliet to the west (see

Figure 8). The Delfland Water Board (Hoogheemraadschap van Delfland) maintains an archival inventory documenting the historical administration and operation of the Tedingerbroekpolder from 1605 to 1976. The collection provides valuable insights regarding agricultural heritage, water engineering legacy, cultural landscapes, and infrastructure developments within the polder over several centuries (Delfland Water Board). First mentioned in Delfland's keurboek (charter book) from 1440–1445, the Tedingerbroekpolder is a testament to the Netherlands' centuries-long mastery of land reclamation and water management (Delfland Water Board). Despite urbanization, the polder's remnants offer a window into Dutch identity, shaped by ingenuity and adaptation to a water-rich environment. From fertile meadows to turf extraction, rural estates to infrastructural developments, the Tedingerbroekpolder encapsulates the evolution of a landscape central to national culture.

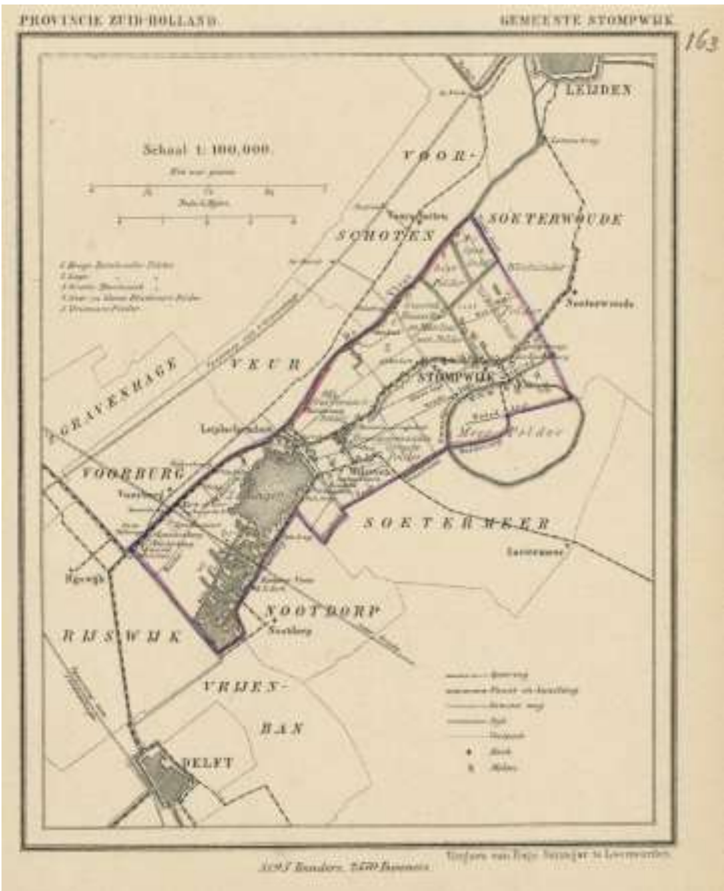

Figure 8. Location of the Tedingerbroekpolder (source: Wikipedia)

Water management is a cornerstone of the Tedingerbroekpolder's heritage, embodying the Dutch tradition of hydraulic engineering and resilience. As a low-lying polder, it required sophisticated drainage systems to prevent flooding and maintain arable land. The Delfland Water Board, responsible for regional water control, supervised the polder's maintenance, a task rooted in centuries of expertise. Historical records detail the presence of a sluice and the management of water levels, critical for balancing agricultural needs with flood prevention (Delfland Water Board).

Among the most significant elements of the Tedingerbroekpolder's heritage are the pump in Broekweg (Figure 9 a),and the dikes along the Goo Wetering channel (Figure 9 b), both of which played pivotal roles in sustaining the polder's functionality and cultural identity. The pump in Broekweg, a vital component of the polder's drainage system, exemplifies the ingenious engineering that defines Dutch heritage. Installed as part of the broader efforts to manage water levels, this pump ensured the removal of excess water from the low-lying lands, protecting the fertile meadowland and enabling continuous agricultural productivity. Its operation, documented in the Delfland Water Board's archives, underscores the polder's reliance on mechanical innovation to conquer water—a hallmark of Dutch cultural identity and a testament to the nation's historical struggle against flooding. This pump not only safeguarded the polder's economic foundation but also became a symbol of human ingenuity, preserved in historical records as a key artifact of the region's water management heritage (Delfland Water Board).

Similarly, the dikes along the Goo Wetering channel, including the one used as Demosite in the MULTICLIMACT project, are of immense heritage value, representing the physical and cultural backbone of the polder's water control system. These dikes, meticulously maintained and documented in archival maps and reports, prevented flooding by channelling water effectively through the polder and into the Vliet. Their strategic placement and robust construction reflect centuries of accumulated knowledge about land reclamation, a practice central to Dutch identity. As enduring features of the landscape, these dikes connect the Tedingerbroekpolder to the broader narrative of Dutch dike-building traditions, celebrated in national heritage sites and UNESCO listings like Kinderdijk. Their preservation in the polder's topography and archives highlights their role in shaping both the environment and the cultural memory of the region.

a)

b)

Figure 9. a) Tedingerbroekpolder pumping station in Broekweg (source: https://www.gemalen.nl/gemaal_detail.asp?gem_id=1169); b) Aerial 3D view of Tedingerbroek dike along the Goo Wetering channel (source: Google maps)

The polder's proximity to the Vliet and its delineation by natural and administrative boundaries (e.g., the landscheiding with Rijnland) further emphasize its integration into a broader hydraulic network. The transformation of waterlogged peatlands into usable land through these systems exemplifies Dutch resilience, a cultural hallmark celebrated nationwide.

3. RISK ASSESSMENT OF CULTURAL HERITAGE SITES

3.1. Riga Central Market

3.1.1. Hazard Analysis

3.1.1.1. Climatic hazards

Latvia's climate is undergoing significant shifts that intensify natural hazards, impose significant stress on infrastructure and public health, and demand increasingly robust adaptation strategies. Analyses by the Climate-ADAPT platform and Latvia's National Adaptation Plan (NAP) emphasize that warming temperatures, altered precipitation regimes, more intense storms, and sea-level rise are among the principal stressors facing the country. Evidence indicates that riverine flooding remains a key threat, especially under changing snowmelt and precipitation patterns, while coastal zones face erosion and inundation risks as sea levels rise. Concurrently, heatwaves are becoming more frequent and persistent, with implications for public health, urban comfort, and the integrity of infrastructure and perishable-goods supply chains. Table 2 provides a concise overview of six key climate hazards in the Riga area, addressing their occurrence, possible impacts, and statistical trends. Particularly, extreme temperature events such as prolonged heat waves or severe cold spells pose indirect risks to the Riga Central Market. These risks include accelerated material degradation, increased thermal stress on structural elements, and potential impacts on indoor environmental conditions critical for food storage and market operations.

Table 2: Overview of Key Climate Hazards, Impacts, and Statistical Trends in Riga

HAZARD TYPE	FREQUENCY	POTENTIAL IMPACT	STATISTICAL INSIGHTS	REFERENCE
Flooding	High	Damage to infrastructure, market disruptions, economic losses, contamination of goods.	- Major floods historically occurred every 10-15 years. - Sea levels rising ~1-3 mm/year in the Baltic Sea region.	(Capital Riga 2019; Hieronymus et al. 2018; Latvian National Plan 2019; Sustainable Development Strategy of Riga 2014)
Heatwaves	Moderate	Reduced foot traffic, health risks to vendors/visitors, spoilage of perishable goods.	- Average temperatures in Latvia have risen by 1.5°C since 1880. - Heatwaves occurring every 2-3 years recently.	(Latvian National Plan 2019)
Storm Surges	Low to Moderate	Physical damage to structures, flooding, and wind-driven rain impacts.	- Frequency of extreme storms increasing by 15-20% in the Baltic region over the last 50 years.	(Hieronymus et al. 2018)
Strong Winds	Moderate	Property damage, disruptions to outdoor activities, potential safety hazards for vendors and visitors.	- Wind speeds exceeding 20 m/s reported in ~5-10% of annual weather events.	(Capital Riga 2019; Avotniece, Aniskevich, and Malinovskis n.d.)

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Heavy Rainfall	Moderate	Localized flooding, strain on drainage systems, impact on outdoor stalls.	- Rainiest day recorded in Riga saw over 80 mm of rainfall. - Increasing unpredictability in rainfall patterns.	(European Commission 2013)
Sea-Level Rise	Gradual (Long-term hazard)	Amplifies flood risks, affects drainage efficiency, and increases vulnerability of riverside infrastructure.	- Baltic Sea levels rising at 1–3 mm annually. - Projected increase of 10–30 cm by 2100.	(Hieronymus et al. 2018; Füssel, Jol, and European Environment Agency 2012)

Flooding is a major hazard for Riga due to its geographical location and hydrological characteristics. The city is situated at the confluence of three major rivers: Daugava, Lielupe, and Gauja, making it vulnerable to riverine floods (Kūle et al. 2013). Riga's excessive moisture regime, combined with heavy precipitation and snowmelt, contributes to the risk of inland flooding. This is exacerbated by outdated urban drainage infrastructure, which lead to flash floods particularly during intense rainfall events. Moreover, the 15 km-long coastline of Riga city is exposed to coastal flooding caused by storm surges and sea level rise (Kūle et al. 2013). The growing impacts of climate change, including an increase in the frequency and intensity of storm surges, further heighten the flood risk for the city.

As shown in Figure 10, the most flood-prone areas in Riga include both natural and built environments. Approximately 60% of the city's urban waterline is vulnerable to sea level rise, and many of these areas have been identified as critical hotspots for climate change adaptation measures (Kūle et al. 2013). Low-lying districts, particularly along the Daugava River, are also at significant risk of flooding, including some areas within the protection zone of the UNESCO Historic Centre of Riga. Records indicate that catastrophic floods have occurred in the Historic Centre of Riga since at least the 14th century, with events such as the 1358 flood submerging large sections of the city, including the Riga Dome Cathedral (Moskovkina 1960). To commemorate this major flood event, an iron cross was mounted on the cathedral's wall, marking the estimated 5.5 to 6 meters rise of the Daugava River above the mean summer water level. Similarly, the spring floods of 1578 were devastating, submerging vast areas around Riga with estimated water levels rising by 5 to 6 meters, causing extensive damage. Other significant spring floods occurred in 1589, 1597, and 1615, with water levels also reaching approximately 5.5 to 6 meters, highlighting the historical vulnerability of the city to extreme flood events.

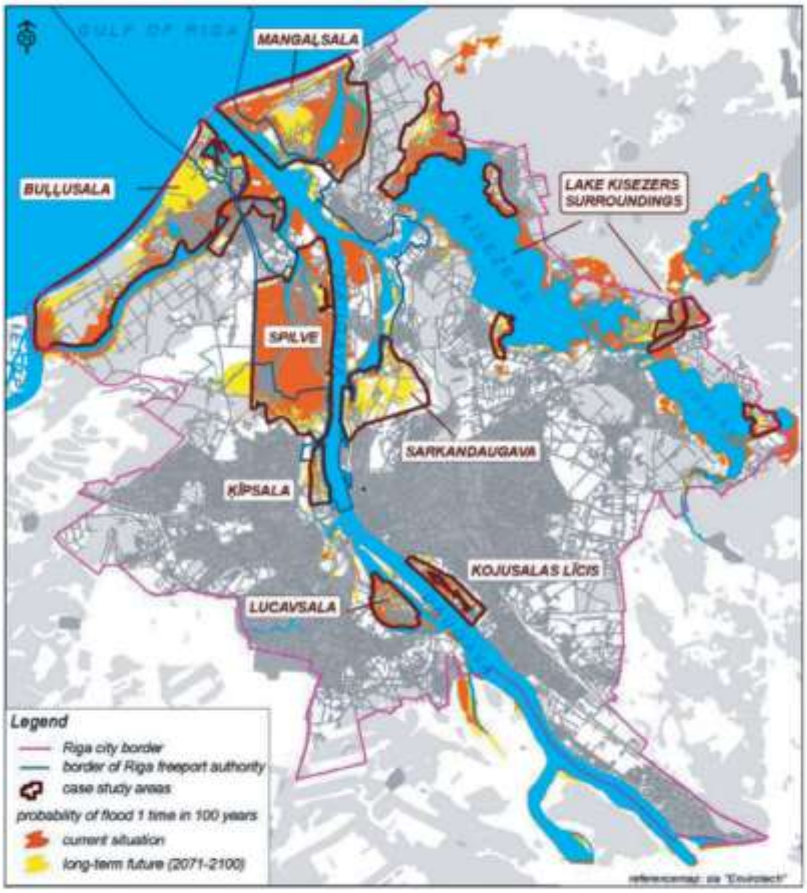


Figure 10. Hot spots map for climate change adaptation measures for flood risk management (source: (Kūle et al. 2013), reproduced from Riga City Council)

In response to recurrent flood hazards, various flood protection measures have been implemented in Riga over the centuries. Historically, flood mitigation relied on hydraulic engineering works, including riverbed modifications and embankments along the Daugava River. However, these interventions were often insufficient to prevent large-scale inundations, particularly during extreme flood events caused by storm surges and ice jams (Kūle et al. 2013). The construction of hydro-engineering structures has played a key role in modern flood mitigation. The Ķegums Hydropower Plant (HPP), completed in 1939, significantly reduced the formation of ice jams, which had historically contributed to severe flooding in the city (Kūle et al. 2013). Additionally, riverbed modifications, such as the deepening and straightening of the Daugava in the late 19th century, improved water flow and helped mitigate flood risks. Despite these engineering solutions, floods remain a persistent threat due to climate variability, changing precipitation patterns, and the increasing likelihood of storm-driven surges affecting the Gulf of Riga.

In response to increasing flood risks, Riga has integrated climate adaptation into its urban planning framework. The Riga Flood Risk Management Plan, drafted in 2011 and assessed in 2012, includes detailed flood hazard assessments and evaluates vulnerable areas under different climate change scenarios (Council 2012). Mapping efforts have identified various types of flood-prone zones, including inner-city areas, residential, industrial, and commercial zones, as well as cultural heritage sites. The plan outlines strategies for flood risk mitigation, considering different probabilities of occurrence in the near future (2021–2050) and distant future (2071–2100). The mitigation strategies include a combination of structural measures, e.g. engineering solutions, and non-structural adaptation measures, e.g., regulatory frameworks. Additionally, stakeholder engagement has been emphasized, with the University of Latvia facilitating discussions involving municipal authorities, planners, and experts to integrate climate adaptation strategies into urban planning (Kūle et al. 2013).

3.1.1.2. Non-climatic hazards

3.1.1.2.1. Agents of deterioration

Agents of deterioration refer to cumulative or recurrent processes that cause material degradation or functional impairment over time. The Guide to Risk Management of Cultural Heritage from ICCROM (Pedersoli Jr, Antomarchi, and Michalski 2016) introduces ten agents of deterioration for assessing the risks to cultural heritage assets: physical forces, thieves and vandals, fire, water, pests, pollutants, light and ultraviolet radiation, incorrect temperature, incorrect relative humidity, and dissociation. These agents of deterioration are depicted in
Figure 11.

Figure 11. The 10 'agents' of deterioration and loss of cultural heritage assets (source: (Pedersoli Jr, Antomarchi, and Michalski 2016))

Based on the findings from a technical inspection report performed by a structural engineer in August 2024 (Peredistijs 2024), several agents of deterioration are currently acting on the Riga Central Market (RCM) building. The most prominent agent of deterioration in the RCM building is prolonged moisture exposure, which encompasses both water infiltration and persistently high relative humidity (RH). Moisture can penetrate building materials, dissolve salts, and trigger chemical, biological, and physical degradation processes (Pedersoli Jr, Antomarchi, and Michalski 2016). In the basement, insufficient or absent waterproofing has allowed water to migrate through structural elements, while consistently high RH and poor ventilation have accelerated corrosion of embedded steel in slabs and beams. Traces of infiltration were also observed beneath sealed historic lightwell windows, indicating ineffective drainage, and on the roof, water damage is evident around chimney and roof window joints. Additionally, construction deficiencies, such as poor concrete compaction or insufficient cover, have further exposed steel components to the wet microclimate. These combined moisture-related effects have led to delamination of concrete surfaces and corrosion of steel elements, highlighting the critical role of moisture as a unifying agent of deterioration (Peredistijs 2024).

Closely linked to water ingress is the agent of incorrect relative humidity (RH), which refers to the prolonged presence of ambient moisture conditions outside the acceptable range for material stability. Fluctuations in RH cause swelling and shrinkage cycles in porous materials, while consistently high RH promotes corrosion in metals and microbial growth (Pedersoli Jr, Antomarchi, and Michalski 2016). In the case of the RCM building, the basement environment is marked by persistently high humidity and poor ventilation. These conditions have accelerated the corrosion of embedded steel elements in both the slab and the beams. In several locations, reinforcement bars were observed to be corroded and exposed due to the loss of protective concrete cover (Peredistijs 2024). In some cases, construction deficiencies such as poor compaction resulted in insufficient concrete cover, further exposing steel to the wet microclimate.

Pollutants are another relevant agent of deterioration acting on the building, particularly due to its location in an urban environment with regular traffic and market activity. Airborne pollutants, such as sulphur and nitrogen oxides from vehicle emissions, can interact with moisture to form acidic compounds that chemically attack stone, concrete, and metal surfaces (Pedersoli Jr, Antomarchi, and Michalski 2016). Although direct measurements of pollutants were not part of the inspection, the localized weathering and staining on the exterior masonry and plinths are consistent with pollutant-related surface degradation. Particulate matter may also accumulate in joints and crevices, retaining moisture and promoting micro-level deterioration in the building fabric.

Lastly, physical forces also contribute to ongoing deterioration in the RCM building. These include static and dynamic mechanical stresses caused by uneven settlement, load redistribution, or construction activity in adjacent areas. Such forces can lead to cracking, dislocation, or deformation of structural elements (Pedersoli Jr, Antomarchi, and Michalski 2016). The technical inspection revealed diagonal and vertical cracks in several masonry walls, as well as localized cracking in the slab near foundation supports. On the roof, deformation of steel truss components was observed, in some cases requiring reinforcement with welded angle sections. These issues suggest overstressed elements and insufficient structural rigidity in certain areas, which may compromise the performance of the load-bearing system over time (Peredistijs 2024).

3.1.1.2.2. Earthquakes

The Global Earthquake Model (GEM) Foundation provides a seismic risk profile for all the countries/territories in the world (Silva et al. 2023). The Latvian seismic risk profile, shown in Figure 12. indicates a relatively low level of seismic hazard, with peak ground acceleration (PGA) for an average return period of 475 years ranging between 0.01g and 0.05g across the country, and Riga city falling in lower ground motion potential. While the seismic hazard is moderate, earthquake-induced forces represent an additional form of physical stress on the RCM building, complementing the other mechanical and structural stresses discussed previously. This highlights that, even in regions of low seismicity, older or heritage structures may remain vulnerable to dynamic loads and require consideration in resilience planning. However, localized ground motions could still pose risks to vulnerable structures, particularly older buildings that may not comply with modern seismic design standards. Additionally, cumulative effects should be considered: for example, if an earthquake damages critical infrastructure, a subsequent flood or heatwave could have more severe impacts on affected populations.

The seismic risk profile from Figure 12 also includes spatially distributed data of exposed values, average annual losses and average annual loss ratios. The exposed value map illustrates the spatial distribution of replacement costs for residential, commercial, and industrial buildings. The highest exposure is concentrated in urban centres, particularly in Riga, where the density of built infrastructure is greatest. This suggests that potential economic losses in the event of seismic activity would be highest in these regions. The average annual losses (AAL) map provides insight into the expected absolute economic losses from earthquake-induced damage to buildings. The darkest areas on the map correspond to regions with the highest projected losses, which are predominantly located in urbanized zones. While Latvia's seismic hazard remains relatively low, the presence of concentrated high value assets in specific locations elevates the financial impact of even moderate seismic events. Lastly, the average annual loss ratio (AALR) map normalizes the expected losses by the exposed value, revealing regions that may experience disproportionately high damage relative to their total asset value. The results indicate that some areas with lower exposed value still exhibit elevated loss ratios, suggesting structural vulnerability in specific building typologies. The implications of these findings emphasize the importance of enforcing seismic-resistant construction practices, particularly in regions where historical buildings or older infrastructure may lack adequate seismic resilience.

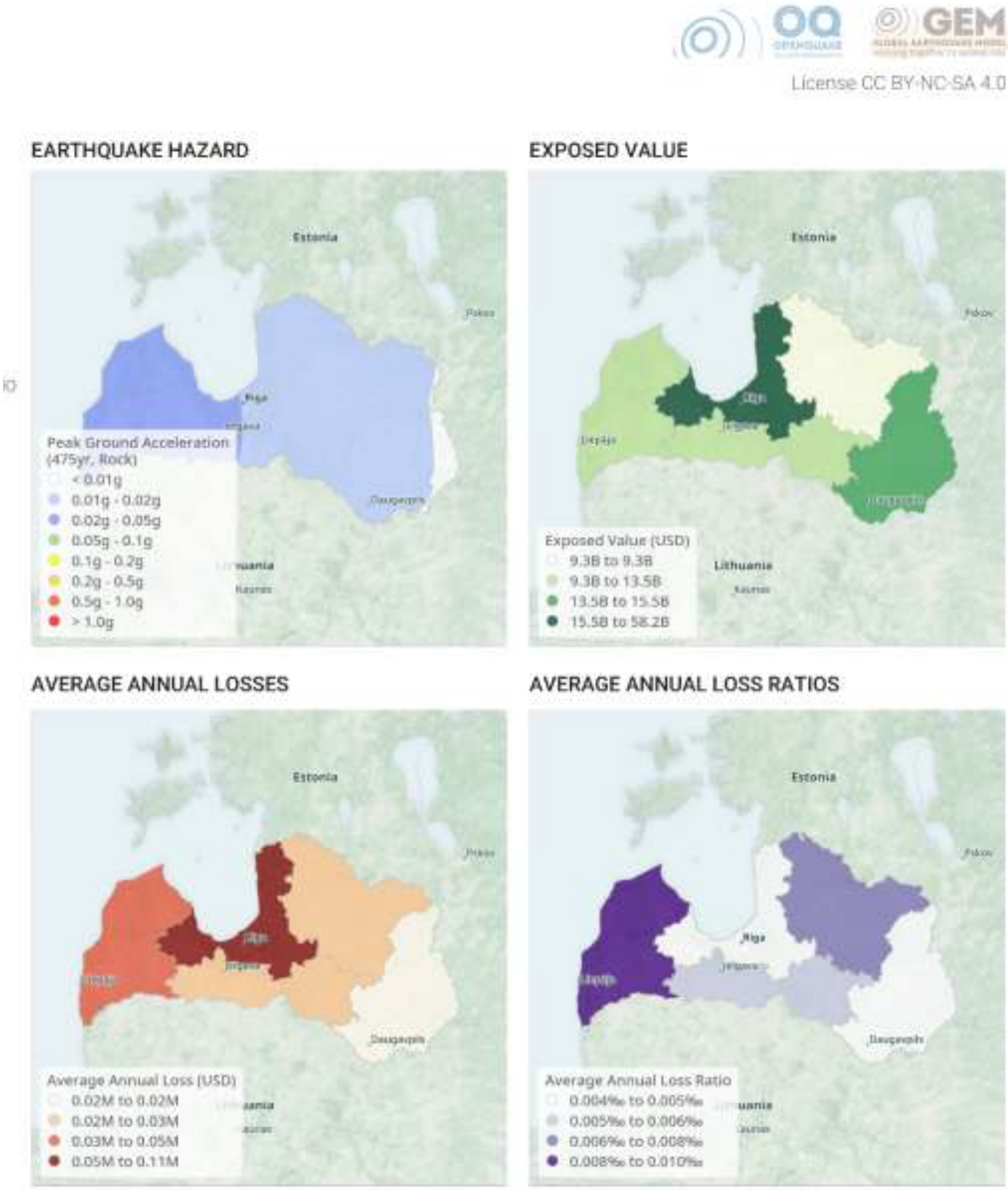


Figure 12. Latvian seismic risk profile. Source: (Silva et al. 2023)

3.1.2. Vulnerability Analysis

Vulnerability can be defined as the susceptibility of a system to experience damages or failures caused by a disturbance event (Turksezer, Limongelli, and Faber 2022). To conduct the vulnerability assessment of the RCM Dairy pavilion, the findings from a technical inspection report performed by a structural engineer in August 2024 were used (Peredistijs 2024). The vulnerability of the building is analysed in the following subsections for each of the main structural components.

3.1.2.1. Basement and foundation

The foundation of the Dairy Pavilion was inspected from the basement level. The inspection confirmed that the perimeter wall foundations were constructed using cast concrete, evidenced by wooden formwork impressions on some surfaces, as shown in Figure 13a. Given the material choice, it is likely that the pile foundations under the masonry columns were also built with cast concrete. Cracks were observed in the load-bearing walls of the basement (Figure 13b, Figure 13c) and above ground floors, indicating minor general deformations in the building (Peredistijs 2024).

Additionally, moisture-related deterioration was observed in the basement, likely resulting from defective or absent waterproofing, allowing water to infiltrate through the foundation structure (Figure 13d). Additional traces of moisture infiltration were found beneath historic basement window openings on the south and north facades, previously designed to provide daylight to the basement, where window pits had been sealed with concrete. The inspection suggests that the sealing work was incomplete, permitting surface water to enter the basement, as evidenced by sediment deposits and moisture damage in the finishes beneath these areas (Figure 13e). Moreover, the plinth finish above these locations exhibits missing stone lining panels, which may exacerbate moisture ingress into the foundation and basement (Figure 13f). The protective kerbs, consisting of pavestone pavements and asphalt surfaces, exhibit settlement and cracking, suggesting soil leaching and inadequate drainage (Peredistijs 2024).

Based on the damages identified in the technical inspection report, the basement and foundation are primarily vulnerable to moisture infiltration and localized structural deformations. However, the overall structural condition of the foundation is considered satisfactory, as the existing damages do not currently compromise the mechanical strength and stability of the building. Nonetheless, the presence of cracks in the load-bearing walls requires continued monitoring to help determine whether structural reinforcement is needed to mitigate the effects of foundation deformations and soil instability. Additionally, intervention measures are needed to improve surface water drainage and prevent further moisture infiltration, particularly in areas where incomplete concrete sealing of former lightwells has led to water ingress. Restoration of the protective kerbs, including pavestone and asphalt pavement repairs, are also necessary to ensure effective drainage and minimize soil leaching near the foundation.

a) Cast concrete foundation structure

b) Diagonal cracks in basement walls

c) Diagonal cracks in the stairwell wall extending from the expansion joint in the slab

d) Damage due to prolonged moisture saturation in the basement walls of the building

e) Moisture penetration into the basement through the old lightwells.

f) Damage in the plinth of the building potentially allowing moisture penetration into the basement

Figure 13. Main damages identified in the basement and foundation of the building. Source: (Peredistijs 2024)

3.1.2.2. Load-bearing walls and arch lintels

The Dairy Pavilion is an arched hangar-type structure, where steel trusses extend to the first-floor level and are supported on the foundation approximately 30 cm below the basement slab level. These truss structures provide load-bearing support in the longitudinal plane, making the longitudinal masonry walls (on the east and west side of the building) self-supporting. The roof truss beams are supported by masonry load-bearing walls at the north and south ends of the building, while additional load-bearing masonry walls are present in the central part of the pavilion, surrounding the stairwell leading to the basement (Peredistijs 2024).

The inspection revealed cracks in the load-bearing masonry walls at the ends of the building, which were also observed in adjacent pavilions. The window structures are covered with an arched reinforced concrete lintel supported by masonry pillars built between the windows and a masonry wall at their lower ends. According to the information provided, all pavilions in the Central Market have natural ventilation shafts positioned between the top of the window lintels and the masonry wall above. These shafts create localized weak points in the wall, contributing to the formation of arched cracks in these areas. Additionally, insufficient anchoring between the reinforced concrete lintel and the masonry wall has caused deformations and settlement at the lower ends of the lintels (see Figure 14a - Figure 14d). In locations where previous cracks were refinished, small cracks have reappeared, indicating that deformations are still occurring (Figure 14c). Further vertical and diagonal cracks were observed in longitudinal walls of the building (Figure 14e - Figure 14f).

Based on the damages identified in the technical inspection report, the load-bearing walls and arch lintels are primarily vulnerable to deformations resulting from insufficient anchoring between the reinforced concrete lintels and the masonry wall, as well as the weakening effect of ventilation shafts. However, their overall structural condition is deemed satisfactory, as the extent of the cracks at the identified locations indicate a local structural problem, which does not currently compromise the mechanical strength and stability of the building. To prevent further deterioration and cracking of the finish, it is necessary to develop and implement a strengthening and anchoring solution for the arch lintels, ensuring that further settlement is prevented.

a) Cracks in the arched lintel - north side of the building

b) Cracks in the arched lintel - south side of the building.

c) Cracks in the arched lintel (on the inside) with renovated finish - north wall of the building

d) Cracks in the arched lintel (on the inside) - south wall of the building

e) *Cracks in the longitudinal wall on the east side of the pavilion*

f) *Cracks in the longitudinal wall on the west side of the pavilion*

Figure 14. Main damages identified in the load-bearing walls and arch concrete lintels. Source: (Peredistijs 2024)

3.1.2.3. Basement slab

The basement slab of the Dairy Pavilion consists of a cast reinforced concrete slab supported by steel H-profile load-bearing beams and a grid of masonry columns (Figure 15a). The steel beams, spaced approximately 3 meters apart, rest on concrete rafts at the top of the masonry columns, providing structural support. The basement slab is 150mm thick, with a span of approximately 3.5 meters, and is divided into nine equal panels by expansion joints, with each section measuring approximately 24 × 11.3 meters. Longitudinal expansion joints are integrated into the concrete structure, while transversal expansion joints are formed using two adjacent H-beams (Peredistijs 2024). Based on the findings from an additional technical survey (Strazdiņš 2024), the slab is composed of C16/20 reinforced concrete, the reinforcement consists of smooth class A-I bars with a diameter of Ø10mm installed at an interval of 150 mm, and the protective concrete layer covering the reinforcement has a thickness of 25 mm.

The inspection revealed moisture infiltration in several areas, particularly through the expansion joints of the concrete slab (Figure 15b-Figure 15c). This issue was most pronounced in basement hallways, where moisture from the first-floor infiltrates through cracks in the floor, allowing water to seep into the basement (Figure 15d). In several locations, reinforcement bars within the slab panel exhibited corrosion, leading to spalling of the protective concrete layer (Figure 15e). In some cases, poor compaction during construction resulted in insufficient concrete cover, leaving the reinforcement exposed and vulnerable to corrosion (Figure 15f). The combination of high humidity levels and poor basement ventilation creates a favorable environment for corrosion progression.

Load-bearing calculations (Strazdiņš 2024) confirmed that the basement slab satisfies structural requirements, as the required reinforcement for the design loads in the panel span is 521 mm^2/m, while the actual reinforcement measured during the inspection was 523 mm^2/m. However, its load capacity is near 100% utilization, and the calculation was performed assuming that the structure had no significant damage. The presence of corrosion in the reinforcement bars and steel beams may reduce the slab's actual capacity, especially in areas where damage has progressed. Additionally, if the reinforcement spacing in certain areas differs from the observed 150 mm, or if the concrete cover layer is thicker than 25 mm, localized overloading of the slab could occur, increasing the risk of failure during operation.

Based on the damages identified in the technical inspection reports, the basement slab is primarily vulnerable to moisture infiltration, corrosion of reinforcement bars and potential overloading. Although the overall structural condition is deemed satisfactory, it is necessary to implement mitigation measures to prevent further moisture migration from the first floor to the basement (e.g., by properly sealing the expansion joints), treat the corroded reinforcement bars, and repair the concrete surfaces. The implementation of these measures must be carried out before constructing the planned new floor structure to install UPONOR's energy solution (refer to Deliverable 3.3 (Luprano et al. 2024)). Moreover, lightweight materials, such as expanded clay concrete, are recommended during the floor modifications to prevent excessive additional loads on the slab.

a) Reinforced concrete slab and column connection in the basement

b) Moisture damage in the basement slab with corroded reinforcement

c) Expansion joint in the concrete slab, aligned in the N-S direction.

d) Floor cracks and surface layer chipping on the first floor

e) *Locally corroded slab reinforcement with spalling of concrete*

f) *Exposed reinforcement due to poor concrete compaction during construction*

Figure 15. Main damages identified in the basement slab. Source: (Peredistijs 2024)

3.1.2.4. Frame elements: Columns and beams

The structural system of the Dairy Pavilion basement slab consists of masonry columns and steel beams that provide load-bearing support. The columns are distributed throughout the basement (Figure 16a), have a cross-section of approximately 360 × 360 mm, and are constructed from masonry materials. These columns support steel H-profile beams, which are embedded within the reinforced concrete slab structure. The beams, identified as 23B1 design standard according to GOST 26020-83, span approx. 3 meters between column supports and are spaced at intervals of approx. 3.5 meters. The steel used for these beams is classified as S235 (Strazdiņš 2024).

The technical inspection did not identify major deformations or critical damage in the masonry columns (Figure 16b), which indicates that their mechanical strength and stability remain uncompromised (Peredistijs 2024). However, localized cracks were observed in areas where the steel beams are supported by the foundation walls, indicating stress concentrations (Figure 16c). Additionally, signs of corrosion were observed in many of the steel beams supporting the slab. The corrosion process has caused concrete delamination, exposing the steel beams and leading to further deterioration of the protective concrete layer (Figure 16d). The most significant damage was found in steel beams supported by the foundation of the perimeter walls, indicating that moisture infiltration occurs through the foundation structure (Figure 16e). Moreover, during the additional technical survey to measure the geometry of the steel beams (Strazdiņš 2024), the protective concrete cover was removed and superficial corrosion damage was also observed (Figure 16f). While the current level of corrosion does not compromise the mechanical strength or stability of the steel beams, the high humidity levels in the basement create conditions for progressive deterioration. This is exacerbated by the fact that the load-bearing capacity calculations indicate that the steel beams are operating at a high load capacity, close to 100% (Strazdiņš 2024). Therefore, while no immediate structural failure is expected under normal design loads, any further corrosion degradation could lead to localized overloading.

Based on the damages identified in the technical inspection reports, the steel beams and masonry columns are primarily vulnerable to humidity-induced corrosion and potential overloading. Although the overall structural condition is deemed satisfactory, interventions are necessary to mitigate moisture exposure and ensure long-term durability. Before the planned renovation of the floor structure, it is essential to repair the existing damage to the beams, addressing the causes of deterioration. Similarly to the recommendation given for the basement slab, the planned floor layering should consider lightweight materials to prevent excessive additional loads on the slab.

a) Frame structure in the basement: masonry columns supporting steel beams

b) Masonry column supporting steel beams and a reinforced concrete slab

c) Cracking in the slab and foundation walls at the support of steel beams

d) Corroded steel beam causing delamination of the protective concrete layer

e) Corroded steel beam causing delamination of the protective concrete layer

f) Superficial corrosion damage in the bottom flange of the steel beam

Figure 16. Main damages identified in the columns and beams supporting the basement slab. Sources: (Peredistijs 2024; Strazdiņš 2024)

3.1.2.5. Roof structure

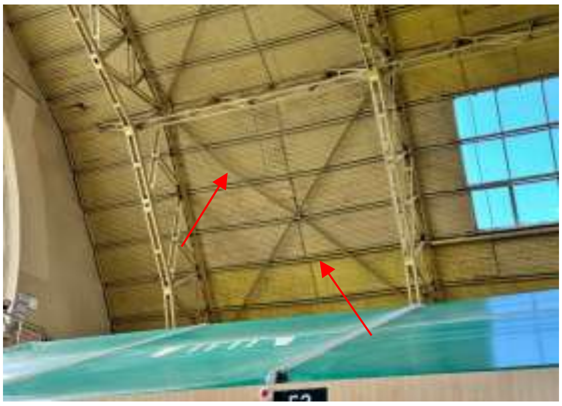
The roof structure of the Dairy Pavilion consists of an arched truss system made of steel angle sections and U-sections, forming a series of cross frames that span the width of the building (Figure 17a). The trusses are assembled using metal plates and rivets at their upper and lower joints, as well as at brace connections. The spatial rigidity of the structure is ensured by the installation of steel trusses between the cross frames, connecting the arched frames longitudinally (Figure 17b), and steel H-shaped beams, which also function as tie beams to stabilize the truss system (Figure 17c). Additionally, diagonal steel ties are placed in certain areas along the roof plane and the longitudinal self-supporting masonry walls, providing further stability (Figure 17c). The trusses are supported on link supports embedded within the building's structure, approximately 30 cm below the basement slab level. These supports were concreted after the installation of the trusses, and at the first-floor level, the concrete section of the support is visible, measuring 450 × 750 mm (Figure 17d). The roof system is completed with wooden rafters and lathing placed above the truss beams, supporting a metal sheet roof covering. The underside of the rafters is lined with interlocking wooden planks, serving as the interior finish of the ceiling (Peredistijs 2024).

The technical inspection identified several types of structural damage in the roof system. Localized deformations due to compressive forces were observed in the upper truss elements near the roof ridge in multiple locations, indicating inadequate compressive load capacity of these members (Figure 17e). In certain areas, additional welded angle sections have been installed as reinforcements (Figure 17f). The report suggests that it is likely that most of the roof trusses had this damage (Peredistijs 2024), which is evidenced by the settling and deformations of the roof plane near the ridge, where the original upper truss sections were removed and replaced with welded steel angle pieces (Figure 17g). The H-shaped beams exhibited noticeable deflection, especially in sections where the roof slope exceeds 60° (Figure 17c). Additionally, localized deformations were observed in some of the diagonal ties, suggesting that they have experienced compressive forces instead of the intended tensile forces (Figure 17c). Lastly, moisture damage was observed on the underside of the wooden plank lining, including peeling paint and localized rot, likely resulting from leaks in the roofing or an absent/damaged anti-condensation membrane (Figure 17h).

Based on the damages identified in the technical inspection, the roof structure is primarily vulnerable to deformations due to inadequate load-bearing capacity of certain truss members, overloading, and moisture-related deterioration. The damage in the ridge truss members is particularly critical, as loss of strength in these components shifts additional loads onto other truss elements, increasing the risk of overloading. In fact, the technical inspection report assessed the overall condition of the roof structure as unsatisfactory (Peredistijs 2024). To address these issues, a structural analysis of the roof trusses under actual operating loads must be performed to verify their load-bearing capacity, and a reinforcement solution for the damaged ridge truss elements must be developed and implemented. Additionally, repairs are required at the points where precipitation moisture infiltrates the roof, particularly at the roof window joints and the areas adjacent to the chimney, to prevent further deterioration of both the wooden and steel elements of the structure.

a) *Roof structure - steel trusses*

b) *Roof structure - steel trusses*



c) *Cross wind braces on the roof plane and H-shaped beams with minor deformations*

d) *Concreting of the roof truss support assembly*

e) *Upper truss elements near the roof ridge exhibiting localized deformations*

f) *Upper truss elements near the roof ridge exhibiting localized deformations*

g) *Locally replaced sections of the upper truss where the roof has settled*

h) *Wooden plank ceiling with signs of precipitation moisture infiltration*

Figure 17. Main damages identified in the roof structure. Source: (Peredistijs 2024)

3.2. Tedingerbroekpolder Dike

3.2.1. Hazard Analysis

3.2.1.1. Climatic hazards

The Tedingerbroekpolder dike, located in a low-lying deltaic region of the Netherlands, is exposed to a range of climate-related hazards that pose risks to its structural integrity and long-term performance. These climatic hazards were thoroughly investigated in the Deliverable 3.1 (Aguilar-López, Nöter, and Ingrosso 2024). The deliverable identified intense precipitation, riverine flooding, drought, and temperature variations, as the principal climatic hazards affecting this type of flood defence infrastructure. These hazards can lead to shock-driven or stress-driven failure mechanisms of the dike, depending on the temporal scale and intensity of the event.

Shock-driven failure mechanisms refer to sudden failures such as slope instability and erosion, which may be the result of heavy rainfall, overtopping, and storm surges. Essentially, intense or prolonged precipitation can increase pore water pressure within the dike body, reducing the shear strength of the soil and leading to slope failure. Riverine flooding and surface water runoff may also contribute to saturation of the structure, increasing the risk of internal erosion mechanisms such as piping. These hazards are particularly critical during high water periods, when the dike is subjected to elevated hydraulic loads (Aguilar-López, Nöter, and Ingrosso 2024).

On the other hand, stress-driven failure mechanisms refer to gradual degradation processes resulting from hazards such as drought and thermal fluctuations. Periods of drought lead to desiccation and the formation of shrinkage cracks, especially in clayey soils, which can compromise the dike's integrity by allowing deeper water infiltration during subsequent wet periods. Seasonal variations in temperature and moisture content affect the mechanical behaviour of the soil, altering pore pressure and internal stress distribution. These conditions can reduce the overall stability of the dike structure over time, even in the absence of extreme weather events (Aguilar-López, Nöter, and Ingrosso 2024).

The combined effect of these climatic hazards is amplified by projected climate change trends, which are expected to increase the frequency and intensity of both drought and extreme precipitation events (Seneviratne et al. 2022). Consequently, the Tedingerbroekpolder dike is exposed to evolving environmental stressors that necessitate continuous monitoring and adaptive risk management strategies.

3.2.1.2. Dike breach hazard

III. Tedingerbroekpolder Dike

The Tedingerbroekpolder dike is located in a historical polder in the region between Zoetermeer, Leidschendam, Voorburg, The Hague, and Nootdorp, in the Netherlands. It encompasses an area of about 780 hectares. Mostly founded on peat soil, it was formed through turf extraction in the late Middle Ages and has been managed for water control since around 1480. Since 1977, it has been under the jurisdiction of the Hoogheemraadschap Delfland (Associated partner in the MULTICLIMCT project) while being politically administrated by the City hall of Leidchendam-Voorburg Gemente. Much of its rural character has been lost due to urbanization following its incorporation into The Hague in 2002 (*https://noitdorpsche-historien.nl/wp/?page_id=1199*).

Historically, it relied on windmills (e.g., Westmolen and Oostmolen) and later steam and electric pumping stations to manage inland water levels. The MULTICLIMACT Demonstrator in this area consists of the development of a fiber optics-based monitoring system for soil dikes and movable barriers. In the case of the Tedingerbroek polder dike, the demonstrator flood defence protects the flood-prone area over the east side from an eventual flood derived from a dike breach event along the canal (See figure below) that drains the pumped water by the electric pump II A located in the Kortelandseweg (Red roof structure at the end of the channel in the lower right side of image). The Tedingerbroekpolder, being a low-lying peat polder, is particularly susceptible to flooding if a dike fails while having elevations as low as -2 meters below sea level. Its proximity to urban areas like The Hague and one of the national railway maintenance workshop locations, increases the potential impact in terms of not only monetary costs but interruptions to the regular operation of national railway systems.

Figure 18. Overview of the Tedingerbroekpolder dike and its flood defence system

IV. Tedingerbroek polder dike breach simulation

The Landelijk Informatiesysteem Water en Overstromingen (LIWO) is a Dutch national information system for water and flood management which contains the map layers required by practitioners and policy makers that allows them to get an overview of the results from different dike breach simulations along the main and regional Dutch flood defence systems in the Netherlands. It provides spatial geographic data such as expected maximum flood depths, flood probabilities, expected damages and expected number of casualties as main outputs. It is developed by Rijkswaterstaat, Deltares, and HKV, and integrates with the Landelijke Databank Overstromingsinformatie (LDO) (*https://www.hkv.nl/projecten/landelijk-informatiesysteem-water-en-overstromingen-liwo/*).

For the specific case of the flooding scenario of the Tedingerbroek dike, LIWO provides detailed flood scenario data, including specific breach scenarios identified by codes like "scenario 3301" and "ID 20564." The "LIWO dike breach Tedingerbroekpolder is characterized as scenario 3301 ID 20564 and corresponds to a specific flood scenario in which an eventual dike breach with a water level return period of 1/1000 years. The simulation was produced in 01/05/2019 and the dike breach coordinates are (y= 454474 mts, x= 86461, with a projected coordinate system EPSG:28992 Amersfoort/RD New which is the official projection system for flood risk analysis in the Netherlands. The Water depth maxima presented in the figure below correspond to the maximum extension area from the flood event which present a flooding depth ranges between 0.5 mts and 5 mts. It can already be observed that the original data set was arbitrarily cut in the locations at the east of the highway most probably from automated procedures in the system.

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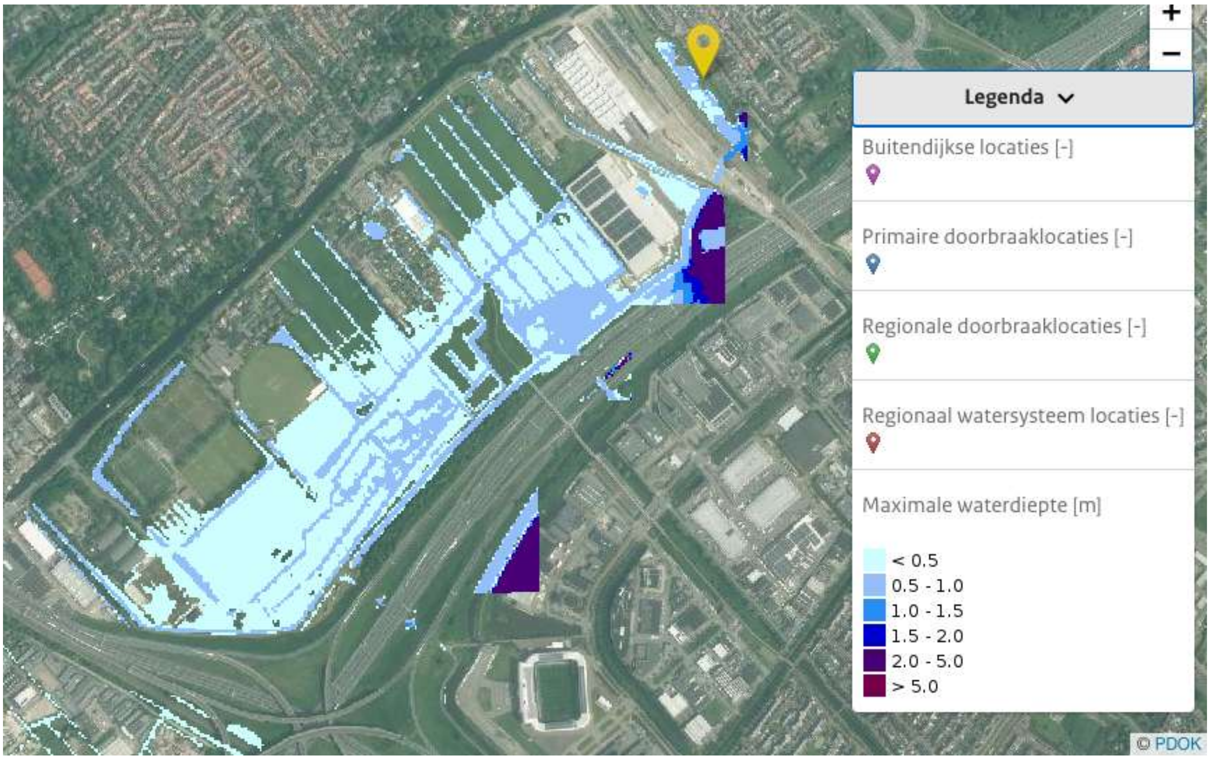

Figure 19: Flood depth maxima from the LIWO simulation, showing the extent of flooding from the dike breach, with depths ranging from 0.5 meters to 5 meters. The data also indicates artificial clipping on the eastern side of the highway.

For the same event, based on damage estimation curves produced by the Dutch government based on land use and cadaster estimations, the simulated water depths are later used as input so that the expected monetary cost of damages is calculated for the same resolution. The results are shown in the next Figure 20, and it can already be seen that the maximum value for this vent is below 10k Euros/ha. It can also be noted that the damage raster file was also arbitrarily clipped by the system, so squared trims are observed in the damage of the lower south area just below the highway.

Figure 20. Damage Estimation Based on Simulated Flood Depths, Showing Expected Monetary Damage Below €10,000 per Hectare and Total Estimated Damage of €19 Million per Year.

From the technical description presented in the Liwo it can also be infereed that there are no casualties expected for this event and that the total expected monetary damage is estimated to be around 19 million Euros / year. Metadada image presented below (Figure 21):

Metadata

Title	T1000 Tedingerbroekpolder 3301
Abstract	Scenarionaam = T1000 Tedingerbroekpolder 3301 Beschrijving scenario = Doorbraak boezemkade Tedingerbroekpolder op locatie 3301 met buitenwaterstand T1000 Scenario ID = 20564 Scenariodatum = 2019/06/03 Eigenaar = HHRS van Delfland Type overstroming = C Naam doorbraaklocatie = locatie 3301 X-coordinaat doorbraaklocatie = 86462 Y-coordinaat doorbraaklocatie = 454475 Overschrijdingsfrequentie = 1000 Gebiedsnaam = Tedingerbroekpolder Naam buitenwater = Delfland boezem Buitenwater type = boezemwater Totaal schade (Meuro) = 19 Totaal aantal slachtoffers = 0 Aantal getroffenen = 135 Modelleersoftware = 3Di Modelversie = ROR calimiteitenmodel T1000 Motivatie rekenmethode = Nauwkeurigheid Doel scenario = Opstellen inundatiebeeld tbv de ROR Berekeningsmethode = 2d model Modelresolutie = 5,0 Standzekere regionale keringen = Ja

Figure 21. Expected Casualties and Total Monetary Damage Estimate, with an Annual Damage of €19 Million

3.2.2. Vulnerability Analysis

The vulnerability of the Tedingerbroekpolder dike is primarily linked to its physical characteristics and material behaviour under variable environmental conditions. As part of the work presented in Deliverable 3.1 (Aguilar-López, Nöter, and Ingrosso 2024), Finite Element Modelling (FEM) was used to simulate the hydro-geo-thermal behaviour of the dike throughout the year 2023. The results of the simulations show seasonal variations in three key parameters: moisture content, pore pressure, and temperature within the dike body. These variations reflect how internal conditions evolve under natural environmental influences, such as rainfall and ambient temperature.

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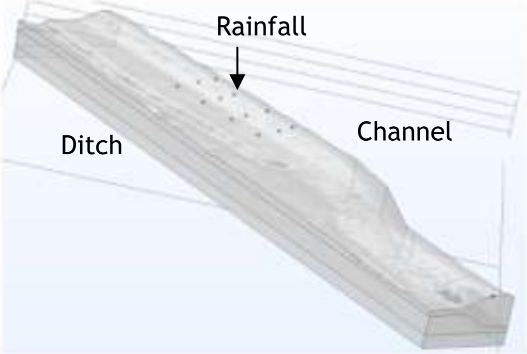


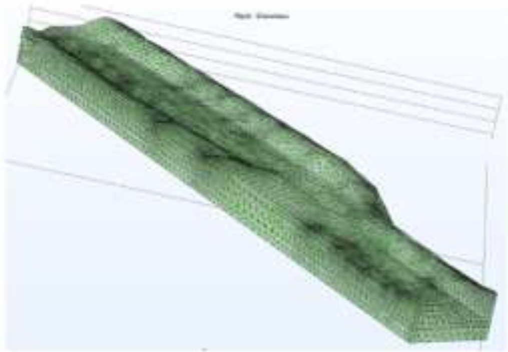


Figure 22. Interpolated Surface and generated Mesh from 3D finite element model of the Tedingerbroekpolder dike. Source: Deliverable 3.1 (Aguilar-López, Nöter, and Ingrosso 2024)

According to the FEM results, moisture accumulation in the dike body fluctuates significantly during the year, with the highest saturation levels observed during early spring, and the lowest saturation during dry summer periods. These changes lead to a corresponding variation in pore water pressure, which is a key factor influencing the dike's internal condition (Aguilar-López, Nöter, and Ingrosso 2024). As explained in Deliverable 3.1, increased pore water pressure can reduce the effective stress in the soil, which in turn lowers the shear strength and may contribute to structural instability when combined with other stressors.

In addition, Deliverable 3.1 highlights that geotechnical properties such as cohesion, internal friction angle, and density play a critical role in the dike's resistance to internal and external loads. Therefore, these parameters are central to assessing vulnerability to failure mechanisms such as slope instability, erosion, and internal deformation. The presence of shrinkage cracks, infiltration pathways, and saturation zones further compounds the vulnerability, particularly under extreme or prolonged environmental stress (Aguilar-López, Nöter, and Ingrosso 2024).

The findings from the study conducted in Deliverable 3.1 underscore that the vulnerability of the Tedingerbroekpolder dike is dynamic and evolves seasonally as a result of environmental exposure. Due to the internal hydro-thermal fluctuations in the dike, the importance of continuous monitoring and real-time data collection is highlighted to detect early signs of internal instability. For this reason, the use of distributed fiber optic sensors (DFOS) is proposed in Deliverable 3.1 as a promising solution for long-term and spatially resolved monitoring, enabling improved preparedness and maintenance of the dike under climate-induced stress conditions.

3.2.3. Consequence Analysis

In the case of a dike breach along the Tedingerbroekpolder, the economic consequences are significant, with expected monetary damage calculated to be around €19 million annually which showed in Table 3. The damage estimation is based on damage curves derived from land use and cadastral data, factoring in simulated water depths. The damage is spread across the area with localized impacts, where the maximum damage per hectare is estimated to be below €10,000. The breach scenario also results in a loss of agricultural land, and the financial impacts extend to critical infrastructure, including railway systems and urban settlements.

Table 3. Summary of the Economic, Environmental, and Social Consequences of the Dike Failure in the Tedingerbroekpolder Study Area

IMPACT CATEGORY	DESCRIPTION	ESTIMATED IMPACT
Economic Damage	Total estimated damage of €19 million annually, with maximum damage per hectare below €10,000.	€19 million per year (under €10,000 per hectare)
Environmental Impact	Flooding of agricultural land, disruption to natural habitats, and long-term soil degradation.	Loss of agricultural land, disruption of local ecosystems
Social Impact	Potential displacement of residents, railway disruption, and limited access to essential services.	Displacement of residents (if applicable), major transportation interruptions

From an environmental perspective, a dike breach would lead to the flooding of low-lying peat soils, affecting local ecosystems and potentially causing long-term degradation to the soil and water quality. The floodwaters may also disrupt natural habitats, including those that support both local flora and fauna.

On the social side, the potential for displacement of local populations due to flooding is high. Furthermore, the disruption of transportation services, particularly the national railways, could severely affect mobility and access to essential services, creating broader societal impacts on the region.

4. RESILIENCE ENABLING INTERVENTIONS ON CULTURAL HERITAGE

4.1. List of Interventions for Riga Central Market

Based on the vulnerability analysis conducted in Chapter 3.1.2, several structural elements from the RCM Dairy Pavilion require some protection and repair interventions to prevent further degradation that may compromise the strength and stability of the building. Moreover, the construction of the planned floor structure to install UPONOR's energy solution (see Figure 23) will increase the load demands on some of the structural elements, namely the basement slab and the supporting beams and columns. Therefore, this section proposes four types of intervention strategies targeted to increase the structural resilience of RCM building. These strategies include the strengthening of the reinforced concrete slab to withstand the load demands of the planned floor structure, and monitoring solutions such as fiber optic-based monitoring systems and electrochemical corrosion sensors. The last intervention strategy consists of implementing satellite remote sensing for monitoring the RCM building ground displacements. This strategy is proposed due to the presence of localized cracks in load-bearing wall structures, which may indicate uneven foundation settlement over time. It should be noted that energy retrofit interventions are not the focus of the present deliverable but those that increase the structural resilience of the RCM building. Resilience-enabling energy retrofit interventions are addressed in Deliverable D8.4, D9.3, and D10.5.

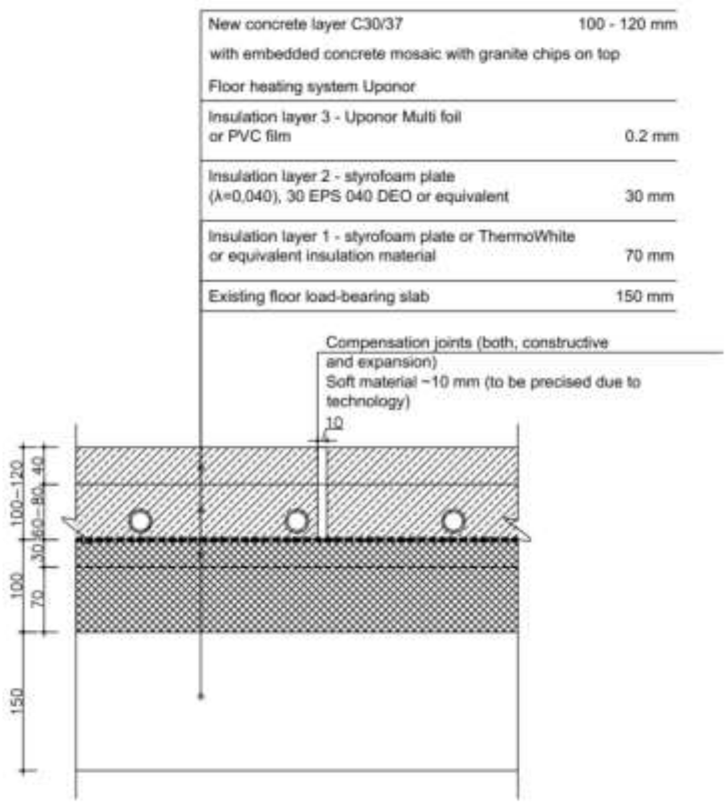


Figure 23. Planned floor structure to install UPONOR's energy solution. Source: Riga Energy Agency

4.1.1. Strengthening with concrete overlays

To strengthen the reinforced concrete basement slab of the Riga Central Market, a bottom-surface concrete overlay method can be implemented in accordance with the recommendations from *fib* Bulletin 103 (Júlio *et al.*, 2022a). This intervention method is particularly appropriate when structural demands related to flexural and shear capacity must be increased, as it entails placing new reinforcing materials on the tension side of an existing member, i.e., the underside of the slab in this case, and integrating cement-based overlays. The intervention is necessary due to the slab's current utilization nearing 100% under existing loads (Strazdiņš 2024) and the presence of reinforcement corrosion and moisture-related deterioration.

Before the intervention, the existing conditions must be carefully assessed. As described in Section 3.1.2.3, the concrete slab is 150mm thick and was originally cast using C16/20 concrete. The existing reinforcement consists of smooth class A-I bars with a diameter of 10 mm, spaced at 150 mm, and a concrete cover of 25 mm. The assessment must determine the extent of damage to this reinforcement and the surrounding concrete. Severely corroded bars should be removed and replaced. Where the existing bars remain serviceable, new reinforcement may be added to enhance structural performance.

To ensure full load transfer between the existing concrete and the overlay (a monolithic behavior), intersecting reinforcement or mechanical connectors must be installed through the interface. These connectors are particularly necessary when adhesive bonding alone does not provide sufficient shear transfer. According to the European Standard EN 1504-10 (CEN, 2017), mechanical anchorage of new reinforcement into existing concrete can be achieved by installing steel bars into drilled holes using cement-based or synthetic resin bonding materials. These anchoring systems must achieve a minimum pull-out capacity of 75 kN at a displacement of 0.6 mm. The installation process requires rotary percussion drilling equipment, compressed air or vacuum cleaning tools, and injection guns or pumps for introducing bonding grout or resin into the holes for anchoring the connectors. The connector system may include cup-shaped heads (see Figure 24) optimized to introduce loads from the overlay and serve as support for the reinforcement layers, which also facilitate proof loading and placement checks (Júlio *et al.*, 2022a).

Figure 24. Cup-shaped connectors serving as reinforcement support (source: Júlio et al., 2022a)

The substrate surface preparation is a critical step in the intervention process. As outlined in *fib* Bulletin 103 (Júlio *et al.*, 2022a) and EN 1504-10 (CEN, 2017), the bottom surface of the slab must be roughened to a degree that allows mechanical interlock between old and new concrete. This is typically accomplished through high-pressure water jetting, with pressures ranging from 400 to 2000 bar, which can effectively remove deteriorated concrete and expose a clean, sound surface without causing micro-cracking or damaging the substrate. The cleaned surface must be brought to a saturated surface-dry (SSD) condition, where the pores are water-filled but no water film is present on the surface. This moisture state is crucial for proper adhesion and hydration of the new concrete. The roughness of the prepared surface must be verified before overlay placement. The fib guideline specifies the sand patch method as a suitable on-site control technique. To assess the bond between the old and new concrete, tensile pull-off tests following ASTM C1583 / C1583M–13 may be used, although these tests provide only an indication of tensile bond strength and not shear resistance. Still, they offer a lower bound estimate of bonding performance.

All steel reinforcement exposed must be thoroughly cleaned before any overlay is applied. According to EN 1504-7 (CEN, 2006), steel bars should be cleaned to a visual standard of Sa2 (EN ISO 8501-1), i.e., thorough blast cleaning, using abrasive blasting or equivalent methods. The entire circumference of exposed bars must be cleaned, and should extend at least 20 mm beyond visible corrosion. If the steel reinforcement exhibits significant corrosion, the first step involves evaluating the section loss of the reinforcement bars by measuring their diameter using calipers or non-destructive testing methods. According to EN 1504-7 (CEN, 2006), if the cross-sectional area of the bars has been reduced by more than 30%, they must be replaced. In such cases, new reinforcement bars must be installed with proper anchorage, ensuring that the minimum lap length requirements specified in the Eurocode are met. The new bars should be securely tied to the existing reinforcement using stainless steel tie wire or connected with mechanical couplers to ensure structural continuity.

Given that the original slab was constructed with C16/20 concrete, the new overlay concrete should be of similar class, with good workability and preferably low shrinkage to minimize differential movements that could compromise the bond. The overlay material may be cast using standard techniques, i.e., employing vibrators to ensure full compaction and eliminate entrapped air. Self-compacting concrete (SCC) may be considered if the geometry or access conditions of the basement favor its use. Curing must be applied according to conventional procedures to ensure proper hydration and strength development, and to protect the bond at the interface. Special care is required in edge zones, as these are particularly prone to peeling forces from shrinkage.

Lastly, to prevent water infiltration from the first floor into the basement and preserve the durability of the strengthened and repaired slab structure, all expansion joints must be properly sealed. To this end, the EN1504 (CEN, 2017) recommends polyurethane-based sealants such as MasterSeal NP 474, due to their high elasticity, excellent adhesion, and chemical and mechanical resistance, forming an elastic and durable joint. The application process involves cleaning the joint area thoroughly, applying a closed-cell backer rod to control the sealant depth and prevent three-point adhesion, and filling the joint with the sealant using a manual or pneumatic caulking gun. The sealant is then tooled and smoothed to ensure full adhesion to the sides of the joint, and allowed to cure under ambient temperature and humidity conditions, as no special curing measures are required.

Throughout the execution phase, strict quality control is required. According to EN 1504-10 (CEN, 2017), inspections should be carried out before, during, and after the repair process. This includes verification of surface preparation, pull-off testing to confirm bond strength, inspection of installed reinforcement, checking thickness, and sampling of repair materials for laboratory testing where applicable. If large areas of the concrete slab are removed or weakened during preparation, temporary structural shoring should be installed to maintain safety. All operations must be performed by trained and competent personnel familiar with repair systems and procedures, and the site must comply with applicable health, safety, and environmental regulations.

Table 4 summarizes the activities, materials, equipment, and labour for the strengthening of the reinforced concrete slab. The execution of this strengthening intervention involves a sequence of specialized tasks each with distinct labour requirements and equipment setup. Given the confined working conditions of the basement slab and the need for overhead work, the work is best conducted in a phased sequence, dividing the basement slab into multiple work zones. This phased approach allows for overlapping activities, such as initiating surface preparation in one zone while curing occurs in another, thereby optimizing resource utilization and minimizing downtime. The overall duration will depend on the total area to be treated, access constraints, and available human resources, with an estimated duration of 4 to 6 weeks for strengthening 100 m² of reinforced concrete slab.

Table 4. Summary of activities, materials, equipment, and labour for the strengthening of the reinforced concrete slab

ACTIVITY	MATERIALS	EQUIPMENT	LABOUR REQUIREMENTS	MATERIAL CONSUMPTION (PER M² OR M³)
Condition assessment	N/A	Inspection tools, calipers, NDT equipment	Engineers or inspectors	N/A
Surface preparation	Water (for hydrodemolition)	High-pressure water jetting system (400-2000 bar)	Skilled workers, supervisor	32,000 litres/ m³
Reinforcement cleaning	Abrasive blasting media (e.g., grit, sand, or metallic abrasives)	Abrasive blasting equipment (grit or sandblasting)	Skilled workers with blasting experience	Steel grit approx. 25kg/m²
Replacement of corroded reinforcement and placement of new reinforcement	New steel reinforcing bars, stainless steel tie wire or mechanical couplers, bonding agents or anchoring materials	Rebar cutting tools, drilling equipment and injection guns (for anchoring), binding tools (for tie wire) or torque wrench (for mechanical couplers).	Skilled workers, supervisor	Function of the amount of new reinforcement required per m²
Installation of connectors	Steel reinforcing connectors, bonding agents or anchoring materials	Rotary percussion drill (for anchor holes), compressed air or vacuum systems (to clean dust), injection guns	Skilled workers, supervisor	Function of the number of connectors required per m²
Casting and curing of overlay concrete	Concrete or repair material, admixtures (for SCC), water (for curing)	Mortar or concrete mixer, formwork, vibrators or pumping system, water spraying devices (for curing)	Skilled workers, supervisor, safety personnel	Volume of concrete as a function of the overlay thickness
Sealing of Expansion Joints	Polyurethane-based elastic sealant, closed-cell backer rod	Manual or pneumatic caulking gun, cutting tools, spatulas	Skilled workers	100 ml/m of joint
Quality control	Sand (for sand patch method)	Pull-off tester, sand patch kit, thickness gauges (for overlay verification)	Quality control technicians or engineers	N/A

4.1.2. Fiber optic-based monitoring system

Historical buildings represent not only architectural heritage but also cultural identity, often standing for centuries through natural degradation, environmental stresses, and human interventions. Ensuring the safety, stability, and conservation of these structures is a responsibility that combines engineering, historical knowledge, and cutting-edge technology. Structural Health Monitoring (SHM) is a critical tool in this context, allowing for continuous, non-invasive assessment of the building's condition. SHM helps detect early signs of deterioration, measure the impact of environmental loads (e.g., temperature changes, wind, seismic activity), and inform timely maintenance or restoration efforts. In historic buildings, where invasive interventions are limited or undesirable, SHM becomes especially vital. In fact, non-invasive monitoring systems are particularly important for historic buildings as they minimize the risk of damage to the structure and do not interfere with the daily activities of the building's occupants. Fiber optic-based monitoring systems offer a sophisticated and reliable solution for detecting and analysing structural changes, such as cracks and fissures, without compromising the integrity of the building.

An effective SHM system requires careful planning and customization to the building's materials, structural layout, and conservation goals. A typical SHM system comprises:

- **Sensors**: Devices to measure physical parameters such as strain, temperature, displacement, or vibrations.
- **Data Acquisition (DAQ) System**: Converts sensor signals into digital data.
- **Data Transmission Network**: Wired or wireless systems that transfer data from the building to a central processing unit.
- **Data Processing and Visualization**: Software that analyzes the incoming data and generates meaningful outputs such as alerts or trend graphs.
- **Power Supply**: Especially important in remote or difficult-to-access heritage sites.

Sensor placement is critical and often informed by structural analysis models. Sensors must be unobtrusive, minimally invasive, and capable of long-term operation.

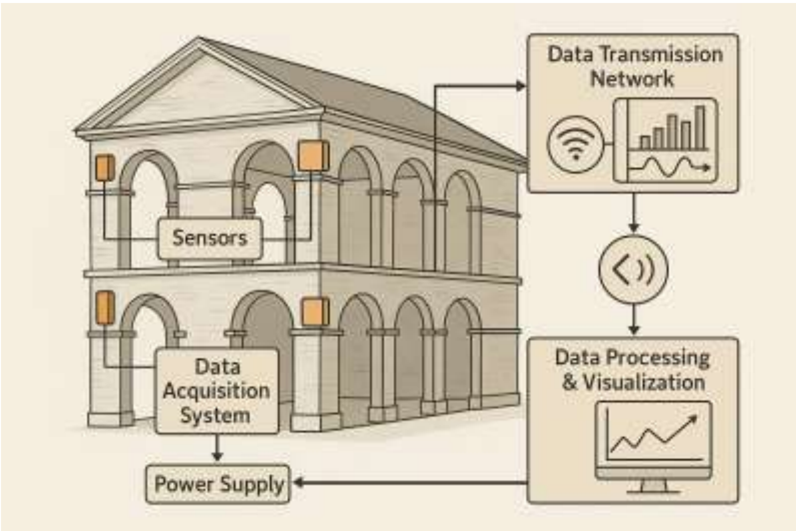


Figure 25: Generic schematic of a SHM system, highlighting sensors, acquisition units, and data processing pipeline

Fiber optic sensors (FOS) are highly suited for SHM in historical buildings due to their unique advantages: immunity to electromagnetic interference, long-range transmission capabilities, high sensitivity, and the possibility of embedding or attaching them in a minimally invasive way. Moreover, fibre optic (FO) sensors-based monitoring systems have the advantage of reduced number of wires to be installed, because of their capability of being multiplexable, thus, in the case of punctual sensors it is possible to create a chain of up to 50 sensors on a single cable (for distributed sensors this characteristic is intrinsic). FOS – based SHM system can perform continuous and real-time monitoring of the structure.

Several types of fiber optic sensing technologies are employed in SHM:

- **Fiber Bragg Gratings (FBG)**: These sensors reflect specific wavelengths that shift in response to strain or temperature changes. They are highly precise and compact, making them ideal for embedding in masonry or structural joints.
- **Distributed Sensing (e.g., Brillouin or Rayleigh Scattering)**: Enables continuous sensing along the entire length of an optical fiber, suitable for monitoring large surfaces like walls or arches.
- **Fabry-Pérot Interferometers**: Offer ultra-sensitive point measurements, useful in applications requiring extremely fine resolution.
- **Microbend and Intensity-Based Sensors**: Cost-effective but generally less sensitive and accurate, used for general trends rather than precise diagnostics.

A wide range of parameters essential for historical building preservation can be monitored using FOS based monitoring system (Table 5).

Table 5: Different parameters and relative technologies that can be monitored with FOS.

PARAMETER	TECHNOLOGY	NOTES
Strain	FBG, Distributed Brillouin	FBG for local points; Brillouin for entire structural elements
Temperature	FBG, Rayleigh, DTS (Distributed Temperature Sensing)	Enables compensation for thermal effects
Displacement	FBG with special mechanical setup	Often used at crack joints or beam ends
Crack propagation	FBG, Optical Time-Domain Reflectometry (OTDR)	Highly sensitive; requires precise calibration
Vibration/Seismic	FBG arrays, interferometric sensors	Suitable for dynamic analysis and heritage site earthquake monitoring

Two main application methodologies are commonly used in the implementation of FOS based monitoring systems: **embedded sensors in reinforced concrete elements** and **surface-mounted sensors** on existing structures.

In cases where historical buildings undergo structural strengthening or partial reconstruction using reinforced concrete (RC) elements, fiber optic sensors can be embedded directly into the concrete during casting. These sensors are typically installed in the following ways:

- **Bonded to Reinforcing Bars**: Before concrete pouring, optical fibers (often in ruggedized cables) are bonded along the surface of steel rebars using epoxy adhesives or mechanical clamps. This approach ensures that the sensor becomes an integral part of the structure and deforms in sync with the reinforcement.
- **Placed in Protective Conduits**: In more sensitive applications, the fibers are placed in protective plastic or stainless steel tubes that are then fixed along reinforcement cages. This setup allows partial mechanical decoupling and protects the sensor during pouring.

- **Strategic Layouts**: The sensors are positioned in areas expected to experience the most stress, such as beam-column joints, foundations, or zones near cracks. This enables early detection of structural degradation or excessive loading.

Embedded sensors provide highly reliable strain and temperature data but require careful planning during the design and construction phases.

For historical buildings where invasive interventions are not permitted or feasible, surface mounting of fiber optic sensors offers a non-destructive monitoring solution. This technique includes:

- **Adhesive Bonding to the Surface**: Fiber optic sensors are bonded directly to the surface of walls, vaults, beams, or columns using special epoxies or cyanoacrylate adhesives. The surface must be cleaned and prepared to ensure proper adhesion and signal quality.
- **Integration with Protective Sheaths**: In exposed environments, fibers may be housed in protective sheaths or grooves cut into the surface, then sealed with compatible materials to protect against physical and environmental damage.
- **Use of Pre-stressed Optical Cables**: For crack monitoring or displacement measurements, optical cables can be installed under pre-tension between two fixed points. Any movement or deformation between the anchor points is captured by the sensor.

Considering the typology of defects reported in the vulnerability analysis (cfr. Chapter 3.1.2) and based on the consideration briefly reported above on the main aspects/characteristics of FOS – based SHM systems, the technology that is most suited for the monitoring of the RCM is FBG, which is a punctual technology, able to be multiplexed on a single optic fibre up to 50 times, that covers all the parameters that can be monitored. Moreover FBG DAQ are usually multichannel unit, permitting to read simultaneously more optical cables (usually 4/8 channels).

In the following sections, for each of the analyzed components of the structure is reported the qualitative design of a FBG based SHM system able to monitor the main problem of the component. Where possible, the SHM system is considered together with a reinforcement/restoration intervention.

4.1.2.1. Load-bearing walls

The vulnerability analysis of basement and foundation reported the presence of cracks in the load-bearing walls (see section 3.1.2.1), as well as in the load-bearing walls at the north and south ends of the building (see section 3.1.2.2), which requires continued monitoring to help determine whether structural reinforcement is needed to mitigate the effects of foundation deformations and soil instability. FBG crack sensors (or Optic Strain Gage - OSG) can be installed on the cracks to monitor its increase (Figure 26), considering that the gage is sensitive to strains parallel to the axis of the fiber.

Figure 26: Example of FBG crack sensors applied to cracks.

OSGs usually come from the factory ready to install on the cracks. The different phases of installation are below and showed in Table 6:

- **Surface Preparation:** Mounting surface must be reasonably flat and free of surface defects. The surface should be free of rust, scale, oxides, loose paint, or other coatings, thus degreaser or abrasion can be necessary to remove surface irregularities and contamination. Then a spare or dummy gage needs to be used to determine how the gage will be positioned on the crack. Using a drafting pencil, burnish whatever alignment marks are necessary on the specimen for repositioning the gage.
- **Apply Gage:** Remove any protective backing from bottom surface of gage and then carefully position gage over test specimen and press firmly into place. If multiple gages are to be mounted in close proximity, wear latex gloves or cover gage with plastic film before pressing down on gage.
- **Inject and Cure of Adhesive** (preferably Epoxy): Prepare the adhesive in its dispenser and inject it following the OSG producer instructions. Then wait for the cure of the adhesive.
- **Cable laying down and connection:** Connect the connector at the end of the OSG cable with a patchcord. Such patchcord, which can be selected to be as less visually invasive as possible (ϕ under 1 mm and transparent), can cover hundreds of meter distance to reach the DAQ without relevant signal losses. Connect the patchcord to the DAQ.

Table 6: Summary of activities, materials, equipment, and labour for implementation of the FBG crack monitoring system.

ACTIVITY	MATERIALS	EQUIPMENT	LABOUR REQUIREMENTS	MATERIAL CONSUMPTION (PER M²)
Surface preparation	Water (for hydrodemolition), Degreaser, Abrasive blasting media (Sandpaper)	Pressure washer	Technicians, Safety personnel	N/A
Bonding of FBG sensors to wall	FBG sensors, Adhesive	Adhesive applicator (depending on the adhesive typology)	Fixing sensors to wall surface	Depending on cracks number and length

Co-funded by the European Union

ACTIVITY	MATERIALS	EQUIPMENT	LABOUR REQUIREMENTS	MATERIAL CONSUMPTION (PER M²)
Cable laying down and connection	Fibre Optic patchcord, cable clip	Hammer to fix the cable clip	Technicians	Depending on the location of the DAQ
DAQ connection	-	DAQ	Technicians	N.A.

The fixing activity of OSG can take up to 15 minutes for sensor (the cure time of the adhesive is not considered), while the cable connection and lay down can take from ½ hour to 3 hours, depending on the distance to be covered to reach the DAQ, which need to be placed in a safe place (both in terms of safety and environmental aspect).

4.1.2.2. Basement slab strengthening and SHM system

Considering the bottom-surface concrete overlay method (section 4.1.1) as restoration intervention, a SHM system based on FBG can be embedded in concrete layer bonded to the reinforcing rebar that needs to be replaced.

Such rebars can be both steel and fiber-reinforced polymer (FRP) rebars, depending on the structural design of the intervention of restoration. Such sensors, designed for being placed truly in-line with the customers' rebars for the accurate measurement of rebar strain after embedding into concrete, can be inserted in number of three or five for rebar, depending on the geometry of the concrete layer, to monitor strain of the rebars in different points.

The FBG sensors can be bonded to the replacement rebars just before their installation by means of plastic tightening ties, to be stopped during the application of the repairing mortar. The ends of the FO cable are left outside the mortar to be connected to other FO cable. Once installed all the FBG sensors and realized the slab strengthening, cables are connected one next the other and the final one is connected to the DAQ by means of a patchcord. Such patchcord, which can be selected to be as less visually invasive as possible (¤ under 1 mm and transparent), can cover hundreds of meter distance to reach the DAQ without relevant signal losses. A summary of the necessary activities to realize the intervention is reported in Table 7.

The bonding activities can take up to 10 minutes for each sensor, while the cable connection and lay down can take from ½ hour to 3 hours, depending on the distance to be covered to reach the DAQ, which need to be placed in a safe place (both in terms of safety and environmental aspect).

Table 7: Summary of activities, materials, equipment, and labour for repair of the reinforced concrete slab with the implementation of the SHM system

ACTIVITY	MATERIALS	EQUIPMENT	LABOUR REQUIREMENTS	MATERIAL CONSUMPTION (PER M²)
Surface preparation	Water (for hydrodemolition)	High-pressure water jetting system (400-2000 bar)	Skilled workers, supervisor	32,000 litres/ m^3
Reinforcement cleaning	Abrasive blasting media (e.g., grit, sand, or metallic abrasives)	Abrasive blasting equipment (grit or sandblasting)	Skilled workers with blasting experience	Steel grit approx. 25kg/m^2

ACTIVITY	MATERIALS	EQUIPMENT	LABOUR REQUIREMENTS	MATERIAL CONSUMPTION (PER M²)
Bonding of FBG sensors to rebars	FBG sensors, plastic tightening ties	scissors	Technicians,	Depending on rebar number and length
Replacement of corroded reinforcement and placement of new reinforcement	New steel reinforcing bars, stainless steel tie wire or mechanical couplers, bonding agents or anchoring materials	Rebar cutting tools, drilling equipment and injection guns (for anchoring), binding tools (for tie wire) or torque wrench (for mechanical couplers).	Skilled workers, supervisor	Function of the amount of new reinforcement required per m^2
Installation of connectors	Steel reinforcing connectors, bonding agents or anchoring materials	Rotary percussion drill (for anchor holes), compressed air or vacuum systems (to clean dust), injection guns	Skilled workers, supervisor	Function of the number of connectors required per m^2
Casting and curing of overlay concrete	Concrete or repair material, admixtures (for SCC), water (for curing)	Mortar or concrete mixer, formwork, vibrators or pumping system, water spraying devices (for curing)	Skilled workers, supervisor, safety personnel	Volume of concrete as a function of the overlay thickness
Sealing of Expansion Joints	Polyurethane-based elastic sealant, closed-cell backer rod	Manual or pneumatic caulking gun, cutting tools, spatulas	Skilled workers	100 ml/m of joint
Quality control	Sand (for sand patch method)	Pull-off tester, sand patch kit, thickness gauges (for overlay verification)	Quality control technicians or engineers	N/A
Cable laying down and connection	Fibre Optic patchcord, cable clip	Hammer to fix the cable clip	Technicians	Depending on the location of the DAQ
DAQ connection	-	DAQ	Technicians	N.A.

4.1.2.3. Frame elements: Columns and beams

The vulnerability analysis of frame elements reports that the steel beams and masonry columns are primarily vulnerable to humidity-induced corrosion and potential overloading. Although the overall structural condition is deemed satisfactory, interventions are necessary to mitigate moisture exposure and ensure long-term durability. Before the planned renovation of the floor structure, it is essential to repair the existing damage to the beams, addressing the causes of deterioration. Moreover, energy efficiency intervention on the structure will increase the load on the structure, thus a strengthening intervention on the beams, which actually work in near to the limit conditions, would be useful.

In the context of structural rehabilitation, existing steel beams that exhibit slight corrosion but maintain overall structural integrity can be effectively reinforced using composite materials such as Carbon Fiber Reinforced Polymers (CFRP). This technique provides not only an increase in load-bearing capacity and stiffness but also serves as a protective barrier against moisture ingress, thereby mitigating future corrosion.

From a structural standpoint, the composite materials significantly increase the tensile strength of the steel members and improve their performance under bending and shear loads. This is particularly beneficial in cases where the original load conditions have increased or where serviceability requirements (e.g., deflection limits) must be improved.In addition to the mechanical benefits, the CFRP layers act as a protective coating that isolates the steel surface from ambient humidity. This dual function—reinforcement and moisture barrier—makes the solution particularly suitable for environments with fluctuating humidity levels or poor ventilation, where corrosion could otherwise progress rapidly.The overall intervention is lightweight, minimally invasive, and reversible if needed, making it especially attractive for the conservation of historic or architecturally sensitive structures. Moreover, the application process is relatively fast and does not require significant alterations to the existing structure, thereby reducing downtime and associated costs.

The intervention involves the surface preparation of the steel elements to remove rust, scale, and contaminants, typically through sandblasting or mechanical brushing. Once cleaned, the surface is treated with a suitable primer to enhance adhesion and inhibit further oxidation. The CFRP laminates or fabrics are then applied to the web and/or flanges of the beam using high-performance epoxy resins. During this step of the process FBG sensors can be fixed on the CFRP reinforcement to monitor the deformation of the beam, by means of local strain. FBG sensors can be inserted in number of three or five for rebar, depending on the geometry of the beams and on the number of monitored beams. Not all the beams need to be sensorized, but the most relevant ones can be individuated and instrumented to be representative of the overall structure. The ends of the FO sensors are connected one to another, forming a chain. Once installed, all the FBG sensors cables are connected one next the other and the final one is connected to the DAQ by means of a patchcord. Such patchcord, which can be selected to be as less visually invasive as possible (ϕ under 1 mm and transparent), can cover hundreds of meter distance to reach the DAQ without relevant signal losses.

To maintain the architectural integrity of the reinforced steel beams and further prevent corrosion, a protective concrete overlay must be cast over the strengthened surfaces. This layer serves two key purposes: it encapsulates the CFRP reinforcement and fiber optic sensors, and it restores the original visual appearance of the embedded steel beams. Recasting using self-compacting concrete or equivalent high-performance repair mortar is appropriate in such situations, particularly where surface integrity, mechanical protection, and aesthetic continuity are required (fib Bulletin 102). The concrete overlay is placed using conventional formwork shaped to the original geometry of the beams, ensuring that the visual identity of the heritage structure is preserved. The use of self-compacting concrete reduces the risk of sensor displacement or damage. Once cast, the overlay is cured adequately to ensure bond development and long-term durability. A summary of the necessary activities to realize the intervention is reported in Table 8.

The bonding activities can take up to 10 minutes for each sensor, while the cable connection and lay down can take from ½ hour to 3 hours, depending on the distance to be covered to reach the DAQ, which need to be placed in a safe place (both in terms of safety and environmental aspect).

Table 8: Summary of activities, materials, equipment, and labour for reinforcement of steel beams with the implementation of the SHM system

ACTIVITY	MATERIALS	EQUIPMENT	LABOUR REQUIREMENTS	MATERIAL CONSUMPTION (PER M²)
Surface preparation	Water (for hydrodemolition), Filler / Leveling Compound	High-pressure water jetting system (400–2000 bar)	Skilled workers, supervisor	32,000 litres/ m^3
Beams cleaning	Abrasive blasting media (Steel Grit), Surface Cleaner / Degreaser	Abrasive blasting equipment (grit or sandblasting)	Skilled workers with blasting experience	Steel grit approx. 25kg/m^2
Application of CFRP laminate/fabric	CFRP Sheets or Laminates, Epoxy Resin (Impregnating Resin / Adhesive), Primer (Optional but recommended),	Rollers or brushes for resin application, Protective gloves and masks, Heating tools or lamps (for curing in low temperatures, if necessary), Compression tools (if applying pre-cured laminates)	Technicians	Depending on the beams geometry
Bonding of FBG sensors to Beams	FBG sensors		Technicians	Depending on rebar number and length
Impregnating the CFRP laminate/fabric and FBG sensor	Epoxy Resin (Impregnating Resin / Adhesive),	Rollers or brushes for resin application, Protective gloves and masks, Heating tools or lamps (for curing in low temperatures, if necessary),	Technicians	Depending on the beams geometry
Casting and curing of protective concrete overlay	Concrete or repair material, admixtures (for SCC), water (for curing)	Mortar or concrete mixer, formwork, pumping system, water spraying devices (for curing)	Skilled workers, supervisor, safety personnel	Volume of concrete as a function of the protective layer thickness
Cable laying down and connection	Fibre Optic patchcord, cable clip	Hammer to fix the cable clip	Technicians	Depending on the location of the DAQ
DAQ connection	-	DAQ	Technicians	N.A.

4.1.3. Corrosion monitoring systems

This strategy consists of carrying out the strengthening process described in Section 4.1.1, while further increasing the resilience of the basement slab to the corrosion degradation process. To this end, two additional steps are introduced to the procedure previously described.

The first additional step consists of adding corrosion inhibitors to the steel reinforcement bars and the concrete overlay. This technique provides a protective action that delays or mitigates the initiation and propagation of corrosion in reinforced concrete, particularly in aggressive environments such as the one found in the basement slab, where high humidity, poor ventilation, and moisture infiltration through expansion joints and cracks have been documented (see Section 3.1.2.3). According to fib Bulletin 102, corrosion inhibitors can be implemented using three techniques: *(i)* direct coatings applied to the exposed reinforcement before casting, *(ii)* incorporation into the repair mortar or overlay as admixed inhibitors, and *(iii)* penetrating (migrating) surface-applied inhibitors, which are applied to hardened concrete and migrate to the reinforcement. The proposed intervention adopts a combination of the first two techniques, which are both compatible with the strengthening sequence and suitable for the environmental conditions of the basement.

The first corrosion protection measure consists of applying a protective coating directly onto the cleaned and exposed reinforcement. This is to be done after surface preparation and removal of all corrosion products, ensuring the steel surface is free of rust and contaminants. The coating must be continuous, defect-free, and fully encapsulate the bar circumference. According to fib Bulletin 102, these coatings may contain active pigments acting either by anodic passivation or by sacrificial galvanic action. They must be applied following the manufacturer's instructions, typically using a brush or roller, and avoiding any contamination of adjacent concrete surfaces to preserve the bond of repair materials. This technique is especially effective in controlling incipient anodes and preventing future corrosion propagation from rebar-concrete interfaces.

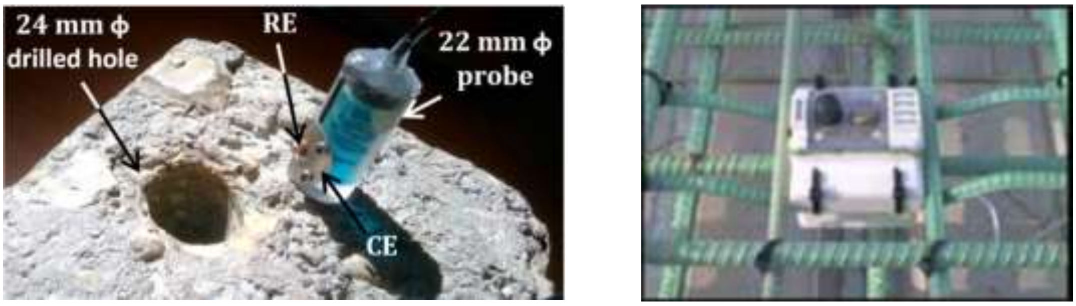
The second protection measure is the incorporation of a corrosion inhibitor as an admixture in the repair mortar or overlay concrete. These inhibitors, once mixed into the overlay material, provide distributed protection by altering the electrochemical environment of the steel, reducing the corrosion rate through anodic, cathodic, or mixed mechanisms. The inhibitor must be compatible with the binder system and must not compromise the mechanical performance or durability of the repair material. Typical product types include organic amines, calcium nitrite, or carboxylates, and their dosage and integration must follow the supplier's specifications. These admixtures are particularly useful in ensuring long-term corrosion control and maintaining passivity around newly embedded or supplemented reinforcement (fib bulletin 102).

The execution of these protection measures requires conventional equipment, i.e., wire brushes or blasting tools for steel cleaning, brushes or rollers for coating application, and standard mixers for admixed mortars. The labour should include experienced personnel trained in steel protection and repair product application. Quality control measures include verification of coating continuity, confirmation of correct inhibitor dosage in repair mixes, and documentation of all steps as part of the site records.

The second additional step to increase the resilience of the basement slab to the corrosion degradation process consists of installing corrosion sensors to monitor the onset and progression of corrosion over time. Reinforcement corrosion is mainly driven by carbonation and chloride ingress. These processes reduce the pH at the steel interface, eventually depassivating the reinforcement and leading to cross-sectional loss, cracking, and even structural instability. As highlighted by Martínez and Andrade (2009), embedded sensor systems allow for the early detection of corrosion activity before structural consequences become significant. These systems enable the measurement of electrochemical parameters such as corrosion potential, resistivity, and the corrosion rate. Monitoring data can then be used to assess structural durability, trigger maintenance actions, and inform predictive models of service life. Despite external factors like moisture and temperature influencing measurements, embedded sensors have been successfully installed and operated in a wide range of real structures, from marine docks to bridges and nuclear waste containers, offering years of continuous performance without compromising the concrete matrix (Martinez and Andrade, 2009).

In the context of the Riga Central Market basement slab, the proposed intervention involves embedding electrochemical corrosion rate sensors based on the polarization resistance technique during the execution of the strengthening works. These sensors provide direct, quantitative information on the corrosion rate (Icorr), which is the only electrochemical parameter that allows the corrosion process to be quantified in terms of metal loss. While other parameters such as corrosion potential or concrete resistivity can indicate the probability or risk of corrosion, Icorr enables estimation of the rate at which steel is actively corroding (Martinez and Andrade, 2009). Through Faraday's law, Icorr can be used to calculate the amount of metal loss over time, making it a critical input for evaluating the loss of bearing capacity and thus the structural reliability, which is a KPI used in the resilience assessment framework implemented in this deliverable.

Commercial examples of sensors using the polarization resistance technique include the DIAMOND Monitoring Probe and the ECi-2 sensor, both designed for long-term, in-situ corrosion monitoring in reinforced concrete structures. The DIAMOND Monitoring Probe is a compact embedded device that measures corrosion potential (Ecorr), concrete resistivity, and corrosion rate (Icorr) through a galvanostatic polarization resistance method. It includes a ring-shaped counter electrode and a $Cu/CuSO_4$ reference electrode. While in typical applications it is installed in mortar-filled boreholes drilled near reinforcement, in the basement slab intervention it can be directly placed adjacent to the exposed steel during the strengthening works. The probe is aligned to face the reinforcement and then embedded within the overlay layer. Data acquisition is supported by a wireless system (CAPTAE) that enables multi-year corrosion tracking. The ECi-2 sensor is a fully embedded corrosion monitoring instrument that also applies the polarization resistance method using a sacrificial black steel working electrode, a 316L stainless steel counter electrode, and a MnO_2 reference electrode. It is capable of simultaneously measuring Icorr, corrosion potential, resistivity, temperature, and a voltage related to chloride concentration. The ECi-2 includes embedded microelectronics for analog-to-digital conversion at the sensor head, minimizing signal degradation from electromagnetic interference. During the slab intervention, it can be integrated into the new reinforcement layout and cast into the overlay, positioned to reflect the exposure conditions of the structural steel. Data are transmitted via SDI-12 protocol to an external datalogger for real-time or remote analysis.



a) b)

Figure 27. Examples of electrochemical sensors: a) DIAMOND Monitoring Probe; b) ECi -2 sensor

Table 9 summarizes the activities, materials, equipment, and labour for the strengthening of the reinforced concrete slab with the implementation of the corrosion monitoring system. The application of corrosion inhibitors and the installation of the corrosion sensors will not significantly increase the estimated duration of the strengthening procedure described in section 4.1.1, so the total duration of the intervention can be considered the same.

Table 9. Summary of activities, materials, equipment, and labour for the strengthening of the reinforced concrete slab with the implementation of corrosion monitoring

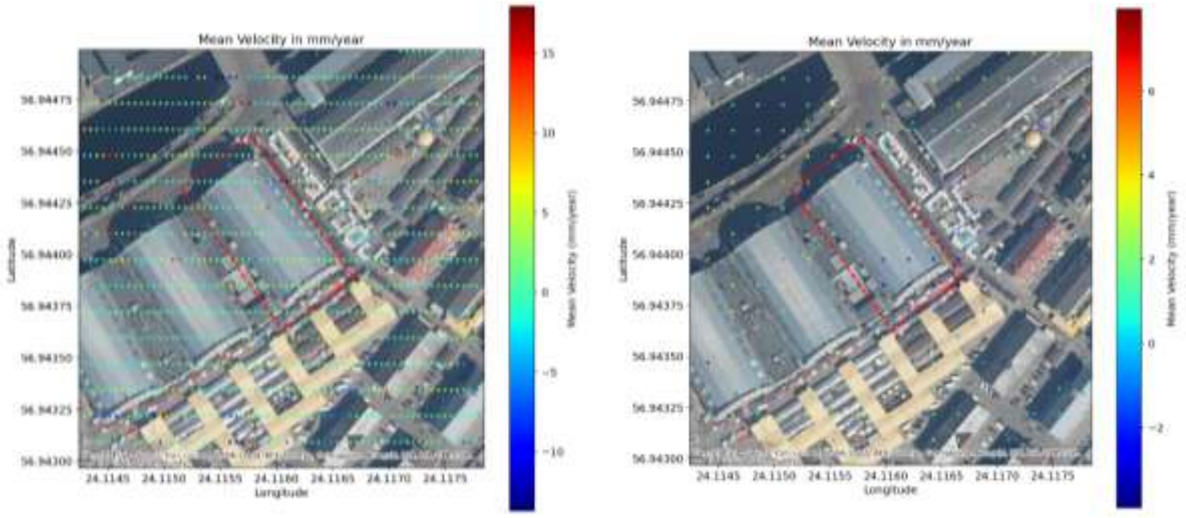
ACTIVITY	MATERIALS	EQUIPMENT	LABOUR REQUIREMENTS	MATERIAL CONSUMPTION (PER M^2 OR M^3)
Condition assessment	N/A	Inspection tools, calipers, NDT equipment	Engineers or inspectors	N/A
Surface preparation	Water (for hydrodemolition)	High-pressure water jetting system (400-2000 bar)	Skilled workers, supervisor	32,000 litres/m^3
Reinforcement cleaning	Abrasive blasting media (e.g., grit, sand, or metallic abrasives)	Abrasive blasting equipment (grit or sandblasting)	Skilled workers with blasting experience	Steel grit approx. 25kg/m^2
Replacement of corroded reinforcement and placement of new reinforcement	New steel reinforcing bars, stainless steel tie wire or mechanical couplers, bonding agents or anchoring materials	Rebar cutting tools, drilling equipment and injection guns (for anchoring), binding tools (for tie wire) or torque wrench (for mechanical couplers).	Skilled workers, supervisor	Function of the amount of new reinforcement required per m^2
Corrosion inhibitor coating on reinforcement	Corrosion inhibitor coating	Brushes or rollers (for application)	Skilled workers	Approx. 0.5kg/m^2
Installation of connectors	Steel reinforcing connectors, bonding agents or anchoring materials	Rotary percussion drill (for anchor holes), compressed air or vacuum systems (to clean dust), injection guns	Skilled workers, supervisor	Function of the number of connectors required per m^2
Corrosion inhibitor admixture in overlay concrete	Admixed corrosion inhibitors (e.g., calcium nitrite)	Mortar or concrete mixer	Skilled workers	Typically 10-30 litres/m^3 (for calcium nitrite admixtures)
Installation of corrosion sensors	Electrochemical sensor (e.g., DIAMOND, Eci-2, fixing elements)	Hand tools for sensor positioning	Technicians, engineers	Number of sensors depending on the monitoring layout
DAQ connection	N/A	DAQ (e.g. CAPTAE wireless receiver or SDI-12 logger)	Technicians, engineers	N/A
Casting and curing of overlay concrete	Concrete or repair material, admixtures (for SCC), water (for curing)	Mortar or concrete mixer, formwork, vibrators or pumping system, water spraying devices (for curing)	Skilled workers, supervisor, safety personnel	Volume of concrete as a function of the overlay thickness

ACTIVITY	MATERIALS	EQUIPMENT	LABOUR REQUIREMENTS	MATERIAL CONSUMPTION (PER M² OR M³)
Sealing of Expansion Joints	Polyurethane-based elastic sealant, closed-cell backer rod	Manual or pneumatic caulking gun, cutting tools, spatulas	Skilled workers	100 ml/m of joint
Quality control	Sand (for sand patch method)	Pull-off tester, sand patch kit, thickness gauges (for overlay verification)	Quality control technicians or engineers	N/A

4.1.4. Satellite remote sensing for monitoring building ground displacements

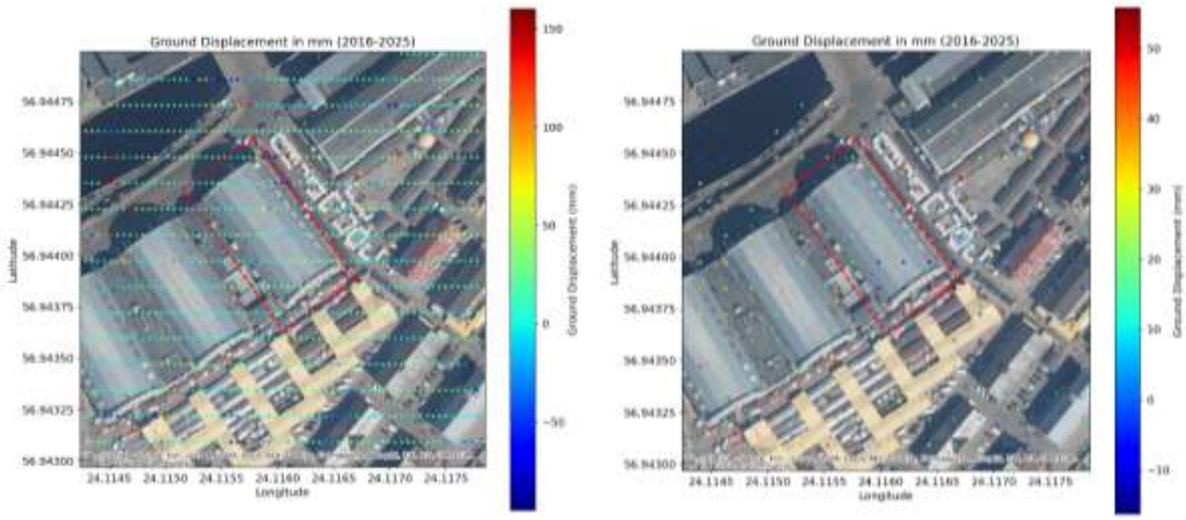
The presence of localized cracks in load-bearing wall structures suggests minor general deformations in the building, which may indicate uneven foundation settlement over time. This ground displacement can be measured and monitored using terrestrial methods, which are labor-intensive and time-consuming. Alternatively, spaceborne techniques like Persistent Scatterer Interferometric Synthetic Aperture Radar (InSAR) offer a more efficient solution. InSAR enables automated data collection over large areas, making it a scalable and effective approach (Drougkas 2021). In recent years, InSAR has proven effective in detecting geographic areas where CH buildings may be at risk, offering an efficient and scalable monitoring solution (Chen et al. 2018/01/01; Rodríguez-Antuñano et al. 2024).

In (Varma 2025), InSAR, specifically Persistent Scatterer Interferometry (PSI) and Small Baseline Subset (SBAS), were used to monitor ground deformation at the RCM Dairy Pavilion. Sentinel-1 data from 2016 to 2025 were processed to obtain mean velocity and displacement trends, which were later integrated into finite element modelling of the structure for risk assessment. The InSAR analysis captured extensive deformation trends across Riga, but when filtered to the RCM Dairy Pavilion, 64 PSI points and 16 SBAS points were retained. The PSI results (Figure 28a) indicated a maximum mean uplift rate of 14.1 mm/year and a maximum mean subsidence rate of –7.2 mm/year, while SBAS (Figure 28b) showed lower deformation magnitudes, with uplift rates up to 2.2 mm/year and subsidence down to -3.9 mm/year. The cumulative displacement trends revealed significant differences: PSI recorded a maximum uplift of 120.4 mm and subsidence of –87.0 mm (Figure 29a), whereas SBAS showed lower values of 21.4 mm uplift and –16.3 mm subsidence (Figure 29b). To visualize spatial variability over time, combined contour maps of deformation (Figure 30) were produced, which highlighted high subsidence on the north-eastern periphery of the pavilion and uplift concentrated toward the center and southern façade.



a) b)

Figure 28. Mean Velocity plot for the Dairy Pavilion derived from a) PSI; b) SBAS



a) b)

Figure 29. Ground Displacement plot for the Dairy Pavilion derived from a) PSI; b) SBAS

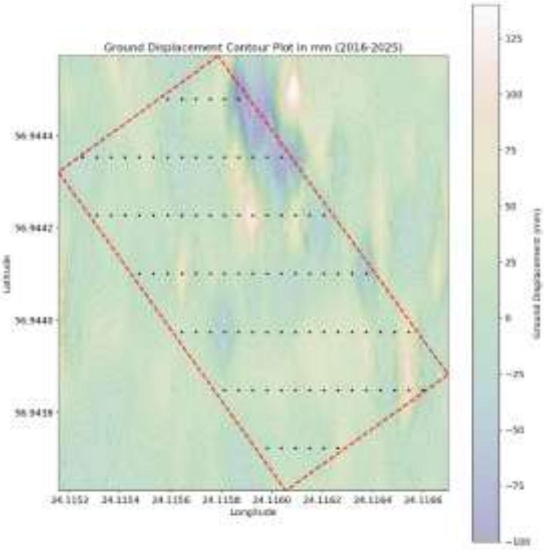
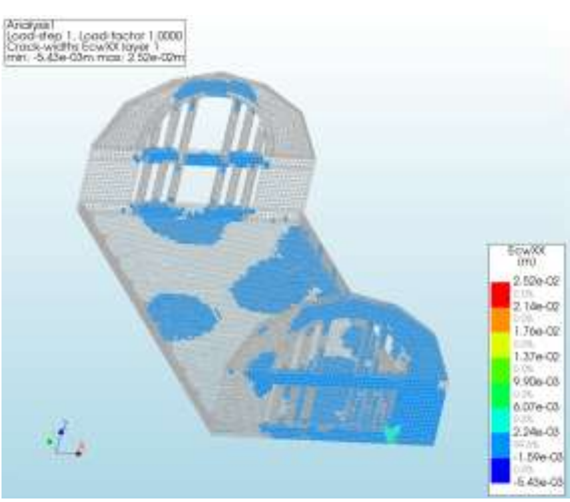
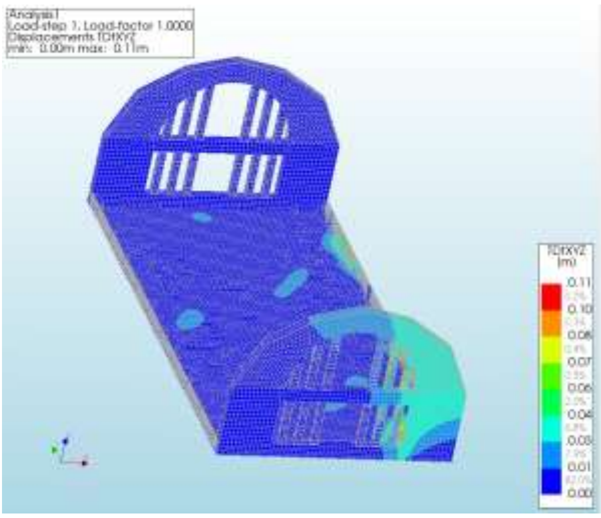


Figure 30. Contour plots for the duration 2016-2025 with areas showing subsidence

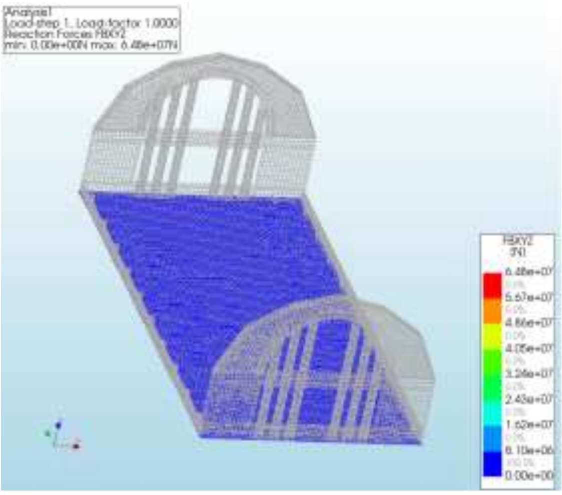
The InSAR-derived displacements were integrated into a finite element model of the RCM building (Varma 2025). The FE model revealed localized cracking in the building for the period 2016–2025, concentrated in the north and south load-bearing walls where damage had already been observed (refer to Chapter 3.1.2.2). Four damage states (DS) were defined: DS1 corresponded to hairline cracks up to 0.1 mm, DS2 to slight cracks between 0.1–1.0 mm, DS3 to moderate cracks from 1.0–2.0 mm, DS4 to severe cracks between 2.0–5.0 mm, and DS5 to very severe cracks wider than 5.0 mm. The crack width distribution (Figure 31a) confirmed that most elements remained within lower damage states (DS1–DS2), while the elemental displacements (Figure 31b) and reaction forces (Figure 31c) showed stress concentrations in these vulnerable regions. The classification of elements by damage state (Figure 31d) indicated that the majority of the structure retained low levels of deterioration, consistent with the limited risks detected in the short term.



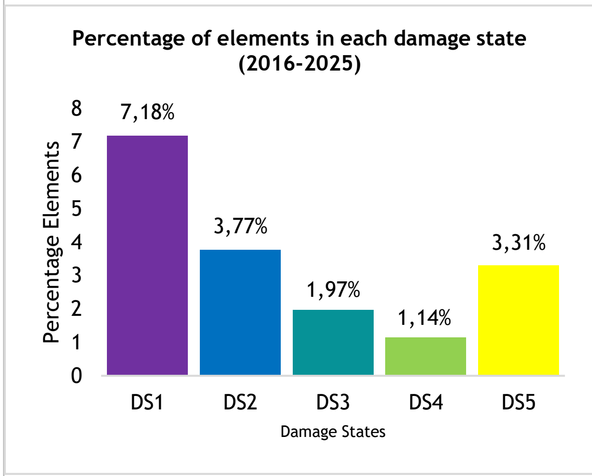
a) Crack Widths (EcXX)values for the duration of 2016-2025



b) Elemental displacements (TDXYZ) for the duration of 2016-2025



c) Reaction forces (FBXYZ) for the duration of 2016-2025



d) Percentage of elements within each Damage States for 2016-2025

Figure 31. Results from InSAR-derived displacements integration into a finite element model of the RCM building

Projections for 2075 demonstrated a progressive deterioration driven by long-term ground movements. Crack widths increased substantially, with deformation fields and reaction forces highlighting intensified settlement effects, particularly in the northeastern periphery. The distribution of damage states shifted markedly, with a significant portion of elements reaching DS4, associated with severe structural damage. These results confirm that while present risks remain low, sustained subsidence poses a long-term threat to the structural integrity of the RCM building (Varma 2025).

4.2. Site plan for restoration interventions

The overall site plan should be designed to ensure a rational organization of space, optimize internal traffic within the market, and maintain business operations without significant disruptions. Therefore, a proposal for the site plan layout for conducting the restoration interventions at the RCM Dairy pavilion is described in this section.

The main business areas will be preserved to ensure normal trading activities, while the construction zones will be clearly defined to ensure safety for both the public and workers. Additionally, the site plan must facilitate the transportation of materials and the proper arrangement of waste collection and disposal areas. The construction area will be divided according to the level of deterioration of each item. Seriously damaged areas should be renovated first. Reasonable division of construction phases will help minimize the impact on the daily operations of the market. The material gathering area will be arranged in the parking lot north of the market to ensure that it does not obstruct the movement of people and vehicles. This should be a covered area to protect weather-sensitive materials such as cement, mortar and steel. Materials will be arranged according to the principle of reasonable rotation to avoid congestion and optimize the construction process.

The waste treatment area will be located in a separate location, ensuring effective collection and classification of construction waste. Waste materials will be divided into groups that can be recycled or need to be treated according to environmental regulations. This arrangement will help ensuring the hygiene of the construction and minimize the impact on the surrounding area.

Internal access and traffic will be reorganized to ensure smooth business operations. Main access routes will be maintained, while construction areas will be fenced off and safety signs will be posted. In addition, fire exits will be inspected and kept clear throughout the renovation process.

During construction, safety measures will be applied to protect both workers and residents. A fence system will be installed around the construction area to prevent risks. In addition, traffic diversion plans will be implemented to ensure that vehicles transporting materials do not obstruct market operations. Dust and noise control is an important factor in minimizing impacts on the surrounding area. Covering, watering and using less polluting machinery will be implemented to minimize negative impacts on the environment. A system of signs and safety warning lights will be installed in dangerous areas, helping people easily recognize and avoid areas with potential safety risks. In addition, the construction schedule will be adjusted appropriately, avoiding stages that cause loud noise during peak hours so as not to affect trading activities in the market.

4.3. Supply Chain Analysis for interventions in Riga Central Market

4.3.1. Concrete overlays

The supply-chain framework begins with the designation of a covered materials-staging area in the northern parking lot, well outside of the main trading halls yet with direct access to the basement ramps. Here, ready-mix concrete deliveries (self-compacting as required) arrive each morning from the nearby batching plant under just-in-time schedules, while bulk admixtures (superplasticizer, shrinkage-reducing agents) are off-loaded into weather-proof drums. Steel reinforcement, including 10 mm bars, stainless tie-wire and cup-headed connectors, arrives on flatbed trucks under a 14-day lead time, with mill certificates pre-inspected by **Quality Assurance** (QA) before unloading. All materials are rotated FIFO (first in, first out) to avoid on-site spoilage, and daily stock checks ensure that critical items never fall below a two-day buffer.

Adjacent to this, the equipment compound houses rental units for hydro-demolition, abrasive blasting and concrete placement. The high-pressure jetting skid and abrasive-blasting rig arrive on skid-trailers under a single multiweek lease, complete with hoses, nozzles and dust-extraction modules. Formwork panels, vibrators, pumps and curing tents are similarly reserved through a master rental agreement, guaranteeing that all mechanical interfaces (couplings, power requirements) are standardized. Rental providers deliver and commission each system one day before mobilization, and a local service technician remains on standby to avert breakdowns.

Labour is subcontracted through two specialist crews to minimize coordination risk. A structural inspection team (engineer, NDT technician, field assistant) kick-off the condition assessment, followed immediately by a hydro-jet crew (operators, hose handlers, QA supervisor) and blasting crew (blaster, assistant, safety officer). Each crew is block-booked with seven days’ notice, and their schedules are slotted to overlap surface preparation with connector drilling, ensuring that no trade is idle. Pour crews (formwork carpenters, pourers, finishers, curing crew) are sequenced to follow reinforcement installation, with the entire cast-in-place operation planned in 50 m^2 work zones to allow simultaneous curing and cleanup.

Waste management and quality-control activities run in parallel. Used abrasives, hydro-demolition slurry and removed concrete are loaded into skip bins and sediment-filter units stationed at the site's southern edge, then hauled off by an environmental contractor on a three-day call-off. Pull-off testing rigs, ultrasonic gauges and compression machines are delivered under a weekly rental, with data logged each evening by the QA lab team. All waste bins are clearly labelled—recyclable aggregate, hazardous grout residue, general construction debris—to meet local disposal regulations.

To preserve uninterrupted market operations, internal traffic routes are maintained along the east-west axis, with temporary fencing and directional signage guiding visitors around work zones. A dedicated delivery window (07:00–09:00) is enforced, preventing concrete and steel trucks from conflicting with peak trading hours. Dust suppression (water misting, covering stockpiles) and low-noise equipment selections (electric pumps, muffled generators) further mitigate impacts. Fire exits and emergency access lanes are checked daily, and noise-intensive tasks (core drilling, blasting) are scheduled outside of market peak times, ensuring that both public safety and commercial continuity are upheld throughout the strengthening intervention.

From a supply-chain lens, the activities with the highest criticality, Overlay Casting & Curing, Connector Installation, and Removal & Replacement of Bars, demand the most rigorous coordination, buffer planning and vendor management. For Overlay Casting & Curing, the just-in-time delivery of ready-mix concrete (0.05 m^3/m^2) and specialist admixtures must be dovetailed with pump and vibrator rentals, so any delay ripples through curing schedules and downstream finishing crews. In Connector Installation, securing 21-day lead-time connectors and high-strength epoxy grout under consignment deals or dual sourcing reduces the risk of rework or idle drilling crews; concurrent rental of proof-load rigs and grout pumps ensures commissioning tests aren't bottle-necked. Likewise, Removal & Replacement of Bars' rebar, tie-wire and drilling consumables, with their 7–14-day lead times, must be ordered in phase quantities aligned to block-booked steel-fixer crews, while standardized cutter and injection-pump interfaces avert mobilization hiccups.

4.3.2. Structural health monitoring

The supply-chain model for the Fiber-Optic Structural Health Monitoring (SHM) solution is organized around a covered materials-staging area in the north parking lot, well clear of the trading halls yet with direct access to the installation zones, to support just-in-time delivery, secure storage and efficient rotation of all sensor components, adhesives and cabling. FBG crack sensors and strain gauges arrive in factory-calibrated kits on 14-day lead times; epoxy adhesives and bonding agents are delivered in 7- and 14-day drum batches. FO patchcords (m) and cable clips are trucked in on 7-day schedules, then FIFO-rotated to prevent excess dwell time; daily stock checks maintain a two-day buffer of critical items to avoid downtime in the event of a late shipment.

Adjacent to materials staging, the equipment compound holds all rental and mobilization gear under a single weekly lease. A pressure washer and water-jet skid prepare mounting surfaces; epoxy dispensers and applicator guns deliver resin precisely during gage installation; percussion drills and hammers and proof-load rigs are reserved for patchcord anchorage. Pull-off testers, sand-patch kits and ultrasonic gauges are delivered two days before QA campaigns, ensuring calibration and compatibility across all diagnostic tasks.

Labor is deployed in two overlapping specialist crews to minimize idle time and maintain a continuous workflow. A surface-prep team (technician + safety attendant) kicks off the program, followed by an FBG-installation crew (technician + adhesive applicator: 2–4 h per gage/h) and a patchcord-routing squad (technician with helper). For larger-scale monitoring on reinforced elements, a concrete overlay crew (rebar fitter, concreter, supervisor) and QC lab team are block-booked under single contracts, guaranteeing qualified operators on seven days' notice.

All residuals and consumables are managed under a lean waste-stream protocol. Rinse water from surface cleaning is captured in portable slurry tanks and passed through sediment filters before discharge. Epoxy packaging, cable-tie wrappers and adhesive drums are segregated and consolidated in labeled skip bins at the site's southern edge, then hauled off by the environmental contractor on a three-day call-off. Pull-off test discs and sand from patch tests are recycled where possible; any non-recyclable residue is collected separately to comply with local hazardous-waste regulations.

To maintain uninterrupted market operations, pedestrian and vehicle routes along the main east–west axis remains open at all times. Installation zones are clearly fenced, with high-visibility signage and temporary lighting marking off limits. A morning delivery window (07:00–09:00) is enforced for sensor and cable trucks, preventing congestion during peak trading hours. Dust is controlled via misting nozzles on the pressure washer, while low-noise epoxy dispensers and electric mixers minimize disturbance. Fire exits and emergency access lanes are verified daily, and noise-intensive drilling is scheduled outside core market hours to safeguard both traders and visitors throughout the SHM rollout.

From a supply-chain perspective, the most critical pressure points in this SHM rollout revolve around the delivery and staging of factory-calibrated fiber-optic sensors for both reinforcement bars and beams, whose extended lead times and unit value make uninterrupted replenishment—and the maintenance of a two-day buffer absolutely essential. Closely trailing these are the specialized epoxy adhesives and bonding agents used during wall sensor installation, along with self-compacting concrete and admixtures for overlay works, where any delay in drum-batch delivery or mixer availability can stall entire work fronts. Secondary but still significant are the supply of ultra-thin patchcords and cable clips for routing, and CFRP fabrics for beam strengthening, which require strict FIFO rotation and daily stock checks to prevent material expiry or excess dwell time. To safeguard overall continuity, the supply chain is planned to prioritize firm sensor order management and proactive adhesive/drum scheduling, then synchronize concrete and mixer rentals, all while leveraging just-in-time truck deliveries and on-site staging to absorb any residual variability without compromising the live trading environment.

4.3.3. Corrosion monitoring system

The supply-chain framework begins with the designation of a covered materials-staging area in the northern parking lot, well clear of the trading halls yet with direct vehicular access to the basement ramps. Here, twenty factory-calibrated half-cell probes and matching reference electrodes arrive every two weeks in sealed crates; five 25 L drums of copper sulfate solution and five 25 L drums of calcium-nitrite admixture are off-loaded on a weekly schedule. three 20 kg barrels of epoxy potting mortar and fifteen 0.5 kg tins of active-pigment inhibitor coating sit on weather-proof pallets, while bundles of 50 cable clips and 200 m of wiring loom hang from racking for FIFO rotation. Daily stock audits verify that no material falls below a two-day buffer (e.g. maintaining at least 20 probes, 25 L of inhibitor, and 50 m of cable in hand) to protect against delayed shipments.

Adjacent to materials staging, the equipment compound holds every rental and mobilization asset under a unified two-week master lease. Two core drills, two cover-meters, two pachometers and a half-cell meter are delivered and commissioned one day before works begin. Surface-prep is handled by two high-pressure washer skids and two water-jet rigs, each mounted on trailers with hoses and nozzles; an industrial dehumidifier stands by for immediate moisture control. Heavy cleaning uses two abrasive-blasting rigs paired with dust-extraction units. For anchor installation and sensor embedment, four rotary percussion drills, two injection pumps and a set of torque wrenches arrive as a consolidated kit—guaranteeing tool compatibility. Pull-off testers, sand-patch kits and ultrasonic thickness gauges are staged forty-eight hours before each QA round to ensure calibration continuity.

Labour is organized into three overlapping specialist crews to eliminate idle time. An initial mobilization team—structural engineer, NDT technician, field assistant and supervisor, sets up instrumentation and clears all mounting surfaces. Immediately thereafter, a surface-prep crew of two hydro-jet operators, one labourer and a QA supervisor runs hydro-demolition and abrasive blasting over three days. Concurrently on day 4, a coatings squad of two applicators plus supervisor applies 0.5 kg/m² of pigment inhibitor and mixes a 0.05 m³ inhibitor-admixture overlay. Beginning day 7, a sensor-embedment team, technician, assistant, helper and supervisor, drills 0.05 holes/m², installs probes, clips and ties wiring to the DAQ cabinet. Finally, a QA lab team (QC tech, lab assistant, QA engineer, safety officer) completes pull-off, ultrasonic and data-logger tests.

Waste management and quality-control activities run in parallel. Rinse water from hydro-jetting (32 000 L/d capacity) is captured in portable slurry tanks and filtered on-site before discharge. Spent abrasive media (≈ 75 kg over three days), used epoxy cartridges and empty chemical drums are segregated into five labeled skip bins at the site's southern edge and collected by an environmental contractor on a three-day call-off. Pull-off test discs, sand from patch tests (15 kg/test) and residual cable ties are recycled where possible, while non-recyclable residues enter non-hazardous construction waste streams. QA staff log all results nightly into the central database for full traceability.

To preserve uninterrupted market operations, pedestrian and vehicle corridors along the main east-west axis remains open at all times. Work zones are fenced with temporary barriers, high-visibility signage and LED floodlights. A strict delivery window is planned overs all probe, chemical and equipment trucks, preventing conflicts with peak trading. Dust suppression is achieved via water-misting nozzles on the washers and by covering stockpiles. Low-noise electric mixers and muffled generators minimize disturbance, while emergency exits and fire lanes are inspected daily. Noise-intensive tasks—core drilling and abrasive blasting—are scheduled outside core market hours, ensuring both public safety and seamless business continuity throughout the corrosion-monitoring rollout.

The corrosion-monitoring supply chain is anchored by a weatherproof staging area in the north parking lot, where bi-weekly crates of factory-calibrated half-cell probes and reference electrodes, weekly drums of copper-sulfate and calcium-nitrite admixtures, barrels of epoxy potting mortar and tins of active-pigment inhibitor, plus racks of cable clips and wiring loom, are all FIFO-rotated and audited daily to maintain two-day buffers. Under a two-week master lease, core drills, half-cell meters, hydro-jet and abrasive-blasting rigs, injection pumps and torque-wrench kits are commissioned just before each work phase, while pull-off testers, sand-patch kits and ultrasonic gauges arrive forty-eight hours ahead of QA rounds to allow recalibration. Overlapping specialist crews, mobilization, surface-prep, coatings, sensor-embedment and QA, are choreographed to material and tool arrivals, eliminating idle time. Parallel waste-management runs include on-site filtration of rinse water, segregation of spent abrasives and empty drums into labeled skips, and recycling of pull-off discs and sand, all under a three-day environmental call-off. Throughout, east–west pedestrian and vehicle corridors remain open, work zones are fenced with high-visibility signage and LED lighting, a strict 07:00–09:00 delivery window avoids peak trading conflicts, dust is suppressed via misting nozzles, and low-noise electric equipment preserves market continuity. The most critical pinch-points in this model are the half-cell probes and reference electrodes, with their long lead times and calibration requirements, followed by the bulk chemical drums and inhibitor tins that feed the coatings squad; ensuring dual sourcing or consignment agreements, maintaining rolling buffers, and tightly synchronizing equipment commissioning with crew schedules are therefore paramount to prevent any interruption to both the intervention and live trading environment.

4.4. List of Interventions for Tedingerbroekpolder Dike

Based on the hazard and vulnerability assessments conducted for the Tedingerbroekpolder dike, this section presents two proposed interventions aimed at increasing the resilience of the structure against climate-related stressors. The first intervention consists of a fiber optic-based monitoring system, proposed as part of Task 3.1 and currently being further developed in Task 9.1, which enables spatially continuous and real-time sensing of temperature, strain, and moisture conditions within the dike. The second intervention involves the use of satellite remote sensing monitoring, offering a large-scale, non-invasive method to observe surface displacements and environmental changes over time.

4.4.1. Fiber optic-based monitoring

As part of the MULTICLIMACT project, a fiber optic-based monitoring solution was designed to improve the resilience and early warning capacity of flood defences, including dikes such as the Tedingerbroekpolder dike. This solution was designed under Task 3.1 and is detailed in Deliverable 3.1 (Aguilar-López, Nöter, and Ingrosso 2024), which presents a conceptual prototype for a quasi-real-time monitoring system based on Distributed Fiber Optic Sensing (DFOS). The system integrates spatially distributed sensors to continuously monitor critical physical parameters such as temperature, pore pressure, moisture content, and strain along the body of the dike. The proposed technology for the Tedingerbroekpolder dike relies on Brillouin Optical Frequency Domain Analysis (BOFDA) as the primary interrogation system. This technique enables distributed measurements with high spatial resolution and frequency, allowing for the detection of anomalies that may indicate early-stage failure mechanisms. These include desiccation, slope instability, internal erosion, and water infiltration, all of which can compromise dike stability under changing environmental conditions (Aguilar-López, Nöter, and Ingrosso 2024).

As described in Deliverable 3.1, a fiber optic cable was embedded into the dike structure, with installation and mapping processes carried out to ensure precise sensor positioning (see Figure 32). The cable layout enables continuous measurement along its length, which is crucial for detecting localized anomalies. The sensing system can operate under varying environmental conditions and is suitable for long-term deployment due to the robustness and durability of fiber optic materials. The system design includes provisions for signal interrogation, post-processing, and data transmission, forming the basis for future integration with an early warning system. The hydro-geo-thermal finite element simulations of the dike's behavior under seasonal conditions (conducted in Deliverable 3.1 and summarized in Section 3.2.2) were used to estimate the necessary spatial resolution and monitoring frequency for effective sensing. For instance, the rates of change in moisture content and pore pressure informed the sensor requirements to ensure sufficient responsiveness for early warning applications.

Figure 32. Aerial view of Tedingerbroek dike and the mapped location of the embedded fiber optic cable. Source: (Aguilar-López, Nöter, and Ingrosso 2024)

The fiber optic-based monitoring system for the Tedingerbroekpolder dike is currently being further developed under Task 9.1, where it will be tested and refined. The final goal is to create a reliable and scalable solution that enhances preparedness and response capabilities by enabling early detection of deterioration processes that could compromise the structural integrity of the flood defence.

4.4.2. Satellite remote sensing monitoring

Satellite radar interferometry, particularly Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR), has emerged as a powerful tool for monitoring dike deformation with millimeter-level precision and high temporal resolution (Özer et al. 2019). Traditional inspection methods, such as visual assessments, are limited by their infrequency, subjectivity, and inability to detect small-scale (mm- to cm-level) deformations that may indicate potential failure mechanisms (Bakkenist and Zomer 2010). In contrast, satellite-based monitoring provides weekly observations of dike conditions, enabling the detection of both long-term subsidence and short-term swelling and shrinkage behaviors influenced by meteorological factors like precipitation and temperature(Hanssen and Van Leijen 2008).

Key Advantages of Satellite Monitoring for Dike Resilience

I. Sub-Seasonal Deformation Detection

PS-InSAR can identify reversible swelling and shrinkage of dike materials, which are critical for understanding dynamic responses to hydrological loading. For instance, clay-rich soils exhibit delayed but significant volume changes due to moisture variations, while sandy soils react more quickly but with smaller magnitudes (Özer et al. 2019).

II. Predictive Modeling (vPT-Model)

The vPT-model integrates meteorological data (precipitation and temperature) to predict dike behavior under normal and extreme conditions (Özer et al. 2019). This model helps distinguish between expected deformations and anomalies that may signal instability, improving early warning capabilities.

III. Early Warning for Failure Prevention

By correlating deformation patterns with historical failures (e.g., the 2003 Wilnis peat dike failure), satellite data can flag problematic locations (Van Baars 2005). For example:

- Excessive shrinkage during droughts (indicating potential cracking)
- Swelling after heavy rainfall (risk of internal erosion)

Such insights enable proactive measures, such as targeted watering or reinforcement (Jorissen, Kraaij, and Tromp 2016).

IV. Cost-Effectiveness and Scalability

Satellite monitoring covers extensive dike networks at lower costs compared to traditional methods (Bonì et al. 2017). This makes it particularly valuable for countries with large flood defense systems, such as the Netherlands and China (F.K.S. Chan et al. 2022).

V. Conclusion

Satellite-based deformation monitoring enhances dike resilience by providing continuous, objective, and quantitative data, supporting proactive maintenance and early warning systems. This technology reduces the risk of catastrophic failures by addressing vulnerabilities before they escalate.

5. ASSESSMENT OF KEY PERFORMANCE INDICATORS TO QUANTIFY RESILIENCE OF CULTURAL HERITAGE

Key Performance Indicators (KPIs) enable stakeholders to monitor changes in performance over time and evaluate the success of interventions, adaptation, and recovery efforts. In the Deliverable 2.6, four KPIs that have been widely accepted to quantify the resilience of infrastructure systems were proposed to evaluate the impact of interventions. These KPIs were reliability, robustness, resourcefulness, and recovery. While these four KPIs provide a shared framework for assessing resilience, their application differs between the two demonstration sites. For example, in the Riga Central Market (building scale), reliability and robustness are prioritized, whereas in the Dutch Tedingerbroek Polder (landscape scale), resourcefulness and rapidity are more relevant due to broader governance and environmental factors. Reliability refers to the ability of a system to meet target performance levels during its service life and under set conditions of interest. As shown in Figure 33, reliability can be used as the performance indicator in a resilience curve. At time t_0, the system has an initial reliability β_0. Over time, the system reliability decreases due to the exposures, e.g., degradation effects or the occurrence of extreme hazards events. If the system reliability reaches a minimum value β_{min} , which does not guarantee the safety of the users and requires urgent actions, this can be defined as a failure event occurring at time t_f. As illustrated in Figure 33, the ability of the system to sustain the damages implied by the exposures while preserving its functionality, refers to the system robustness. After t_f, intervention actions are needed to recover the system performance to the original level. This recovery process is defined by the resourcefulness, which refers to the capacity of a system to mobilize materials and human resources to recover and meet performance goals after a disruption event (Biringer , Vugrin , and Warren 2013), and the rapidity, which relates to the capacity to achieve the performance goals in a timely manner in order to contain losses, recover functionality, and avoid future disruption (Bruneau et al. 2003). Therefore, as depicted in Figure 33, the shape of the recovery curve is determined by the interaction between both resourcefulness and rapidity, and the system performance is fully recovered at time t_r. It should be noted that depending on the intervention actions implemented, the system performance can reach a higher level compared to its original state, for a better adaptive capacity to the exposures.

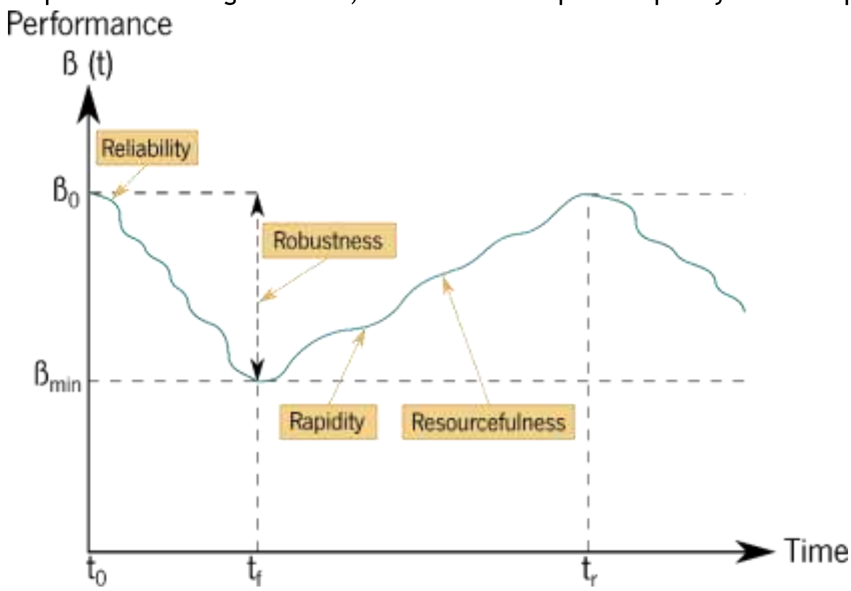


Figure 33. The four KPIs and their interaction with the resilience curve

In the following subsections, the methodology to quantitatively assess each of the KPIs is detailed and applied to the case studies to evaluate their current state.

5.1. Reliability Analysis

Reliability is commonly defined as the probability that a system will fulfil its intended functions under specified conditions over a given time interval. This definition emphasizes the probabilistic nature of reliability assessment, grounded in the principles of probability theory, and requires careful specification of the system's *mission*, its expected functions, operational conditions, and the duration over which performance is to be evaluated (Sánchez-Silva and Klut 2016).

To evaluate whether a system fulfils its mission, it is necessary to distinguish between two states: satisfactory performance and failure. In probabilistic terms, reliability can thus be interpreted as the likelihood that the system remains in a satisfactory state throughout the mission time. More formally, reliability may be expressed as the probability that the system's performance measure remains above a defined threshold within the specified period (Sánchez-Silva and Klut 2016). This threshold value, which delineates the boundary between successful and failed performance, is referred to as the limit state. The limit state is a critical concept in engineering design, representing the point at which a system no longer meets its functional requirements. Limit states are typically classified into two categories: ultimate limit states, which correspond to conditions where system functionality is completely compromised (e.g., structural collapse or loss of stability), and serviceability limit states, which represent conditions where the system, although still operational, performs below acceptable standards (e.g., excessive deflections, vibrations, or aesthetic deterioration).

To assess whether a system remains within the safe operational domain or enters failure, a mathematical representation of these boundaries is required. This is made through the definition of a limit state function, which enables the probabilistic quantification of failure and, consequently, the system's reliability. The limit state function is generally defined as:

$$g(\mathbf{X}) > 0 \rightarrow \text{Safe domain}$$
$$g(\mathbf{X}) \leq 0 \rightarrow \text{Failure domain}$$

Equation 1

where $g(\mathbf{X})$ is a function of the basic random variables $\mathbf{X} = \{X_1, X_2, \dots, X_n\}$, which represent uncertain parameters such as loads, resistances, or material properties. Failure occurs when the performance measure crosses the critical threshold defined by $g(\mathbf{X}) = 0$. Accordingly, the probability of failure P_f is defined as the probability that the system lies within the failure domain:

$$P_f = P\,[g(\mathbf{X}) \leq 0]$$

Equation 2

This can be expressed as an integral over the failure region:

$$P_f = \int_{g(\mathbf{X})\leq 0} f_{\mathbf{X}}\,(\mathbf{x})\,d\mathbf{x}$$

Equation 3

where $f_{\mathbf{X}}\,(\mathbf{x})$ is the joint probability density function of the basic random variables $\mathbf{X}$. Equation 3 is frequently referred to as the generalized reliability problem (Sánchez-Silva and Klut 2016). The simplest case of the reliability problem involves two basic variables: resistance (R) and load effect (S). The limit state function in this case is expressed as:

$$g(R, S) = R - S$$

Equation 4

Failure occurs when the applied load exceeds the resistance, i.e., when $R - S \leq 0$. Therefore, the probability of failure becomes (Schneider 1997):

$$P_f = P(R - S \leq 0) = \int_D \int f_{\mathbf{R},\mathbf{S}}(\mathbf{r},\mathbf{s})\, d\mathbf{r}\, d\mathbf{s} \qquad \text{Equation 5}$$

where D represents the failure domain. Equation 5 can be solved analytically for the special case when variables R and S are independent and normally distributed with mean values μ_R and μ_S, and standard deviations σ_R and σ_S respectively. By introducing a new variable, referred to as the *safety margin*, the limit state function can be expressed as $Z = R - S$. According to the properties of normal distributions, the sum or difference of two independent normally distributed variables is also normally distributed. Therefore, Z follows a normal distribution with the following mean and standard deviation:

$$\mu_Z = \mu_R - \mu_S$$
$$\sigma_Z = \sqrt{\sigma_R{}^2 - \sigma_S{}^2} \qquad \text{Equation 6}$$

The probability of failure P_f defined as the probability that the safety margin is less than zero, can then be calculated as:

$$P_f = P(Z \leq 0) = \Phi\left(\frac{0 - \mu_Z}{\sigma_Z}\right) = \Phi(-\beta) \qquad \text{Equation 7}$$

where Φ represents the cumulative distribution function of the standard normal distribution, with zero mean and unit variance, and the term β, known as the reliability index, quantifies the number of standard deviations the mean safety margin lies above the failure threshold, as depicted in Figure 34. The reliability index (β) is a fundamental parameter in structural reliability analysis. It is commonly employed as a proxy for the probability of failure and serves as a widely accepted criterion in engineering design practices.

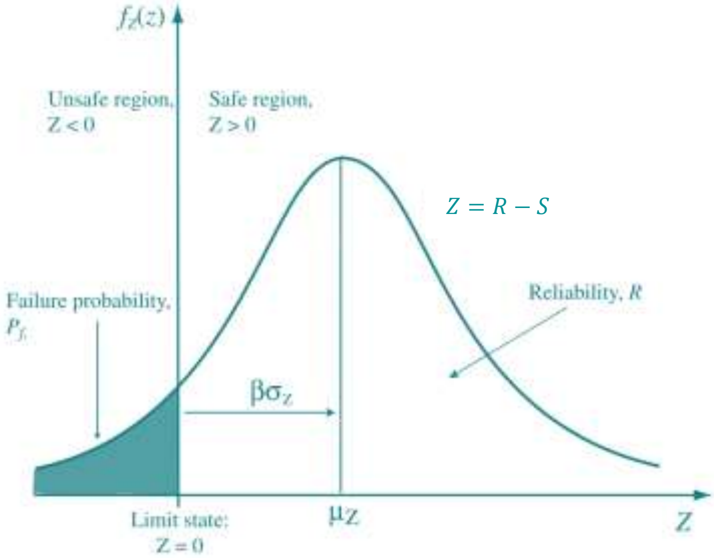


Figure 34. Graphical definition of the reliability index for the case of two normal random variables. Source: (Sánchez-Silva and Klut 2016)

Acknowledging that the formulation of the reliability problem in terms of resistance (R) and load effect (S) is either impractical or insufficient as it may not account for other relevant factors that influence system performance, the solution of Equation 3 for common structural problems is often a non-trivial task. The complexity may arise due to the involvement of numerous variables, a non-explicit limit state function (meaning it cannot be represented by a single closed-form expression) or the absence of an analytical or numerical solution. Consequently, various alternative strategies have been developed to solve Equation 3 including analytical or numerical techniques (e.g., direct integration), simulation-based approaches (e.g., Monte Carlo methods), and approximation methods (e.g., FORM/SORM) (Sánchez-Silva and Klut 2016).

5.1.1. Riga Central Market

As discussed in Section 4.1, the construction of the planned floor structure to install UPONOR's energy solution will increase the load demands on the basement slab and the supporting beams and columns. Therefore, the reliability of these structural elements should be assessed to verify their capability to withstand the new loads.

To assess the structural performance and reliability of the reinforced concrete (RC) basement slab, a 3D finite element model was developed using DIANA FEA software (DIANA 2024). The model employs phased analysis and non-linear material constitutive laws to simulate the maximum load-carrying capacity of the slab under combined dead, live, and additional loads from the planned UPONOR energy system. Material parameters include the RC slab's concrete grade, steel reinforcement properties, and the mechanical characteristics of the supporting H-profile beams. The ultimate limit state (ULS) is adopted as the reference for failure, linking the structural assessment directly to the reliability KPI defined in Section 5.1. The basement slab, described in 3.1.2, is 150 mm thick, supported by steel H-profile beams spanning approximately 3.5 meters, and divided into panels by expansion joints. For the analysis, a representative panel of 7 meters × 6 meters was modeled, capturing local stress distribution and deformation patterns. While this analysis primarily addresses the reliability KPI, the remaining KPIs — robustness, resourcefulness, and rapidity are considered through complementary interventions such as fiber-optic monitoring systems, electrochemical corrosion sensors, and satellite-based ground displacement monitoring (see Sections 5.1.2.2 and 5.1.2.3).This approach ensures that the structural reliability of the RCM building is evaluated within the same KPI framework applied across both demonstration sites, while highlighting the building-specific factors that necessitate detailed finite element modeling, unlike the landscape-scale Dutch demo described in Section 5.1.2.1. As depicted in Figure 35, the structural model analyzed consists of a panel of 7 meters x 6meters.

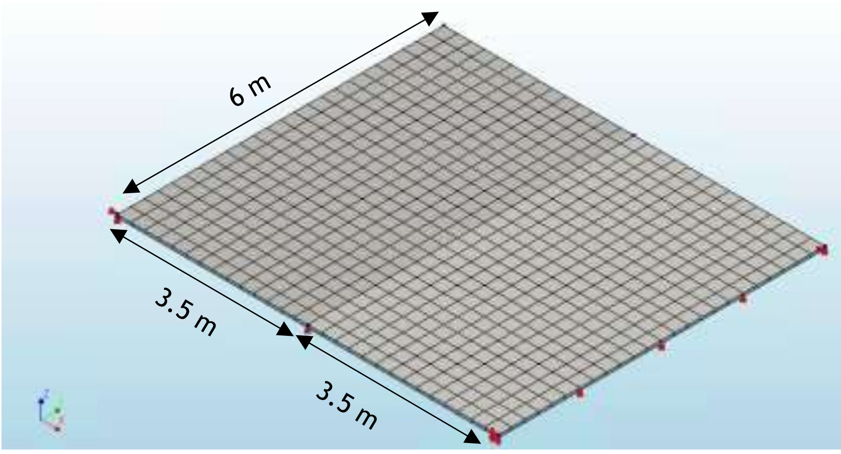


Figure 35. Finite element model of the RC basement slab in DIANA FEA software

The probabilistic models of the random variables to characterize the slab resistance are summarized in Table 10, based on literature and the information available at the technical survey (Strazdiņš 2024) regarding the construction materials and geometry.

Table 10. Probabilistic characterization of resistance random variables: materials and geometry

RANDOM VARIABLE		NOTATION	MEAN VALUES	COV	PDF	REFERENCE
C16/20 concrete	Compressive strength	f_{cm}	24 MPa	0.12	Lognormal	(D.F. Wisniewski, Casas, and Ghosn 2009)
	Tensile strength	f_{ctm}	1.9 MPa	0.2	Lognormal	(D.F. Wisniewski, Casas, and Ghosn 2009)
	Modulus of elasticity	E_{cm}	28608 MPa	0.08	Normal	(Wiśniewski et al. 2012)
	Slab thickness	t	150 mm	0.035	Normal	(Casas and Wisniewski 2013)
A-1 reinforcing bars	Yielding stress	f_{sy}	235 MPa	0.07	Lognormal	(USSR 1982); (JCSS 2001)
	Ultimate strength	f_{su}	373 MPa	0.04	Lognormal	(USSR 1982); (JCSS 2001)

RANDOM VARIABLE		NOTATION	MEAN VALUES	COV	PDF	REFERENCE
	Area	A_s	523 mm^2/m	0.02	Normal	(JCSS 2001)
	Effective depth	d_s	125 mm	0.15	Lognormal	(Casas and Wisniewski 2013)

The probabilistic models of the random variables to characterize the loads acting on the slab are summarized in Table 11. The mean value of the self-weight is estimated based on the concrete density and the thickness of the slab specified at the technical survey (Strazdiņš 2024). The additional loads were estimated based on the materials specified in the planned floor structure to install UPONOR's energy solution (Figure 23) and the approximate loads from electrical wiring, lights, etc., attached to the basement ceiling. Lastly, the mean value of the live load was taken as 3.0 kN/m², based on Load Category D2 from the Latvian national annex to Eurocode EN 1991-1-1 (LVS EN 1991-1-1+AC:2014), which applies to department store premises characterized by high occupancy levels and significant storage or display loads. This value was derived by adjusting the Eurocode's characteristic live load (5.0 kN/m²), which corresponds to a 5% probability of exceedance over a 50-year reference period, to represent the statistical mean of the assumed lifetime maximum distribution (Costa and Beck 2024).

Table 11. Probabilistic characterization of load random variables: permanent loads and live loads

RANDOM VARIABLE	NOTATION	MEAN VALUES	COV	PDF	REFERENCE
Self-weight load	D_L	3.45 kN/m^2	0.04	Normal	(JCSS 2001)
Additional loads	A_L	3 kN/m^2	0.04	Normal	(JCSS 2001)
Live loads	L_L	3 kN/ m^2	0.35	Gumbel	(Costa and Beck 2024)

The structural reliability for the ultimate limit state (ULS) of the positive flexural capacity of the existing slab was assessed by considering the statistical variability of both the applied loads and the slab resistance. The reliability index obtained from this analysis was $\beta = 2.36$, which is significantly below the target reliability level prescribed for structures of this type. According to Eurocode EN 1990, for a reference period of 50 years, the minimum recommended reliability index for consequence class 3 structures is $\beta = 4.3$. This class includes buildings where the consequences of failure are high, such as public buildings, including markets, schools, or hospitals, due to potential loss of human life or significant economic, social, or environmental impact. Given that the Riga Central Market is a nationally significant public building due to its heritage value, it clearly falls into this high-consequence category. Therefore, the current floor slab does not meet the required safety level to support the additional loads introduced by the planned installation of UPONOR's energy solution. For this reason, the strengthening and monitoring measures proposed in Chapter 4 are essential to ensure that the slab achieves the necessary level of structural reliability and long-term safety.

5.1.2. Tedingerbroekpolder dike

The safety factor (FS) in the context of slope stability for a dike is a critical metric used to assess the stability of the dike's slopes against failure, such as sliding or collapse, under various loading and environmental conditions. It quantifies the ratio of forces resisting slope failure to the forces driving it. A higher safety factor indicates greater stability, while a lower value signals a higher risk of failure.

I. Definition of Safety Factor for Slope Stability

The safety factor is typically defined as:

$$FS = \frac{Resisting\ Forces}{Driving\ Forces}$$

- **Resisting Forces**: These are the forces that contribute to the stability of the slope, primarily derived from the shear strength of the soil or material composing the dike. Shear strength depends on parameters like cohesion (c) and the angle of internal friction (φ), which are influenced by material properties, compaction, and moisture content.
- **Driving Forces**: These are the forces that promote slope failure, such as the weight of the soil, water pressure (e.g., from seepage or flooding), and external loads (e.g., traffic or surcharge).

For a dike, slope stability is analyzed using methods like the Limit Equilibrium Method (e.g., Bishop's, Morgenstern-Price, or Spencer's methods), which calculate the FS by dividing the slope into slices and evaluating forces along a potential failure surface. Alternatively, numerical methods like finite element analysis can be used for more complex conditions.

II. Typical Safety Factor Values

- **FS > 1.5:** Generally considered safe for most dike applications under normal conditions.
- **FS = 1.3-1.5:** Marginally stable, requiring monitoring or mitigation.
- **FS < 1.0:** Indicates instability, with a high likelihood of slope failure.
- **FS = 1.0:** The slope is at the point of equilibrium, where resisting and driving forces are equal.

5.1.2.1. Reliability assessment based on slope stability safety factor

The reliability of a dike's slope can be assessed by incorporating the safety factor (FS) into a probabilistic framework that accounts for uncertainties in material properties, environmental conditions, and loading scenarios. Unlike deterministic methods that yield a single FS value, reliability analysis uses statistical techniques to evaluate the probability of slope failure, often expressed as a reliability index or probability of failure (Pf). This involves modeling key parameters—such as soil cohesion, friction angle, and pore water pressure—as random variables with defined probability distributions (e.g., normal or lognormal) based on field and laboratory data. Methods like Monte Carlo simulations or First-Order Reliability Method (FORM) can then be used to compute the likelihood that FS falls below 1.0, indicating failure. For instance, a reliability index (β) can be derived, where a higher β corresponds to lower failure probability (e.g., β = 3.0 implies Pf ≈ 0.14%). By integrating FS with reliability analysis, engineers can quantify the confidence in slope stability, identify critical parameters driving uncertainty, and set target reliability levels to guide design and monitoring. This approach enhances decision-making by providing a probabilistic measure of safety, complementing the deterministic FS as a KPI for dike performance.

I. Using Safety Factor to Monitor Dike Safety Over Time

To use the safety factor as a Key Performance Indicator (KPI) for monitoring dike safety and structural performance, the following steps can be implemented:

1. **Baseline Assessment**:

- Conduct an initial slope stability analysis using geotechnical data (e.g., soil properties, groundwater levels, and dike geometry) to establish a baseline FS.
- Use field investigations (e.g., boreholes, soil sampling) and laboratory tests to determine material properties like cohesion, friction angle, and permeability.

2. **Periodic Monitoring:**

- **Geotechnical Instrumentation:** Install sensors such as piezometers (to measure pore water pressure), inclinometers (to detect lateral movement), and settlement gauges to monitor changes in conditions that affect FS.
- **Environmental Factors:** Track external factors like rainfall, river levels, or tidal fluctuations, as increased water pressure can reduce FS by increasing driving forces or reducing effective shear strength.
- **Visual Inspections:** Regularly inspect for signs of instability, such as cracks, slumping, or seepage, which may indicate a declining FS.

3. **Recalculation of FS:**

- Periodically recalculate the FS using updated data from monitoring systems. For example, increased pore water pressure from heavy rainfall can reduce the effective stress in the soil, lowering the FS.
- Use software tools (e.g., GeoStudio, PLAXIS) to model the dike under current conditions and compare FS values over time.

4. **Time-Series Analysis:**

- Track FS trends over time to identify patterns or degradation. For instance, a gradual decrease in FS could indicate ongoing erosion, soil weakening, or increased seepage.
- Create a time-series chart to visualize FS changes and correlate them with environmental or operational events (e.g., floods, construction activities).

5. **Thresholds and Alerts:**

- Establish FS thresholds for different risk levels (e.g., FS < 1.3 triggers a warning, FS < 1.0 triggers immediate action).
- Implement automated alert systems based on real-time monitoring data to notify engineers if FS approaches critical levels.

6. **Maintenance and Mitigation:**

- If FS declines, take corrective actions such as reinforcing the dike (e.g., adding berms, geotextiles, or drainage systems), reducing slope angles, or improving vegetation cover to reduce erosion.
- Use FS as a KPI to evaluate the effectiveness of these interventions by comparing pre- and post-maintenance FS values.

II. Using Safety Factor as a KPI

The FS serves as an effective KPI for dike performance because it:

- **Quantifies Stability:** Provides a clear, numerical measure of how safe the dike is against slope failure.
- **Guides Decision-Making:** Helps prioritize maintenance or upgrades when FS values fall below acceptable thresholds.
- **Tracks Performance Over Time:** Allows engineers to assess whether the dike's stability is improving, stable, or deteriorating.
- **Supports Risk Management:** Enables proactive measures to prevent catastrophic failures, protecting lives, property, and infrastructure.

III. Example Workflow for FS as a KPI

1. Data Collection:

Gather geotechnical data, monitor groundwater levels, and assess external loads.

2. FS Calculation:

Use a slope stability model to compute FS under current conditions.

3. Chart FS Trends:

Assume that this chart shows a hypothetical decline in FS over six months, indicating a need for investigation or intervention.

4. **Action Triggers**:

- If FS drops below 1.5, schedule detailed inspections.
- If FS approaches 1.3, implement immediate stabilization measures (e.g., drainage improvements).
- If FS falls below 1.0, issue an emergency alert and consider evacuation or reinforcement.

5. **Reporting**:

Use FS trends in reports to stakeholders, demonstrating the dike's performance and justifying maintenance budgets.

IV. Practical Considerations

- **Dynamic Conditions:** Dikes are subject to changing conditions (e.g., seasonal flooding, earthquakes), so FS should be recalculated frequently, especially after extreme events.
- **Data Quality:** Accurate soil and groundwater data are critical for reliable FS calculations. Poor data can lead to misleading FS values.
- **Regulatory Compliance:** Ensure FS thresholds align with local engineering standards or guidelines (e.g., Eurocode 7, USACE standards).
- **Integration with Other KPIs:** Combine FS with other metrics like seepage rates, deformation, or vegetation health for a comprehensive assessment of dike performance.

By regularly calculating and monitoring the safety factor, engineers can proactively manage dike stability, prevent failures, and use FS as a robust KPI to track the structure's long-term performance.

5.2. Robustness Assessment

Robustness has emerged as a key concept in structural safety assessment, particularly in the context of deteriorated structures such as corroded reinforced concrete systems. Despite its growing importance, the notion of robustness lacks a universally accepted definition. As discussed by (Cavaco et al. 2013), this lack of consensus stems from differing perspectives regarding the scope and attributes of robustness. Some authors define it strictly as a structural property, independent of environmental factors (e.g., (D. Wisniewski, Casas, and Ghosn 2006)), focusing solely on the system's ability to maintain functionality after damage. In contrast, others adopt a broader viewpoint, considering robustness as a property of both the structure and its environment (e.g., (Baker, Schubert, and Faber 2008)), thereby incorporating aspects such as exposure, indirect consequences, and societal impacts. Deliverable D2.6 (Sousa, Ingrosso, and Urciuoli 2024) defined robustness as the ability of cultural heritage systems to resist the impacts of external stressors without significant degradation, emphasizing the role of internal structures, feedback mechanisms, and buffering capacities in maintaining system identity, functions, and performance when exposed to hazards.

Considering that the concept of robustness should be measurable to enable the quantification of the impacts of intervention measures, and flexible to accommodate different types of heritage assets/components and damage mechanisms, the approach adopted in this deliverable aligns with the interpretation of robustness as a structural property, focused on performance degradation under damage scenarios. The definition proposed by (Cavaco et al. 2013) is particularly well-suited to this objective, as it conceptualises robustness as the extent to which a system retains its performance following the onset of damage. This perspective enables the derivation of a single robustness indicator from continuous performance degradation curves, thus facilitating comparative assessments across different intervention strategies. The robustness indicator, designated as robustness index $I_{R,D}$, is defined as the area under the curve of normalised structural performance $f(D)$ plotted against normalised damage D. Mathematically, the index is expressed as (Cavaco et al. 2013):

$$I_{R,D} = \int_0^1 f(D)\, dD \quad \text{Equation 8}$$

where $D \in [0,1]$ is the normalised damage, representing the relative extent of deterioration (e.g., corrosion level), and $f(D) \in [0,1]$ is the normalised performance, given by the ratio between the structural performance at damage level D and the performance in the undamaged state. An index of 1 indicates no performance degradation, while a value approaching 0 corresponds to immediate or severe loss of capacity with minimal damage.

Figure 36 illustrates three conceptual cases of normalised performance $f(D)$ versus normalised damage D, each corresponding to a different robustness level. In the case of the left curve, performance drops sharply with increasing damage, indicating low robustness and a brittle response. The curve from the middle shows a gradual performance decline, representing an intermediate robustness level. In contrast, the curve from the right depicts a nearly horizontal curve, suggesting minimal performance loss even under significant damage, thus characterising a highly robust system. The integral under each curve, i.e., the area between the curve and the damage axis, quantifies the robustness index $I_{R,D}$.

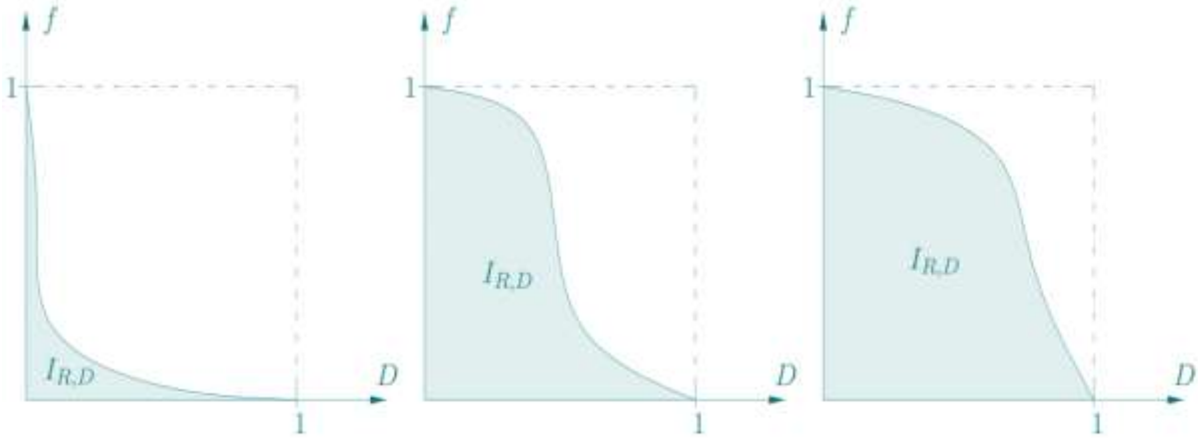


Figure 36. Graphical definition of Robustness Indicator. Source: (Cavaco et al. 2013)

5.2.1. Riga Central Market

The robustness index is herein estimated to assess the performance degradation of the RC basement slab from the RCM exposed to corrosion. The RC slab is analyzed in terms of its capacity to retain functionality as deterioration progresses, with reinforcement corrosion-induced section loss considered the primary damage mechanism. By examining the robustness index, it is possible to quantify the extent to which the slab maintains its structural performance, i.e., its load-carrying capacity, under increasing levels of reinforcement corrosion.

Following the approach proposed by (Cavaco et al. 2013), the robustness index is computed using the reliability index as the structural performance indicator. Figure 37 depicts the normalized performance of the slab under the scenario of reinforcement corrosion damage, i.e., expressed as a reduction in the reinforcing steel area. The obtained robustness index $I_{R,D}$ employing Equation 8, corresponds to 0.25. This value indicates a severe loss of capacity with minimal damage, i.e., a low level of robustness. Considering the slab's vulnerability to corrosion as highlighted in Chapter 3.1.2, there is a need for structural strengthening to ensure the safety.

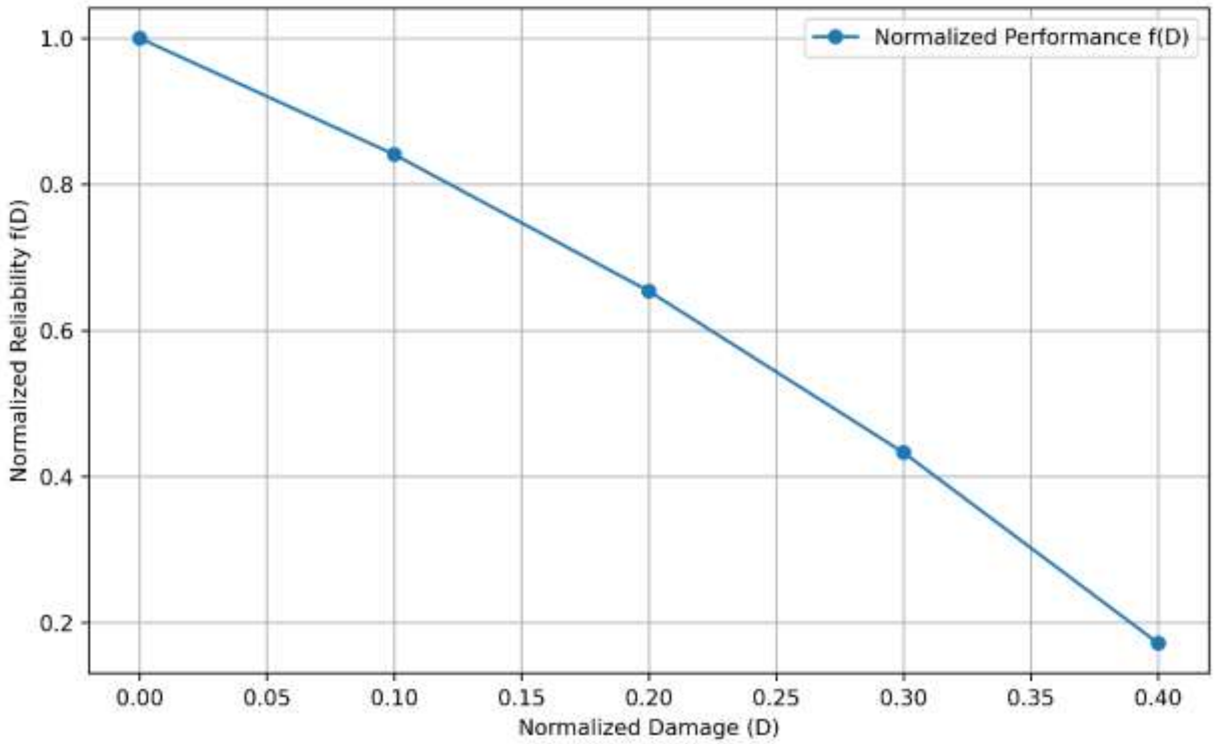


Figure 37. Normalized performance (reliability) under reinforcement corrosion damage

5.3. Resourcefulness Modelling

Resourcefulness, one of the four core attributes in the resilience framework proposed by (Bruneau et al. 2003), can be defined as a system's capacity to identify problems, establish priorities, and mobilize resources whenever conditions threaten to disrupt operations. It involves the ability to apply both material resources, financial, physical, technological, and informational and human capital to address emergent needs and achieve critical objectives. In the context of cultural heritage risk management, where interventions must satisfy strict conservation requirements and contend with climate-related or physical hazards, resourcefulness plays an especially pivotal role. Thomas and Ellis (2017) further operationalize this concept through a "factor - resource" model that assesses four principal resource domains: (1) financial assets, (2) human expertise, (3) materials and equipment, and (4) information and governance. Their approach emphasizes not only the inventory of available resources but also the speed and flexibility of their deployment under uncertainty, combining qualitative measures (e.g., decision-making timeliness) with quantitative metrics (e.g., contingency budget ratios, equipment lead times) to capture a holistic picture of system readiness and agility.

The resourcefulness index is computed as (Thomas and Ellis 2017):

$$R = \frac{\sum_{i=1}^{n}(A_i \times W_i)}{\sum_{i=1}^{n} W_i}$$

Where:

- A_i is the availability and mobilization capacity of resource i, scored from 0 (lowest) to 1 (highest) based on a set of sub-criteria.

- W_i is the weight reflecting the relative importance of resource iii, determined via pairwise comparison (AHP) or expert consensus. The sum to 1.
- N is the total number of resource categories being evaluated.

Figure 38 The factor resource model adapted from (Thomas and Ellis 2017)

The graphic representation of the Resourcefulness Index is divided into color-coded bands corresponding to different levels of resourcefulness. This chart visually conveys the system's resourcefulness level based on its calculated score. The specific value of R is indicated on the gauge to facilitate quick assessment and comparison of the system's mobilization capability.

All quantitative results and illustrations presented in the following sub-sections were drawn from the supply chain analysis conducted in Chapter 4.3.

5.3.1. Concrete Overlays

Overall Resource Distribution

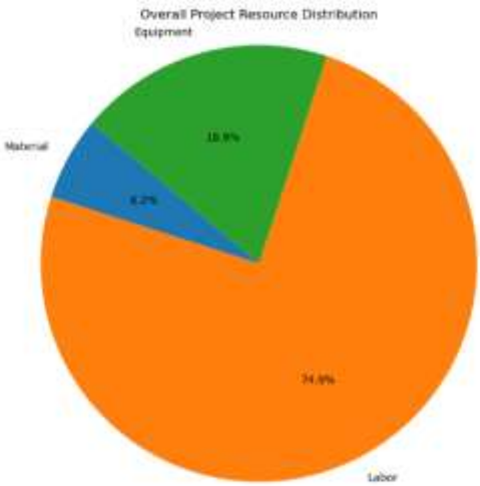


Figure 39. Overall Project Cost Breakdown

Figure 39 shows that labor accounts for 74.9 % of total resources, equipment 18.9 %, and only 6.2 % for materials. This breakdown reflects the nature of the concrete overlay intervention: the installation demands highly skilled labor (transport, screeding, forming) while bulk materials (cement, reinforcing steel, admixtures) are procured in large lots and existing equipment is reused, yielding a relatively low materials share.

Activity-Level Resource Analysis

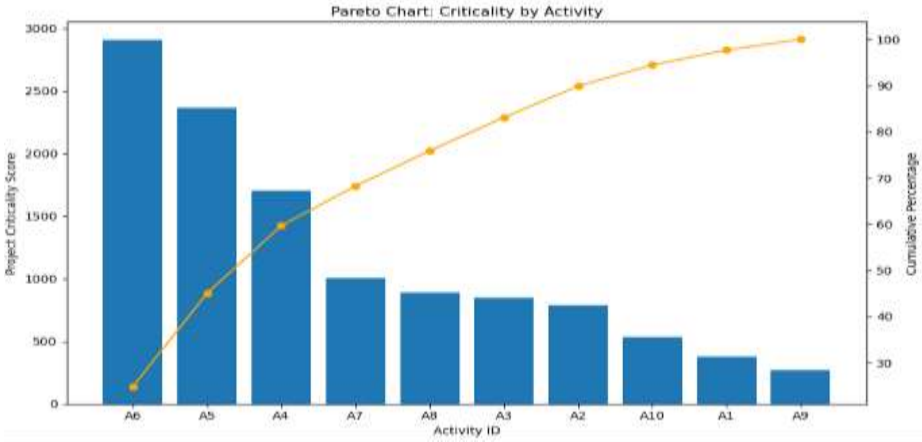


Figure 40. Pareto Chart: Criticality by Activity

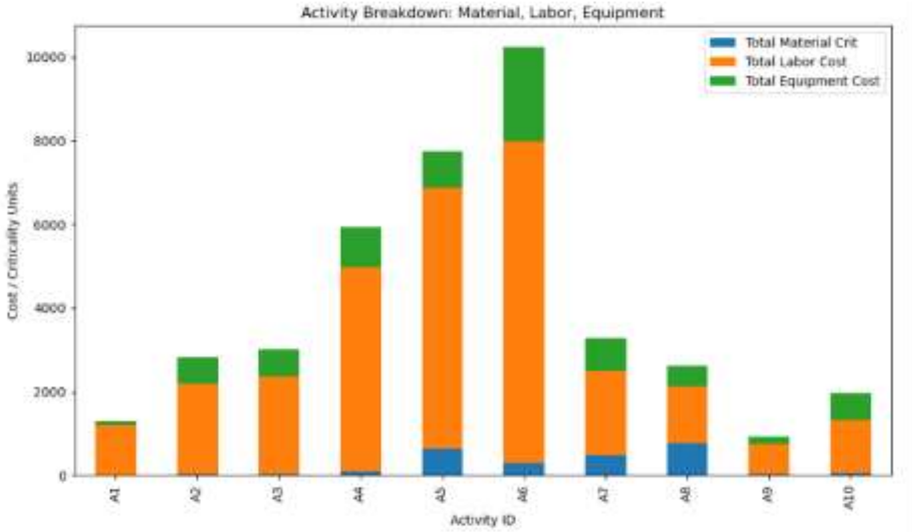


Figure 41. Activity Breakdown: Material, Labor, Equipment

Figure 40 and Figure 41rank the criticality of steps A1–A10:

- A6 (Overlay Casting & Curing) has the highest criticality, driven by intensive labor and equipment use for concrete placement, vibration, and ensuring bond with the existing substrate.
- A5 (Connector Installation) and A4 (Removal & Replacement of Bars) are second and third, since each anchor must be tested for bond strength and load capacity.
- Surface-preparation and reinforcement cleaning steps (A2, A3) and condition assessment (A1), while consuming fewer resources, are prerequisites for a clean, bondable surface and safe work in confined spaces.

Assessment of Resourcefulness

Using the weighted factor – resource model (Thomas and Ellis 2017):

$$R_{co} = W_{mat}A_{mat} + W_{lab}A_{lab} + W_{eq}A_{eq}$$

where the resource shares from Figure 29 are (W_{mat} , W_{lab}, W_{eq}) = (0.062, 0.749, 0.189) and the mobilization scores for concrete overlay are estimated as:

- A_{mat} = 0.85: Domestic supply of cement, sand, and rebar is stable (lead time 7 ~ 14 days).
- A_{lab} = 0.90: A crew of 8 ~ 10 skilled installers can add shifts or hire urgently within 24 h.
- A_{eq}= 0.80: Long-term rental of mixers, pumps, and vibrators with 48 ~ 72 h replacement guarantee.

Substituting:

$$R_{co} = 0.062 \times 0.85 + 0.749 \times 0.9 + 0.189 \times 0.80 \approx 0.88$$

With $R_{co} \approx 0.88$, the concrete overlay intervention is highly resourceful, labor and materials can be mobilized rapidly, and rental equipment is reliably available. To target $R \geq 0.90$:

- Maintain on-site stock of reinforcing steel and admixtures at ≥ 15 %.
- Train 2-3 additional installers in vibration and bond-testing techniques (raising $A_{lab} \longrightarrow 0.95$)
- Expand master rental agreements to guarantee equipment lead times ≤1 week (raising $A_{eq} \longrightarrow 0.90$)

Implementing these measures will further strengthen rapid response capability and ensure quality and schedule for the entire overlay system.

5.3.2. Corrosion Monitoring System

Overall Resource Distribution

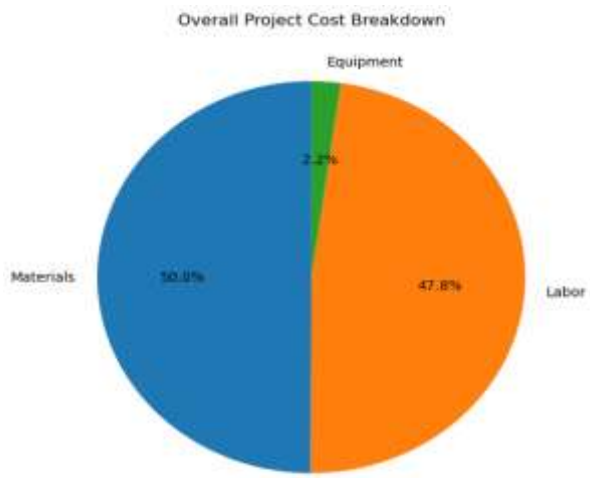


Figure 42. Overall Project Cost Breakdown

The overall cost distribution chart shows that materials dominate with 50 % of the total budget, followed by labor at 47.8 % and equipment at only 2.2 %. This breakdown reflects the chemically intensive nature of the corrosion-monitoring solution: $Cu/CuSO_4$ reference electrodes and calcium-nitrite admixtures account for the bulk of material costs, while highly skilled labor (core-drilling and electrode installation, tubing injection, DAQ operation) represents nearly half the budget. The very modest equipment share indicates that existing signal-recording systems and instruments are leveraged, minimizing upfront capital expenditure.

Activity - Level Resource Analysis

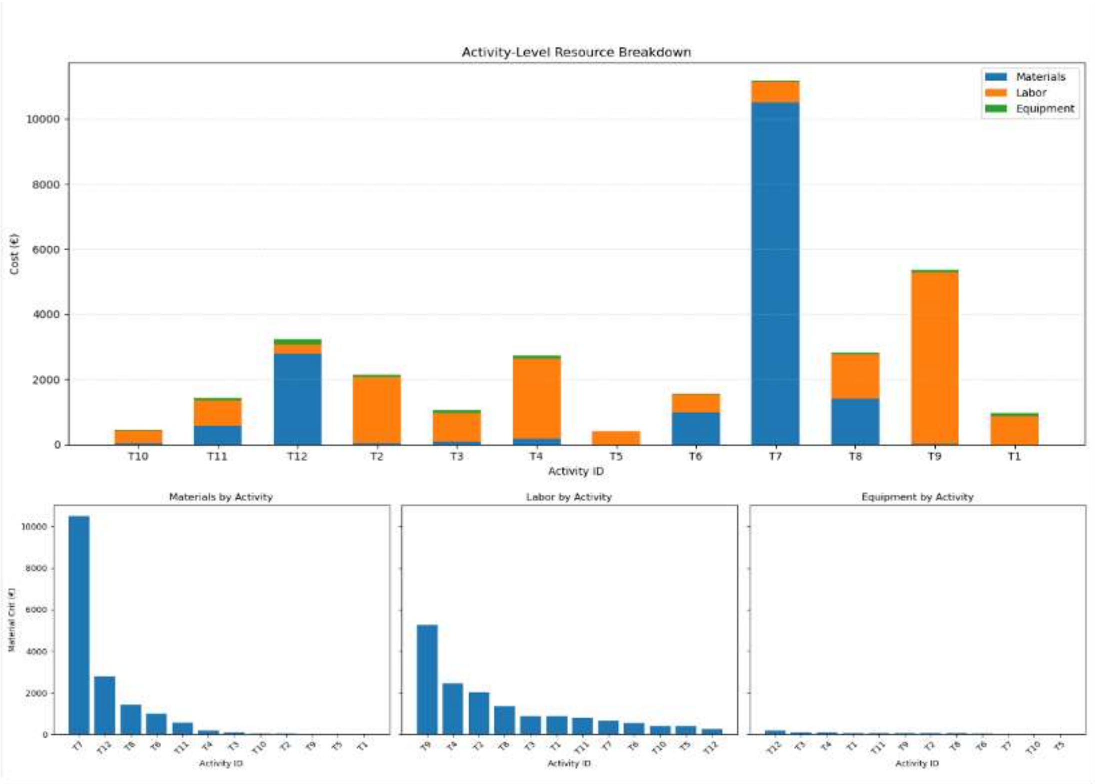


Figure 43. Activity- Level Resource Breakdown

The resource-allocation analysis in Figure 43 shows that the electrode-installation phase (T7) dominates material costs about €10500 mainly because of the large volume of epoxy potting needed to shield the DIAMOND/ECi-2 probes from aggressive exposure. In contrast, overlay casting and curing (T9) is the most labor-intensive stage (≈ €5280), involving a four-person crew working continuously for seven days to ensure the self-compacting concrete reaches its specified density and strength. For equipment outlays, system commissioning and baseline recording (T12) leads the list (≈ €163) owing to the mobilization of SCADA modules and specialized calibration devices, even though its labor requirement is minimal. Surface-preparation tasks (T2, T3) and the cable-installation and joint-sealing sequence (T8→T11) consume only moderate-to-low resources yet are critical for achieving proper bond conditions, signal continuity, and water tightness across the structure. Overall, the distribution highlights that the highest expenditures occur in activities demanding specialized materials or extended execution times, whereas seemingly secondary steps despite their smaller shares ultimately determine the long-term durability of the repair and corrosion monitoring system.

Using the weighted factor - resource model (Thomas & Ellis 2017):

$$R_{CMS} = W_{mat}A_{mat} + W_{lab}A_{lab} + W_{eq}A_{eq}$$

The cost weightings (W_{mat}, W_{lab}, Weq) = (0.50, 0.478, 0.022) are taken from Figure 33, and the resource readiness indices (A) = (0.85, 0.90, 0.80) are based on supply-chain stability and personnel capacity. Specifically:

- Material Readiness (A_{mat} =0.85): Assesses the ability to mobilize materials at 85 % based on two main factors: (i) for basic materials such as cement, sand, and rebar, the domestic supply chain is very stable with lead times of 7 - 14 days and buffer stock, and (ii) for specialty chemicals (calcium nitrite, Cu/ electrodes) that must be imported and can face occasional customs-document delays. Although admixtures account for less than 20 % of the mix, their "irreplaceable" nature justifies a readiness index below 1 (0.85) to reflect residual risk.
- Labor Readiness (A_{lab} =0.90): The installation crew comprises 6 - 8 skilled workers with safety certifications and conservation experience, who can be augmented by 2 - 3 more within 24 - 48 hours. Rapid redeployment and overtime ensure schedule adherence, yet specialized training takes 1 - 2 weeks and cannot be instantly duplicated; hence it is set at 0.90 indicating very high agility but with a slight training constraint.
- Equipment Readiness ($A_{eq} = 0.80$): Specialized equipment (percussion drills, electronic pumps, data loggers) is rented under framework agreements guaranteeing replacement within 48 hours. Assuming a peak season in which rental demand surges sharply, orders would need to be placed 7–14 days in advance and identifying suppliers of comparable high quality would prove extremely difficult. Dependence on rental sources therefore limits proactive deployment, so is set at 0.80 to reflect this potential bottleneck.

Substituting into the weighted-sum model gives:

$$R_{CMS} = 0.50 \times 0.85 + 0.478 \times 0.90 + 0.022 \times 0.80 \approx 0.87$$

With $R_{CMS} = 0.87$, the corrosion monitoring solution demonstrates high resourcefulness, confirming that specialty materials and skilled labor can be mobilized in a timely fashion, and that equipment availability is secured via long term service contracts. To raise resourcefulness closer to 0.90, the following measures are recommended:

- Maintain a minimum two-week on-site reserve of key admixtures and epoxy potting compounds.
- Train additional technicians in the SDI-12 protocol to raise $A_{lab} \geq 0.95$.
- Execute multi-year maintenance and reservation agreements with equipment providers to lift $A_{eq} \geq 0.90$.

Implementing these steps will further enhance operational agility, ensure continuous monitoring, and protect the heritage structure over the long term.

5.3.3. SHM Monitoring System

Overall Project Resource Allocation

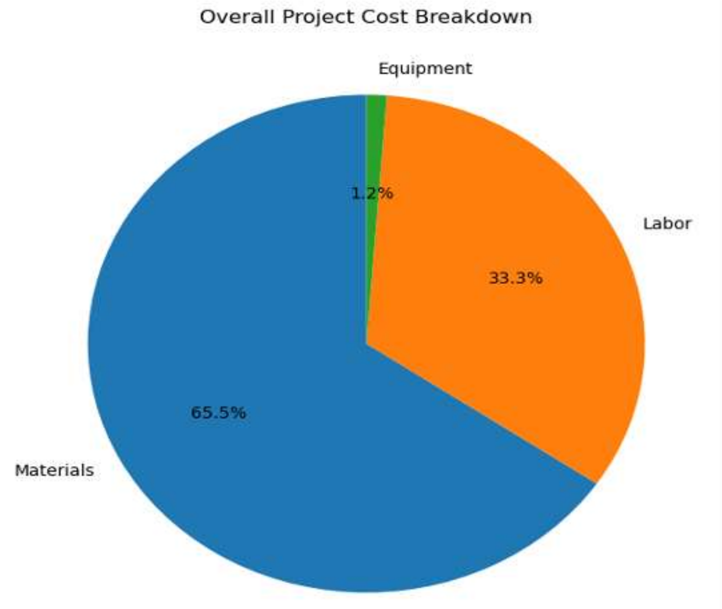


Figure 44. Overall Project Cost Breakdown

The cost breakdown for the SHM intervention is heavily skewed toward materials, which account for 65.5 % of the total budget; labor comprises 33.3 %, and equipment just 1.2 %. This distribution reflects the material-intensive nature of fiber-optic monitoring: high-precision components such as FBG sensors, patch cords, and DAQ modules dominate the expenditure, whereas specialized technician labor (drilling, sensor installation, system calibration) represents roughly one-third of the total cost, and rented plant (drillers, blast systems, data loggers) incurs minimal outlay.

Activity-Level Resource Analysis

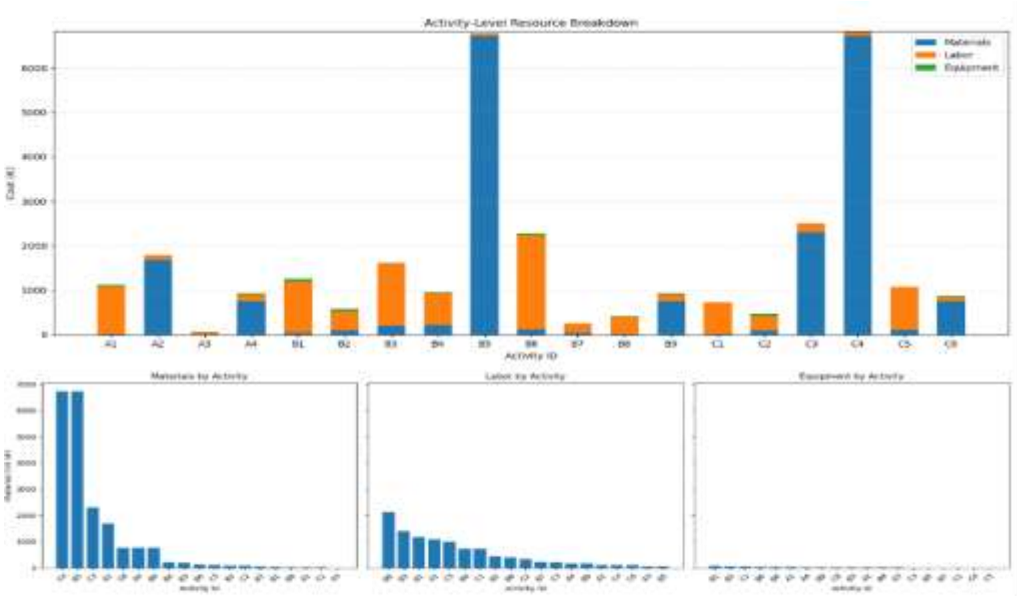


Figure 45. Activity-Level Resource Breakdown

A quantitative, activity-level cost analysis (Figure 41) shows that the materials budget is almost entirely dominated by two fibre-optic sensor installation operations: C4 – Sensor Bonding (Beams) and B5 – Sensor Bonding (Rebar). Each activity requires approximately € 6,722, and together they consume ≈ 71 % of the project's total materials expenditure (€ 13,444 of € 18,871).

By contrast, labor costs are concentrated in three concrete-related tasks: B6 – Casting & Curing Overlay Concrete (≈ € 2,120), B3 – Reinforcement Replacement & Placement (≈ € 1,400), and B1 – Hydro-demolition & Surface Preparation (Slab) (≈ € 1,160). Collectively, these activities account for ≈ 47 % of total payroll expenses (€ 4,680 of € 10,050), reflecting the extended work shifts needed for demolition, bar installation, and the seven-day moist curing of the self-compacting overlay.

Equipment rental remains tightly controlled at ≈ € 590 (only ≈ 2 % of the overall € 29,512 budget), with the largest single line item being C5 – Casting & Curing Protective Concrete Overlay (≈ € 163 for mixer-pump and curing sprayer hire). This allocation confirms that specialized sensing hardware and labor-intensive concrete restoration activities are the principal cost drivers, whereas a strategy of short-term rental and cross-task reuse of equipment keeps machinery expenses to a minimum.

Resourcefulness Evaluation

Applying the weighted resourcefulness model (Thomas & Ellis 2017):

$$\mathrm{R_{SHM}} = w_{mat}A_{mat} + w_{lab}A_{lab} + w_{eq}A_{eq}$$

With weights $(W_{mat}, W_{lab}, W_{eq})$ = (0.655; 0.333; 0.012) and the resource-availability coefficients for the SHM intervention are defined as follows:

- Materials (A_{mat}= 0.80): The FBG sensors and optical connectors must be imported, with an actual lead time of 10 - 14 days. Although the supply chain is generally stable, this imports dependency introduces a non-negligible risk of delays.
- Labor (A_{lab}= 0.90): The core team consists of 6 - 8 fully trained technicians who can be supplemented by 2 - 3 additional staff within 24 hours. However, specialized training on SDI-12 protocols and DAQ software still requires 1 - 2 weeks, limiting immediate scalability.
- Equipment (A_{eq}= 0.75): Key items percussion drills and data loggers are rented under a framework agreement with a 48-hour replacement guarantee. In peak seasons, though, actual waiting times of 5 - 7 days occur before replacements arrive.

Substituting into the weighted-sum model gives:

$$\mathrm{R_{SHM}} = 0{,}655 \times 0.8 + 0.333 \times 0.90 + 0.012 \times 0.75 \approx 0.83$$

An $R_{SHM} = 0.83$ places the SHM intervention firmly in the "High" resourcefulness band, confirming that both specialized materials and labor can be mobilized rapidly, although there remains room to approach the excellence threshold of 0.90. Recommendations to Enhance Resourcefulness Toward 0.90

- Increase component stock: Maintain a minimum on-site reserve of 10 % of FBG sensors and patch cords.
- Expand skilled labor: Cross train 2 - 3 additional technicians in SDI-12 protocols and DAQ software (targeting $A_{lab} \longrightarrow 0.95$).
- Strengthen equipment contracts: Secure multi-year rental agreements with guaranteed lead times ≤ 7 days (raising $A_{eq} \longrightarrow 0.95$).

Implementing these measures will further bolster flexibility, ensure uninterrupted monitoring, and improve the overall resilience and reliability of the SHM system.

5.4. Recovery Analysis

Recovery is defined here as the time-dependent ability of the cultural-heritage asset to regain its target functionality F(t) after a disruptive event. Following the KPI framework presented in Section 5.1, recovery is characterized by both resourcefulness and rapidity, which together determine how quickly and effectively the asset can restore its functionality. The analysis adopts the three-phase resilience curve proposed by (Limongelli et al 2019) and formalized in Deliverable D2.6 (Figure 46), ensuring consistency with the earlier discussion of rapidity as a key performance indicator. The Character of parameter are showed in Table 12.

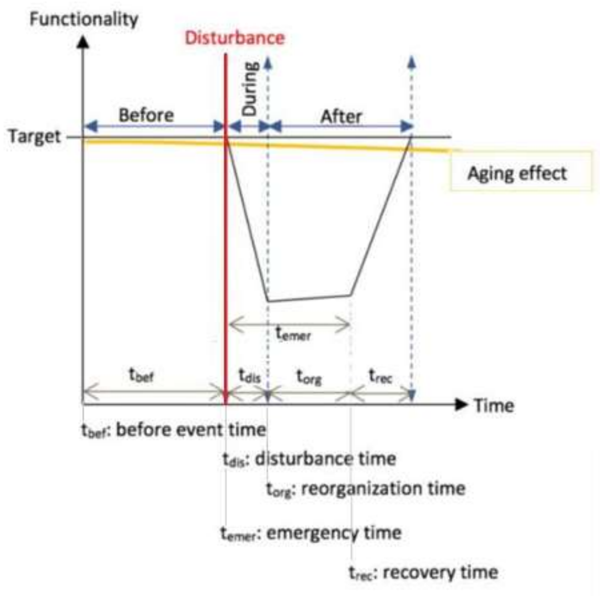


Figure 46. Evolution of functionality in CHs in time [Limongelli et al 2019]

Components of the recovery curve

- Base (Before) (t_{bef}) : Prior to the disruptive event, the functionality F(t) is close to its target level but decreases slightly owing to the aging effect.
- Disturbance time (t_{dis}): A shock (e.g., flood, scour or fire) triggers an instantaneous loss of functionality equal to ΔF.
- Emergency phase (t_{emer}): Immediate response actions designed to contain damage; F(t) typically continues to decline to its minimum value.
- Reorganization phase (t_{org}): Resources are mobilized, and recovery is planned; functionality remains at its lowest plateau.
- Recovery phase (t_{rec}): Corrective measures are executed; F(t) rises gradually and approaches the new target level (which may be slightly lower owing to aging).

Table 12. Characteristic Parameters

PARAMETER	SYMBOL	INTERPRETATION	GOVERNING FACTORS
Instantaneous loss of functionality	ΔF	Vertical drop from $F(t_{bef})$ to $F(t_{dis})$	Structural robustness, event intensity
Emergency time	t_{emer}	From t_{dis} to the end of first-response actions	Emergency capacity, availability of real-time SHM
Reorganization time	t_{org}	Resource mobilization and planning prior to repair	Supply-chain efficiency, labor availability
Recovery time	t_{rec}	From the start of repairs to attainment of the target functionality	Construction capacity, intervention strategy

Linkage to the four MULTICLIMACT KPIs

- Reliability: The pre-event reliability curve β(t) is used as the reference F(t); ΔF expresses the drop in reliability.
- Robustness: The capacity to limit ΔF and the initial post-event slope of decline.
- Resourcefulness: Directly influences t_{org} and the slope of the recovery phase.
- Rapidity: Defined as the inverse of t_{rec}

By quantifying ΔF, t_{emer}, t_{org}, t_{rec} from SHM data, hazard records and construction schedules, the AI index can be computed. This delivers a quantitative bridge between the component KPIs and the overall appraisal of a heritage asset's recovery capacity.

6. MULTI-SCALE ANALYSIS OF INTERVENTION IMPACTS

6.1. Multi-scale impacts of interventions

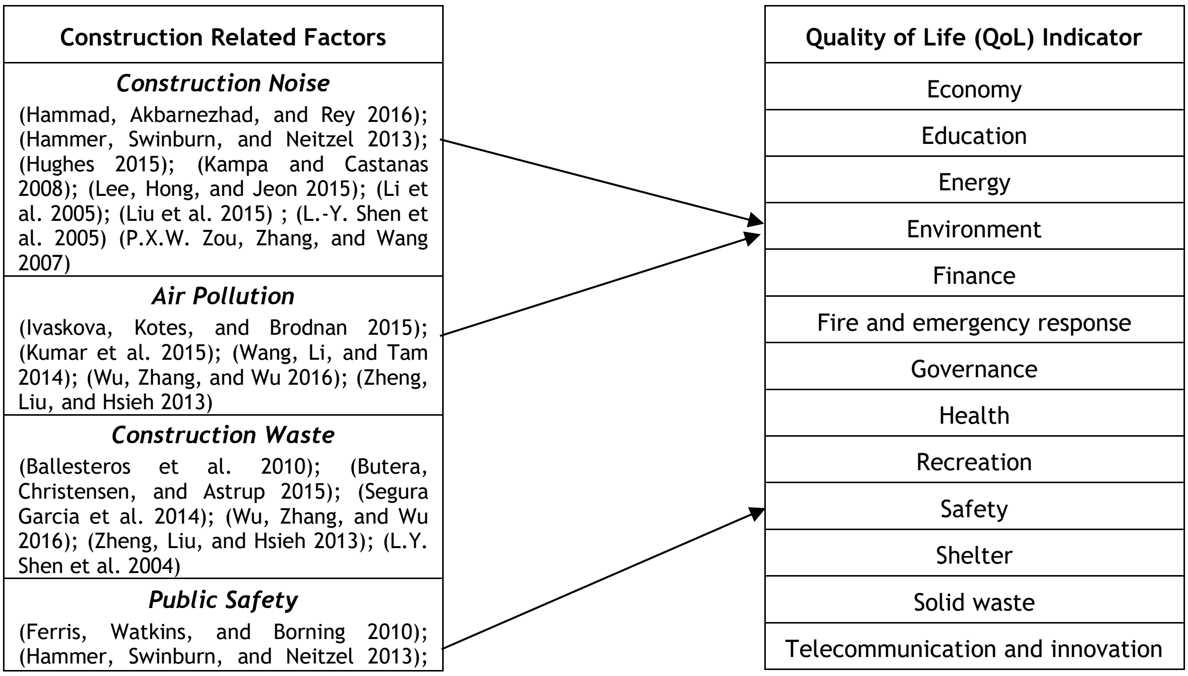
This chapter evaluates the impacts of the interventions outlined in Chapter 5 on QoL at urban or rural scale, as well as their economic, social and environmental impacts. The analysis focuses on the interventions proposed for the Riga Central Market, as the supply chain assessment, which is an essential input for this evaluation, was conducted only for the Latvian case study.

6.1.1. Impacts on QoL – Urban and rural scales

To systematically assess how construction interventions on Cultural Heritage (CH) assets affect QoL, a data-driven approach based on (Z. Zou and Ergan 2019) is adopted. These interventions produce both direct and indirect impacts that vary by scale, i.e., urban projects often affect noise levels, safety, and emergency response, while rural interventions influence landscapes and community cohesion.

A critical first step is mapping construction-related activities to standardized QoL indicators. This is achieved by aligning with ISO 37120:2014, which defines 17 objective indicators across domains such as health, safety, environment, and infrastructure. Figure 47 illustrates the main construction related impacts and their connection with the 17 QoL indicators. Depending on the CH project's scope, relevant indicators can be selected to quantify societal impact.

Research highlights that QoL is shaped by both objective conditions (e.g., infrastructure safety, air quality) and subjective experience (e.g., user satisfaction) (Liao et al. 2014). For example, Structural Health Monitoring (SHM) helps ensure safety in CH sites by providing real-time data on structural integrity (Rossi et al. 2023), and corrosion monitoring systems mitigate long-term degradation risks that affect both heritage preservation and public well-being (Laohaviraphap et al. 2024).



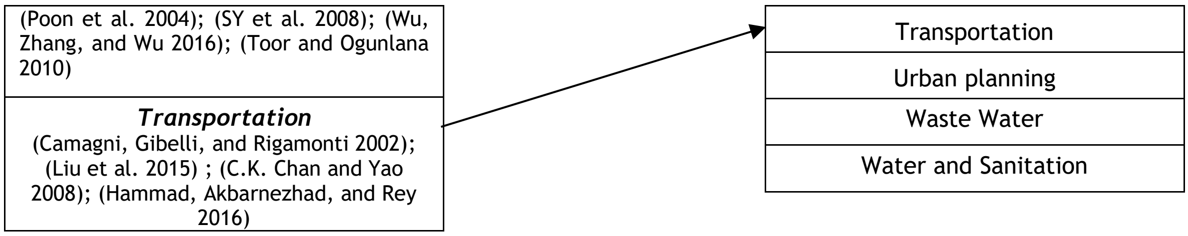


Figure 47. Main construction related impacts framed within QoL indicators according to (Z. Zou and Ergan 2019)

6.1.1.1. Datasets for the QoL analysis

To implement the data-driven methodology, the datasets from the supply chain analysis from Section 4.3 are employed:

I. Concrete Overlays dataset:

To quantify the impacts of concrete overlay interventions on urban QoL, detailed project data are used. This includes material consumption (e.g., hydrodemolition water usage, abrasive media quantities), labour hours (specialized tasks like rebar installation and formwork setup), and cost breakdowns (material, labour, and equipment expenses). Visualizations such as the Activity Breakdown chart, Pareto Chart, and Overall Project Resource Distribution pie chart further contextualize these elements, highlighting critical activities (e.g., A5, A6) and resource allocations (with labour dominating at 74.9%). By integrating these datasets, the analysis captures how specific aspects of concrete overlay interventions, such as noise generated by labor-intensive operations or environmental impacts linked to material use, connect to QoL indicators like health, environment, and economy, enabling targeted mitigation of negative effects.

II. Structural Health Monitoring dataset

To analyse the impacts of construction interventions on urban QoL, Structural Health Monitoring (SHM) data are incorporated as supporting evidence. This dataset captures key elements like sensor density (e.g., 3-5 Fiber Bragg Grating (FBG) sensors per rebar for precise strain and damage detection), vibration thresholds (defining acceptable structural movement to prevent hazards), and maintenance workflows (scheduled inspections and repair protocols). Visualizations, such as the Activity - Level Resource Breakdown chart (showing resource allocation across construction tasks) and the Overall Project Cost Breakdown (highlighting budget distribution for materials, labour, and equipment), contextualize how SHM contributes to the broader understanding of construction impacts. By linking SHM variables to QoL indicators, for example, ensuring structural safety via vibration monitoring to uphold “Public Safety” and “Health” QoL metrics, the analysis highlights how monitoring contributes toto urban resilience and liveability, enabling targeted strategies to mitigate risks and enhance long term QoL.

III. Corrosion Monitoring System dataset

To assess construction intervention impacts on urban QoL, the Corrosion Monitoring System dataset is used as supporting information. This includes details like inhibitor dosages (e.g., 10-30 L/m^3 to curb steel degradation in concrete structures), sensor installation costs (e.g., €10,501.25 per 100 m^2 for corrosion - detecting devices), and measured corrosion rates. Visualizations such as the Overall

Project Cost Breakdown (showing budget shares for materials, labour, and equipment) and Activity Level Resource Breakdown (detailing resource distribution across tasks) contextualize how corrosion monitoring is integrated into project workflows. By linking these variables to QoL indicators, for example, using inhibitor data to safeguard “Health” (via reduced hazardous material leaching) and “Sustainability” (through extended infrastructure lifespan), the analysis demonstrates how the Corrosion Monitoring System contributes to mitigating long term risks, enhancing urban resilience and liveability in line with the framework.

6.1.1.2. Methodology for the QoL analysis

This study adopts a descriptive engineering analysis methodology to assess how different construction interventions affect urban QoL. The approach integrates structured resource data with international standards, particularly ISO 37120:2014 – Sustainable Development of Communities, to map construction activities to measurable QoL indicators. The process unfolds in four main phases:

I. Data Collection and Structure

The three intervention types proposed in Section 4.1 were analysed based on the datasets elaborated from the supply chain analysis from Section 4.3. Each dataset includes detailed records of material, labour, and equipment use, enabling quantification of cost and resource consumption per task.

- **Concrete Overlays:** Includes activities like abrasive blasting, hydrodemolition, and rebar installation. Data fields include material quantities, labor hours, and equipment usage.
- **Structural Health Monitoring (SHM):** Covers sensor installation, calibration routines, and maintenance protocols.
- **Corrosion Monitoring Systems:** Encompasses inhibitor dosing, embedded sensor costs, and follow-up repairs.

I. Descriptive Resource Analysis

The analysis demonstrates the connection between key tasks from each intervention (Concrete Overlay, Corrosion Monitoring, and Structural Health Monitoring) and the relevant construction-related factors, including noise, air pollution, and public safety. This approach provides a foundational understanding of how construction activities influence the surrounding community and workers, setting the stage for a more in-depth exploration of their subsequent impacts on QoL indicators. The results for the concrete overlay intervention are summarized in Table 13.

Table 13. Concrete Overlay tasks linked to construction-related factors

ACTIVITY	CONSTRUCTION RELATED FACTORS	IMPACT ON QOL	REFERENCES
CO-01 (Condition Assessment)	Noise, Air Pollution, Safety	Health (stress, noise exposure), Public Safety	(Hammad, Akbarnezhad, and Rey 2016); (Hughes 2015); (Poon et al. 2004)
CO-02 (Abrasive Blasting)	Noise, Air Pollution, Public Safety	Health (respiratory issues), Public Safety (workplace)	(Hammad, Akbarnezhad, and Rey 2016); (Poon et al. 2004); (Lee, Hong, and Jeon 2015)

ACTIVITY	CONSTRUCTION RELATED FACTORS	IMPACT ON QOL	REFERENCES
CO-03 (Reinforcement Cleaning)	Health, Environment	Health (exposure to chemicals), Environment	(Ivaskova, Kotes, and Brodnan 2015); (Zheng, Liu, and Hsieh 2013)
CO-04 (Removal & Replacement of Bars)	Noise, Safety, Public Safety, Infrastructure	Health (dust, noise), Safety (workplace accidents)	(P.X.W. Zou, Zhang, and Wang 2007); (Kumar et al. 2015)
CO-05 (Connector Installation)	Safety, Infrastructure, Health	Public Safety (worker safety), Health (health risks)	(Liu et al. 2015); (Wu, Zhang, and Wu 2016)
CO-06 (Surface Preparation)	Noise, Air Pollution, Safety, Environment	Health (respiratory issues, noise stress), Environment	(Kumar et al. 2015); (Zheng, Liu, and Hsieh 2013)
CO-07 (Rebar Installation)	Public Safety, Infrastructure, Health	Public Safety (accident prevention), Health (manual labour strain)	(Hammer, Swinburn, and Neitzel 2013); (Lee, Hong, and Jeon 2015)
CO-08 (Hydro-Demolition)	Noise, Air Pollution, Public Safety	Health (exposure to debris, noise), Public Safety (risk of falling debris)	(Toor and Ogunlana 2010); (Hammad, Akbarnezhad, and Rey 2016)

The Concrete Overlay tasks involve several construction activities aimed at reinforcing and restoring existing structures. These tasks, including condition assessments, abrasive blasting, reinforcement cleaning, and the installation of connectors, are closely linked to various construction-related factors such as noise, air pollution, and public safety. For instance, activities like abrasive blasting and surface preparation generate noise and airborne pollutants, which can negatively impact health by causing respiratory issues and contributing to environmental degradation. Additionally, tasks like rebar installation and connector installation carry safety risks for workers, emphasizing the importance of public safety. The environmental and health risks posed by construction waste and other related factors further highlight the necessity of incorporating safety protocols and sustainable practices during these tasks. The references given in Table 14 indicate studies that discuss the various impacts of these construction activities, underscoring the critical links between construction practices and quality of life indicators, such as health, safety, and environment.

The Corrosion Monitoring tasks focus on activities related to monitoring the health of structural components to prevent and manage corrosion. These tasks, which include sensor bonding, rebar cleaning, and overlay casting, intersect with critical construction-related factors like noise, air pollution, health, and safety, as summarized in Table 14. For example, hydro-demolition and abrasive blasting used during surface preparation generate noise and produce dust, both of which can have negative health effects on workers and the surrounding community. Corrosion inhibitors applied in concrete structures may pose chemical risks to workers, highlighting the need for health and safety measures. These tasks also impact the environment, particularly through potential contamination from hazardous chemicals. The references given in Table 14 offer evidence on how construction-related factors such as noise, air pollution, and waste management affect both worker and public safety, as well as environmental sustainability. Each task is explicitly linked to QoL indicators like health, environment, safety, and public safety, providing a comprehensive view of the potential risks involved in corrosion management.

Table 14. Corrosion Monitoring tasks Linked to Construction-Related Factors

ACTIVITY	CONSTRUCTION RELATED FACTORS	IMPACT ON QOL	REFERENCES
T1 (Condition Assessment)	Safety, Public Safety, Environment	Public Safety (risk of accidents), Environment (air quality)	(Poon et al. 2004); (Liu et al. 2015)
T2 (Hydro-demolition Surface Prep)	Noise, Air Pollution, Public Safety, Health	Health (respiratory risks), Public Safety (injuries, falls)	(Zheng, Liu, and Hsieh 2013); (Wu, Zhang, and Wu 2016)
T3 (Abrasive Blasting of Reinforcement)	Noise, Air Pollution, Public Safety, Health	Health (lung issues, dust), Public Safety (safety hazards)	(Kumar et al. 2015);(Ferris, Watkins, and Borning 2010)
T4 (Replacement & Placement of New Reinforcement)	Noise, Safety, Public Safety, Infrastructure	Health (noise stress), Public Safety (workplace hazards)	(Ballesteros et al. 2010); (Liu et al. 2015)
T5 (Corrosion-inhibitor Coating)	Health, Safety, Public Safety	Health (chemical exposure), Public Safety (slippery floors)	(Zheng, Liu, and Hsieh 2013);(Butera, Christensen, and Astrup 2015)
T6 (Admixed Corrosion Inhibitor in Concrete)	Health, Environment	Health (chemical risks), Environment (air and water pollution)	(Segura Garcia et al. 2014); (Toor and Ogunlana 2010)
T7 (Sensor Fixing & Embedment)	Safety, Public Safety, Health	Public Safety (electrical risks), Health (manual labour strain)	(Wu, Zhang, and Wu 2016); (Poon et al. 2004)
T8 (DAQ Installation & Cabling)	Safety, Infrastructure, Health	Health (cabling work hazards), Infrastructure (site setup)	(Zheng, Liu, and Hsieh 2013); (Liu et al. 2015)
T9 (Overlay Casting & Curing)	Noise, Public Safety, Health	Health (exposure to materials), Public Safety (slippery surfaces)	(Kumar et al. 2015); (Zheng, Liu, and Hsieh 2013)
T10 (Expansion Joint Sealing)	Public Safety, Health	Public Safety (maintenance), Health (chemical exposure)	(Hammad, Akbarnezhad, and Rey 2016); (Wu, Zhang, and Wu 2016)
T11 (Quality Control & Testing)	Public Safety, Health	Health (inspection for safety), Public Safety (safety standards)	(Liu et al. 2015); (Zheng, Liu, and Hsieh 2013)
T12 (System Commissioning & Baseline Recording)	Public Safety, Infrastructure, Health	Public Safety (data safety), Infrastructure (monitoring)	(Liu et al. 2015); (Zheng, Liu, and Hsieh 2013)

The Structural Health Monitoring (SHM) tasks encompass the assessment, installation, and maintenance of monitoring systems used to evaluate the integrity of structures over time. These tasks, such as surface preparation for sensor bonding and cable laying, are influenced by construction-related factors like noise, air pollution, and safety, as summarized in Table 15. For instance, sensor bonding and adhesive curing processes, though essential for SHM, can involve exposure to chemicals and dust, impacting both health and safety. Tasks like hydro-demolition and surface preparation also generate noise, potentially affecting the environment and public health. SHM tasks, though critical for structural durability, are thus intrinsically linked to QoL indicators, including public safety, health, environment, and safety. The references provided in Table 15 highlight how these construction-related factors significantly affect worker safety and the overall well-being of communities. They reinforce the importance of proper health, safety, and environmental management to mitigate risks and ensure the effectiveness of SHM practices.

Table 15. Structural Health Monitoring (SHM) tasks linked to construction-related factors

ACTIVITY	CONSTRUCTION RELATED FACTORS	IMPACT ON QOL	REFERENCES
T1 (Surface Preparation - Walls)	Noise, Air P`ollution, Safety	Health (stress, noise exposure), Public Safety (accidents)	(Hammad, Akbarnezhad, and Rey 2016); (Lee, Hong, and Jeon 2015)
T2 (Sensor Bonding - Walls)	Health, Safety, Public Safety	Health (chemical exposure), Public Safety (worker safety)	(Zheng, Liu, and Hsieh 2013); (Liu et al. 2015)
T3 (Adhesive Injection & Curing)	Health, Safety, Environment	Health (skin irritation), Environment (material emissions)	(Ivaskova, Kotes, and Brodnan 2015);(Kampa and Castanas 2008)
T4 (Cable Laying & DAQ Connection - Walls)	Safety, Infrastructure, Health	Health (manual labor risks), Infrastructure (site setup)	(Ferris, Watkins, and Borning 2010); (Liu et al. 2015)
T5 (Hydrodemolition & Surface Prep - Slab)	Noise, Air Pollution, Public Safety, Health	Health (respiratory issues), Public Safety (risk of falling debris)	(Poon et al. 2004); (Zheng, Liu, and Hsieh 2013)
T6 (Rebar Cleaning)	Safety, Health	Health (dust inhalation), Safety (equipment use)	(Butera, Christensen, and Astrup 2015); (Zheng, Liu, and Hsieh 2013)
T7 (Reinforcement Replacement & Placement)	Safety, Public Safety, Infrastructure	Safety (manual labor), Public Safety (worker safety)	(Ballesteros et al. 2010); (Liu et al. 2015)
T8 (Installation of Connectors)	Safety, Infrastructure, Health	Health (manual labor), Public Safety (electrical risks)	(Wu, Zhang, and Wu 2016); (Liu et al. 2015)

ACTIVITY	CONSTRUCTION RELATED FACTORS	IMPACT ON QOL	REFERENCES
T9 (Sensor Bonding - Rebars)	Health, Safety, Public Safety	Health (chemical exposure), Safety (electrical risks)	(Ferris, Watkins, and Borning 2010); (Poon et al. 2004);
T10 (Casting & Curing Overlay Concrete)	Noise, Public Safety, Health	Health (respiratory issues), Public Safety (slippery floors)	(Hammad, Akbarnezhad, and Rey 2016); (Kumar et al. 2015);
T11 (Sealing Expansion Joints)	Safety, Public Safety, Infrastructure	Health (manual labor strain), Safety (slippery floors)	(Ballesteros et al. 2010); (Segura Garcia et al. 2014)
T12 (Quality Control)	Public Safety, Infrastructure	Health (manual work), Public Safety (quality hazards)	(Poon et al. 2004); (Wu, Zhang, and Wu 2016);

III. Mapping to QoL Indicators (ISO 37120)

Using engineering judgment, guidance from ISO 37120, and supported on the literature review (Z. Zou and Ergan 2019), each activity was mapped to applicable QoL indicators. Table 16 categorizes each activity based on the level of impact it has on QoL indicators. Activities with a high impact are associated with significant effects on health, safety, and the environment, such as abrasive blasting or rebar installation. Others, like sensor setup and system commissioning, have a medium impact as they have indirect or less frequent effects on the surrounding environment and community.

Table 16. Impact of activities on QoL indicators

ACTIVITY	IMPACT ON QOL INDICATORS	IMPACT LEVEL (LOW/MEDIUM/HIGH)
Concrete Overlay	Health, Environment, Urban Planning	High
Abrasive Blasting	Health, Environment	High
Rebar Installation	Public Safety, Health	High
Surface Preparation	Noise, Air Pollution, Safety	High
Reinforcement Cleaning	Health, Environment	Medium
Connector Installation	Public Safety, Infrastructure	Medium
Rebar Installation	Safety, Health	High
Hydro-Demolition	Noise, Public Safety, Health	High
System Commissioning	Infrastructure, Safety	Medium
DAQ Installation & Cabling	Safety, Infrastructure, Health	Medium
Sensor Setup & Calibration	Public Safety, Health, Environment	Medium

Table 17 provides an overview of the three main interventions (Concrete Overlay, Structural Health Monitoring, and Corrosion Monitoring), with the total number of tasks, the number of high impact tasks, the key QoL indicators affected, and examples of the activities involved in each intervention.

Table 17. Mapping of interventions to QoL indicators

ACTIVITY	TOTAL TASKS	HIGH QOL IMPACT TASKS	KEY QOL INDICATORS AFFECTED	EXAMPLE ACTIVITIES
Concrete Overlay	12	4	Health, Environment, Urban Planning	Abrasive Blasting, Rebar Installation
Structural Health Monitoring (SHM)	10	6	Public Safety, Infrastructure, Governance	Sensor Installation, Calibration
Corrosion Monitoring	12	7	Durability, Water Quality, Health	Sensor Setup, Inhibitor Application

6.1.2. Impacts on Sustainability

In recent years, the growing importance of sustainable development has significantly influenced building rehabilitation practices, particularly in the context of old urban centres. Rehabilitation plays a crucial role in reducing urban sprawl, preserving historical identity, and minimizing resource consumption (McGranahan and Satterthwaite 2002; Laefer and Manke 2008). To assess the sustainability of building rehabilitation actions, several methodologies have been developed, with the MARS (Model to Assess Sustainable Rehabilitation) methodology being one of the most comprehensive tools for evaluating sustainability across five key areas: Water Management, Energy Efficiency, Materials Use, Emissions, and Cultural, Economic, and Social Environments. By applying the MARS methodology, this study analyses the sustainability impacts of building rehabilitation projects, with a focus on both environmental and social outcomes. The following sections provide an overview of the interventions applied in each area, detailing their sustainability impacts and aligning them with the criteria of the MARS methodology.

6.1.2.1. Water Management (SA)

Water conservation plays a pivotal role in the sustainable rehabilitation of buildings, especially in areas facing water scarcity. The interventions implemented in this area are designed to optimize water use and minimize waste throughout the renovation process. Techniques like hydrodemolition and corrosion monitoring systems, as outlined in the MARS methodology, enhance water efficiency by recycling water used in surface preparation and detecting corrosion early, thus preventing significant water-related damage (Almeida, Ramos, and Silva 2018). These strategies not only conserve water resources but also reduce the environmental impact of rehabilitation projects. The impact of sustainability interventions in Table 18.

Table 18: Sustainability Interventions and Their Impact on MARS Criteria (Water Management)

INTERVENTION	DESCRIPTION	SUSTAINABILITY IMPACT	RELEVANT MARS METHOD CRITERIA
Hydrodemolition Surface Preparation	Water-intensive surface preparation method for	Efficient water usage by recycling water and minimizing	SA1 (Water consumption);

INTERVENTION	DESCRIPTION	SUSTAINABILITY IMPACT	RELEVANT MARS METHOD CRITERIA
	concrete cleaning and preparation.	waste during surface preparation (Waidyasekara, De Silva, and Rameezdeen 2014)	SA4 (Rainwater use)
Corrosion Monitoring Systems for Water Management	Use of advanced monitoring tools to track and manage water-related corrosion, extending system lifespan.	Prevents water wastage by identifying corrosion early and extending the life of building water systems(Hangan et al. 2022).	SA1 (Water consumption); SA4 (Rainwater use)

These interventions focus on reducing water usage and improving water system longevity, which minimizes environmental impact through recycling and reduced demand on municipal water systems. The use of hydrodemolition for surface preparation and corrosion monitoring effectively reduces water wastage and improves system durability.

6.1.2.2. Energy Efficiency (SE)

Energy efficiency in building rehabilitation focuses on reducing energy consumption and incorporating renewable energy sources in Table 19. Key interventions include the installation of energy-efficient systems, the integration of smart technologies for real-time energy consumption management, and the use of renewable energy solutions such as photovoltaic panels. These measures help lower long-term energy costs, reduce the carbon footprint of rehabilitation projects, and improve overall energy performance. Additionally, smart energy management systems enhance energy efficiency by enabling real-time monitoring and control, further optimizing energy use (Gligor et al. 2025).

Table 19: Energy Efficiency and Sustainability Interventions for Building Rehabilitation

INTERVENTION	DESCRIPTION	SUSTAINABILITY IMPACT	RELEVANT MARS METHOD CRITERIA
Surface Preparation (Hydrodemolition & Roughening)	High-pressure water jetting for surface preparation of concrete surfaces.	Indirectly improves building energy efficiency by ensuring better energy performance over time and reducing repair costs(Hangan et al. 2022).	SE1 (Energy performance)
Corrosion Monitoring Systems	Advanced monitoring tools used to track and manage corrosion in building structures.	Extends the lifespan of building systems, reducing the need for energy-intensive replacements and repairs(Aljibori, Al-Amiery, and Isahak 2024).	SE1 (Energy performance); SE5 (Use of renewable resources)
Structural Health Monitoring (SHM)	Installation of sensors to monitor the integrity of the structure, helping	Helps optimize energy use by preventing damage that may result in energy waste, thus	SE1 (Energy performance); SE5 (Use of renewable resources)

INTERVENTION	DESCRIPTION	SUSTAINABILITY IMPACT	RELEVANT MARS METHOD CRITERIA
	with early detection of issues.	improving long-term energy efficiency(Omer 2009).	

These interventions focus on improving energy efficiency and sustainability in building rehabilitation projects. By incorporating methods such as hydrodemolition for surface preparation, corrosion monitoring systems, and structural health monitoring, these measures not only enhance the energy performance of buildings but also extend their lifespan. These strategies contribute to reducing long-term energy consumption, preventing unnecessary repairs, and promoting the use of renewable resources, ultimately supporting more sustainable and energy-efficient building practices.

6.1.2.3. Material Use (SM)

Sustainable material usage in building rehabilitation projects focuses on minimizing waste and conserving resources by reusing existing materials and integrating low-impact alternatives showed in Table 20. This approach supports the circular economy by prioritizing material reuse and recycling, thereby reducing the demand for new materials and lowering environmental impact. By emphasizing resource-efficient strategies, it ensures that building materials are reused wherever possible, promoting sustainability and reducing the ecological footprint of the rehabilitation process (Cortiços 2025).

Table 20: Materials Use Sustainability Interventions and Their Impact on MARS Criteria

INTERVENTION	DESCRIPTION	SUSTAINABILITY IMPACT	RELEVANT MARS METHOD CRITERIA
Reinforcement Cleaning (Abrasive Blasting)	Cleaning the exposed reinforcement bars using abrasive blasting to remove corrosion and allow reuse.	Reduces waste generation by reusing materials, contributing to sustainable practices in rehabilitation(Zulkarnain et al. 2021).	SM2 (Use of local materials); SM3 (Recycling materials)
Surface Preparation (Hydrodemolition)	Hydrodemolition of deteriorated concrete using high-pressure water for surface preparation.	Minimizes the need for new materials by potentially recycling removed concrete(Momber 2011).	SM2 (Use of local materials); SM3 (Recycling materials)
Removal & Replacement of Severely Corroded Bars	Removing and replacing severely corroded reinforcement bars, selectively replacing only damaged components.	Minimizes waste by selectively replacing only severely corroded materials(Hansson, Poursaee, and Jaffer 2012).	SM2 (Use of local materials); SM3 (Recycling materials)

These interventions emphasize the reuse and recycling of materials in building rehabilitation, aiming to minimize waste and reduce the need for new resources. By incorporating methods such as reinforcement cleaning (abrasive blasting), hydrodemolition for surface preparation, and selective replacement of corroded bars, these strategies contribute to more sustainable construction practices. They align with key MARS criteria, promoting the use of local materials and recycling, thereby supporting the long-term sustainability of rehabilitation projects.

6.1.2.4. Emissions (SAE)

Controlling emissions is a vital component of sustainable building rehabilitation, particularly in urban environments where air quality is a concern. Key interventions include the use of dust suppression techniques during abrasive processes and the integration of low-emission equipment and smart energy management technologies. These measures help reduce both carbon and particulate emissions, contributing to better air quality, improved health outcomes, and a smaller carbon footprint for rehabilitation projects (Munarim and Ghisi 2016).

Table 21: Emissions Control and Sustainability Interventions in Building Rehabilitation and Their Impact on MARS Criteria

INTERVENTION	DESCRIPTION	SUSTAINABILITY IMPACT	RELEVANT MARS METHOD CRITERIA
Reinforcement Replacement	Replacing only severely corroded reinforcement bars, preserving undamaged materials.	Reduces material consumption and minimizes waste during the rehabilitation process(Asmara 2023).	SM2 (Use of local materials)
Corrosion Monitoring Systems	Systems used to monitor and manage corrosion in building structures.	Prevents further material degradation, reducing the need for energy-intensive repairs(Aljibori, Al-Amiery, and Isahak 2024).	SE1 (Energy performance); SAE2 (Control of greenhouse gases)
Energy-Efficient Equipment and Smart Technologies	Integration of energy-efficient and smart technologies for energy management in rehabilitation projects.	Enhances energy efficiency and reduces emissions from the building's operational systems(Metallidou, Psannis, and Egyptiadou 2020).	SE1 (Energy performance); SE5 (Use of renewable resources)
Material Reuse (Concrete)	Reusing concrete from demolition or hydrodemolition processes.	Reduces waste and conserves natural resources by recycling materials(Kühlen, Volk, and Schultmann 2016).	SM2 (Use of local materials); SM3 (Recycling materials)
Corrosion Monitoring Systems	Systems used to monitor and manage corrosion in building structures.	Prevents further material degradation, reducing the need for energy-intensive repairs(Aljibori, Al-Amiery, and Isahak 2024).	SE1 (Energy performance); SAE2 (Control of greenhouse gases)

These interventions focus on reducing emissions and improving the sustainability of building rehabilitation processes and showed in Table 21. By incorporating methods such as hydrodemolition for surface preparation, abrasive blasting with dust suppression techniques, and the use of corrosion monitoring systems, these measures help control particulate emissions, extend the lifespan of building materials, and enhance overall energy efficiency. The integration of energy-efficient equipment and smart technologies further supports long-term sustainability by optimizing energy performance and minimizing environmental impact. These interventions align with key MARS criteria, promoting cleaner rehabilitation practices and contributing to the reduction of carbon emissions and resource consumption.

6.1.2.5. Cultural, Economic, and Social Environments (CES)

Sustainable building rehabilitation not only focuses on the physical aspects of buildings but also emphasizes the importance of preserving cultural heritage. This approach aims to protect the historical and social significance of buildings while promoting economic growth and community well-being. By preserving cultural heritage, rehabilitation projects can foster community engagement, stimulate economic revitalization through heritage tourism, and improve public services. These efforts contribute to the overall sustainability of urban areas by balancing the preservation of cultural identity with the social and economic needs of the community (Ndrevataj 2025).

Table 22: Cultural, Economic, and Social Environment (CES) Interventions and Their Impact on MARS Criteria

INTERVENTION	DESCRIPTION	SUSTAINABILITY IMPACT	RELEVANT MARS METHOD CRITERIA
Waste Management & Disposal	Segregating and managing concrete waste from demolition and rehabilitation activities.	Reduces environmental impact by managing waste efficiently, contributing to cleaner communities and sustainable practices(Ponnada and Kameswari 2015).	SAE2 (Control of greenhouse gases); SE5 (Use of renewable resources)
Heritage Preservation through Concrete Overlays	Restoration of historic elements while incorporating modern materials to preserve cultural heritage.	Promotes cultural sustainability by maintaining historical identity while ensuring structural integrity(Kaur et al. 2025).	CES2 (Architectural valorisation); CES1 (Community impact)
Community Well-Being Through Improved Housing	Enhancing living spaces and providing new services (e.g., healthcare units, schools) within rehabilitated areas.	Improves the quality of life for residents, fosters social inclusion, and strengthens community cohesion(Thompson and Kent 2014).	CES2 (Architectural valorisation); CES1 (Community impact)
Economic Revitalization Through Heritage Tourism	Encouraging tourism by preserving historical sites and promoting cultural heritage.	Stimulates local economy through job creation and tourism, helping revitalize urban areas(Chong and Balasingam 2019).	CES2 (Architectural valorisation); CES1 (Community impact)

The Table 22 outlines key interventions related to Cultural, Economic, and Social Environments (CES) in building rehabilitation projects, focusing on the preservation of cultural heritage, enhancement of community well-being, and stimulation of economic growth. It highlights the importance of restoring historic elements while integrating modern materials, improving living conditions through enhanced housing, and fostering economic revitalization through heritage tourism. These interventions contribute to sustainable urban development by promoting cultural sustainability, strengthening social inclusion, and boosting local economies. The listed activities align with relevant MARS criteria for architectural valorisation and community impact, ensuring that rehabilitation efforts benefit both the cultural and socio-economic fabric of urban areas.

7. RESILIENCE SCORECARD FOR ASSESING INTERVENTIONS IN CULTURAL HERITAGE

The UNDRR's Disaster Resilience Scorecard for Cities – Cultural Heritage Addendum (UNDRR 2022) provides a structured framework to assess and enhance the disaster resilience of cultural heritage (CH) by aligning with the *Ten Essentials* of the Making Cities Resilient initiative. It expands on the original Scorecard by incorporating 44 additional questions, scored from 0 to 3, where 0 indicates no preparation, and 3 represents comprehensive understanding and robust resilience measures. The CH Resilience Scorecard promotes the integration of cultural heritage considerations, including tangible, intangible, and natural heritage, into disaster risk reduction and urban resilience strategies. It emphasizes the importance of incorporating traditional knowledge, local construction techniques, and materials into planning and recovery efforts, aiming to preserve authenticity while improving safety. The CH Resilience Scorecard supports cities in establishing a baseline, identifying vulnerabilities, prioritizing interventions, engaging diverse stakeholders, and monitoring progress over time. It also encourages the recognition of cultural heritage as a critical asset in governance, financial planning, institutional strengthening, and recovery processes.

The CH Resilience Scorecard for Cities should be completed through inclusive and participatory consultations involving all concerned groups and institutions in the cultural heritage sector. These include organizations responsible for cultural heritage management, first responders, academia, museums, belief organizations, organized civil society groups, creative sectors, the private sector, and, where applicable, indigenous and marginalized communities (UNDRR 2022).

For the Latvian demo site, REA identified different stakeholders to respond to the CH Resilience Scorecard during the 4th MULTICLIMACT General Assembly in Bilbao (Figure 48). These included representatives from various Riga city departments, such as strategic planning, urban planning, the city architect’s office, and historical centre planning, as well as the University of Latvia, specifically the Spatial Development Planning Studies Centre, the Riga Investment and Tourism Agency, and the Latvian National Cultural Heritage Board. It should be noted that not all questions in the Scorecard were completed; stakeholders only responded to those questions relevant to their respective fields of action and competences, in alignment with their institutional responsibilities and the expertise of the individuals interviewed.

Co-funded by the European Union

Figure 48. Identification of stakeholders for the Latvian case study at the 4th General Assembly in Bilbao

For the Dutch demo site, the Delfland Water Board was an associated partner of the MULTICLIMACT project, with no resources allocated to identify and contact different stakeholders to complete the CH Resilience Scorecard. Therefore, this section presents the results from the implementation of the fourth step of the methodology (Figure 1) for the Latvian demo only.

7.1. Current resilience condition

The current resilience condition of Riga's cultural heritage was assessed using the Cultural Heritage Resilience Scorecard. The scorecard covers ten essential areas that contribute to enhancing disaster resilience for cultural heritage, each of which was evaluated based on responses from various stakeholders, including city departments, academic institutions, and heritage boards. The scorecard responses are provided in the ANNEX. The following section presents the key findings from the scorecard results, which reflect the overall preparedness of the city regarding cultural heritage resilience.

I. Current Baseline Assessment of Essential 01: Stakeholder Feedback Visualization

Figure 49 to Figure 59 present the spider plot visualizations of the current resilience condition of Riga's cultural heritage, structured according to the ten essentials of the Cultural Heritage Resilience Scorecard, derived directly from stakeholder questionnaire responses prior to any interventions. It reveals distinct patterns in the city's cultural heritage resilience planning: strong performance in inclusive planning processes and sustainability integration forms clear peaks, while significant dips highlight gaps in socio-economic valuation and institutional coordination. A mid-range result for heritage acknowledgment in city plans bridges these extremes. This visualization serves as a diagnostic snapshot, objectively capturing existing strengths to preserve and vulnerabilities to address providing a clear foundation for future resilience-building strategies. The stark contrast between high and low scores immediately directs attention to priority areas for improvement while acknowledging current capabilities.

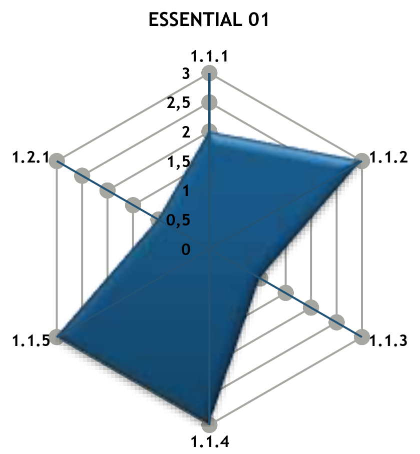


Figure 49. Essential 01 spider chart

II. Current Baseline Assessment of Essential 02: Risk Scenario Understanding

The spider chart visualization of Essential 02 reveals significant gaps in the city's current capacity to identify and assess risks to cultural heritage. Stakeholder responses show particularly weak performance in understanding tangible heritage vulnerability (2.1.3: 0/3) and incorporating tourism risks into hazard updates (2.2.1: 0/3), represented as deep valleys in the chart. Knowledge of exposure levels for tangible heritage (2.1.1: 1/3) and consideration of transient populations (2.1.2: 1/3) also score poorly. The sole strong point appears in intangible heritage knowledge (2.1.4: 3/3), creating a single prominent peak amid otherwise low scores. This stark imbalance highlights an urgent need to strengthen risk assessment methodologies, particularly for physical heritage assets and demographic factors, while maintaining the existing understanding of intangible cultural elements. The visualization clearly shows risk identification as a critical vulnerability in the city's current cultural heritage resilience framework.

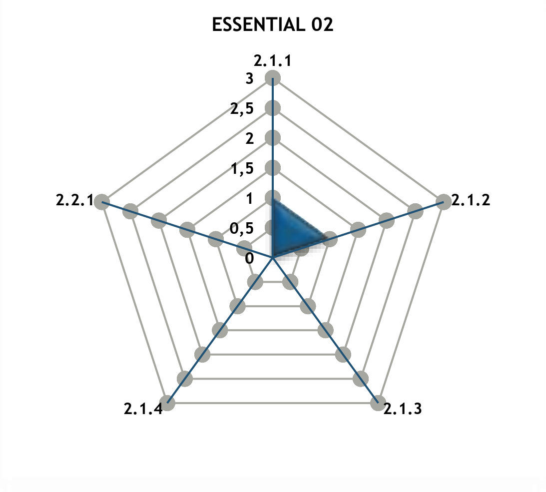


Figure 50. Essential 02 spider chart

III. Current Baseline Assessment of Essential 03: Financial Resilience Capacity

The spider chart reveals critical gaps in financial preparedness for cultural heritage resilience. Stakeholder responses show moderate performance in awareness of funding mechanisms (3.1.1) and basic protection against fund diversion (3.2.1), both scoring 2/3. However, the visualization highlights two severe vulnerabilities: insurance coverage for cultural heritage remains entirely absent, and no incentives exist to encourage heritage owners' participation in resilience measures. These financial shortcomings pose significant risks to long-term heritage protection, despite the existing foundational knowledge of funding options. The chart's pattern clearly directs attention to where urgent financial interventions are needed most.

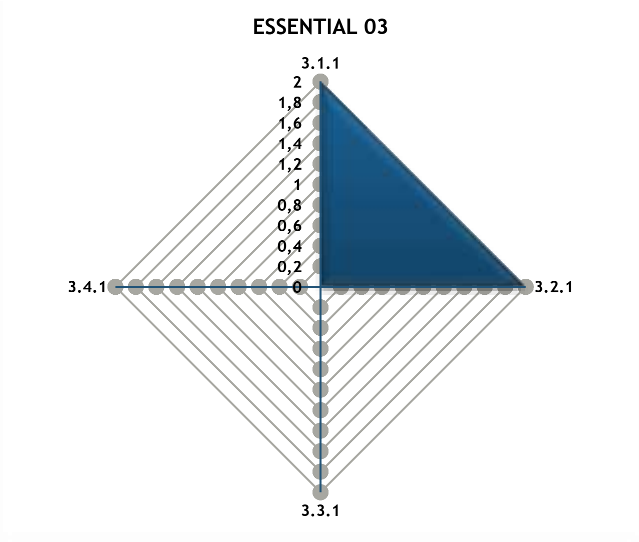


Figure 51. Essential 03 spider chart

IV. Current Baseline Assessment of Essential 04: Urban Development Resilience

The spider chart analysis reveals strong urban planning foundations for cultural heritage protection. Stakeholder responses demonstrate excellent performance in three key areas: land use zoning effectively promotes balanced, multiple uses around heritage sites (4.1.2: 3/3), building codes successfully incorporate traditional design principles (4.2.1: 3/3), and comprehensive guidelines exist for strengthening heritage structures (4.2.2: 3/3). These results form a near-perfect triangular peak in the visualization. The only moderate score appears for risk exposure of heritage areas (4.1.1: 2/3), showing room for improvement in damage prevention strategies. This overall pattern indicates the city has successfully integrated heritage considerations into its urban development framework, with strengths in adaptive reuse and traditional design preservation. The visualization suggests maintaining these successful policies while enhancing risk mitigation measures for at-risk heritage

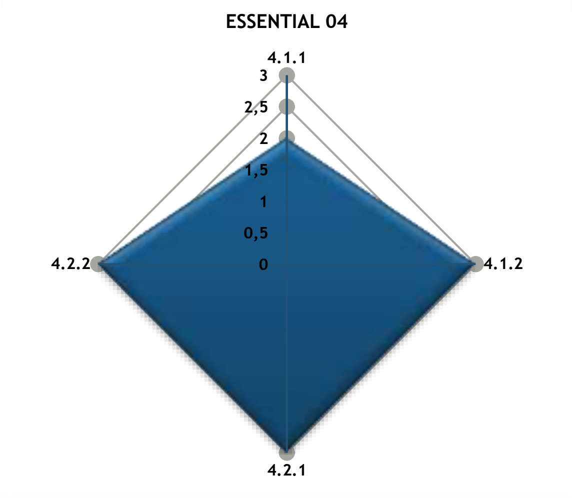


Figure 52. Essential 04 spider chart

V. Current Baseline Assessment of Essential 05: Natural Buffer Protection

The spider chart reveals significant gaps in leveraging natural systems for cultural heritage protection. Stakeholder responses show weak recognition of ecosystem services as critical heritage assets (5.1.1: 1/3), forming a concerning trough in the visualization. While traditional knowledge integration scores slightly better (5.2.1: 2/3), the overall pattern demonstrates inadequate utilization of nature-based solutions. This imbalance highlights a missed opportunity to strengthen heritage resilience through ecological approaches. The chart clearly identifies the need to enhance both scientific and traditional understanding of natural buffers to better protect cultural assets from disasters.

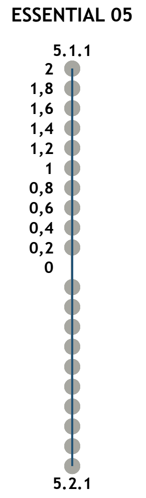


Figure 53. Essential 05 spider chart

VI. Current Baseline Assessment of Essential 06: Institutional Capacity for Resilience

The spider chart reveals systemic weaknesses in institutional preparedness for cultural heritage protection. Stakeholder responses show uniformly low performance across all measured areas: limited awareness of available skills (6.1.1: 1/3), minimal educational outreach in schools (6.2.1: 1/3), no higher education programs (6.2.2), poor data sharing practices (6.3.1: 1/3), and insufficient knowledge exchange initiatives (6.4.1: 1/3). These results create a concerning inward collapse pattern in the visualization, indicating across-the-board deficiencies in building institutional knowledge and coordination. The complete absence of higher education engagement appears as the most severe gap. This comprehensive institutional shortfall jeopardizes the city's ability to develop and retain critical expertise for heritage resilience. The chart clearly signals an urgent need for capacity-building investments at all levels - from school programs to professional knowledge sharing - to establish a sustainable foundation for cultural heritage protection.

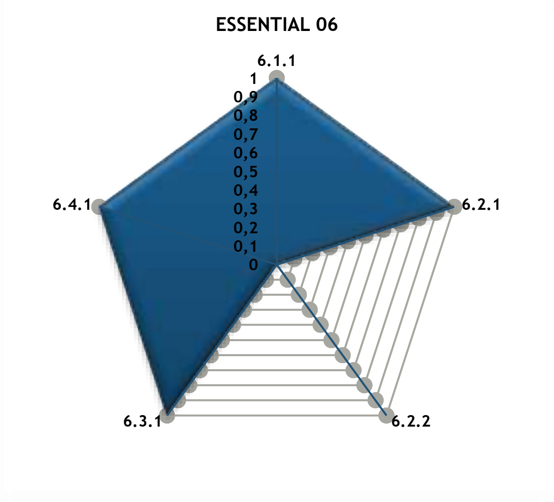


Figure 54. Essential 06 spider chart

VII. Current Baseline Assessment of Essential 07: Societal Capacity for Resilience

The spider chart reveals mixed engagement levels in cultural heritage protection across different societal groups. Community participation remains limited (7.1.1: 1/3), forming a noticeable trough in the visualization. However, municipal communication efforts show moderate effectiveness, with clear heritage messaging (7.3.1: 2/3) and public engagement strategies (7.3.2: 2/3) creating balanced mid-range points. This pattern suggests that while top-down communication systems function adequately, grassroots involvement and local ownership of heritage protection remain underdeveloped. The visualization highlights the need to bridge this gap between institutional outreach and meaningful community participation to build comprehensive societal resilience for cultural heritage.

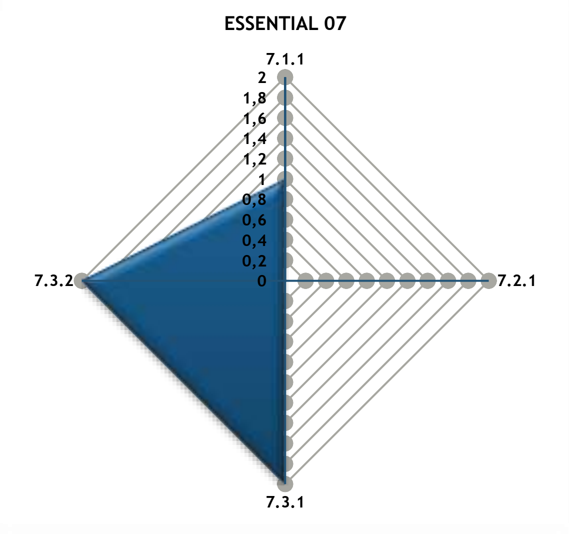


Figure 55. Essential 07 spider chart

VIII. Current Baseline Assessment of Essential 08: Infrastructure Resilience

The spider chart reveals critical vulnerabilities in the protection of heritage infrastructure. The most severe gap appears in essential services, with no cultural heritage structures currently hosting critical functions (8.1.1: 0), creating a deep trough in the visualization. The chart shows better but still concerning performance for tourism and worship sites, with moderate expected service loss for visitation activities (8.2.1: 2/3) contrasting with higher vulnerability for worship services (8.3.1: 3/3) and significant projected tourism revenue declines (8.2.2: 3/3). This pattern indicates that while the city recognizes potential economic and social impacts, it has failed to integrate heritage assets into essential service networks. The visualization's sharp asymmetry - with one extreme low point amid clustered higher-risk indicators - highlights infrastructure resilience as a priority intervention area, particularly for safeguarding both the functional and socio-economic value of cultural heritage sites.

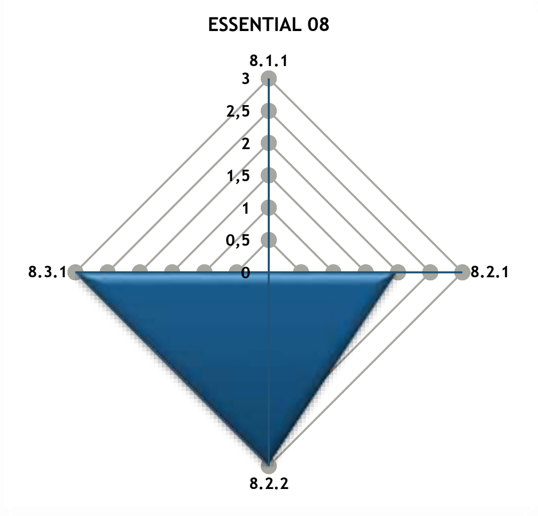


Figure 56. Essential 08 spider chart

IX. Current Baseline Assessment of Essential 09: Disaster Response Preparedness

The spider chart reveals critical deficiencies in the city's emergency response framework for cultural heritage. Key gaps emerge in three areas: early warning systems show no integration of traditional knowledge (9.1.1: 0), emergency plans lack heritage-specific considerations (9.2.1: 0), and relief supplies fail to address cultural needs (9.5.1: 0). These scores create deep troughs in the visualization. The only modest performance appears in evacuation capacity for transient populations (9.4.1: 1), forming a slight outward point. This lopsided pattern demonstrates how current response systems overwhelmingly neglect cultural heritage protection requirements. The visualization clearly identifies where fundamental improvements are needed to develop heritage-sensitive emergency protocols.

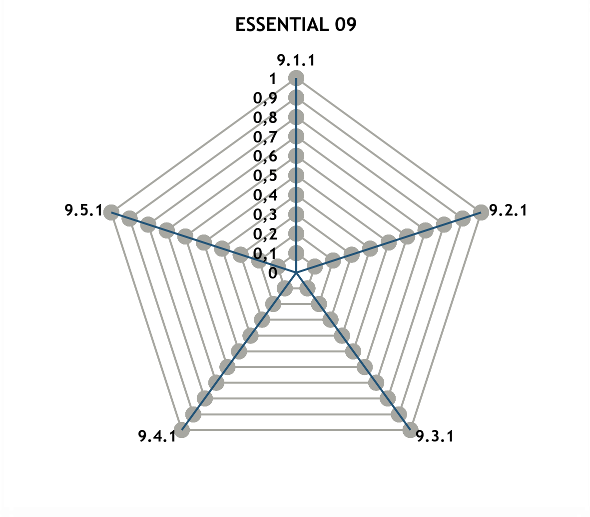


Figure 57. Essential 09 spider chart

X. Current Baseline Assessment of Essential 10: Post-Disaster Recovery Preparedness

The spider chart reveals a stark contrast in recovery planning capabilities. While the city demonstrates strong commitment to traditional craftsmanship preservation (10.2.2: 3/3), forming a single prominent peak, all other recovery elements score zero. The visualization shows complete gaps in: heritage integration in Post-Disaster Needs Assessments (10.1.1: 0), inclusive recovery planning (10.1.2: 0), area-wide heritage considerations (10.1.3: 0), and Build Back Better implementation (10.2.1: 0). This extreme imbalance creates a dramatic visual - with one isolated high point amid a collapsed polygon - highlighting how current recovery strategies successfully preserve traditional skills but completely fail to incorporate heritage into broader reconstruction frameworks. The chart clearly identifies the need to expand the existing craftsmanship focus into comprehensive, heritage-sensitive recovery systems.

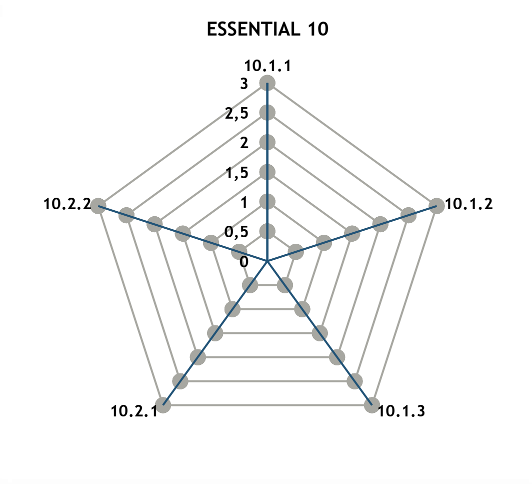


Figure 58. Essential 10 spider chart

XI. Overall Resilience Assessment Summary

The city's cultural heritage resilience assessment reveals a mixed picture, with an overall score of 57 out of 132 points (43.2%). The results show both significant strengths and critical vulnerabilities across different aspects of heritage protection. While Essential 01 (Organization) demonstrates perfect performance in governance and planning frameworks, other areas reveal substantial gaps - particularly in financial capability (Essential 03), natural buffer protections (Essential 05), and disaster response systems (Essential 09). The assessment highlights strong performance in urban development strategies (Essential 04) and traditional craftsmanship preservation, but these successes contrast sharply with weaknesses in recovery planning and infrastructure resilience. This uneven performance pattern indicates that while the city has established excellent foundational policies, operational implementation remains inconsistent. The results clearly identify where the city should focus immediate improvement efforts while maintaining its existing strengths, providing a roadmap for developing more comprehensive cultural heritage resilience. With nearly 60% of potential resilience measures not yet implemented, the assessment underscores both the progress made, and the substantial work still needed to fully protect the city's cultural assets.

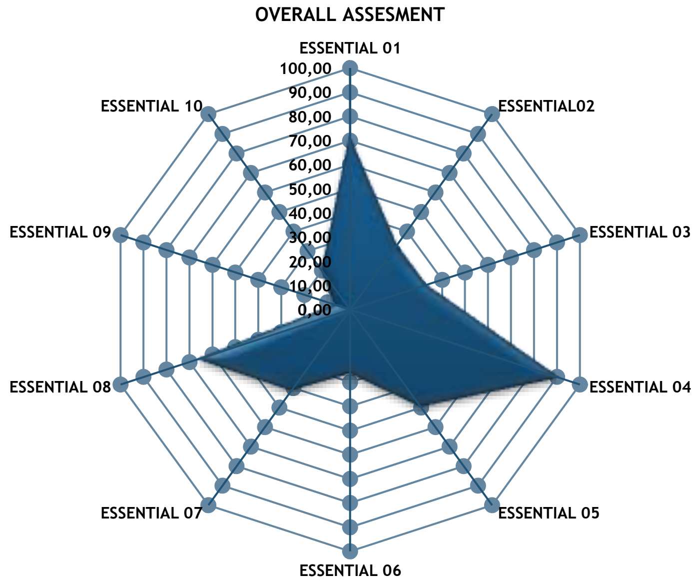


Figure 59. Overall Essential Assesment spider chart

7.2. Classification of resilience enabling interventions

To assess the effect of the interventions proposed in Chapter 40 on resilience, the procedure outlined in the deliverable D2.6 is followed (Sousa, Ingrosso, and Urciuoli 2024). Essentially, Table 7 from D2.6, which contains the list of possible interventions in CH, is used to identify the interaction of each intervention with relevant disciplines, including social sciences (S), management/governance (Mg), economics (Eco), environmental (Env), and engineering (Eng). This allows 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. Subsequently, Table 1 from D2.6, which contains the disciplines associated with each scorecard question, is used to correlate which of the essentials are expected to be affected by the proposed interventions by linking the multidisciplinary impacts. Table 7 and Table 1 from D2.6 are reproduced herein as Table 23 and Table 24, respectively.

*Table 23: List of possible interventions in CH and its interaction with disciplines and KPIs: * S: social; MG: management/governance; ECO: economics; ENV: environmental; ENG: engineering (structural + construction); ** REL: reliability; ROB: robustness; RES: resourcefulness; REC: recovery.*

INTERVENTIONS		DISCIPLINES*					IMPACT SCALE	KPI**				INNOVATION TECHNIQUES
phase	action	S	MG	ECO	ENV	ENG		REL	ROB	RES	REC	
Pre-event	Monitoring and sensing				X	X	Building, system	X	X			Digitalization
	Strengthening and reinforcement					X	Building	X	X			Innovative compatible materials
	Protection and safeguard					X	Building to Region	X	X	X		Innovative compatible construction techniques
	Management restrictions (governance)		X	X			Building, system and region		X	X		--
	Maintenance plans		X				Building, system and region	X	X	X		Use of predictive maintenance
	Social and community participation (co-creation)	X	X				Building, system and region		X		X	Use of social networks
	Change on exposure/ vulnerability (environmental conditions)					X	Building, system	X	X			Use of GIS combined with digitalization
	Adaptation measures				X	X	Building, system	X	X		X	Use of GIS combined with digitalization
	Knowledge transfer and people awareness	X	X	X			System, Region			X	X	--
Event	Emergency plans (management strategies)	X	X	X			Building to region			X	X	Use of predictive models for scenario based inference
	Early warning systems	X	X				Building to region			X	X	Digitalization, digital twins

	Mitigation interventions					X	Building, system	X			X	Innovative compatible materials
	Cleaning and demolition	X			X	X	Building, system			X	X	--
Pos-event	Monitoring and sensing				X	X	Building, system	X	X			Digitalization
	Repair to prior performance	X				X	Building, system	X	X			Innovative compatible materials
	Strengthening and reinforcement					X	Building	X	X			Innovative compatible materials
	Recovery management	X	X	X			Building to region				X	Use of predictive models for scenario based inference
	Adaptation measures				X	X	Building, system	X	X		X	Use of GIS combined with digitalization

*Table 24: Disciplines considered for each scorecard question: * S: social; MG: management/governance; ECO: economics; ENV: environmental; ENG: engineering (structural + construction)*

SCORECARD QUESTION		DISCIPLINES*					KEYWORDS / ACTIONS
		S	MG	ECO	ENV	ENG	
Essential 1	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, compatible materials
	1.2.1		X	X			Reduce disaster risk, protection, maintenance and reutilization
Essential 2	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
Ess enti al 3	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
Essential 4	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
E. 5	5.1.1	X			X		Natural heritage
	5.2.1	X	X				Traditional knowledge
Essential 6	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
Essential 7	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
Essential 8	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
Essential 9	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
Essential 10	10.1.1	X	X	X			Post recovery plans
	10.1.2	X	X				Post recovery plans inclusivity and participatory nature
	10.1.3	X	X	X			Post recovery plans of surrounding areas
	10.2.1	X				X	Traditional design guidelines for building back better
	10.2.2	X				X	Promotion of traditional materials and construction techniques

7.2.1. Summary of Score Increases Based on Stakeholder Responses and Reference Standards Review

The score increases in this assessment are the result of a thorough re-evaluation using Annex (stakeholders Responses) and Table 25 (Reference Standards), which highlighted a stronger alignment with recognized best practices and provided clearer evidence of effective cultural heritage resilience measures. Specifically, improvements were noted in Essential 01, where planning processes demonstrated greater inclusivity and participatory approaches. Essential 02 showed enhanced understanding of exposure and vulnerability to hazards, indicating more comprehensive risk awareness. In Essential 03, the local government's knowledge and pursuit of diverse financial mechanisms for heritage management were found to be more proactive than initially recorded. Furthermore, Essentials 05 and 06 reflected better integration of traditional knowledge in managing natural buffers and a higher level of institutional capacity through improved data sharing and education programs. These adjustments offer a more accurate and positive perspective on the city's resilience efforts, addressing previous gaps and underestimations in the initial assessment. The inclusion of extreme temperature considerations in the hazard analysis further supports the score increases for Indicators 3.1.1.1 and 3.1.1.2 by strengthening the assessment of exposure and vulnerability, contributing to a more complete resilience profile.

Table 25: Summary of Score Increases Based on Reassessment Using Stakeholder Responses (Table 1) and Reference Standards (Table 7)

ESSENTIAL AREA	INDICATOR	PREVIOUS SCORE	UPDATED SCORE	REASON FOR INCREASE
Essential 01: Organize for Disaster Resilience	1.1.2 Inclusive & participatory planning	2	3	Demonstrated improved stakeholder engagement and inclusive consultations in cultural heritage planning.
	1.1.4 Recognition of cultural heritage as enabler for sustainable development	2	3	Stronger integration of cultural heritage into sustainability goals observed in city master plans.
	1.1.5 Consideration of traditional design guidelines in renewal	2	3	Increased acknowledgment and incorporation of traditional design principles in planning documents.
	1.2.1 Entities responsible for cultural heritage management properly resourced	1	2	Improved coordination and allocation of resources to cultural heritage entities within inter-agency frameworks.
Essential 02: Identify and Use Risk Scenarios	2.1.1 Knowledge of exposure level of tangible heritage	1	2	Expanded data collection and better hazard mapping enhanced understanding of exposure.
	2.1.2 Consideration of transient population in exposure scenarios	1	2	Inclusion of transient population data into risk assessments acknowledged.
	2.1.3 Knowledge of vulnerability of tangible heritage	0	1	Initial vulnerability assessments for tangible heritage started.
	2.2.1 Hazard updates including tourism as risk driver	0	1	Tourism now recognized as a factor in hazard and exposure updates.

ESSENTIAL AREA	INDICATOR	PREVIOUS SCORE	UPDATED SCORE	REASON FOR INCREASE
Essential 03: Strengthen Financial Capability	3.4.1 Incentives for owners to support resilience actions	0	1	Some incentive schemes introduced for heritage owners promoting resilience.
Essential 05: Safeguard Natural Buffers	5.1.1 Acknowledgment of ecosystem services as natural heritage	1	2	Ecosystem services formally recognized as critical cultural and natural assets.
	5.2.1 Consideration of traditional knowledge in ecosystem management	2	3	Greater integration of traditional knowledge into ecosystem service management.
Essential 06: Strengthen Institutional Capacity	6.2.1 Education on local history and heritage in schools	1	2	Enhanced promotion of cultural heritage education in school curricula.
	6.2.2 Education on disaster risk and resilience in higher education	0	1	Initiation of heritage-focused disaster risk education in higher learning institutions.
	6.3.1 Data sharing among organizations	1	2	Increased interdepartmental data sharing on disaster risk and resilience of heritage.
	6.4.1 Knowledge exchange with other cities/countries	1	2	More regular and systematic knowledge exchange activities implemented.
Essential 07: Strengthen Societal Capacity	7.2.1 Business continuity plans reviewed	0	1	Some heritage-related businesses have begun documenting continuity plans.
	7.3.1 Communication strategy on cultural heritage importance	2	3	Communication strategies refined and more effectively disseminated to the public.
	7.3.2 Population engagement in heritage management	2	3	Enhanced efforts to actively engage citizens in cultural heritage initiatives.
Essential 08: Increase Infrastructure Resilience	8.2.1 Expected loss of visitation services	2	3	Better assessment of tourism risk scenarios with more detailed data.
	8.2.2 Expected loss of city revenue from tourism	2	3	Improved economic impact analysis related to tourism loss due to hazards.
	8.3.1 Expected loss of service for places of worship	2	3	More accurate evaluation of risks affecting places of worship integrated.

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ESSENTIAL AREA	INDICATOR	PREVIOUS SCORE	UPDATED SCORE	REASON FOR INCREASE
Essential 09: Ensure Effective Disaster Response	9.1.1 Integration of traditional knowledge in early warning	0	1	Early efforts to incorporate traditional knowledge into warning systems initiated.
	9.2.1 Emergency response plans consider heritage peculiarities	0	1	Heritage-specific considerations included in emergency response planning.
	9.3.1 Training of first responders on heritage	0	1	Initial training programs established for responders on cultural heritage issues.
	9.5.1 Culturally appropriate disaster relief needs defined	0	2	Improved efforts to tailor disaster relief to cultural and local needs.
Essential 10: Expedite Recovery and Build Back Better	10.1.2 Inclusive post-event recovery planning consultations	0	1	Initial participatory approaches to recovery planning implemented.
	10.1.3 Integration of heritage in economic reboot plans	0	1	Early integration of cultural heritage in economic reboot and recovery strategies.

7.2.2. Overall Resilience Assessment Summary

The city’s cultural heritage resilience assessment shows notable improvement, achieving an overall score of 81 out of 132 points (61.4%). This reflects a stronger and more balanced performance across multiple resilience dimensions compared to prior evaluations. The use of detailed stakeholder inputs (Annex) and reference standards (Table 24) revealed enhanced alignment with best practices, particularly in governance and planning frameworks (Essential 01), risk knowledge (Essential 02), and financial capability (Essential 03). Furthermore, there is greater integration of traditional knowledge in natural buffer management (Essential 05) and improved institutional capacity demonstrated through education, data sharing, and skills development (Essential 06). While strengths are evident in urban development (Essential 04), citizen engagement (Essential 07), and tourism-related infrastructure resilience (Essential 08), some areas such as disaster response (Essential 09) and recovery planning (Essential 10) still require targeted attention. This more optimistic assessment underscores the city’s progress in embedding resilience within its cultural heritage management but also highlights key gaps where focused action is essential to ensure comprehensive protection and sustainability. Overall, the results offer a clearer roadmap to consolidate gains and address vulnerabilities, supporting the city’s ambition to build robust, culturally sensitive resilience.

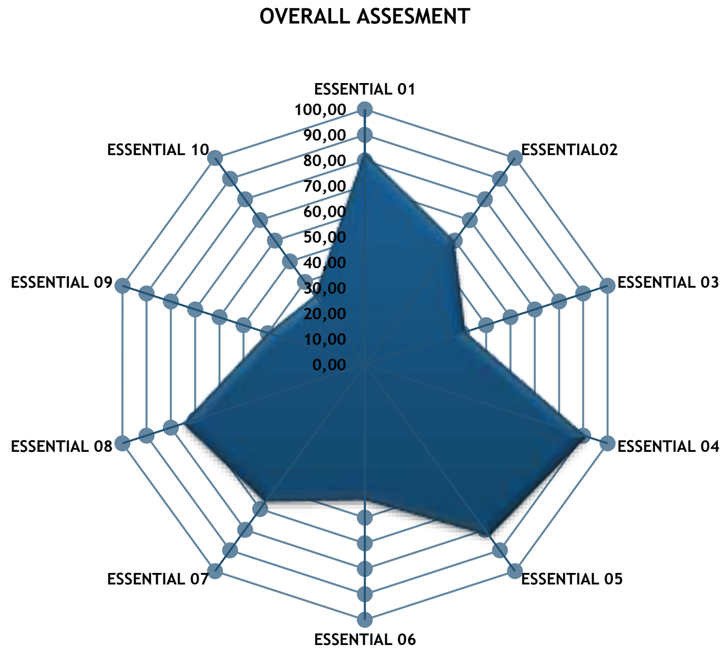

Figure 60. Overall Resiliente summary assesment Spider Chart

8. OUTPUTS FOR OTHERS WPS

The results of Deliverable 8.6 will contribute directly to WP11 and WP15 by providing the technical basis and structured methodologies for assessing resilience-enabling interventions in cultural heritage contexts. These outputs translate the multi-scale approach developed in WP2 into case-specific analyses for the Latvian and Dutch demonstration sites, preparing the ground for the validation and refinement of strategies in collaboration with local stakeholders.

More specifically, the outputs will support WP11, Task 11.4 (demonstration of the MULTICLIMACT framework in a cultural-heritage context). The intervention portfolio identified in D8.6 for the Riga Central Market and surrounding areas, including strengthening options, advanced monitoring strategies, and tailored supply-chain considerations, will form the core of the discussions and assessments carried out with REA and other partners. These elements will be analysed in terms of their suitability to the site-specific hazards and constraints, supported by the KPI framework (reliability, robustness, resourcefulness, recovery) and the adapted UNDRR Disaster Resilience Scorecard for cultural heritage. The integration of social, economic, climatic, and technical factors outlined in D8.6 will guide the scenario analyses and stakeholder workshops foreseen in Task 11.4, ensuring that the potential measures are prioritised and contextualised for future application.

In WP15, these results will underpin Task 15.4 (deployment in the cultural-heritage context), where the focus shifts to continuous monitoring, evaluation, and refinement of the strategies developed in WP8. The methodologies and indicators introduced in D8.6 will be used to assess the performance, feasibility, and scalability of the proposed interventions, incorporating feedback from the demonstration phase. The work will build on the supply-chain analysis and resilience KPIs to inform decision-making, adjust priorities, and generate transferable knowledge for replication in other cultural-heritage settings. This process will ensure that the findings of D8.6 are fully integrated into the MULTICLIMACT decision-support framework and provide a robust reference for future resilience planning.

9. CONCLUSIONS

This deliverable applied the multi-scale methodology for designing resilience-enabling interventions proposed in Deliverable 2.6, to two demonstration sites, the Riga Central Market (Latvia) and the Tedingerbroekpolder dike (Netherlands). The methodology integrates risk assessment, the analysis of technical solutions, supply chain considerations, and stakeholder engagement. The results demonstrate that a combined technical and governance-oriented approach is essential to address the complex challenges of preserving cultural heritage under different hazards and agents of deterioration.

For the Riga Central Market, the assessment identified structural vulnerabilities exacerbated by existing deterioration and future load increases from planned energy efficiency upgrades. Four intervention strategies were proposed: strengthening the reinforced concrete basement slab with concrete overlays, implementing fiber optic-based monitoring systems, installing corrosion monitoring systems, and applying satellite remote sensing for displacement monitoring. These were evaluated not only for their engineering effectiveness but also for their impacts on reliability, robustness, resourcefulness, recovery capacity, as well as their impacts on sustainability and QoL indicators. Particularly, the integration of corrosion inhibitors and embedded monitoring sensors was shown to enhance durability and enable proactive maintenance, thereby reducing long-term risks. The supply chain analysis underscored the importance of secure procurement channels, skilled labor availability, and logistical planning to ensure that these resilience measures can be deployed without disrupting essential urban functions.

In the Dutch case, interventions focused on real-time distributed fiber optic monitoring and satellite remote sensing to detect early signs of instability in the dike system. These measures address both gradual degradation processes and hazard scenarios, improving early warning capabilities and informing timely maintenance interventions.

Stakeholder engagement, particularly in the Latvian demo site, was a critical component of the methodology. Using the UNDRR Disaster Resilience Scorecard for Cities – Cultural Heritage Addendum, stakeholders from municipal departments, academia, tourism, and national heritage agencies provided input on the current resilience condition. This process revealed both strengths and capacity gaps across the Ten Essentials, offering a baseline for prioritizing future interventions.

Finally, the outcomes of Task 8.6 confirm that enhancing the resilience of cultural heritage requires a multidisciplinary framework that combines structural engineering solutions, technological monitoring, governance alignment, and community participation. The integration of performance-based assessment with socio-economic and environmental considerations ensures that proposed measures are technically sound, contextually appropriate, and operationally feasible. The findings from Task 8.6 will serve to inform city planning and decision-making processes, ensuring that intervention measures effectively increase the resilience of historic urban environments.

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10. REFERENCES

Aguilar-López, Juan, Niels Nöter, and Ilaria Ingrosso. 2024. D3.1 – Review, design and specifications of Fiber optic-based monitoring systems for flood defences.

Aljibori, Hakim, Ahmed Al-Amiery, and Wan Nor Roslam Isahak. 2024. "Advancements in corrosion prevention techniques." Journal of Bio-and Tribo-Corrosion 10 (4): 78.

Almeida, Cláudia Peres, Ana Ferreira Ramos, and J. Mendes Silva. 2018. "Sustainability assessment of building rehabilitation actions in old urban centres." Sustainable Cities and Society 36: 378-385. https://doi.org/https://doi.org/10.1016/j.scs.2017.10.014. https://www.sciencedirect.com/science/article/pii/S2210670717305358.

Asmara, Yuli Panca. 2023. Concrete Reinforcement Degradation and Rehabilitation: Damages, Corrosion and Prevention. Springer Nature.

Avotniece, Zane, S. Aniskevich, and E. Malinovskis. n.d. "Climate Change Scenarios for Latvia."

Baker, Jack W., Matthias Schubert, and Michael H. Faber. 2008. "On the assessment of robustness." Structural Safety 30 (3). https://doi.org/10.1016/j.strusafe.2006.11.004. https://www.sciencedirect.com/science/article/pii/S0167473006000737.

Bakkenist, SW, and WS Zomer. 2010. Inspectie van waterkeringen: een overzicht van meettechnieken. STOWA Amersfoort, the Netherlands.

Ballesteros, Ma Jesús, Marcos D. Fernández, Samuel Quintana, José A. Ballesteros, and Isabel González. 2010. "Noise emission evolution on construction sites. Measurement for controlling and assessing its impact on the people and on the environment." Building and Environment 45 (3). https://doi.org/10.1016/j.buildenv.2009.08.011. https://www.sciencedirect.com/science/article/abs/pii/S0360132309002054.

Biringer , Betty, Eric Vugrin , and Drake Warren. 2013. Critical Infrastructure System Security and Resiliency. edited by CRC Press. Boca Raton.

Bonì, Roberta, Claudia Meisina, Francesca Cigna, Gerardo Herrera, Davide Notti, Stephanie Bricker, Harry McCormack, Roberto Tomás, Marta Béjar-Pizarro, and Joaquín Mulas. 2017. "Exploitation of satellite A-DInSAR time series for detection, characterization and modelling of land subsidence." Geosciences 7 (2): 25.

Bruneau, Michel, Stephanie E. Chang, Ronald T. Eguchi, George C. Lee, Thomas D. O'Rourke, Andrei M. Reinhorn, Masanobu Shinozuka, Kathleen Tierney, William A. Wallace, Detlof von Winterfeldt, and Stephanie E. Chang Michel Bruneau, Ronald T. Eguchi, George C. Lee, Thomas D. O'Rourke, Andrei M. Reinhorn, Masanobu Shinozuka, Kathleen Tierney, William A. Wallace, Detlof von Winterfeldt. 2003. "A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities." Earthquake Spectra 19 (4). https://doi.org/10.1193/1.1623497. https://journals.sagepub.com/doi/10.1193/1.1623497.

Butera, Stefania, Thomas H. Christensen, and Thomas F. Astrup. 2015. "Life cycle assessment of construction and demolition waste management." Waste Management 44. https://doi.org/10.1016/j.wasman.2015.07.011. https://www.sciencedirect.com/science/article/abs/pii/S0956053X15300283.

Camagni, Roberto, Maria Cristina Gibelli, and Paolo Rigamonti. 2002. "Urban mobility and urban form: the social and environmental costs of different patterns of urban expansion." Ecological Economics 40 (2). https://doi.org/10.1016/S0921-8009(01)00254-3. https://www.sciencedirect.com/science/article/abs/pii/S0921800901002543.

Casas, Joan Ramon, and Dawid Wisniewski. 2013. "Safety requirements and probabilistic models of resistance in the assessment of existing railway bridges." Structure and Infrastructure Engineering 9 (6). https://doi.org/10.1080/15732479.2011.581673. https://www.tandfonline.com/doi/full/10.1080/15732479.2011.581673.

Cavaco, Eduardo S., Joan R. Casas, Luis A.C. Neves, and Alfredo E. Huespe. 2013. "Robustness of corroded reinforced concrete structures - a structural performance approach." Structure and Infrastructure Engineering. https://doi.org/10.1080/15732479.2010.515597. https://www.tandfonline.com/doi/full/10.1080/15732479.2010.515597.

CEN. 2006. EN 1504-7: Products and Systems for the Protection and Repair of Concrete Structures — Definitions, Requirements, Quality Control and Evaluation of Conformity: Part 7: Reinforcement Corrosion Protection. European Standard EN 1504-7:2006. Brussels: European Committee for Standardization.

CEN. 2017. *EN 1504-10: Products and Systems for the Protection and Repair of Concrete Structures — Definitions, Requirements, Quality Control and Evaluation of Conformity: Part 10: Site Application of Products and Systems and Quality Control of the Works*. European Standard EN 1504-10:2017. Brussels: European Committee for Standardization.

Chan, Chak K., and Xiaohong Yao. 2008. "Air pollution in mega cities in China." Atmospheric Environment 42 (1). https://doi.org/10.1016/j.atmosenv.2007.09.003. https://www.sciencedirect.com/science/article/abs/pii/S1352231007007911.

Chan, Faith Ka Shun, Liang Emlyn Yang, Gordon Mitchell, Nigel Wright, Mingfu Guan, Xiaohui Lu, Zilin Wang, Burrell Montz, and Olalekan Adekola. 2022. "Comparison of sustainable flood risk management by four countries-the United Kingdom, the Netherlands, the United States, and Japan-and the implications for Asian coastal megacities." Natural Hazards and Earth System Sciences 22 (8): 2567-2588.

Chen, Fulong, Jiangbin You, Panpan Tang, Wei Zhou, Nicola Masini, and Rosa Lasaponara. 2018/01/01. "Unique performance of spaceborne SAR remote sensing in cultural heritage applications: Overviews and perspectives." Archaeological Prospection 25 (1).

https://doi.org/10.1002/arp.1591. https://onlinelibrary.wiley.com/doi/full/10.1002/arp.1591.

Chong, Kar Yee, and Ann Selvaranee Balasingam. 2019. "Tourism sustainability: Economic benefits and strategies for preservation and conservation of heritage sitesin Southeast Asia." Tourism Review 74 (2): 268-279.

Cortiços, Nuno. 2025. "Circular Economy in the Conservation, Restoration and Rehabilitation."

Costa, Luis G.L., and André T. Beck. 2024. "A critical review of probabilistic live load models for buildings: Models, surveys, Eurocode statistics and reliability-based calibration." Structural Safety 106. https://doi.org/10.1016/j.strusafe.2023.102411. https://www.sciencedirect.com/science/article/pii/S016747302300098X?via=ihub.

Capital Riga. 2019. "IF WE SURVIVE THIS... Heat, Flood, and Climate Change in Riga." Accessed January 6, 2025. http://www.capitalriga.eu/2019/07/if-we-survive-this-heat-flood-and.html.

Council, Riga City. 2012. Integrated Strategy for Riga City to Adapt to the Hydrological Processes Intensified by Climate Change Phenomena . http://www.rigapretpludiem.lv.

Delfland Water Board. Tedingerbroekpolder, 1605-1976. Historical Archive: Delft City Archives.

DIANA, TNO. 2024. User's Manual DIANA 10.9. T**NO Building** and **Construction Research**.

Drougkas, A., Verstrynge, E., Van Balen, K., Shimoni, M., Croonenborghs, T., Hayen, R. and Declercq, P.Y. 2021. "Country-scale InSAR monitoring for settlement and uplift damage calculation in architectural heritage structures." Structural Health Monitoring 20 (5). https://doi.org/10.1177/1475921720942120. https://journals.sagepub.com/doi/epub/10.1177/1475921720942120.

European Commission. 2013. "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions." Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52013DC0216&from=EN.

Ferris, Brian, Kari Watkins, and Alan Borning. 2010. "OneBusAway | Proceedings of the SIGCHI Conference on Human Factors in Computing Systems." Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. https://doi.org/10.1145/1753326.1753597. https://dl.acm.org/doi/10.1145/1753326.1753597.

Füssel, Hans-Martin, Andries Jol, and European Environment Agency, eds. 2012. Climate Change, Impacts and Vulnerability in Europe 2012: An Indicator-Based Report. Luxembourg: Publications Office of the European Union. https://doi.org/10.2800/66071.

Gligor, E, D Gomboș, Cristina Hora, FC Dan, H Hora, and Noemi Majoros. 2025. "Energy-Efficient Rehabilitation of Buildings: Mitigating Heat Loss and Structural Risks in Pre-1990 Constructed Structures." Journal of Applied Engineering Sciences 15 (1).

Hammad, A.W.A., A. Akbarnezhad, and D. Rey. 2016. "A multi-objective mixed integer nonlinear programming model for construction site layout planning to minimise noise pollution and transport costs." Automation in Construction 61. https://doi.org/10.1016/j.autcon.2015.10.010. https://www.sciencedirect.com/science/article/abs/pii/S0926580515002150.

Hammer, Monica S, Tracy K Swinburn, and Richard L Neitzel. 2013. "Environmental Noise Pollution in the United States: Developing an Effective Public Health Response." Environmental Health Perspectives 122 (2). https://doi.org/10.1289/ehp.1307272. https://pmc.ncbi.nlm.nih.gov/articles/PMC3915267/.

Hangan, Anca, Costin-Gabriel Chiru, Diana Arsene, Zoltan Czako, Dragos Florin Lisman, Mariana Mocanu, Bogdan Pahontu, Alexandru Predescu, and Gheorghe Sebestyen. 2022. "Advanced techniques for monitoring and management of urban water infrastructures—An overview." Water 14 (14): 2174.

Hanssen, Ramon F, and Freek J Van Leijen. 2008. "Monitoring water defense structures using radar interferometry." 2008 IEEE Radar Conference.

Hieronymus, M., C. Dieterich, H. Andersson, and R. Hordoir. 2018. "The Effects of Mean Sea Level Rise and Strengthened Winds on Extreme Sea Levels in the Baltic Sea." Theoretical and Applied Mechanics Letters 8 (6): 366-371. https://doi.org/10.1016/j.taml.2018.06.008.

Hansson, CM, A Poursaee, and SJ Jaffer. 2012. "Corrosion of reinforcing bars in concrete." The Masterbuilder 15 (3): 106-124.

Hughes, Sara. 2015. "A meta-analysis of urban climate change adaptation planning in the U.S." Urban Climate 14. https://doi.org/10.1016/j.uclim.2015.06.003. https://www.sciencedirect.com/science/article/abs/pii/S2212095515300018.

Ivaskova, Martina, Peter Kotes, and Miroslav Brodnan. 2015. "Air Pollution as an Important Factor in Construction Materials Deterioration in Slovak Republic." Procedia Engineering 108. https://doi.org/10.1016/j.proeng.2015.06.128. https://www.sciencedirect.com/science/article/pii/S1877705815010826.

JCSS. 2001. "Probabilistic model code." Joint Committee on Structural Safety.

Jorissen, Richard, Erik Kraaij, and Ellen Tromp. 2016. "Dutch flood protection policy and measures based on risk assessment." E3S Web of Conferences.

Júlio, Eduardo, Eduardo Cavaco, et al. 2022a. Guide for Strengthening of Concrete Structures: Guide for Good Practice. fib Bulletin No. 103. Fédération Internationale du Béton (fib). ISBN 978-2-88394-158-8.

Júlio, Eduardo, Eduardo Cavaco, et al. 2022b. Guide for Protection and Repair of Concrete Structures: Guide for Good Practice. fib Bulletin No. 102. Fédération Internationale du Béton (fib). ISBN 978-2-88394-156-4.

Kampa, Marilena, and Elias Castanas. 2008. "Human health effects of air pollution - PubMed." Environmental pollution (Barking, Essex : 1987) 151 (2). https://doi.org/10.1016/j.envpol.2007.06.012. https://pubmed.ncbi.nlm.nih.gov/17646040/.

Kaur, Manpreet, P Selvakumar, N Dinesh, Pankaj Singh Chandel, and TC Manjunath. 2025. "Reconstruction and Preservation Strategies for Cultural Heritage." In Preserving Cultural Heritage in Post-Disaster Urban Renewal, 385-412. IGI Global Scientific Publishing.

Kumar, Prashant, Mukesh Khare, Roy M. Harrison, William J. Bloss, Alastair C. Lewis, Hugh Coe, Lidia Morawska, Prashant Kumar, Mukesh Khare, Roy M. Harrison, William J. Bloss, Alastair C. Lewis, Hugh Coe, and Lidia Morawska. 2015. "New directions: Air pollution challenges for developing megacities like Delhi." Atmospheric Environment 122. https://doi.org/10.1016/j.atmosenv.2015.10.032. https://ui.adsabs.harvard.edu/abs/2015AtmEn.122..657K/abstract.

Kühlen, Anna, Rebekka Volk, and Frank Schultmann. 2016. "State of the art of demolition and reuse and recycling of construction materials." Proceedings of the CIB World Building Congress.

Kūle, Laila, Agrita Briede, Māris Kļaviņŝ, Guntis Eberhards, and Andris Loĉmanis. 2013. "Adaptation to Floods in Riga, Latvia: Historical Experience and Change of Approaches." Climate Change Adaptation in Practice. https://doi.org/10.1002/9781118548165.ch6. https://onlinelibrary-wiley-com.ezproxy.uniandes.edu.co/doi/10.1002/9781118548165.ch6.

Laefer, Debra F, and Jonathan P Manke. 2008. "Building reuse assessment for sustainable urban reconstruction." Journal of construction engineering and management 134 (3): 217-227.

Laohaviraphap, Neeraparng, Tanut Waroonkun, Neeraparng Laohaviraphap, and Tanut Waroonkun. 2024. "Integrating Artificial Intelligence and the Internet of Things in Cultural Heritage Preservation: A Systematic Review of Risk Management and Environmental Monitoring Strategies." Buildings 2024, Vol. 14, Page 3979 14 (12). https://doi.org/10.3390/buildings14123979. https://www.mdpi.com/2075-5309/14/12/3979.

Lee, Sung Chan, Joo Young Hong, and Jin Yong Jeon. 2015. "Effects of acoustic characteristics of combined construction noise on annoyance." Building and Environment 92.

https://doi.org/10.1016/j.buildenv.2015.05.037. https://www.sciencedirect.com/science/article/abs/pii/S0360132315002577.

Li, Heng, Zhen Chen, Liang Yong, and Stephen C.W. Kong. 2005. "Application of integrated GPS and GIS technology for reducing construction waste and improving construction efficiency." Automation in Construction 14 (3). https://doi.org/10.1016/j.autcon.2004.08.007. https://www.sciencedirect.com/science/article/abs/pii/S0926580504001050.

Liao, Pei-shan, Daigee Shaw, Yih-ming Lin, Pei-shan Liao, Daigee Shaw, and Yih-ming Lin. 2014. "Environmental Quality and Life Satisfaction: Subjective Versus Objective Measures of Air Quality." Social Indicators Research 2014 124:2 124 (2). https://doi.org/10.1007/s11205-014-0799-z. https://link.springer.com/article/10.1007/s11205-014-0799-z.

Liu, Xingjian, Yan Song, Kang Wu, Jianghao Wang, Dong Li, and Ying Long. 2015. "Understanding urban China with open data." Cities 47. https://doi.org/10.1016/j.cities.2015.03.006. https://www.sciencedirect.com/science/article/abs/pii/S0264275115000372.

Luprano, Vincenza A.M., Gloria Cosoli, Alessandra Mobili, Gian Marco Revel, and Chiara Giosuè. 2024. D3.3 - Review, design and specifications of cuttingedge, evolutive, selfsensing and multifunctional materials and technologies for improving the resilience of buildings, including cultural heritage.

Latvian Ministry of Environmental Protection and Regional Development. 2019. "Latvian National Plan for Adaptation to Climate Change until 2030." https://www.varam.gov.lv/en/media/32915/download?attachment.

McGranahan, Gordon, and David Satterthwaite. 2002. "The environmental dimensions of sustainable development for cities." Geography 87 (3): 213-226.

Metallidou, Chrysi K, Kostas E Psannis, and Eugenia Alexandropoulou Egyptiadou. 2020. "Energy efficiency in smart buildings: IoT approaches." IEEE access 8: 63679-63699.

Momber, Andreas. 2011. Hydrodemolition of concrete surfaces and reinforced concrete. Elsevier.

Moskovkina, E. 1960. Floodings on the Daugava River.

Munarim, Ulisses, and Enedir Ghisi. 2016. "Environmental feasibility of heritage buildings rehabilitation." Renewable and Sustainable Energy Reviews 58: 235-249.

Ndrevataj, Mersida. 2025. "Cultural Sustainability for Sustainable Cities Development: Notes from UNESCO and Venice City." In The Sustainable Organization: How Organizations Address the 17 UN SDGs Using the 3-P-Model, 219-235. Springer.

Neighborhood. 2023. "Rīgas Centrāltirgus." Accessed 16/01/2024. https://neighborhood.lv/en/real-estate/rigas-centraltirgus/.

Omer, Abdeen Mustafa. 2009. "Energy use and environmental impacts: A general review." Journal of renewable and Sustainable Energy 1 (5): 053101.

Pedersoli Jr, José Luiz, Catherine Antomarchi, and Stefan Michalski. 2016. A guide to risk management of cultural heritage. ICCROM.

Peredistijs, Artūrs. 2024. Technical Inspection Report: Riga Central Market, Dairy Pavilion.

Ponnada, Markandeya Raju, and P Kameswari. 2015. "Construction and demolition waste management—a review." safety 84: 19-46.

Poon, Chi Sun, Ann Tit Wan Yu, Sze Wai Wong, and Esther Cheung. 2004. "Management of construction waste in public housing projects in Hong Kong." Construction Management & Economics 22 (7). https://doi.org/10.1080/0144619042000213292. https://www.tandfonline.com/doi/abs/10.1080/0144619042000213292.

Rodríguez-Antuñano, I., Joaquim J. Sousa, M. Bakoň, A. M. Ruiz-Armenteros, J. Martínez-Sánchez, and B. Riveiro. 2024. "Empowering intermediate cities: cost-effective heritage preservation through satellite remote sensing and deep learning." International Journal of Remote Sensing. https://doi.org/10.1080/01431161.2024.2358544. https://www.tandfonline.com/doi/full/10.1080/01431161.2024.2358544.

Rossi, Michela, Dionysios Bournas, Michela Rossi, and Dionysios Bournas. 2023. "Structural Health Monitoring and Management of Cultural Heritage Structures: A State-of-the-Art Review." Applied Sciences 2023, Vol. 13, Page 6450 13 (11). https://doi.org/10.3390/app13116450. https://www.mdpi.com/2076-3417/13/11/6450.

Riga City Council. 2014. "Sustainable Development Strategy of Riga until 2030 and Development Programme of Riga for 2014-2020: Summary." https://rdpad.lv/wp-content/uploads/2014/11/ENG_STRATEGIJA.pdf.

Schneider, Jörg. 1997. Introduction to Safety and Reliability of Structures. IABSE.

Segura Garcia, Jaume, Santiago Felici Castell, Juan J. Pérez Solano, Máximo Cobos, Juan Miguel Navarro, Jaume Segura Garcia, Santiago Felici Castell, Juan J. Pérez Solano, Máximo Cobos, and Juan Miguel Navarro. 2014. "Low-Cost Alternatives for Urban Noise Nuisance Monitoring Using Wireless Sensor Networks." IEEE Sensors Journal 15 (2). https://doi.org/10.1109/JSEN.2014.2356342. https://repositorio.ucam.edu/handle/10952/9348.

Seneviratne, Sonia I., Muhammad Adnan, Wafae Badi, Claudine Dereczynski, Alejandro Di Luca, Subimal Ghosh, Iskhaq Iskandar, James Kossin, Sophie Lewis, Friederike Otto, Izidine Pinto, Masaki Satoh, Sergio M. Vicente-Serrano, Michael Wehner, and Botao Zhou. 2022. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth

Assessment Report of the Intergovernmental Panel on Climate Change.{Weather and Climate Extreme Events in a Changing Climate. Cambridge: Cambridge University Press.

Shen, L. Y., Vivian W. Y. Tam, C. M. Tam, D. Drew, L. Y. Shen, Vivian W. Y. Tam, C. M. Tam, and D. Drew. 2004. "Mapping Approach for Examining Waste Management on Construction Sites." Journal of Construction Engineering and Management 130 (4). https://doi.org/10.1061/(ASCE)0733-9364(2004)130:4(472). https://ascelibrary.org/doi/10.1061/%28ASCE%290733-9364%282004%29130%3A4%28472%29.

Shen, Li-Yin, Wei-Sheng Lu, Hong Yao, and De-Hua Wu. 2005. "A computer-based scoring method for measuring the environmental performance of construction activities." Automation in Construction 14 (3). https://doi.org/10.1016/j.autcon.2004.08.017. https://www.sciencedirect.com/science/article/abs/pii/S0926580504001037.

Silva, V., A. Calderon, M. Caruso, C. Costa, J. Dabbeek, M.C. Hoyos, Z. Karimzadeh, L. Martins, N. Paul, A. Rao, M. Simionato, C. Yepes-Estrada, H. Crowley, and K. Jaiswal. 2023. Country/Territory Seismic Risk Profiles of the GEM Foundation. GitHub.

Sousa, H., I. Ingrosso, and L. Urciuoli. 2024. D2.6 - Planning and designing resilience enabling interventions in

cultural heritage buildings, urban and rural contexts.

Strazdiņš, Māris. 2024. Check calculation of the Central Market Dairy Pavilion basement slab.

SY, Wang, Li YH, Chi GB, Xiao SY, Ozanne-Smith J, Stevenson M, and Phillips MR. 2008. "Injury-related fatalities in China: an under-recognised public-health problem - PubMed." Lancet (London, England) 372 (9651). https://doi.org/10.1016/S0140-6736(08)61367-7. https://pubmed.ncbi.nlm.nih.gov/18930527/.

Sánchez-Silva, Mauricio, and Georgia-Ann Klut. 2016. Reliability and Life-Cycle Analysis of Deteriorating Systems.Springer Series in Reliability Engineering.

Thomas, H. Randolph, and Ralph D. Ellis. 2017. "Construction Site Management and Labor Productivity Improvement | Books." https://doi.org/10.1061/9780784414651. https://ascelibrary.org/doi/book/10.1061/9780784414651.

Thompson, Susan, and Jennifer Kent. 2014. "Connecting and strengthening communities in places for health and well-being." Australian Planner 51 (3): 260-271.

Toor, Shamas-ur-Rehman, and Stephen Ogunlana. 2010. "Beyond the 'iron triangle': Stakeholder perception of key performance indicators (KPIs) for large-scale public sector development projects." International Journal of Project Management 28 (3). https://doi.org/10.1016/j.ijproman.2009.05.005. https://www.sciencedirect.com/science/article/abs/pii/S0263786309000623.

Turksezer, Zehra Irem, Maria Pina Limongelli, and Michael Havbro Faber. 2022. "On a generic framework for systems resilience modelling of bridges - accounting for historic and cultural values." Sustainable and Resilient Infrastructure 7 (5). https://doi.org/10.1080/23789689.2020.1859272. https://www.tandfonline.com/doi/full/10.1080/23789689.2020.1859272.

UNDRR. 2022. Disaster Resilience Scorecard for Cities - Cultural Heritage Addendum. (UN Office for Disaster Risk Reduction).

UNESCO. 2024. "Historic Centre of Riga." Accessed 15/01/2024. https://whc.unesco.org/en/list/852/.

USSR. 1982. GOST 5781 -82 Specifications: Hot-rolled steel for reinforcement of ferroconcrete structures. Standards Publishing House, Moscow: USSR STATE STANDARD.

Van Baars, Stefan. 2005. "The horizontal failure mechanism of the Wilnis peat dyke." Géotechnique 55 (4): 319-323.

Varma, Aditya Kumar. 2025. "Risk Assessment and Preservation for Cultural Heritage Buildings using InSAR Monitoring." International Masters in Risk Assessment and Management of Civil Infrastructures, Civil Engineering Department, University of Minho.

Waidyasekara, KGAS, ML De Silva, and R Rameezdeen. 2014. "A critical review of water studies in construction industry." The 3rd World Construction Symposium.

Wang, Jiayuan, Zhengdao Li, and Vivian W.Y. Tam. 2014. "Critical factors in effective construction waste minimization at the design stage: A Shenzhen case study, China." Resources, Conservation and Recycling 82. https://doi.org/10.1016/j.resconrec.2013.11.003. https://www.sciencedirect.com/science/article/abs/pii/S0921344913002309.

Wisniewski, Dawid, Joan R. Casas, and Michel Ghosn. 2006. "Load Capacity Evaluation of Existing Railway Bridges based on Robustness Quantification." Structural Engineering International 16 (2). https://doi.org/10.2749/101686606777962440. https://www.tandfonline.com/doi/abs/10.2749/101686606777962440.

Wisniewski, Dawid F., Joan R. Casas, and Michel Ghosn. 2009. "Simplified probabilistic non-linear assessment of existing railway bridges." Structures & Infrastructure Engineering 5 (6). https://doi.org/10.1080/15732470701639906. https://www.tandfonline.com/doi/full/10.1080/15732470701639906.

Wiśniewski, Dawid F., Paulo J.S. Cruz, A. Abel R. Henriques, and Rui A.D. Simões. 2012. "Probabilistic models for mechanical properties of concrete, reinforcing steel and pre-stressing steel." Structure and Infrastructure Engineering 8 (2). https://doi.org/10.1080/15732470903363164. https://www.tandfonline.com/doi/abs/10.1080/15732470903363164.

Wu, Zezhou, Xiaoling Zhang, and Min Wu. 2016. "Mitigating construction dust pollution: state of the art and the way forward." Journal of Cleaner Production 112. https://doi.org/10.1016/j.jclepro.2015.01.015. https://www.sciencedirect.com/science/article/abs/pii/S0959652615000190.

Zheng, Yu, Furui Liu, and Hsun-Ping Hsieh. 2013. "U-Air | Proceedings of the 19th ACM SIGKDD international conference on Knowledge discovery and data mining." Proceedings of the 19th ACM SIGKDD international conference on Knowledge discovery and data mining. https://doi.org/10.1145/2487575.2488188. https://dl.acm.org/doi/10.1145/2487575.2488188.

Zou, Patrick X.W., Guomin Zhang, and Jiayuan Wang. 2007. "Understanding the key risks in construction projects in China." International Journal of Project Management 25 (6). https://doi.org/10.1016/j.ijproman.2007.03.001. https://www.sciencedirect.com/science/article/abs/pii/S0263786307000488.

Zou, Zhengbo, and Semiha Ergan. 2019. "Leveraging Data Driven Approaches to Quantify the Impact of Construction Projects on Urban Quality of Life." https://doi.org/10.48550/arXiv.1901.09084. https://arxiv.org/abs/1901.09084.

Zulkarnain, Iskandar, Nor Adila Mohamad Kassim, MI Syakir, Azhar Abdul Rahman, Mohamad Shaiful Md Yusuff, Rosdin Mohd Yusop, and Ng Oon Keat. 2021. "Sustainability-based characteristics of abrasives in blasting industry." Sustainability 13 (15): 8130.

Özer, Işıl E, Stephan JH Rikkert, Freek J van Leijen, Sebastiaan N Jonkman, and Ramon F Hanssen. 2019. "Sub-seasonal levee deformation observed using satellite radar interferometry to enhance flood protection." Scientific Reports 9 (1): 2646.

11. ANNEX

Responses of the Resilience Scorecard questionnaire from identified stakeholders as outlined in Chapter 7.

ESSENTIAL 01 ORGANIZE FOR DISASTER RESILIENCE		
1.1	**PLAN MAKING**	
1.1.1		**QUESTION**
To what extent does the city master plan (or relevant disaster risk reduction/vision plan) acknowledge all forms of cultural heritage, its prioritization and management?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	3 - Full acknowledgment, prioritization and management of all forms of cultural heritage. Actions are included directly responding to current and anticipated future risks.
☑	☑	2 - Acknowledgment, prioritization and management of cultural heritage with only some limitations. Actions are included directly responding to current and anticipated future risks.
☐	☐	1 - Broad acknowledgment, prioritization and management of cultural heritage. Actions not included or with significant short falls.
☐	☐	0 - No acknowledgment, prioritization or management of cultural heritage
1.1.2		**QUESTION**
Has the city master plan (or relevant strategy/plan) been developed through inclusive and participatory consultations of all concerned groups and institutions in the cultural heritage sector?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☑	☑	3 - All concerned groups and institutions have been engaged/consulted.
☐	☐	2 - More than half of the concerned groups and institutions have been engaged/consulted.
☐	☐	1 - Only few of the concerned groups and institutions have been engaged/consulted.
☐	☐	0 - Concerned groups and institutions have not been engaged/consulted.

1.1.3		QUESTION
Are the socio-economic benefits of cultural heritage acknowledgment, prioritization and management clearly recognized in the city master plan (or relevant strategy/plan)?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	3 - Benefits are quantitatively recognized.
☐	☐	2 - Benefits are qualitatively but not quantitively recognized.
☐	☑	1 - Benefits are broadly recognized but there are significant shortfalls.
☑	☐	0 - Benefits are not recognized.
1.1.3		**QUESTION**
Does the city master plan (or relevant strategy/plan) acknowledge and promote culture and cultural heritage as an enabler for sustainable development?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☑	☐	3 - Full acknowledgment, actions are included.
☐	☑	2 - Full acknowledgment, but actions are not included.
☐	☐	1 - Broad acknowledgment.
☐	☐	0 - No acknowledgment.
1.1.5		**QUESTION**
Does the city master plan (or relevant strategy/plan) consider traditional design guidelines in the renewal of places?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☑	☐	3 - Traditional design guidelines are considered in all places and are mandatory.
☐	☑	2 - Traditional design guidelines are considered in all places but are not mandatory.
☐	☐	1 - Traditional design guidelines are considered only in some places.
☐	☐	0 - Traditional design guidelines are not considered.
1.2		**ORGANIZATION AND COORDINATION**
1.2.1		**QUESTION**
Are entities responsible for cultural heritage management well established, properly resourced/funded and have authority to act within an inter-agency framework with those responsible for disaster risk reduction?		

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Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	3 - Entities are well established, properly resourced/funded and have authority to act.
☐	☐	2 - Entities are well established and are properly resourced/founded but do not have authority to act.
☑	☑	1 - Entities are well established but lack proper authority and resources/funding.
☐	☐	0 - Entities are not well established, therefore may lack inter-agency support.

ESSENTIAL 02 IDENTIFY, UNDERSTAND, AND USE CURRENT AND FUTURE RISK SCENARIOS		
2.1	KNOWLEDGE OF EXPOSURE AND VULNERABILITY	
2.1.1		**QUESTION**
What is the level of knowledge regarding the exposure level of all tangible cultural heritage to possible hazards?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	3 - Comprehensive knowledge of the exposure with regular updates.
☐	☑	2 - Comprehensive knowledge of the exposure but no updates.
☑	☐	**1 -** Some shortcomings in the knowledge of the exposure and no updates.
☐	☐	**0 -** Only generalized knowledge of the exposure and no updates.
2.1.2		**QUESTION**
Is transient population considered when setting out exposure scenarios?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Transient population is considered with its short period variation (daily/weekly).

☐	☑	**2** - Transient population is considered with average seasonal variations.
☑	☐	**1** - Transient population is considered using fixed values for the whole year.
☐	☐	**0** - Transient population is not considered.
2.1.3		**QUESTION**
What is the level of knowledge regarding the vulnerability of all tangible cultural heritage to possible hazards?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3** - Comprehensive knowledge of the vulnerability with regular updates.
☐	☑	**2** - Comprehensive knowledge of the vulnerability but no updates.
☐	☐	**1** - Some shortcomings in the knowledge of the vulnerability and no updates.
☑	☐	**0** - Only generalized knowledge of the vulnerability and no updates.
2.1.4		**QUESTION**
What is the level of knowledge regarding all forms of intangible cultural heritage?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☑	☑	**3** - The Municipality has comprehensive knowledge of all its intangible cultural heritage.
☐	☐	**2** - The Municipality has good knowledge of its intangible cultural heritage and only a limited portion of it may be left out.
☐	☐	**1** - The Municipality has knowledge of its intangible cultural heritage but there are significant shortcomings in the definition.
☐	☐	**0** - The Municipality has only a generalized knowledge of its intangible cultural heritage.
2.2 UPDATING INFORMATION ABOUT SCENARIOS, RISK, VULNERABILITY AND EXPOSURE		
2.2.1		**QUESTION**

Does the update process of hazard and exposure information include tourism as a potential risk driver?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Tourism is fully included as a potential risk driver and its effects are quantified also with the help of third parties.
☐	☐	**2 -** Tourism is fully included as a potential risk driver, but the quantification is still rudimentary.
☐	☑	**1 -** Tourism is broadly included as a potential risk driver, with no systematic attempt to quantify it.
☑	☐	**0 -** Tourism is not included as a potential risk driver.

ESSENTIAL 03 STRENGTHEN FINANCIAL CAPABILITY FOR RESILIENCE		
3.1 KNOWLEDGE OF NEW INVESTMENTS MECHANISMS FOR CULTURAL HERITAGE MANAGEMENT		
3.1.1		**QUESTION**
To what extent is the local government aware of all potential financing and funding mechanisms for cultural heritage management and is actively pursuing them?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☑	**3 -** There is a dedicated responsibility within the city government who has comprehensive knowledge of all potential financing and funding mechanisms.
☑	☐	**2 -** There is a dedicated responsibility within the city government, but knowledge of potential financing and funding mechanisms is incomplete or accessing such funds can be too resource intensive.
☐	☐	**1 -** There is no dedicated responsibility within the city government and only low/partial awareness of potential financing and funding mechanisms.
☐	☐	**0 -** Financing or funding mechanisms are not considered.
3.2 ADEQUACY AND PROTECTION OF FUNDS FOR CULTURAL HERITAGE MANAGEMENT PROJECTS		
3.2.1		**QUESTION**
To what extent are projects for cultural heritage management adequately funded and not likely to be diverted for other purposes?		

Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Projects exist, they are adequately funded, and funds are projected.
☑	☑	**2 -** Projects exist and are adequately funded but funds are likely to be diverted for other purposes.
☐	☐	**1 -** Projects exist but funds are not adequate and are likely to be diverted for other purposes.
☐	☐	**0 -** There are no funds for cultural heritage management projects.
3.3		**INSURANCE**
3.3.1		**QUESTION**
What is the extent of insurance coverage of the city's cultural heritage from "most probable" scenarios?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** 75-100% of likely losses is covered by insurance.
☐	☐	**2 -** 50-75% of likely losses is covered by insurance.
☐	☐	**1 -** 25-50% of likely losses is covered by insurance.
☐	☐	**0 -** Less than 25% of likely losses is covered by insurance.
3.4		**INCENTIVES**
3.4.1		**QUESTION**
Are there incentives for the owners of all tangible cultural heritage to support disaster resilience and adaptation actions?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Incentives cover more than 75% of costs invested.
☐	☐	**2 -** Incentives cover between 50-75% of costs invested.
☐	☐	**1 -** Incentives cover between than 25-50% of costs invested.
☑	☐	**0 -** Incentives cover less than 25% of costs invested.

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ESSENTIAL 04 PURSUE RESILIENT URBAN DEVELOPMENT AND DESIGN		
4.1	**LAND USE ZONING**	
4.1.1		**QUESTION**
In the "most probable" scenario, what is the percentage of area occupied by immovable tangible cultural heritage at risk of extensive damage?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Less than 5%.
☑	☑	**2 -** 5%-10%.
☐	☐	**1 -** 10%-20%.
☐	☐	**0 -** More than 20%
4.1.1		**QUESTION**
Does the land use zoning of cultural heritage places promote balanced, multiple, and heterogeneous uses for the whole city?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☑	☑	**3 -** Land use regulations are defined for the whole city.
☐	☐	**2 -** Land use regulations are defined only for limited areas (for example, the historic center).
☐	☐	**1 -** The importance of land use is acknowledged but not included in the zoning process.
☐	☐	**0 -** Land use regulations are not considered.
4.2	**BUILDING CODES AND STANDARDS**	
4.2.1		**QUESTION**
Do building codes include the use and adaptation of traditional design guidelines?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☑	☑	**3 -** Traditional design guidelines exist and are mandatory.

☐	☐	**2 -** Traditional design guidelines exist but are not mandatory.
☐	☐	**1 -** Traditional design guidelines are broadly acknowledged but not advocated.
☐	☐	**0 -** Traditional design guidelines are not considered.
4.2.2		**QUESTION**
Do guidelines exist that address the strengthening of immovable tangible cultural heritage, considering its value and peculiarities?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☑	☐	**3 -** Detailed guidelines exist that consider all heritage peculiarities and the strengthening effectiveness is assessed by a third party.
☐	☑	**2 -** Detailed guidelines exist that consider all heritage peculiarities, but the strengthening effectiveness is not assessed by a third party.
☐	☐	**1 -** Guidelines exist but are overly simplified and do not consider the heritage peculiarities.
☐	☐	**0 -** Guidelines do not exist.

ESSENTIAL 05 SAFEGUARD NATURAL BUFFERS TO ENHANCE THE PROTECTIVE FUNCTIONS OFFERED BY NATURAL CAPITAL		
5.1		**ECOSYSTEM SERVICES**
5.1.1		**QUESTION**
Are ecosystem services acknowledged as natural heritage and managed as critical assets?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Ecosystem services are acknowledged as natural heritage and managed as critical assets.
☐	☑	**2 -** Ecosystem services are acknowledged as natural heritage and managed as critical assets, but prioritization is made to those with a disaster risk reduction role.
☑	☐	**1 -** Ecosystem services are acknowledged as natural heritage but not always managed as critical assets.
☐	☐	**0 -** Ecosystem services are not acknowledged as natural heritage.

5.2	INTEGRATION OF TRADITIONAL KNOWLEDGE IN ECOSYSTEM SERVICES	
5.2.1		QUESTION
Is traditional knowledge considered in the management of ecosystem services?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Traditional knowledge is used and adapted after its effectiveness has been validated by third parties also through the engagement of the community and/or local experts.
☑	☑	**2 -** Traditional knowledge is used and adapted but its effectiveness has not been validated.
☐	☐	**1 -** Traditional knowledge is recognized but not used.
☐	☐	**0 -** No awareness of traditional knowledge.

ESSENTIAL 06 STRENGTHEN FINANCIAL CAPABILITY FOR RESILIENCESTRENGTHEN INSTITUTIONAL CAPACITY FOR RESILIENCE		
6.1	SKILLS AND EXPERIENCE	
6.1.1		QUESTION
Does the local government know the available key skills, knowledge, and experience in disaster risk and resilience of cultural heritage (i.e., inventoried in the last 1 year)?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** There is a complete inventory, and it is regularly updated.
☐	☐	**2 -** There is a complete inventory, but it is not regularly updated.
☑	☑	**1 -** There is only a partial inventory, and it is not regularly updated.
☐	☐	**0 -** There is no inventory.
6.2	EDUCATION AND AWARENESS PROGRAMS	
6.2.1		QUESTION

Does the local government promote education and awareness programs on local history and cultural heritage in Schools?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Schools have structured and mandatory programs.
☐	☑	**2 -** Schools have structured but not mandatory programs.
☑	☐	**1 -** Schools promote occasional programs, but they are not mandatory.
☐	☐	**0 -** Schools do not promote any program.
6.2.2		**QUESTION**
Does the local government promote education and awareness programs on disaster risk and resilience of cultural heritage in Higher Education?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Higher Education has structured and mandatory programs.
☐	☑	**2 -** Higher Education has structured but not mandatory programs.
☐	☐	**1 -** Higher Education promotes occasional programs, but they are not mandatory.
☐	☐	**0 -** Higher Education does not promote any program.
6.3	**DATA CAPTURE, PUBLICATION AND SHARING**	
6.3.1		**QUESTION**
To what extent is data on disaster risk and resilience of cultural heritage mutually shared among organizations involved and departments within the city/local government?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Information is fully shared through a unique database which enables navigation.
☐	☐	**2 -** Information is fully shared but there is not a unique database.
☑	☑	**1 -** Information is partially shared and there is not a unique database.
☐	☐	**0 -** Information is not shared.

6.4	LEARNING FROM OTHERS	
6.4.1		QUESTION
Are knowledge exchange activities regularly carried out to learn from what other cities, states, and countries (and companies) do for disaster risk and resilience of cultural heritage?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☑	**3 -** Knowledge exchange activities regularly occur (say, annually).
☐	☐	**2 -** Knowledge exchange activities occur frequently but not regularly or may be in the context of other meetings as a side-effect.
☑	☐	**1 -** Knowledge exchange activities occasionally occur, but the tend to be ad-hoc.
☐	☐	**0 -** Knowledge exchange activities do not occur.

ESSENTIAL 07 UNDERSTAND AND STRENGHTEN SOCIETAL CAPACITY FOR RESILIENCE		
7.1	COMMUNITY OR “GRASS ROOTS” ORGANIZATIONS	
7.1.1		QUESTION
To what extent do community or “grass roots” organizations participate in cultural heritage management activities?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☑	**3 -** Organization(s) covering almost all population groups (including every neighborhood, irrespective of wealth and other demographics) participate.
☐	☐	**2 -** Organization(s) covering approximately half of population groups participate.
☑	☐	**1 -** Organization(s) covering approximately a quarter of population groups participate.
☐	☐	**0 -** There is no participation.
7.2	BUSINESS CONTINUITY PLANS	
7.2.1		QUESTION

What percentage of businesses directly associated with cultural heritage have a documented continuity plan that has been reviewed within the last 12 months?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Almost all businesses.
☐	☐	**2 -** Approximately half of all businesses.
☐	☐	**1 -** Approximately a quarter of all businesses.
☐	☐	**0 -** None of the business.
7.3	**CITIZEN ENGAGEMENT TECHNIQUES**	
7.3.1		**QUESTION**
Does the city/local government have an understandable and clear communication strategy on the importance of cultural heritage management that is effectively disseminated to the population?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☑	**3 -** There is a structured communication campaign.
☑	☐	**2 -** Frequent messages but not a structured campaign.
☐	☐	**1 -** Occasional messages but not a structured campaign.
☐	☐	**0 -** The population is not informed.
7.3.2		**QUESTION**
How effective is the city/local government engaging the population to actively participate in cultural heritage management?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Cultural days regularly occur (say, annually).
☑	☐	**2 -**Cultural days occur frequently but not regularly or may be in the context of other activities as a side-effect.
☐	☐	**1 -** Cultural days occasionally occur, but they tend to be small scale or limited events.
☐	☐	**0 -** Cultural days do not occur.

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ESSENTIAL 08 INCREASE INFRASTRUCTURE RESILIENCE		
8.1	**ESSENTIAL SERVICES**	
8.1.1		**QUESTION**
What percentage of the total number of structures and infrastructures belonging to the city's cultural heritage host essential services?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Less than 5%.
☐	☐	**2 -** Less than 10%.
☐	☐	**1 -** Less than 20%.
☑	☐	**0 -** More than 20%.
8.2	**TOURISM**	
8.2.1		**QUESTION**
What is the expected loss of service for visitation activities from "most probable" risk scenarios?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Less than a day.
☑	☐	**2 -** Less than a week.
☐	☐	**1 -** Between a week and a month.
☐	☐	**0 -** One month or more.
8.2.2		**QUESTION**
What is the expected decrease of the city revenue associated to the loss of tourism from "most probable" risk scenarios?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☑	☐	**3 -** Less than 5%.
☐	☐	**2 -** Between 5% and 10%.
☐	☐	**1 -** Between 10% and 20%.

☐	☐	**0 -** More than 20%.
8.3	**WORSHIP**	
7.3.1		**QUESTION**
What is the expected loss of service for places of worship in the city from "most probable "risk scenarios?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☑	☐	**3 -** Less than a week.
☐	☐	**2 -**Between a week and a month.
☐	☐	**1 -** Between a month and a year.
☐	☐	**0 -** One year or more.

ESSENTIAL 09 ENSURE EFFECTIVE DISASTER RESPONSE		
9.1	**EARLY WARNING**	
9.1.1		**QUESTION**
Are efforts taken to integrate traditional knowledge into early warning systems to possible hazards?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Traditional knowledge is fully integrated for all possible hazards and its effectiveness is assessed by a third party.
☐	☐	**2 -** Traditional knowledge is fully integrated for all possible hazards, but its effectiveness is not assessed by a third party.
☐	☐	**1 -** Traditional knowledge is broadly integrated for some of the hazards.
☑	☐	**0 -** Traditional knowledge is not integrated.
9.2	**PRE-EVENT PLANNING AND PREPARATION**	
9.2.1		**QUESTION**
Do the emergency response plans consider the heritage peculiarities and prioritization within the city to ensure an effective response?		
Filled By Riga city departments	Filled by University of Latvia	Responses

☐	☐	**3 -** Peculiarities and prioritization of heritage within the city are fully considered and have been tested (possibly in real emergencies).
☐	☐	**2 -** Peculiarities and prioritization of heritage within the city are fully considered but have not been tested.
☐	☐	**1 -** Peculiarities and prioritization of heritage within the city are broadly considered but there are significant shortfalls.
☑	☐	**0 -** Peculiarities and prioritization of heritage within the city are not considered.
9.3		**RESPONDERS TRAINING**
9.3.1		**QUESTION**
Are first responders aware and trained of specific attention required by cultural heritage while carrying out emergency operations?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Mandatory training and drills are provided.
☐	☐	**2 -** Mandatory training is provided, but capacity is not tested.
☐	☐	**1 -** Training is provided, but it is not mandatory.
☐	☐	**0 -** No training nor drills are provided.
9.4		**TOURIST PREPAREDNESS**
9.4.1		**QUESTION**
Does the city/local government have means to safely evacuate transient population during emergencies?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Signage is used to mark “safe” buildings and gathering areas. Information on transient population is collected with the cooperation of visitation activities. Newly created app(s) are available.
☐	☐	**2 -** Signage is used to mark “safe” buildings and gathering areas. Information on transient population is collected with the cooperation of visitation activities.
☑	☐	**1 -** Signage is used to mark “safe” buildings and gathering areas.

☐	☐	**0 -** No, there is no signage or means to safely evacuate ransient population.
9.5		**SHELTERS AND RELIEF SUPPLY NEEDS**
9.5.1		**QUESTION**
Are efforts taken to define the disaster relief supply needs in order to be culturally appropriate for the local population?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Yes, through the engagement of community or "grass roots" organizations.
☐	☐	**2 -** Yes, but without the engagement of community or "grass roots" organizations.
☐	☐	**1 -** Yes, but there are significant shortfalls.
☑	☐	**0 -** No, efforts are not taken.

ESSENTIAL 10 EXPEDITE RECOVERY AND BUILD BACK BETTER		
10.1	**POST EVENT RECOVERY PLANNING - PRE-EVENT**	
10.1.1		**QUESTION**
To what extent do the comprehensive post event recovery plans acknowledge all forms of cultural heritage, its prioritization and management in the definition of the Post-Disaster Needs Assessment (PDNA), opportunities, and economic reboot?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Full acknowledgment.
☐	☐	**2 -** Acknowledgment, but with some shortfalls.
☐	☐	**1 -** Broad acknowledgment.
☑	☐	**0 -** No acknowledgment.
10.1.2		**QUESTION**
Has the post-event recovery plan been developed through inclusive and participatory consultations of all concerned groups and institutions involved in the cultural heritage sector?		
Filled By Riga city departments	Filled by University of Latvia	Responses

☐	☐	**3 -** All concerned groups and institutions have been engaged/consulted.
☐	☐	**2 -** More than half of the concerned groups and institutions have been engaged/consulted.
☐	☐	**1 -** Only few of the concerned groups and institutions have been engaged/consulted.
☑	☐	**0 -** Concerned groups and institutions have not been engaged/consulted.
10.1.3		**QUESTION**
Are efforts taken to integrate the comprehensive post event recovery and economic reboot plans with all forms of cultural heritage and surrounding areas?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Yes, and beyond the city area.
☐	☐	**2 -** Yes, but only in the city area.
☐	☐	**1 -** Some efforts are taken but only in the city area.
☑	☐	**0 -** No, plans are independent.
10.2	**BUILD BACK BETTER**	
10.2.1		**QUESTION**
Are traditional design guidelines integrated with the concept of Build Back Better (BBB)?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☐	☐	**3 -** Traditional design guidelines are fully integrated in BBB concepts and are mandatory.
☐	☑	**2 -** Traditional design guidelines are integrated in BBB concepts but are not mandatory.
☐	☐	**1 -** Traditional design guidelines are broadly integrated in BBB concepts.
☑	☐	**0 -** Traditional design guidelines are not integrated in BBB concepts.
10.2.2		**QUESTION**

Does the city/local government promote the conservation and revitalization of traditional design guidelines and craftsmanship?		
Filled By Riga city departments	Filled by University of Latvia	Responses
☑	☐	**3** - Free and accessible courses and training materials for both professionals and non-professionals are provided.
☐	☑	**2** - Free courses and training materials for professionals are provided. However, they may not be accessible for non-professionals.
☐	☐	**1** - Paid courses and training materials for professionals are provided.
☐	☐	**0** - No, courses and training materials are not provided.