**EREM 82/3**
Journal of Environmental Research, Engineering and Management
Vol. 82 / No. 3 / 2026
pp. 21–36
10.5755/j01.erem.82.3.44956

**Towards Integrated Adaptive Environmental Management of Cultural Heritage Sites: A Thematic Review and Conceptual Framework**

Received 2026/05 | Accepted after revisions 2026/07

**https://doi.org/10.5755/j01.erem.82.3.44956**

# Towards Integrated Adaptive Environmental Management of Cultural Heritage Sites: A Thematic Review and Conceptual Framework

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In recent years environmental management has been raised to a new level in the context of cultural heritage sites. Climate change, urbanization, mass tourism, and limited institutional resources and management capacities are the most pressing challenges facing cultural heritage today. These issues clearly demonstrate that fragmented, segmented approaches are insufficient and unable to adapt effectively or safeguard the cultural values inherited by future generations. This study aims to address the main concern of heritage management fragmentation by conducting a thematic literature review across Scopus, Web of Science, ScienceDirect, Taylor and Francis, Wiley, and MDPI databases. Using a structured thematic synthesis approach, the review has mapped out the major themes that shows risks of climate change, engineering and technical solutions (energy efficiency, environmental monitoring, and modeling tools), and governance systems in the general context of the EU and Lithuania. The review highlights major knowledge and practice gaps related to disciplinary and institutional fragmentation. While climate risk assessments are descriptive and do not lead to any actions; engineering solutions are often in contradiction with conservation ethics; and governance is affected by intersectoral coordination failures, inadequate stakeholder engagement, and a lack of standardized performance indicators not understandable to cross-sector decision makers. To address the identified gaps, this paper develops a novel five-layer integrated adaptive framework for cultural heritage management, consisting of the following layers: 1) Shared values and objectives; 2) Evidence and knowledge integration; 3) Technical interventions; 4) Governance and participation; and 5) Monitoring, evaluation, and adaptation, supported by balanced KPIs and Plan-Do-Check-Act cycles. This conceptual framework attempts to integrate conservation ethics, environmental engineering, and participatory governance into the circular economy concept developed in the Toolkit 2.0, Enhancing Our Heritage.

**Keywords:** environmental management, cultural heritage, integrated frameworks, climate adaptation, energy efficiency, governance.

## Introduction

This paper presents one of the increasingly urgent issues of managing cultural heritage sites: integrating environmental management. The sites are being exposed to climate change pressures, rapid urban planing, mass tourism and uncoordinated institutional action. These growing pressures cannot be met with current approaches, which are grounded in disconnected sectors with different agendas.

Most of the current approaches and methodologies to site management are lacking in a holistic view, balanced, or even brief overviews of the relevant factors, such as environmental engineering, climate risk management, energy efficiency requirements, and more comprehensive urban development strategies (Gravagnuolo et al., 2021). Historical buildings and heritage sites are irreplaceable and nonrenewable resources, similar to complex social-ecological urban systems. These buildings and sites are subjected to impacts by extreme temperature and weather events, air pollution, and flooding (Fatorić and Seekamp, 2017; Orr et al., 2021) while simultaneously being subjected to increasingly strict energy efficiency and environmental standards (Herrera-Avellanosa et al., 2024; Pomponi and Moncaster, 2017). Conservation principles based on authenticity and minimal intervention are therefore challenged by the goals of environmental engineering, especially energy efficiency, carbon reduction, and adaptive reuse.

Despite the growing number of interdisciplinary research in recent years, heritage management has been fragmented, uncoordinated, and lacks performance metrics and indicators to assess heritage management effectiveness, as Wijesuriya et al. (2013) note. Conservation science, environmental engineering, urban planning and governance continue to rest on different methodological and conceptual areas. Disciplinary and institutional isolation then limits the development of sound, responsive, and integrated strategies for managing cultural heritage under rapidly changing environmental conditions.

This study reviews the approaches and frameworks developed in heritage site management literature, with a particular emphasis on the environmental engineering perspective. Using a thematic synthesis approach, the study addresses the following broad questions toward developing more integrated and resilient frameworks of management:

RQ1. What environmental and climate-related risks to cultural heritage sites are most frequently addressed in recent literature?

RQ2. Which engineering, monitoring, modeling and energy-efficiency approaches are proposed for mitigating these risks?

RQ3. How are governance, stakeholder participation and policy instruments integrated into environmental management of cultural heritage sites?

RQ4. What elements are required for an integrated adaptive framework for sustainable cultural heritage management?

## Methods

In this study, a structured thematic literature review combined with conceptual synthesis is carried out to examine the current state of integrated environmental management at cultural heritage sites.

### Research design

According to well-established protocols for conducting reviews, the review was undertaken through four principal phases (Tranfield et al., 2003; Snyder, 2019):

1 Identification of relevant literature;
2 Relevance assessment;
3 Eligibility assessment based on inclusion/exclusion criteria;
4 Thematic synthesis and conceptual integration.

This offers an integrated approach to systematic searching within a frame of thematic and conceptual interpretation and thus responds to the depth that interdisciplinary research requires.

### Data sources and search strategy

The initial and principal source for the literature search was Scopus and Web of Science Core Collection. Other leading databases were used for targeted searches through leading publishers: Elsevier's ScienceDirect, Taylor and Francis Online, Wiley Online Library, and MDPI. The keywords were searched within three sets of concepts linked through Boolean operators:

- Heritage: "cultural heritage" OR "historic buildings" OR "heritage sites" OR "monuments" OR "cultural landscapes"

- Environmental Engineering / Management: "energy efficiency" OR "climate change adaptation" OR "environmental management" OR "indoor climate control" OR "sustainability" OR "carbon reduction"
- Governance and Integration: "integrated management" OR "decision-making framework" OR "adaptive reuse" OR "governance" OR "multi-criteria decision analysis".

Searches were limited to publications in English from 2010 to 2026. The publications included were peer-reviewed articles and high-quality conference papers and reports.

## Inclusion and exclusion criteria

Studies were selected based on the following criteria:

Inclusion criteria:

- Journal articles, conference papers or authoritative institutional reports indexed in Scopus or Web of Science;
- Studies addressing the intersection of cultural heritage with environmental pressures, engineering solutions or governance;
- Empirical studies, methods, frameworks, or systematic reviews;
- Papers focusing on climate change impacts, energy efficiency, monitoring/modeling tools or integrated management approaches.

Exclusion criteria:

- Non-English language publications;
- Studies focused exclusively on archaeological excavation techniques or purely historical analysis, with no element of environmental consideration or management;
- Opinion articles, editorials or non-empirical commentaries;
- Publications lacking clear methodology or theoretical contribution.

A classification matrix (*Table 1*) was drawn to organize the literature research strategy and selection.

**Table 1.** *Search strategy and selection criteria*

| Aspect | Description |
|---|---|
| Databases | Scopus, Web of Science Core Collection, ScienceDirect, Taylor and Francis Online, Wiley Online Library, MDPI |
| Search period | 2010–2026 |
| Language | English |
| Main search strings | ("cultural heritage" OR "historic buildings" OR "heritage sites" OR "monuments") AND ("climate change" OR "energy efficiency" OR "environmental management" OR "adaptive reuse" OR "sustainability") AND ("integrated management" OR "governance" OR "framework" OR "decision-making") |
| Inclusion criteria | • Peer-reviewed journal articles, conference papers, or authoritative reports<br>• Studies addressing the intersection of cultural heritage with environmental, engineering or governance aspects<br>• Publications presenting methodologies, frameworks, empirical data or systematic reviews |
| Exclusion criteria | • Non-English publications<br>• Purely archaeological or historical studies without environmental/management components<br>• Opinion pieces, editorials and non-empirical papers<br>• Duplicate publications |
| Initial records identified | 1856 |
| Duplicates removed | 672 (removed using EndNote reference manager followed by manual verification) |
| Records after duplicate removal | 1184 |
| Records after screening | 347 |
| Full-text articles assessed | 128 |
| Final selected publications | 62 |

*Data analysis: thematic synthesis and conceptual framework development*

After research and selection, a total of relevant studies were analyzed using thematic synthesis (Thomas and Harden, 2008). This involved:

- Identifying main themes (climate risks, engineering approaches, governance systems, etc.);
- Identifying patterns, contradictions, strengths and weaknesses;
- Mapping correlation between environmental risks, technical solutions and governance systems.

A classification matrix (*Table 2*) was made to organize the literature into thematic areas.

The comparative analysis was then used to propose an original integrative conceptual model.

**Table 2.** *Classification of selected literature*

| Theme | Main focus areas | Key references | Number of studies |
|---|---|---|---|
| Climate change risks | Vulnerability assessments, hazard-impact relationships, extreme events | Fatorić and Seekamp (2017); Sesana et al. (2021); Orr et al. (2021) | 18 |
| Engineering solutions | Energy efficiency, retrofitting, hygrothermal performance, adaptive reuse | Herrera-Avellanosa et al. (2024); Lucchi (2022); Pomponi and Moncaster (2017); Pochwala et al. (2023) | 21 |
| Monitoring and modelling tools | IoT sensors, digital twins, HBIM, GIS, BEM, hygrothermal simulation | Lucchi (2023); Salah et al. (2025); Danese et al. (2026); Kawsar et al. (2026) | 12 |
| Governance and policy mechanisms | Policy frameworks, stakeholder participation, implementation gaps | Roders and van Oers (2011); Wijesuriya et al. (2013) | 14 |
| Integrated and circular frameworks | Circular economy, adaptive reuse models, holistic frameworks | Gravagnuolo et al. (2021); Foster (2020) | 9 |

## Thematic synthesis

### Climate change risks and heritage vulnerability

Several climate change risk factors are most frequently studied in terms of cultural heritage:

- Temperature and humidity fluctuations- leading to material expansion and contraction, cracking of stone and masonry, salt crystallization and chemical degradation of organic materials (Sesana et al., 2021; Fatorić and Seekamp, 2017);
- Changes in precipitation patterns and flooding- causing water infiltration, erosion, salt mobilization and structural destabilization (Orr et al., 2021);
- Sea-level rise and coastal erosion- posing existential risks to low-lying and coastal heritage sites;
- Extreme weather events (heatwaves, storms, wildfires and droughts)- which result in both sudden catastrophic damage and long-term secondary effects such as post-fire erosion (Sesana et al., 2021).

Fatorić and Seekamp (2017) were among the first studies to assess widespread vulnerability and document physical, chemical, and biological degradation pathways threatening cultural heritage. Methodologically, Sesana et al. (2021) contributed further by proposing hazard-impact diagrams systematically relating climatic stressors to their potential impacts on outdoor monuments, historic building interiors, and collections. Other updates, for example, by Orr et al. (2021), confirmed the rapid increase in published research between 2016 and 2020 but retained a strong geographic bias toward Europe and North America.

Although, these studies provide a good diagnostic insight but do not direct practical management decisions. Most studies remains focused on the impact identification and modeling rather than translating findings into conservation strategies or management frameworks.

### Environmental engineering and energy performance of historic buildings

Engineering and technical support are one of the main solutions for addressing environmental issues concerning cultural heritage. Historical buildings often exhibit poor energy performance due to outdated construction but has potential for optimization without compromising cultural value (Lucchi, 2022).

### Energy efficiency in historic buildings

This is the most researched technical approaches. Key challenges include minimizing interventions while reducing energy use and carbon emissions.

Major themes in the literature include:

- Energy retrofiting strategies: most common measures involve internal or external insulation (where it is permitted), window upgrades, air tightness improvements and integration of renewable energy systems. Many cases highlight the need for solutions that should be compatible and reversible, using breathable insulation materials to avoid any hygrothermal risk. Heat pump systems and efficient HVAC retrofits have shown reductions in primary energy demand (Pochwala et al., 2023);
- Optimisation and balancing: research consistently highlights balance between energy performance and heritage conservation. Passive measures (e.g., thermal mass utilization, natural ventilation) often perform better than active systems, especially in certain climates. LCAs can be used to assess the long-term environmental benefits of an intervention compared with the immediate environmental cost of its construction (Fokaides et al., 2025);
- Performance outcomes: review papers argue that the buildings have large energy-saving potential, but this depends heavily on the building's heritage, climatic zone, and intervention level. Adaptive reuse projects frequently demonstrate that well-designed retrofits increase usability while reducing emissions (Lucchi, 2022).

Other studies confirm that, using a well-thought-out engineering design, it is possible to meet modern standards such as nZEB while preserving authenticity.

### Environmental monitoring

Environmental monitoring data allows to implement evidence-based decision-making in heritage conservation. It involves continuous and periodic assessment of key parameters (temperature, relative humidity (RH), pollutants, light, and moisture) to prevent degradation in time it can still be managed.

- Traditional and innovative systems: conventional data loggers remain widely used but the field is shifting toward wireless sensor networks, IoT-enabled devices and real-time dashboards for proactive management.
- Applications: monitoring helps detect microclimate anomalies that accelerate material decay (e.g., salt crystallization from RH fluctuations, metal corrosion from pollutants or biodeterioration). In museums and historic interiors, it ensures stable conditions for collections.

Recent trends emphasize integration with climate change adaptation, including leak detection and emergency response capabilities amid rising extreme events (Badman et al., 2026).

### Modeling tools

Modeling tools allow the simulation of heritage building conditions under climate change projections, thus allowing for prior intervention. Key categories are:

- Building energy modeling (BEM) and hygrothermal simulations: tools like EnergyPlus, WUFI or IDA ICE model heat, moisture and energy flows in historic sites. They are critical for assessing retrofit risks (e.g., interstitial condensation after internal insulation);
- Urban-scale and multi-criteria models: urban building energy models (UBEM) evaluate clusters of historic buildings. GIS-integrated models combine spatial data with environmental stressors;
- Machine learning and predictive approaches: XGBoost and random forest models predict indoor RH extremes 24 hours ahead based on historical data, enabling proactive HVAC adjustments (Boesgaard et al., 2022);
- Remote sensors and digital twins: satellite, UAV (drone), and terrestrial laser scanning support large-scale monitoring of degradation, erosion, and land-use impacts. BIM (Building Information Modeling) frameworks facilitate integrated retrofit planning while preserving interior features (Salah et al., 2025).

These tools would enable the use of MCDA to properly weigh the trade-offs between the level of energy savings and the retention of heritage values.

### Challenges

Government officers, heritage managers, engineers, conservators uses different approaches and frameworks. That usually leads to unfinished renovation or data resources are not used for prevention. Heritage management is frequently constrained by governmental regulations and the absence of standardized metrics. Effective standardization in this field remains a challenge because it requires strong interdisciplinary collaboration and the alignment of conflicting sectoral interests.

## Monitoring, Modeling and Digital Decision-Support Tools

Environmental monitoring, modeling and digital technologies form one of the fastest-growing and most promising intersections between environmental engineering and cultural heritage management. While such tools allow conceptual development from reactive toward proactive and predictive conservation, they should contribute practically to improving data-driven decision making.

### Environmental monitoring

Continuously acquired monitoring data underline evidence-based heritage management. Modern systems have evolved from traditional data loggers to wireless sensor networks, Internet of Things (IoT) devices and remote sensing technologies. This allows to monitor continuously, even in real-time, crucial parameters such as temperature, relative humidity, atmospheric pollutants, moisture content, and structural movement, allowing the early detection of degradation processes related to salt crystallization, corrosion, and biodeterioration (Lucchi, 2022; Sesana et al., 2021).

### Modeling and predictive tools

Advanced simulation tools allow heritage managers and conservationists to test and analyze future scenarios, whether projected climate change impacts or planned interventions. Building Energy Modelling (BEM), hygrothermal simulations (e.g., EnergyPlus, WUFI, IDA ICE) and urban-scale models are widely used to assess energy performance, indoor climate stability and retrofit risks in historic structures (Herrera-Avellanosa, 2024; Lucchi, 2022).

### Integrated digital decision-support systems

The integration of monitoring and modelling has developed promising digital platforms:

- Heritage Building Information Modelling (HBIM) combined with Geographic Information Systems (GIS) creates spatially rich, multi-dimensional representations of heritage assets;
- Digital Twins represent the current state-of-the-art, offering dynamic virtual replicas that synchronize real-time sensor data with simulation models. This enables continuous monitoring, predictive analytics, scenario testing and conservation strategies that prevent degradation (Lucchi, 2023; Casillo et al., 2024; Kawsar et al., 2026).

### Decision evaluation methods

Multi-Criteria Decision Analysis (MCDA) and Life Cycle Assessment (LCA) are most widely used. These methods provide frameworks for balancing heritage significance, energy efficiency gains, environmental impacts, economic costs and social benefits (Pomponi and Moncaster, 2016; De Medici et al., 2025).

Together, these technologies constitute a coherent data-to-decision stream that fits seamlessly into the heritage management cycle, in which data from monitoring represent a continuous feed of reality; modeling, including Digital Twins, allows forecasting and simulation; and MCDA and LCA provide the appropriate decision-making tools. While each has achieved important technical breakthroughs, they remain isolated units of application and rarely feed into one another as sub-systems within a broader management unit. Yet their actual use potential is in integrating them in a broader adaptive framework in which technical functionality is matched with shared heritage values, participation, and transparent governance.

## Governance, Policy and Stakeholder Participation

Governance plays a pivotal role in framing scientific knowledge and technical solutions within viable strategies for sustainable heritage management. At the European level, responsibility for cultural heritage resides within Member States. However, policies adopted at the EU level, such as the European Framework for Action on Cultural Heritage, increasingly echo the need for integrated, participatory, and sustainable approaches in line with the overall orientation of the European Green Deal (EC, 2018). This is true, however, despite the fact that most systemic problems in European governance remain at the policy level. The relatively well-articulated policy framework is underpinned by institutional fragmentation and weak inter-agency cooperation. This fragmentation is particularly problematic when attempting to reconcile heritage preservation with stringent energy performance regulations, as the lack of a unified approach prevents the consistent

application of sustainability targets across diverse heritage sites.

Key persistent problems include:

- Weak inter-sectoral integration: cultural heritage policies remain poorly aligned with environmental protection, climate adaptation, energy efficiency and spatial planning frameworks. This disconnection creates difficulties in balancing conservation requirements with energy retrofitting or urban development projects (Roders and van Oers, 2011).
- Institutional and resource fragmentation: responsibilities are frequently divided among multiple institutions at national and local levels, resulting in overlapping mandates, coordination gaps and inefficient use of limited financial and human resources usually not intangible by the stakeholders.
- Limited municipal capacity: local authorities, which are often responsible for day-to-day heritage management, frequently lack sufficient technical expertise, funding and decision-making autonomy (Wijesuriya et al., 2013).
- Insufficient stakeholder participation: although participatory governance is widely promoted in policy documents, the actual involvement of local communities, private owners and civil society remains very limited. Decision-making processes are still predominantly top-down, reducing local ownership and the potential for adaptive, context-sensitive management.

The Lithuanian case exemplifies broader European challenges. Despite a well-developed legislative framework including the Law on Protection of Immovable Cultural Heritage and the Cultural Policy Strategy 2030 implementation remains fragmented. Key shortcomings include insufficient inter-ministerial coordination (Culture, Environment, Energy, and Finance), limited municipal resources, and poor integration of environmental data into management decisions. These gaps are particularly evident in energy efficiency upgrades and private owner engagement in adaptive reuse projects.

Overall, a significant divide persists between policy ambitions and on-the-ground implementation. The limited use of monitoring data and standardized indicators further constrains adaptive capacity. Strengthening inter-ministerial coordination, adopting standardized performance indicators, and developing hybrid governance models that incorporate local communities and technical expertise are essential for effective integrated management of cultural heritage.

## Circular Economy and Adaptive Reuse

The circular economy (CE) offers a powerful bridging concept that can integrate conservation objectives with environmental engineering and urban sustainability goals. Rather than viewing cultural heritage solely as a static object to be protected, the circular economy perspective positions historic buildings and sites as valuable resources- reservoirs of embodied energy, materials and cultural capital that can be used to support sustainable urban transformation.

Key principles of the circular economy applied to cultural heritage include:

- Extension of building lifespan through adaptive reuse- which avoids demolition and reduces demand for new construction materials;
- Preservation of embodied carbon and energy- as reusing existing structures can avoid 50–75% of the embodied carbon emissions associated with new buildings (Foster, 2020);
- Material retention and resource efficiency- prioritizing repair, refurbishment and the use of compatible and reversible materials;
- Adaptive reuse as a regenerative strategy- transforming underused or abandoned heritage assets into new functional spaces while maintaining cultural and social significance;
- Social and cultural value regeneration- fostering community engagement, local identity, and economic revitalization.

Systematic studies highlight that adaptive reuse of cultural heritage strongly supports circular economy principles by slowing and closing material and energy loops (Gravagnuolo et al., 2021; Foster, 2020). The Horizon 2020 CLIC project has advanced practical frameworks, business models, and tools demonstrating the environmental, social, and economic benefits of heritage-led regeneration (Fusco Girard and Gravagnuolo, 2025). By treating historic buildings as long-life material banks, circular adaptive reuse reduces environmental impacts compared to new construction while preserving cultural authenticity.

However, its full potential remains underexploited due to regulatory barriers, fragmented governance, and limited integration with energy efficiency and climate adaptation strategies. Systematically incorporating circular economy principles into heritage management

could serve as a key transformative element within the proposed five-layer integrated framework.

## Proposed Integrated Adaptive Framework

While substantial progress has been made in understanding climate change risks, engineering solutions, and governance structures for cultural heritage, existing approaches remain largely fragmented. True integration remains widely undeveloped area that still needs to combine conservation science, environmental engineering and multi level governance.

### Comparison of approaches

Climate risk and impact assessments (e.g., Fatorić and Seekamp, 2017; Sesana et al., 2021; Orr et al., 2021) excel at identifying vulnerabilities through systematic reviews, hazard-impact diagrams and climate modeling. They provide strong diagnostic tools but are often reactive and limited in translating risks into operational management actions (Guzman et al., 2025).

Engineering and technical approaches focus on energy efficiency retrofits, environmental monitoring (IoT sensors, microclimate logging), and modeling tools (EnergyPlus, hygrothermal simulations, BIM, GIS). These deliver quantifiable improvements in performance and predictive capacity. However, they frequently clash with conservation principles regarding material authenticity, reversibility, and visual integrity, and they tend to operate in technical silos detached from broader governance and social contexts (G. Foster, 2020).

Governance and policy frameworks in Lithuania and Europe Union emphasize strategic documents (European Framework for Action on Cultural Heritage, Lithuanian Cultural Policy Strategy 2030), participatory principles and alignment with sustainability goals. They provide institutional legitimacy and stakeholder coordination mechanisms but often lack operational depth, standardized indicators, and effective inter-sectoral integration (culture-environment-energy-planning). Implementation remains constrained by resource limitations and top-down tendencies (Seduikytė et al., 2025).

Risk assessments offer evidence, engineering provides tools, governance supplies legitimacy and coordination. When aligned, they enable adaptive, resilient management (e.g., circular economy models for adaptive reuse).

The literature consistently reveals several layers of fragmentation: conservation professionals prioritize authenticity and minimal intervention, the engineers focus on performance metrics and policymakers emphasize compliance and participation. These groups use different languages, indicators and time horizons and are not able to come to conclusions that work. Global/EU-level strategies and national policies rarely connect effectively with site-specific technical interventions or local stakeholder realities and local government does not have the policy to adapt accordingly. Most efforts address existing damage rather than anticipating future climate and development scenarios through integrated predictive systems. Strong policies exist, but weak inter-ministerial coordination, limited funding at municipal levels, insufficient data-sharing platforms, and underdeveloped participatory mechanisms hinder translation into practice. There is no widely accepted set of indicators that simultaneously tracks heritage value retention, environmental performance, social benefits and most commonly overseen economic and social viability. This fragmentation results in missed synergies (e.g., using heritage as a resource for climate adaptation), duplicated efforts and inconsistent decision-making that leads to more paperwork but not results.

### Core components of the proposed integrated framework

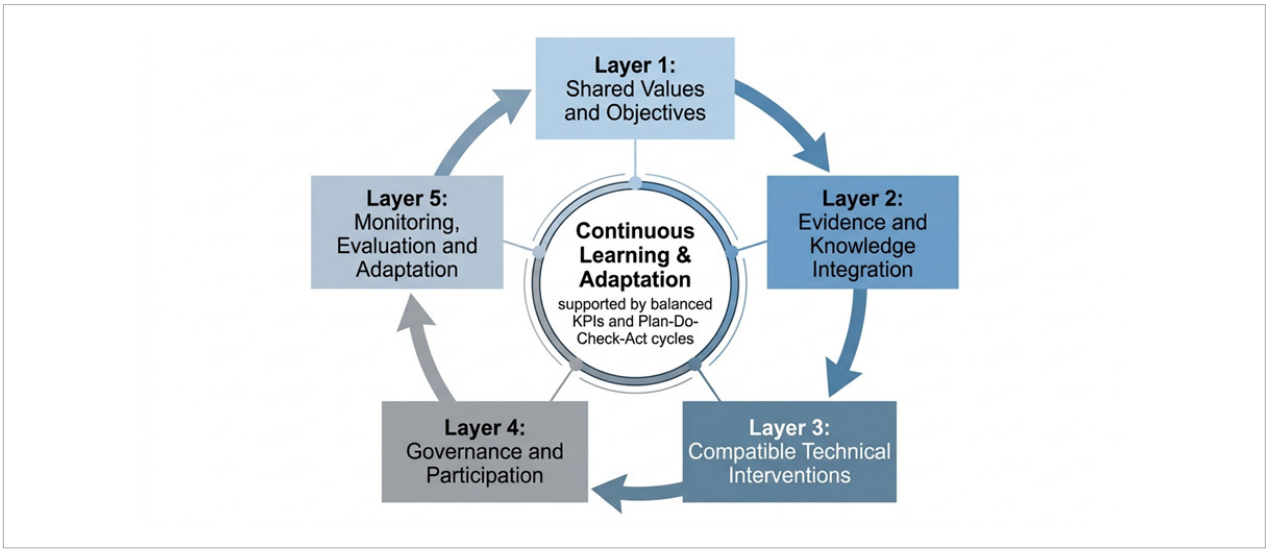
A framework to be effective should adopt a multi-level, adaptive and values-based system approach. The following logic synthesizes insights from the reviewed literature and emerging models.

This figure should visualizes the proposed adaptive management model as a closed-loop system connecting values, evidence, interventions, governance and monitoring.

### Layer 1: shared values and objectives

Integrated environmental management of cultural heritage cannot begin with technical solutions or technological tools. No such framework could stand, long term, effectively and sustainably without a solid first layer of shared and transparent understanding of what values are to be preserved and what the desired outcomes should be. In this first layer, a transparent

**Fig. 1.** *Visualisation of five-layer integrated adaptive framework (composed by the author)*




and participatory process identifies heritage values in cultural, historical, architectural, social, environmental and economic terms. Stakeholders then build a common understanding of the place's meaning and develop high-level strategic objectives that seek to balance the need for conservation with other contemporary imperatives, such as climate resilience, energy efficiency and the well-being of the local community. The Enhancing Our Heritage Toolkit 2.0 (UNESCO, ICCROM, ICOMOS and IUCN, 2023) is well-developed internationally accepted methodology on which this process can be based. It helps site managers and stakeholders systematically assess management effectiveness and align heritage values with broader sustainability agendas, including the United Nations Sustainable Development Goals (SDGs) and the European Green Deal. Thus, this first layer ensures that the following technical interventions, monitoring systems and governance mechanisms will not be applied blindly in isolation, but rather through the lens of a shared vision. Values-based management is less likely to generate conflicts between conservation ethics and environmental engineering goals and is more socially acceptable (Fatorić and Seekamp, 2017; Gravagnuolo et al., 2021). However, without this first layer, even the most advanced digital tools or engineering solutions may not be in tune with what really matters for the site and what long-term aspirations there are for it.

## Layer 2: evidence and knowledge integration

This layer converts diverse knowledge into operational intelligence. It combines climate risk assessments (hazard-impact models), real-time environmental monitoring data (IoT sensors for temperature, humidity, pollutants) and advanced modeling tools into a dynamic digital twin or integrated decision-support platform. Heritage BIM integrated with GIS, for example, allows the development of multi-dimensional site models that can support scenario analysis for different climate and urban development paths. Recent applications in Lithuania (e.g., Kaunas city digital twin) and broader EU projects demonstrate how such platforms facilitate predictive analytics and visualization of intervention impacts (Blagonic et al., 2025). This layer takes a dimension where data are almost exclusively used for reporting purposes and positions them as the basis for proactive decisions and preventive action.

## Layer 3: compatible technical interventions

Technical dimension is crucial in integrated environmental management of cultural heritage but it has to go beyond energy performance. Interventions should be measured against energy savings or carbon footprint reduction potential, however, they should primarily be measured against the dimension of the site's significance and its values and conservation purposes over a long period.

For these reasons, technical interventions should be subjected to a multi-criteria framework, which makes them hardly compatible with many competing or at least demanding criteria:

- Conservation Ethics and Heritage Value Protection: all interventions must respect the principles of minimal intervention, authenticity and reversibility. Any modification should not compromise the cultural, historical, or architectural significance of the site (ICOMOS, 2025).
- Reversibility and Material Compatibility: interventions should be designed to be reversible where possible and use materials that are chemically and physically compatible with historic fabrics to avoid long-term damage.
- Hygrothermal Risk Assessment: a critical value is the evaluation of moisture-related risks. Internal insulation or airtightness improvements, while improving energy efficiency, can cause interstitial condensation, moisture accumulation, and accelerated material decay if not carefully modelled (Lucchi, 2022).
- Life Cycle Assessment (LCA): LCA is increasingly used to evaluate the full environmental impact of interventions, including embodied carbon, operational energy savings, and end-of-life scenarios. Many of case studies show that adaptive reuse and sensitive retrofitting often have significantly lower life-cycle impacts than new construction (Pomponi and Moncaster, 2016; Munarim and Ghisi, 2016).

Multi-Criteria Decision Analysis (MCDA): Multi-Criteria Decision Analysis (MCDA) can provide a structured and transparent process to balance the conflicting criteria of energy performance, retention of heritage values, economic feasibility and social benefits (Olukoya, 2026). Common interventions include breathable insulation systems, compatible window upgrades, high-efficiency HVAC solutions with minimal visual impact, and integration of renewable energy technologies. If properly designed and evaluated, these interventions can realize high energy savings while preserving heritage integrity (Herrera-Avellanosa, 2024; Lucchi, 2022).

### Layer 4: governance and participation

Effective governance is the key mechanism that translates scientific knowledge, technical solutions and shared values and turn it into coordinated action. However, one of the most persistent weaknesses identified in the literature is the significant gap between available technical and scientific knowledge and actual decision-making processes. Institutions often operate in fragmentation with limited communication between cultural heritage authorities, environmental agencies, energy departments and urban planning bodies. As a result, advanced monitoring data, modelling results and engineering recommendations frequently fail to influence strategic or operational decisions (Roders and van Oers, 2011; Taylor et al., 2019).

Effective governance within the proposed framework requires a fundamental shift toward collaborative and participatory decision-making. This involves:

- Establishing formal multi-stakeholder platforms that bring together public authorities (national and municipal), heritage professionals, environmental engineers, private owners, local communities and NGOs;
- Creating clear co-decision mechanisms with clearly defined roles, responsibilities and shared accountability, rather than mere advisory functions;
- Strengthening inter-ministerial and multi-level coordination, particularly between culture, environment, energy and urban planning sectors;
- Embedding technical knowledge (monitoring data, risk assessments, modeling outcomes) directly into governance processes through decision-support systems.

In the Lithuanian context, despite progressive policies such as the Cultural Policy Strategy 2030, these challenges remain evident. Coordination between the Department of Cultural Heritage and other ministries is often insufficient and municipalities frequently lack both resources and influence in decision-making. Similar fragmentation patterns are observed across many European countries.

The proposed five-layer framework addresses these issues by positioning Governance and Participation as a central layer that connects all others. It ensures that values defined in Layer 1, knowledge generated in Layer 2, and technical solutions developed in Layer 3 are not only considered but actively negotiated and integrated into binding management decisions. Only through such genuine participatory and integrated governance can heritage management move from fragmented, reactive practice toward adaptive, resilient and sustainable outcomes.

### Layer 5: monitoring, evaluation and adaptation

The fifth layer closes the adaptive management cycle by ensuring continuous learning, performance tracking and

timely adjustment of strategies. Effective monitoring and evaluation are essential for moving from static preservation to dynamic, responsive heritage management. This layer is based on a balanced, multi-dimensional set of Key Performance Indicators (KPIs) that integrate heritage conservation, environmental performance and social-economic outcomes. The indicators are grouped into six categories presented in *Table 3*.

**Table 3.** *Monitoring, evaluation and adaptation indicators*

| Dimension | Indicator | Definition / Measurement |
|---|---|---|
| Material & Structural Condition | State of material preservation and structural integrity | Assessment of physical condition and degradation rate of heritage elements using standardized condition surveys (e.g., percentage of surface area affected by decay, cracks or material loss) |
| | Authenticity and integrity levels | Degree to which the heritage retains its original form, materials, workmanship and setting, evaluated according to UNESCO Operational Guidelines criteria |
| | Condition of movable heritage | Physical state and conservation level of artifacts, artwork and collections housed within the heritage site |
| Environmental Performance | Energy consumption and energy efficiency | Annual energy use (kWh/m$^2$/year) for heating, cooling, lighting and other operations |
| | Operational and embodied carbon emissions | Total greenhouse gas emissions (kg $CO_2$eq) from operations and embodied carbon in maintenance/retrofit activities |
| | Resource consumption and waste generation | Quantity of water, materials and waste produced per year, including recycling rates |
| | Indoor environmental quality | Stability of temperature and relative humidity levels critical for heritage preservation and visitor comfort |
| Climate Resilience | Vulnerability index to climate hazards | Score assessing exposure and sensitivity to flooding, overheating, storms and other climate-related risks |
| | Effectiveness of adaptation measures | Performance evaluation of implemented adaptation strategies (e.g., % risk reduction achieved |
| | Recovery capacity after extreme events | Time and resources required to restore functionality following climate-related disruptions |
| | Risk exposure level under future climate scenarios | Projected risk level using climate models (e.g., RCP/SSP scenarios) for the next 30–50 years |
| Social and Community | Level of community engagement and participation | Extent of local community involvement in decision-making, measured through participation rates, consultations and co-management initiatives |
| | Public awareness and satisfaction with heritage management | Results from periodic visitor and resident surveys measuring awareness and satisfaction levels |
| | Cultural vitality and educational use of the site | Number and quality of cultural events, educational programs and activities |
| | Social inclusion and accessibility | Degree to which the site is physically and culturally accessible to diverse groups (e.g., disabled, elderly, minorities) |
| Economic Viability | Operational and maintenance costs | Annual expenditure on routine operations and preventive conservation |
| | Revenue generation | Income from tourism, events, commercial activities and grants |
| | Cost-effectiveness of interventions | Economic return on conservation investments (e.g., payback period or cost-benefit ratio) |
| | Contribution to local economic development | Direct and indirect economic impact on surrounding communities (e.g., jobs created, local business revenue) |

| Dimension | Indicator | Definition / Measurement |
|---|---|---|
| Governance Effectiveness | Quality and frequency of stakeholder collaboration | Level of coordination among government, NGOs, private sector and local communities |
| | Level of inter-institutional coordination | Effectiveness of cooperation between different responsible institutions and authorities |
| | Timeliness of decision-making processes | Average time taken to reach and implement key management decisions |
| | Data utilization rate in management decisions | Extent to which collected monitoring data informs strategic and operational decisions |

These indicators are monitored through a combination of digital tools (sensors, digital twins, HBIM), periodic expert assessments and stakeholder surveys. The Plan-Do-Check-Act (PDCA) cycle is applied as the operational mechanism: plans and interventions (Layers 1–4) are regularly evaluated, results are analyzed and necessary adjustments are made particularly feeding back into Layer 1 (Shared values and objectives). By implementing this multi-dimensional monitoring system, heritage managers can detect emerging problems early, measure the success of technical and governance interventions and continuously improve the overall management framework. This layer transforms the proposed model from a theoretical structure into a practical, learning-oriented management system.

This table strongly demonstrates the practical applicability of the model. It transforms the conceptual framework into an operational tool suitable for real heritage sites.

**Table 4.** *Operationalisation of the proposed five-layer integrated adaptive framework*

| Layer | Main Objective | Key Tools & Methods | Main Actors | Expected Outputs | Example Indicators |
|---|---|---|---|---|---|
| 1. Shared Values and Objectives | Define what values to protect and what outcomes to achieve | Enhancing Our Heritage Toolkit 2.0, stakeholder workshops, value mapping | Heritage authorities, local communities, experts, private owners, NGOs | Shared vision statement, value register, strategic objectives | Number of identified values; Stakeholder agreement level; Alignment with SDGs |
| 2. Evidence and Knowledge Integration | Collect and integrate reliable data and knowledge | IoT sensors, digital twins, HBIM + GIS, climate risk models, monitoring systems | Engineers, data scientists, heritage professionals, researchers | Integrated knowledge base, risk maps, real-time dashboards, scenario models | Data coverage (% of site monitored); Model accuracy; Number of climate scenarios tested |
| 3. Compatible Technical Interventions | Implement sustainable technical solutions | LCA, MCDA, hygrothermal simulation (WUFI, EnergyPlus), circular design tools | Environmental engineers, architects, conservators | Approved intervention plans, retrofit projects, adaptive reuse designs | Energy savings (kWh/m$^2$); Embodied carbon reduction; Heritage compatibility score; Reversibility index |
| 4. Governance and Participation | Ensure coordinated and inclusive decision-making | Multi-stakeholder platforms, co-governance agreements, inter-ministerial working groups | National & municipal authorities, communities, private owners, NGOs | Management plans, cooperation agreements, decision protocols | Stakeholder participation rate; Inter-institutional coordination index; Decision-making timeliness |
| 5. Monitoring, Evaluation and Adaptation | Enable continuous learning and improvement | Balanced KPI system, PDCA cycle, digital monitoring platforms | All stakeholders + independent evaluators | Annual performance reports, adaptive management recommendations | Overall framework performance score; KPI achievement rate; Number of adjustments made per year |

## Discussion

Moving beyond the mere identification of challenges, this research contributes a holistic solution-oriented perspective to the environmental management of cultural heritage, fostering a more integrated and actionable approach. While previous research has advanced knowledge in specific domains such as climate risk assessment, energy retrofitting or heritage governance these areas have largely remained fragmented. The primary contribution of this paper lies in synthesizing these domains into a unified and practical framework.

### Theoretical contribution

The main theoretical contribution is the development of a five-layer integrated adaptive framework that bridges previously disconnected research fields: climate change vulnerability studies, environmental engineering, conservation science, circular economy principles and interdisciplinary governance. By positioning Shared Values and Objectives (Layer 1) as the foundational layer the framework addresses a critical limitation in existing literature, where technical solutions are often proposed without sufficient grounding in heritage values (Fatorić and Seekamp, 2017; Sesana et al., 2021). The model further integrates digital technologies and decision-support tools (Layer 2 and 3) with participatory governance (Layer 4) and continuous adaptive learning (Layer 5). This systemic approach responds to repeated calls in the literature for more holistic and interdisciplinary models (Gravagnuolo et al., 2021; Roders and van Oers, 2011). Embedding circular economy logic as a cross-cutting element strengthens the theoretical foundation linking heritage safeguarding with sustainable, regenerative urban growth.

### Practical contribution

From a practical perspective the proposed framework offers a structured and actionable roadmap for heritage site managers, engineers and government planners. It can be directly applied in the development and updating of management plans for individual heritage sites, particularly UNESCO World Heritage properties and nationally significant monuments.

### The framework enables:

- Systematic evaluation of energy retrofit measures using LCA and MCDA while protecting heritage authenticity;
- Integration of real-time monitoring and digital twins into daily management operations;
- Clear guidance on balancing climate adaptation needs with conservation ethics.

The multi-dimensional KPI system presented in Layer 5 provides a concrete tool for measuring success across heritage, environmental, social and economic dimensions- an area that is currently lacking in most management practices.

### Policy contribution

At the policy level, the framework has strong relevance for both European Union and Lithuanian contexts. It offers a practical instrument to reduce institutional fragmentation and improve coordination between ministries responsible for culture, environment, finance and urban planning. In Lithuania, where progressive cultural policies coexist with implementation gaps, the model can support the transition from top-down regulatory approaches toward more collaborative and adaptive governance. It aligns well with the objectives of the Lithuanian Cultural Policy Strategy 2030 and the European Green Deal by demonstrating how cultural heritage can become an active contributor to climate adaptation and sustainable development rather than a competing priority and play an advisory role in creating Lithuanian Cultural Policy Strategy 2040.

Ultimately, this paper advances the discussion by offering not only a critique of existing fragmentation but a concrete, operational model that can help close the gap between scientific knowledge, technical capability and institutional governance. Future research should focus on testing and refining this framework through pilot implementations at different types of heritage sites.

## Limitations

While this study provides a comprehensive review and proposes an integrated framework for environmental management of cultural heritage sites, several limitations should be acknowledged. First, the literature review was restricted to publications in the English language available in major international databases (Scopus, Web of Science, ScienceDirect, etc.). Although English dominates international scientific discourse in this field, relevant research published in other languages (particularly Lithuanian, French, German, or

Spanish) may have been excluded, potentially limiting the cultural and geographical diversity of perspectives (Fatorić and Seekamp, 2017; Sesana et al., 2021). Second, the review primarily focused on peer-reviewed academic literature. Many practical heritage management plans, national policy implementation reports and technical guidelines developed by heritage authorities and municipalities are not indexed in academic databases. This may result in an under-representation of real-world implementation experiences and context-specific solutions (Roders and van Oers, 2011). Third, the five-layer integrated adaptive framework proposed in this paper is conceptual and has not yet been empirically tested or validated through pilot implementation. Its practical feasibility, effectiveness and adaptability therefore remain to be confirmed through action research and long lasting case studies. Fourth, cultural heritage sites are highly diverse in terms of typology (monuments, historic urban landscapes, archaeological sites, cultural landscapes), scale, ownership and geographical context. While the framework is designed to be flexible, its application will require context-specific adaptation and tailoring, particularly when moving from theoretical formulation to practical use. Finally, although the Lithuanian context is used as an illustrative example of broader European challenges, findings drawn from Lithuania may not be directly transferable to other countries with different institutional structures, legal systems, or social-economic conditions. These limitations do not undermine the core contributions of the study but rather highlight important directions for future research, including empirical testing of the framework, expansion to non-English literature, and comparative studies across different cultural and governance contexts.

## Conclusions

This study makes it clear that managing the environment surrounding heritage sites is one of the most challenging tasks facing society today. As these pressures increase due to climate change, energy transitions, and urban expansion, the current fragmented approach to heritage conservation and environmental engineering and management will be insufficient.

The review identified several critical gaps in current practice:

- Persistent disciplinary fragmentation between conservation science, environmental engineering and governance;
- Predominantly reactive rather than proactive strategies;
- Weak inter-sectoral and multi-level policy coordination;
- Insufficient integration of technical knowledge into decision-making processes;
- Lack of standardized, multi-dimensional performance indicators.

Responding to these shortcomings, an integrated adaptive environmental management framework based on five layers is proposed. The first layer is shared values; the second layer is knowledge integration based on evidence; the third layer is compatible technical interventions; the fourth layer is collaborative governance; and the fifth layer is continuous monitoring based on balanced KPIs and Plan-Do-Check-Act cycles. All layers are underpinned by the transversal concept of circular economy thinking. At the theoretical level, the disconnected research areas are synthesized into one system representing adaptive management. From an applied perspective, this tool should help heritage managers, engineers, and policymakers develop sound heritage management plans at various levels, mainly within the EU and Lithuanian contexts.

Empirical application through pilot testing and refinement, development of standardized multidimensional KPIs, and comparative studies across heritage typologies and governance systems are discussed in the context of further research. This will be essential to help improve the resilience and sustainability of cultural heritage assets in times of rapid environmental change.

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