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REVIEW

Smart Environmental Technologies for Safeguarding Tangible Heritage: From Microclimate Control to Predictive Deterioration Modelling

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ABSTRACT

The environmental conditions determine the long-term conservation of tangible cultural heritage, affecting the processes of physical, chemical, and biological degradation of materials and situations over an extensive spectrum. The last few years have seen expansive gains in sensing technology, data acquisition, and analysis procedures, which have facilitated the creation of intelligent environmental practices that surpass the conventional and unchanging conservation policies. This review presents a recap on existing studies in smart environmental technologies to preserve tangible heritage with a focus on the spectrum between environmental monitoring and intelligent microclimate control, predictive deterioration modelling, and decision support. The paper reviews the main environmental hazards to build, movable, and outdoor heritage sites and outlines how high-resolution surveillance systems, sensor networks, and non-invasive methods deliver the data base of adaptive conservation management. Intelligent microclimate control strategies are studied in the context of the ability to achieve conservation performance, energy efficiency, and sustainability. Special focus is made on predictive deterioration modelling, which can include physics-based, empirical, and data-driven models, and the issues of validation, uncertainty, and interpretability in heritage. The combination of these elements as part of decision support structures is noted as a critical move to preventive and risk-based conservation. Through a critical analysis of the existing capacities and capacities, the review outlines the main gaps in the current research and the way forward in the future of designing resilient, data-infused heritage conservation systems that can address the strategic shifts in the environmental and climatic forces.

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1. Introduction

Physical cultural heritage Tangible cultural heritage, such as historic buildings, monuments, archaeological sites, and movable artefacts reflect inestimable historical, artistic, and social values [1]. The physical, chemical, and biological degradation of the material is under the conditions of the surrounding environment, which conditions its long-term preservation. Changes in temperature and relative humidity, air pollution, exposure to light, ingress of moisture, and biological action are well known as important triggers of degradation in a large range of heritage materials, including stone, wood, metals, paper, and textiles. This has led to the development of environmental control, forming a foundation of preventive conservation measures in museums, archives, historic interiors, and complex built heritage settings [2,3].

Historically, the protection of heritage assets has been based on prescriptive norms, regular inspections, and fairly fixed control instruments. Absolute set points on temperature, relative humidity, or light levels, commonly based on lab work or professional judgment, have been widely used as a standard of how acceptable conservation conditions are [4]. Although such strategies have certainly led to positive preservation results, they are becoming questionable due to a number of factors. First, heritage settings are inherently heterogeneous and dynamic, and have both spatial and temporal variation, which cannot be measured by sparse measurement or rigid boundaries. Second, various materials and composite artefacts do not behave in linear and, usually, importantly synergistic responses to environmental stressors, and it is challenging to justify universal standards. Third, the growing pace of the effects of climate change, urban pollution, and growing visitor pressure is putting heritage assets in the face of environmental risks never seen before, often surpassing the assumptions on which traditional conservation advice is based [5–7].

Alongside these difficulties, there is a quickly growing pace of sensing, communication, and data analytics technologies that change the nature of how environmental conditions can be monitored, comprehended, and controlled. Multi-parameter and spatial and temporal monitoring of heritage environments have now become possible at low costs and at a continuous scale due to low-cost, high-resolution sensors, wireless sensor networks, and Internet of Things (IoT) architectures. Further extended monitoring to large, complex, or inaccessible heritage sites is provided by non-invasive and remote sensing, such as imaging, thermography, and laser-based techniques. The emerging trends are producing large amounts of environmental data, transforming the notion of a lack of data in heritage conservation to the idea of excess data [8,9].

Nevertheless, the accessibility of data does not necessarily lead to better conservation results. One of the main weaknesses of most of the existing monitoring practices is that they are descriptive: data on the environment is gathered and presented in visual formats, but they are not always used to their full potential to make proactive decisions. In most instances, the monitoring systems are passive recorders but not part of the integrated approaches of conservation. This void emphasizes the need to go beyond mere monitoring to intelligent systems that can process environment data, change control strategies on-the-fly, as well as predict risks in the future [10].

The environmental technologies Smart is used to serve this purpose by integrating monitoring infrastructures with adaptive control, modelling, and predictive analytics. Within the framework of tangible heritage conservation, these technologies allow transitioning to preventive and predictive measures aimed at reducing the risk before irreversible degradation has begun, and reactive ones are taken. Sophisticated microclimate control systems, such as those, may dynamically reduce or increase the heating, ventilation, air conditioning, or lighting in real time upon sensor feedback, and may optimize conservation needs with energy efficiency and operational limits. More sophisticated methods combine environmental information in physics-based or data-driven models, which predict material response and predict degeneration paths in various environmental situations [8,11].

Predictive deterioration modelling is a highly promising, but difficult, area of heritage science [12]. Mechanistic models based on heat and moisture transfer, salt crystalliza-

tion, corrosion, or biological growth can be a good source of understanding of cause-and-effect relationships, but usually need a detailed characterization of materials and boundary conditions that are hard to measure in actual heritage environments. On the other hand, statistical/machine learning models have the ability to use long-term monitoring data to discover patterns, trends, and damage early warning indicators, even in cases where only part of the underlying processes are well understood [13]. Other combinations of physical knowledge and data-driven learning are studied as more approaches to enhance robustness, accuracy and interpretability.

New digital frameworks like heritage digital twins and heritage-oriented building information modelling further increase the integration of smart monitoring, intelligent control and predictive modelling [14]. It is these platforms that enable the emergence of geometrical, material, environmental and historical information into consistent digital forms to enable simulation, scenario and decision support. With proper deployment, these types of integrated systems have the potential to support prioritization of interventions, optimization of maintenance strategies, and evaluation of long-term risks that may arise under changing climatic and operational conditions, as well as support conservators, facility managers, and policymakers.

Although this has been achieved, the implementation of smart environmental technologies on heritage sites is still unequal and scattered. Technical issues to be tackled include sensor reliability, long-term calibration, interoperability of data and maintenance of the system. The conceptual issues are related to the necessity to align automated, data-driven strategies with the conservation principles, including minimal influence, reversibility, and respect for cultural meaning. Besides, predictive models are always hard to validate because heritage deterioration is a long process, and comprehensive ground-truth is not widely available. These problems give more significance to critical synthesis and cross-disciplinary dialogue [15,16].

It is against this backdrop that the current review reviews smart environmental technology in terms of protecting tangible heritage, especially within the context of the continuum of microclimate monitoring and control to predictive deterioration modelling and decision support. The review does not consider these components separately but has a focus on how they relate to each other and how the integration and interdependence of these systems can support preventive conservation efforts. The aims of the review are threefold: (i) to summarise the existing developments in smart environmental monitoring and adaptive control technologies to be used in heritage settings; (ii) to critically evaluate modelling strategies to predict environmentally-driven deterioration; and (iii) to reveal important gaps, challenges, and directions of a more robust and data-driven heritage conservation system [8,15,17].

The rest of the paper will be organized in the following manner. Section 2 examines the key environmental hazards and degradation factors on tangible heritage materials. Section 3 addresses the smart monitoring technologies and the data acquisition strategies. Section 4 is research on intelligent microclimate control and adaptive management methodologies. In Section 5, the predictive deterioration modelling and decision support systems (DSSs) are discussed. Section 6 provides a conclusion to the review, summarizing the most important insights and sketching future perspectives of smart, sustainable heritage preservation.

2. Environmental Risks and Deterioration Mechanisms in Tangible Heritage

2.1. Tangible Heritage Typologies and Exposure Contexts

Physical cultural heritage covers a broad range of resources that vary significantly in size, material composition, purpose, and vulnerability to environmental forces. Constructions built in the past, such as historic buildings, monuments, and vernacular architecture, are usually typified by multifaceted material groupings and extended experience in outdoor or semi-controlled surroundings. Objects that are movable, like paintings, sculptures, manuscripts, and textiles, are often located in museums, archives, and historic interiors, where conditions are more carefully controlled but subject to spatial variability and operational limitations. Archeological heritage and outdoor artefacts are usually left in open-air environments, and environmental control is not extensive; processes of deterioration are heavily affected by the local climate, soil chemistry, and biological activity [18,19].

The exposure setting of either heritage typology makes

a conclusive determination in the development of deterioration processes. The building envelope performance, heating and ventilation systems, occupancy patterns, and internal heat and moisture loads have an influence on indoor heritage environments. As a contrast, the outdoor heritage assets are exposed to the direct effects of meteorological variability such as precipitation, solar radiation, moisture carried by winds, and the freeze-thaw process. The transitional spaces of historic churches or unconditioned monuments are placed at the intermediate stage; they are partially enclosed and at the same time highly variable environments. These exposure contexts have to be understood so that one can interpret data about the environment and estimate the risks to heritage materials [12].

2.2. Environmental Stressors and Degradation Drivers

Tangible heritage is affected by a set of physical, chemical, and biological stressors that usually interact in a complex manner, leading to environmental degradation of heritage [20]. One of the most active parameters includes temperature and relative humidity which have a direct impact on moisture content, dimensional stability, and reaction kinetics of many heritage materials. Repetitive, or high-rate changes of these parameters may cause mechanical stress, which results in cracking, warping, delamination, or fatigue, especially in hygroscopic substances like wood, paper, and textiles.

Another significant group of drivers of degradation is the air pollutants, particularly in the urban and industrial contexts [21]. Other gaseous pollutants, such as sulfur dioxide, nitrogen oxides, and ozone, may react with the surfaces of materials to produce corrosive by-products or increase chemical degradation. Particulate matter leads to surface soiling, increases the retention of moisture, and may serve as an initiator of other chemical reactions. Exposure to light, especially in the short-wavelength visible and ultraviolet regions, can cause photochemical degradation of organic materials, with the effects of which include fading, embrittlement, and structural loss.

The moisture-related processes are central to most of the deterioration mechanisms. Passage of water, condensation, and capillary rise serve to move the salt and crystallization, which may cause a considerable mechanical pressure in porous substances like stone, brick, and mortar. High moisture content also promotes biological growth such as fungi, algae, lichens, and insects, which may result in aesthetic and structural damage. These stressors seldom act singly, but they tend to interact with each other and, in doing so, increase deterioration rates, which makes it difficult to evaluate and reduce risks [22,23].

2.3. Material-Specific Deterioration Mechanisms

Material properties and microstructural characteristics are highly important to the response of tangible heritage to environmental stressors. Historic buildings and monuments that often use stone materials are susceptible to the effects of weathering, which include dissolution, salt crystal formation, and thermal stress, and deterioration patterns are also different depending on mineral composition, porosity, and fabric. Siliceous stones are likely to be more susceptible to thermal and mechanical stress, whereas calcareous ones are especially vulnerable to acidic contaminants [24,25].

Astronomy Objects and structural elements of wood are highly sensitive to changes in humidity, being hygroscopic. Possible cracks and joint failure, plus deformation, can be caused by swelling and shrinkage due to moisture, and high humidity may result in fungal decay and insects. Iron, copper alloys, and lead are metals whose corrosion processes are highly affected by the relative humidity, concentration of pollutants, and surface contaminants. The slightest shift in environmental conditions can greatly change the rates of corrosion and make preservation hard over a long period of time [26,27].

Combined thermal, hygroscopic, and photochemical stresses are especially susceptible to organic materials such as paper, parchment, textiles, and leather [28]. Polymeric chains are weakened by hydrolysis, oxidation, and photo-oxidation, and embrittle. Ness, discoloration and mechanical strength are lost gradually. The composite artefacts involving the combination of several materials with varying environmental sensitivities are even more complicated because incompatible responses to the same environmental conditions may create internal forces and facilitate damage. The main environmental stressors affecting tangible heritage and their associated deterioration mechanisms are summarized in **Table 1**, highlighting the diversity of materials and exposure contexts involved.

Table 1. Environmental stressors and associated deterioration mechanisms in tangible heritage materials across typical exposure contexts.

Environmental Stressor	Primary Affected Materials	Dominant Deterioration Mechanisms	Typical Heritage Contexts
Temperature fluctuations	Wood, stone, composites	Thermal expansion and contraction, fatigue, cracking	Historic buildings, museums
Relative humidity variability	Wood, paper, textiles, metals	Swelling and shrinkage, corrosion, biological growth	Archives, churches, historic interiors
Airborne pollutants (SO_2, NO_x, O_3, Particulate Matter—PM)	Stone, metals, organic materials	Chemical corrosion, surface soiling, acid attack	Urban monuments, museums
Light and UV radiation	Paper, textiles, paintings	Photochemical degradation, fading, embrittlement	Museums, galleries
Moisture ingress and salts	Stone, brick, mortar	Salt crystallisation, granular disintegration	Outdoor monuments, archaeological sites
Biological agents	Wood, stone, organic materials	Fungal decay, biofilm formation, biodeterioration	Outdoor and semi-enclosed heritage

2.4. Climate Change and Emerging Environmental Risks

Climate change is becoming a highly acknowledged determinant of environmental risks, being transformed into tangible heritage[29]. An increase in average temperature, change in precipitation, more frequent and severe weather events, and changing atmospheric chemistry are all likely to have effects on deterioration processes at various scales. More intense rainfall and flooding events can increase the potential for water ingress, salt mobilization, and structural damage, effects that are exacerbated by heat waves and years of prolonged drought, which intensify thermal and moisture stresses. Changes in the freeze-thaw processes in cold areas can change the weathering process of stone and masonry.

In addition to the direct climatic impacts, there are also the indirect impacts that include the reliance on mechanical climate control, visitor behavior modifications, and urban heat islands that complicate the work of heritage management[6,7]. The current environmental standards and conservation plans, which are usually founded on the past climatic data and relatively constant conditions, might become inadequate in such dynamic situations. This increasing incompatibility highlights the importance of dynamic, adaptive strategies that can be used to constantly determine risk and respond to change in the environment.

2.5. Implications for Preventive Conservation Strategies

The variety of heritage typologies, materials, and exposure conditions, as well as the sophisticated interaction of environmental stressors, demonstrate the drawbacks of the homogenous, threshold-based conservation strategies. The environmental threats are situational and dynamic and cannot be evaluated periodically, but should be assessed on an ongoing basis. One should thus consider a subtle appreciation of the processes involved in deterioration to be able to interpret the information provided by the environmental monitoring systems, in addition to developing effective microclimate control and predictive modelling techniques[30]. **Figure 1** provides a conceptual overview of the relationships between environmental stressors, material-specific vulnerabilities, and dominant deterioration mechanisms across different tangible heritage typologies.

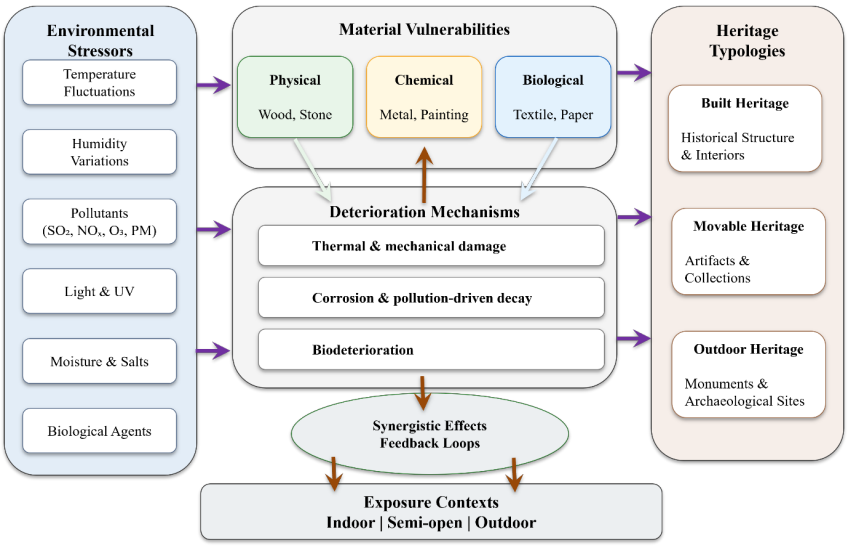

Figure 1. Conceptual framework linking environmental stressors, material vulnerabilities, and deterioration mechanisms in tangible heritage across different exposure contexts.

These are the considerations with which smart environmental technologies in heritage conservation have their conceptual basis [31]. Such technologies can be used to help make smarter, more preventive, and adaptive conservation decisions by connecting careful characterization of the environment with material-specific vulnerability and the emergent risks of climate change. This is the basis of the subsequent sections in which the author discusses the ways in which advanced monitoring systems, intelligent control strategies and predictive models can be combined to protect tangible heritage in a more effective way.

3. Smart Environmental Monitoring and Data Acquisition

3.1. Evolution of Environmental Monitoring in Heritage Contexts

The presence of environmental monitoring has long been established as an essential element of preventive conservation, and it offers the empirical foundation of the comprehension of the situation of exposure and the evaluation of risks to tangible heritage [2]. Initial surveillance strategies were based on infrequent measurements and discontinuous instruments, and could provide little information on spatial changes and changes over time. Even though these techniques proved useful in finding significant correlations between environmental variables and deterioration phenomena, this limitation affected the ability to provide proactive conservation strategies due to low data resolution as well as delayed feedback.

The recent decades have been marked by the development of electronics, communication technologies, and data storage that have significantly altered the practice of environmental monitoring [32]. The data acquisition across time and place in multiple locations in heritage sites has been achievable through the integration of sensing networks, starting with single data loggers and progressing to networks of data loggers connecting these isolated loggers. This development has changed monitoring into a more dynamic process as opposed to the more diagnostic process that can facilitate real-time interpretation and management of the environmental conditions.

3.2. Sensor Technologies and Measured Parameters

Most heritage applications of smart environmental monitoring systems are based on the wide variety of sensors that are developed to measure physical, chemical, and, more recently, biological parameters. The most consistently implemented temperature and relative humidity sensors are due to their pivotal role in the material response and deterioration processes. The sensor miniaturization and the stability of calibration also enhanced accuracy in the measurements and minimized the intrusiveness, which is of paramount importance in the sensitive heritage environments [33].

In addition to simple climatic parameters, chemical sensors allow identifying harmful gaseous pollutants and particulate matter that cause corrosion, soiling, and corrosion of surfaces and chemical decay [34,35]. Corrosion sensors and dosimeters deliver integrative information of environmental aggressiveness that converts complex exposure environments into indicators that are more directly related to material damage. The light exposure including spectral composition, is monitored using optical sensors and assists in controlling photochemical risks of light-sensitive artefacts. The combination of these sensing technologies helps to characterize the surrounding conditions of tangible heritage in a more comprehensive way.

3.3. Wireless Sensor Networks and IoT Architectures

Wireless networks and Internet of Things architecture, as a defining characteristic of smart monitoring systems, can imply the integration of sensors into them [36]. Wireless sensor networks can be deployed flexibly in historic buildings and heritage sites where cabling may not be feasible or acceptable due to conservation issues. Long-term operation is supported by low-power communication protocols and energy-efficient hardware, making it possible to constantly monitor long-term.

The IoT-based architectures also increase monitoring possibilities as remote access to data is possible, automated data aggregation can be ensured, and integration with cloud-based platforms is possible [37]. They enable stakeholders to share data and visualization in real-time, along with the

detection of anomalies, which enhances more effective and coordinated conservation management. Nevertheless, the implementation of this type of architecture also comes with novel issues of data protection, robustness of the system, and long-term sustainability that should be highly considered in heritage settings.

3.4. Non-Invasive and Remote Sensing Approaches

Non-invasive and remote sensors are also becoming more essential to heritage environmental monitoring in addition to in situ sensors [38]. IRT can be used to detect thermal variations, which are related to moisture intrusion, insulation losses, or material heterogeneity, and it can offer spatially resolved information that may be used in addition to point measurements. Multispectral and hyperspectral imaging applications aid in measuring surface compounds, biological development, and material change, and can often display the earliest form of deterioration that cannot be seen by the naked eye.

In case of large-scale or outdoor heritage sites, laser scanning, unmanned aerial vehicles, and satellite-based observations can be used to offer monitoring opportunities outside the immediate surroundings of separate artefacts. The methods aid in the evaluation of exposure to the environment and structural state of whole sites or landscapes, and help in the assessment of risk at a variety of spatial scales. Remote sensing is used together with ground-based surveillance to bring about an overall comprehension of the heritage environments [39]. An overview of the principal smart environmental monitoring technologies currently applied in heritage conservation, together with their measured parameters, spatial scale, advantages, and limitations, is provided in **Table 2**.

Table 2. Smart environmental monitoring technologies and data acquisition methods applied to tangible heritage conservation.

Monitoring Technology	Measured Parameters	Spatial Scale	Key Advantages	Main Limitations
Point sensors (Temperature—T, Relative Humidity—RH, light)	Temperature, humidity, illuminance	Local	Low cost, continuous data	Limited spatial representativeness
Chemical sensors	Gaseous pollutants, particulates	Local	Direct pollution assessment	Calibration drift, selectivity
Wireless sensor networks	Multi-parameter	Building-scale	Flexible deployment, real-time access	Power and data management
Infrared thermography	Surface temperature, moisture anomalies	Surface to building-scale	Non-invasive, spatially resolved	Qualitative interpretation
Multispectral imaging	Material and surface changes	Object to site-scale	Early detection of alteration	Data processing complexity
Unmanned Aerial Vehicle (UAV) and satellite sensing	Climate exposure, structural change	Site to landscape-scale	Large-area coverage	Limited temporal resolution

3.5. Data Quality, Reliability, and Uncertainty

Although these systems can be very useful, there are limitations that exist in regard to the data quality and reliability of smart monitoring systems. Measurement accuracy can be affected by sensor drift, loss of calibration, and environmental interference, especially during long-term applications [16]. Senor placement and local microclimatic differences also complicate the data interpretation process, which explains the necessity of the intensive validation and quality control process.

The unpredictability of environmental monitoring is a part of environmental monitoring which is caused by both limitations of measurements and the dynamic nature of the heritage environment [30,40]. To overcome this ambiguity, it is necessary to have clear documentation on sensor performance, systematic calibration plans, and the application of data analytics techniques that will be able to detect outliers and irregularities. Monitoring data should be used with confidence to make decisions based on control strategies and predictive models, and this is made possible by recognizing and managing uncertainty.

3.6. Role of Monitoring Data in Smart Conservation Frameworks

The real worth of smart environmental monitoring is in the collection of data as well as its incorporation into larger conservation systems [41]. Being based on high-resolution environmental data, adaptive microclimate control allows systems to react in real-time to variations in the conditions. They are also important inputs in the deterioration models and decision support tools to associate the observed material response with environmental exposure.

With increased sophistication in monitoring systems, the role of monitoring systems is changing to be more active in terms of being able to participate in conservation management. Smart monitoring technologies become the primary support of the intelligent and prevention-oriented conservation policies by allowing continuous evaluation, early warn-

ing, and the use of feedback to control processes[42]. This base is further developed in the next section of analysis of utilizing monitoring data to inform intelligent microclimate control and adaptive environmental management in heritage.

4. Intelligent Microclimate Control and Adaptive Management

4.1. From Static Control to Adaptive Microclimate Management

The use of microclimate control has been used as one of the leading tools for alleviating environmentally caused corrosion on physical heritage[43]. Traditional control methods are usually based on predetermined set points and operating schedules, usually based on some general conservation rule or past practice. Though these strategies have the capacity to stabilize the environment to some level, their nature is inherently constrained to address the dynamic and heterogeneous heritage environment. Spatial change in historic buildings, season, changes in occupancy, and external climatic factors often lead to conditions that do not match prescribed targets.

Smart microclimate control is also a conceptual difference between fixed control and adaptive control. The smart control systems can also respond to monitored conditions by continually updating the set environmental parameters since they can consider the current conditions instead of following blindly set limits[41]. This dynamic paradigm fits better with the dynamic behaviors of heritage materials and environments, and more context-specific and subtle control strategies are possible.

4.2. Passive and Low-Intervention Control Strategies

Passive measures of microclimate control are a vital part of smart environmental control measures in heritage. The strategies to be used are to moderate the environmental fluctuations by means of the architectural design, selection of materials, and spatial organization, instead of being overly energy-consuming, the mechanical systems. Performance of a building envelope, thermal mass, natural ventilation, and buffering (like display cases or protective enclosures) can have a great impact on internal microclimates[44].

Passive measures are frequently preferred in heritage conservation because they are compatible with the ideas of minimal intervention and reversibility. Passive strategies may be optimized to become more effective given knowledge of the surrounding environment, such as changing the ventilation pattern or controlling the amount of sunlight exposure. Passive approaches may not necessarily meet the strict targets of environmental control, but they are essential in ensuring that the active control systems are not overloaded and that the general stability of the environment is enhanced.

4.3. Active Control Systems in Heritage Environments

Active microclimate management systems such as heating, ventilation, air conditioning, and lighting are never dispensed with in most heritage environments, especially in situations where fragile artefacts or rigid conservation imperatives are at stake[45]. Unlike typical building services, heritage-specific systems will have to be able to fit into distinct limitations, such as a lack of space to install the systems, low impact on the visual look, and the historical fabric.

Active control systems are being integrated in the smart world, and sensor-driven feedback mechanism is being incorporated in these systems, allowing dynamic adjustment of operating parameters[41]. Such aspects as temperature and humidity control can be adjusted to measured changes so that unnecessary cycling is avoided, and sudden changes that can cause stress to the materials are avoided. Likewise, adaptive lighting mechanisms can control the illumination and spectral balance according to the occupancy, daylight, and conservation requirements, and reduce photochemical hazards without sacrificing visitor experience.

4.4. Data-Driven and Predictive Control Approaches

The combination of data analytics and modelling with microclimate control has presented additional opportunities for predictive and optimized management[46]. Control strategies that are based on data employ past and real-time monitoring data to determine trends and forecast short-term environmental behaviors. The model predictive control frameworks are expansions of this methodology, where predictive models are explicitly included and predict the responses of a system in the future under various control interventions.

Predictive control has the advantage of providing a chance to trade off several goals in heritage contexts, including environmental stability, energy efficiency, and operational constraint[47]. Predictive systems will have an opportunity to deploy a more relaxed control measure by forecasting trends in the environment, instead of responding to the prevailing situation and thereby creating less stress on resources (both material and equipment). Nevertheless, the success of these methods relies on the accessibility of valid models and data of high quality and the attentive adjustment to heritage-related peculiarities. The range of passive, active, and intelligent microclimate control strategies employed in heritage environments, together with their conservation benefits and implementation challenges, is summarized in **Table 3**.

Table 3. Microclimate control strategies for heritage environments, ranging from passive measures to predictive smart control systems.

Control Strategy	Control Type	Typical Applications	Conservation Benefits	Key Challenges
Passive buffering	Passive	Display cases, historic rooms	Reduced fluctuations, low energy use	Limited control precision
Natural ventilation	Passive/Hybrid	Churches, historic buildings	Moisture regulation, minimal intervention	Weather dependency
Conventional heating, ventilation, and air conditioning (HVAC)	Active	Museums, archives	Stable conditions	High energy demand
Sensor-driven HVAC	Active smart control	Sensitive collections	Adaptive response, reduced stress	System complexity
Model predictive control	Predictive smart control	Large heritage buildings	Optimised stability and energy use	Model reliability
Adaptive lighting systems	Active smart control	Exhibitions	Reduced photochemical damage	Integration complexity

4.5. Energy Efficiency and Sustainability Considerations

The importance of energy consumption is becoming a critical consideration in heritage microclimate control due to economic, environmental, and regulatory pressures[48]. High-level environmental control may be power-consuming, especially in old constructions that have low thermal conductivity. The intelligent control strategies have prospects of minimizing energy demands by not over-conditioning them, and utilizing the tolerance of some materials to controlled variability instead of absolute stability.

Energy performance measures can be part of adaptive management strategies, with conservation requirements being established to facilitate making informed trade-offs between conservation interests and sustainability interests. This combined view is especially applicable to the situation with climate change, when the environment on the outside is changing, as well as the expectations of society in relation to energy consumption. This is because intelligent microclimate control has a contribution to the sustainability of heritage as well as the sustainability of conservation practice[49].

4.6. Toward Integrated Adaptive Management Frameworks

The transition from static environmental regulation to adaptive and predictive microclimate management is schematically represented in **Figure 2.** The use of intelligent microclimate control is not independent, but a component of a wider adaptive management that has connections among monitoring, modelling, and decision making[8,50]. Control strategies are effective when they are combined with a continuous environmental assessment process and material response knowledge. Here, the control systems come as risk management tools instead of simply the preservation of the predetermined conditions.

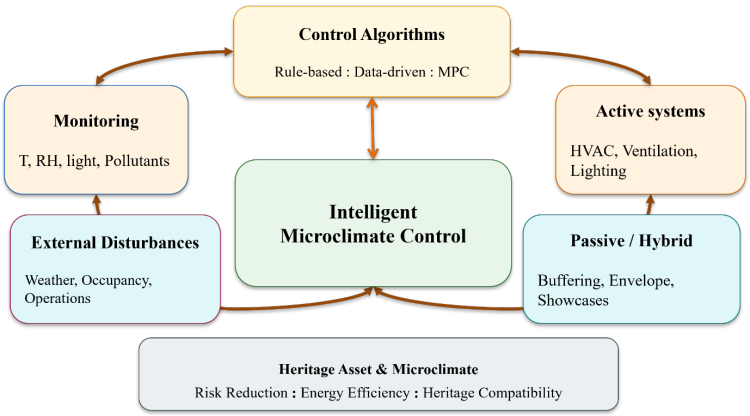

Figure 2. Intelligent microclimate control loop for heritage environments, integrating monitoring data, control algorithms, and passive and active systems under external disturbances.

Expressing microclimate control as a part of feedback loops, which also comprise monitoring and predictive modelling, heritage managers may shift to more resilient and responsive conservation practices. This integration preconditions the development of advanced decision support systems that are able to lead to preventive measures and long-term planning. The following paragraph expands on this view by looking at the predictive deterioration modelling and how the model can be used to convert environmental information and control activities into action-oriented conservation decisions.

5. Predictive Deterioration Modelling and Decision Support

5.1. Rationale for Predictive Approaches in Heritage Conservation

Predictive deterioration modelling has also come to the fore as a very crucial aspect of intelligent environmental technologies, as the necessity to prevent threats instead of doing something with the consequences that have already taken place[8]. In the conventional conservation practice, decisions are usually informed by a retrospective evaluation of condition and also by regulations to environmental standards, where there is little ability to analyze how prevailing conditions can alter future material behaviors. Predictive methods attempt to fill this gap by attempting to connect environmental exposure and anticipated deterioration pathways to allow more proactive and preventive conservation policies.

Predictive modelling offers a systematic format within which monitoring data, material properties, and environmental dynamics are integrated in regard to the ever-complex and changing environmental conditions[51]. Such models help in making informed decisions and prioritizing conservation efforts by estimating the probability, the rate, or the extent of deterioration in various conditions. Their applicability is especially high in the case of heritage assets, where intervention opportunities are few and irreversible damage has serious cultural implications.

5.2. Mechanistic and Physics-Based Deterioration Models

Mechanistic models seek to model the process of deterioration by providing a clear description of the physical, chemical, and biological processes involved in the responses of materials[20,52]. These models are usually applied in the context of heritage conservation, and it is to deal with the heat and moisture transport, salt movement and crystallization, corrosion kinetics, and bio-growth dynamics. Mechanistic models provide explanatory power and extrapolation possibilities of predictions by basing predictions on underlying processes.

Nevertheless, there are significant challenges when it comes to the use of physics-based models in practice with the real heritage[53]. The parameterization of accurate results may entail the precise knowledge of material properties, boundary conditions, and environmental inputs, which prove challenging to obtain on-site. The simplification of assumptions, which is necessary to make the models tractable, can constrain the accuracy of the models when used on a heterogeneous material or a more complex geometry. Despite these limitations, mechanistic models remain valuable tools for exploring cause–and–effect relationships and for informing the development of more pragmatic predictive frameworks.

5.3. Empirical and Statistical Modelling Approaches

Another pathway to prediction is taken by empirical and statistical models, which extract relationships between environmental variables and measured deterioration outcomes using experimental or monitoring data[30,54]. The most common methods include dose response, risk indices, and threshold-based models to estimate the rate or probability of degradation based on measured exposure conditions. These models are sometimes simpler to apply as compared to mechanistic models and may be efficient where they are made out to be backed by sound datasets.

The major weakness of empirical models is the reliance on the quality and representativeness of the underlying data. Relationships based on certain circumstances cannot be applied to other heritage settings and climatic conditions in the future. In addition, purely statistical models might not provide much information about the underlying mechanisms, which decreases their explanatory power. However, the empirical methods are significant in the operational risk evaluation and underlie more sophisticated data-driven methods.

5.4. Machine Learning and Hybrid Modelling Frameworks

The increasing availability of long-term, high-resolution environmental monitoring data has prompted interest in machine learning methods for predicting heritage deterioration [55,56]. Machine learning models can capture complex nonlinear relationships between multiple environmental variables and observed indicators of change, with no or implicit assumptions about underlying processes. Its usage will include time-series forecasting, anomaly detection, and pattern recognition that can be related to early detection of deterioration stages. **Figure 3** presents physics-based, empirical, machine learning, and hybrid approaches along a spectrum of predictive deterioration modelling strategies, highlighting trade-offs between interpretability and data dependency.

Figure 3. Spectrum of predictive deterioration modelling approaches for tangible heritage, illustrating trade-offs between physical interpretability, data requirements, and predictive flexibility.

Hybrid modelling frameworks aim to dissolve the advantages of both physics-based and data-driven models by imposing physical constraints on machine learning models or using data-driven models to guide or calibrate mechanistic models [57]. These methods provide a perspective of better precision, strength, and readability. Nevertheless, there are still issues with the availability of the data, modelling transparency, and overfitting, especially in situations when the process of deterioration takes long durations. The main categories of predictive deterioration modelling approaches, including their data requirements, strengths, limitations, and typical applications, are compared in **Table 4.**

Table 4. Predictive deterioration modelling approaches for tangible cultural heritage and their principal characteristics.

Modelling Approach	Input Data	Strengths	Limitations	Typical Applications
Physics-based models	Material properties, boundary conditions	Mechanistic insight, extrapolation	High data demand, complexity	Moisture transport, salt damage
Empirical/statistical models	Environmental monitoring data	Simple implementation	Limited transferability	Risk indices, dose–response
Machine learning models	Large time-series datasets	Non-linear pattern recognition	Interpretability issues	Anomaly detection, forecasting
Hybrid models	Monitoring + physical constraints	Improved robustness	Development complexity	Long-term risk prediction
Decision support systems	Integrated datasets	Actionable guidance	User adoption challenges	Preventive conservation planning

5.5. Validation, Uncertainty, and Interpretability

Validation remains challenging for long-term deterioration models, particularly because heritage decay unfolds over decades. Beyond conventional split-sample or cross-validation, alternative strategies should be considered. First, accelerated aging experiments (e.g., cyclic salt spray, freeze-thaw, or ultraviolet (UV) exposure) can simulate years of deterioration in weeks to months, providing data for model calibration under controlled conditions. Second, historical damage records, such as repeated laser scanning, photogrammetric surveys, or crack width logs, offer retrospective validation if available for a given site. Third, cross-validation across comparable heritage sites (e.g., multiple limestone churches in similar climatic zones) can assess model generalizability and reduce site-specific overfitting [58]. The lack of comprehensive ground-truth data makes the analysis of model performance difficult and restricts the trust of the results in long-term forecasting. To deal with uncertainty, there are mandatory things to consider, such as measurement error, model assumptions, and variability in material behaviors.

Interpretability is also a factor since predictive models should be applied to make conservation decisions with cultural and ethical consequences [59]. To trust and successfully use models, conservation practitioners need to be capable of comprehending their foundation and the uncertainties that they entail. There should therefore be transparent modelling practice and articulation of the uncertainty in the responsible use of predictive tools in the context of heritage.

5.6. Decision Support Systems for Preventive Conservation

Predictive deterioration models are best when incorporated in decision support systems, whereby analytical results

can be converted into actual direction [60,61]. This kind of system combines monitoring data, predictive models, and management goals as aids to the work in the form of early warning, maintenance, and assessment of intervention scenarios. The decision support tools allow making comparisons between alternative strategies, thus, resource-efficient and risk-based conservation planning.

DSSs in smart conservation systems act as a linkage between technology and human knowledge. They do not substitute professional judgement, but add to it in giving structured, evidence-based information on the complex interactions between the environment and materials. As the predictive modelling approaches keep developing, their incorporation in the available and open-ended decision support systems will play a major role in enhancing preventive and sustainable conservation of heritage [62].

6. Conclusions and Future Perspectives

This review has discussed the changing aspect of smart environmental technologies in preserving tangible cultural heritage with special focus on how the focus on environmental monitoring and microclimate control has changed to anticipate deterioration modelling and decision support. In the various heritage settings, it can be seen that environmental issues are one of the most widespread as well as the most powerful causes of material degradation. Simultaneously, the development of sensing, data acquisition, and analytics is fundamentally changing the way these aspects can be viewed, understood, and controlled.

One of the lessons that comes out of this review is that there is an increased significance of integration. Environmental monitoring, intelligent control, and predictive modelling can be most effectively viewed as not a set of separate technical elements but as part of a set of interdependent components of consistent conservation systems. High-resolution monitoring lends the empirical basis to the study of exposure conditions, whereas adaptive microclimate control converts the former to responsive management measures. In their turn, predictive deterioration models make it possible to predict risks in the future and analyze alternative conservation scenarios. All these factors combine in favor of a transition towards reactive intervention to preventive and risk-based conservation measures.

Although this has come a long way, the use of smart environmental technologies in heritage settings is limited by technical, methodological, and conceptual issues. The ability of monitoring systems to withstand limits continues to be undermined by long-term data reliability, sensor calibration, and interoperability. Predictive modelling has continued to encounter fundamental challenges of data paucity, uncertainty, and validation, especially with the long-term duration that the heritage degradation process takes place. In addition, the introduction of smart and automated systems results in some critical concerns about transparency, interpretability, and alignment with the set conservation principles, including minimal intervention and respect for cultural significance.

Perhaps, looking into the future, several directions can be found to be especially promising in the context of the development of smart heritage conservation. Incorporation of the climate change projections in monitoring and modelling systems will be fundamental in determining the risks in the future in an environment that is becoming quite variable. More plausible ways to make predictions that can be better understood involve hybrid modelling that uses both physical knowledge and data-driven techniques. Meanwhile, this can be closed by the creation of user-friendly decision support systems, which will allow the translation of complex outputs of analysis into practical advice and ethically aware advice.

Finally, smart environmental technologies should be perceived as facilitators and not substitutes for professional judgement. They are useful in developing the ability of conservators, engineers, and heritage managers to perceive the complexity of environmental interactions, predict deterioration, and deploy resources more efficiently. Through interdisciplinary partnership and integration of technological innovation into the conservation theory and practice, smart environmental systems have the potential to add to more adaptive, resilient, and sustainable approaches to protecting the tangible cultural heritage of a moving world.

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