# Sustainable management of heritage buildings in long-term perspective (SyMBoL): current knowledge and further research needs

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## Abstract

**Purpose** – This article introduces the Special Issue on Sustainable Management of Heritage Buildings in long-term perspective.

**Design/methodology/approach** – It starts by reviewing the gaps in knowledge and practice which led to the creation and implementation of the research project SyMBoL—Sustainable Management of Heritage Buildings in long-term perspective funded by the Norwegian Research Council over the 2018–2022 period. The SyMBoL project is the motivation at the base of this special issue.

**Findings** – The editorial paper briefly presents the main outcomes of SyMBoL. It then reviews the contributions to the Special Issue, focussing on the connection or differentiation with SyMBoL and on multidisciplinary findings that address some of the initial referred gaps.

**Originality/value** – The article shortly summarizes topics related to sustainable preservation of heritage buildings in time of reduced resources, energy crisis and impacts of natural hazards and global warming. Finally, it highlights future research directions targeted to overcome, or partially mitigate, the above-mentioned challenges, for example, taking advantage of no sestructive techniques interoperability, heritage building information modelling and digital twin models, and machine learning and risk assessment algorithms.

**Keywords** Editorial paper, Historic and heritage buildings, Stave churches, Risk assessment, Sustainable management, Microclimate, Machine learning, Integrated computational tools, Building energy retrofit, Climate change, Adaptive re-use

**Paper type** Literature review

## 1. Introduction

Heritage and historic buildings (HHBs) are estimated to be circa 30% of the total existing buildings stock in Europe (Troi, 2011; Economidou *et al.*, 2011). They are unique buildings, for

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age, integrity and significance that characterize the skylines of cities and landscapes worldwide. They are considered landmarks familiar to citizens and tourists who live them or that have often seen them on media. HHBs are unique for the power they have to evoke historical times and events, for their aesthetic and architectural value that contributes to reveal the story of a nation, a city, or a district. They are irreplaceable as an economic and socio-cultural capital as they create a sense of community and cultural identity (Spennemann, 1999; UNESCO, 2019; SDG, 2015; Hosagrahar *et al.*, 2016). For all these reasons and because HHBs can help boosting local (or national) economies and the tourist sector, their preservation needs to be planned and implemented on a long-term horizon and with special care. This means that maintenance, restorations and upgrading solutions in HHBs may cope with the conservation criteria of authenticity, non-invasiveness, compatibility with original historic materials and construction techniques, reversibility and minimal intervention/level of change. Nowadays, these requirements represent many challenges because the vulnerability of original HHBs materials has increased over time due to age, exposure to slow-climate change and sudden-onset natural and human-induced hazards; rapid growth of cities and districts; need of energy upgrade intervention and renewable energy source systems integration to cope with climate change mitigation and energy crisis. It becomes critical to understand what long-term HHB management means within this framework.

The long-term management of a HHB should ideally extend its service life well beyond the standard building lifetime (circa 60 years); preserve their tangible and intangible significance; keep it in use while adapting it to climatic, environmental and societal changes; disseminate its sustainable potential (e.g. knowledge of local materials and processes and embedded energy).

Although HHBs have already survived for decades (or centuries) and during their lives they have suffered modifications, restorations and strengthening, some HHBs have still great levels of uncertainty about how they were built (Pallarés *et al.*, 2021). It is for this reason that the monitoring of key parameters on the state of conservation, level of performance, vulnerability, damage assessment and retrofitting evaluation remains of paramount importance (Pallarés *et al.*, 2021). No destructive techniques (NDTs)—being not harmful for the heritage objects under examination—offer the capability of collecting data on structural inspection (e.g. crack patterns, irregularities; ageing, material and element identification; construction technique, elements connections) both periodically and in continuous, *in situ* or in the laboratory. Among the NDTs implemented at macro scale, the simplest one is the visual inspection (VI) usually done to highlight anomalies or factors that may modify the HHB structural response. Tools usually adopted are laser meter, drones, laser scanner or digital photogrammetry (Vincenzi *et al.*, 2019), while an aid to the VI is provided by the analysis of reports, maps, drawings and photographic documentation to discover hidden elements or reconstruct the history of the modifications over time. Terrestrial laser scanning and Digital photogrammetry are noncontact survey techniques which aim to reconstruct the HHB geometry accurately and quickly. Both the two NDTs reconstruct dense point clouds, convert them into grids and triangular elements processed to provide 3D geometric models of the HHB. They give qualitative information on surface defects, deformation, or changes of geometry. As reported by Castellazzi *et al.*, 2015 such 3D model starts nowadays to be integrated to quantitative NDT as the infrared thermography or the finite element modelling (FEM) to analyse stress, strain and mechanical properties of surveyed materials. Data acquired by terrestrial laser scanning and aerial and terrestrial photogrammetry are often integrated with building information modelling (BIM) and/or heritage (HBIM) methodologies and used with spatial information by GIS (Logothetis *et al.*, 2015; Bruno and Roncella, 2019; Yang *et al.*, 2020; Ferreira-Lopes and Pinto-Puerto, 2018). Such integration allows a HHB digital representation (2D and 3D) from point clouds surveys (Almagro, 2019), often enriched with parametric objects (e.g. architectural, artistic, historical, conservation features; consolidation and restoration actions; monitored zones and used tools; visitors number). HBIM permits to generate a centralized repository for heritage info management, preventive conservation (Bruno *et al.*, 2018), building rehabilitation and restoration (Doğan and Güllü, 2022; Karanikoloudis *et al.*, 2020) and sustainable objective achievements (Munarim and Ghisi, 2016; Atmaca *et al.*, 2021). Such repository allows to structure the information collected during each stage of HHB service life and to effectively analyse the data. Information are accessible to stakeholders, can be used to update, revise, or forecast preventive conservation plans thus enhancing their effectiveness, ensuring more sustainable preservation and cost reduction (Pocobelli *et al.*, 2018; García-Valldecabres *et al.*, 2021; Nieto-Julián *et al.*, 2022). Continuing with NDTs, implemented at macro-scale, the infrared thermography (IRT) in its qualitative use (i.e. passive IRT) through false-colours thermograms allows to identify hotter/colder points/areas over surface with middle-high emissivity to highlight temperature anomalies (Tejedor *et al.*, 2022; Dias *et al.*, 2021; Kylili *et al.*, 2014; Fox *et al.*, 2016), cracks, moisture (from capillary rise and percolation) and air leakages presence. While active IRT in its quantitative use (i.e. pulsed, lock-in, step-heating, frequency modulated thermography) can identify debonding in coatings, delamination, corrosion and pitting, as well as cracks and their sub-superficial depth thanks to the forced heating/cooling. The Ground-penetrating radar (GPR) uses a transmitter and receiver located on the surface of the element under analysis to analyse the reflections, attenuation and altered phases of electromagnetic pulses emitted at high-frequency (ranging 500–3,000 MHz) in the material. This NDT is capable to detect sub-superficial defects as voids, flaws, cracks and their depths, separation, or lack of homogeneity between elements, thickness of internal layers and moisture distribution. An example of a radargram and of tomography based on GPR tests are provided in Pérez-Gracia *et al.* (2013). Sonic and ultrasonic testing work in the range 20 Hz–20 kHz and 20 Hz–20 MHz respectively. These NDTs use a transmitter and a receiver and analyse the travel time of the wave along the path between the sensors. Indication on type of material penetrated, cracks, voids and other defect can be extrapolated in case of deviations of the arrival time as the pulse velocities of homogenous and isotropic materials are generally known. An example of sonic test to reveal the presence of discontinuous masonry and the ineffectiveness of strengthening injections in the wall is presented in Grazzini (2019). The acoustic emission testing (AET) is a passive NDT based on the release of elastic energy stored in the material under stress. When stress redistributes in the material, the emission and propagation of elastic waves through the material is captured by surface sensors within the range 50 kHz–1 MHz and crack initiation and/or propagation can be detected. Acoustic waves are analysed in their frequency or time domain by amplitude, energy, counts, or duration to get information about the kind of damage and the acoustic emission source location. Carpinteri and Lacidogna in (2007) combined the AET with flat-jack tests to correlate cracking processes in historic towers. While NDTs implemented at macro scale are useful to study and characterize the physical integrity of HHBs; the NDTs implemented at micro scale are necessary to characterize both historic materials after ageing and conservation materials (e.g. adhesives, coating, fillers) used in consolidation and restoration interventions.

At micro scale, the NDTs are usually selected depending on their portability and type of information to be retrieved. For example, the optical microscope (OM) and the atomic force microscope (AFM) are both selected for obtaining morphology and topography images of architectural/heritage materials. However, while OM may be portable and typically applied for morphology characterization of mortar, black crust, brick, ceramic, glass and their corresponding decay processes; AFM is not portable and is mainly used for surface analysis (roughness, symmetry and gloss level) before and after physical and chemical treatments (Kiele *et al.*, 2014). The laser-induced breakdown spectroscopy (LIBS), Fourier transform IR spectroscopy (FTIR), Raman and X-ray fluorescence (XRF) give all information both at elemental and molecular levels. LIBS is micro-destructive and no portable, and it is used for elemental and cross-section analysis for pigment, stone and bricks (Costantini *et al.*, 2018; Gaona *et al.*, 2013; Vítková *et al.*, 2014). FTIR and Raman spectroscopy being both portable can be of support for identifying respectively organic functional groups in mortar, pigment and black crust as in Barca *et al.* (2011) or to characterize pigment and dye used in architectural heritage as in Edwards *et al.* (1997). Similarly, the portable XRF provides insight on major and trace elemental analysis for pigment, stone and mortar and/or on biological and pollution impact on architectural materials (Sanjurjo Sánchez *et al.*, 2008). The X-ray absorption spectroscopy (XAS) identifies the crystalline substances, chemical state and local environment of the targeted atoms in the samples (Bertrand *et al.*, 2012). In addition, XAS offers higher spatial and spectral resolution because it can be combined with synchrotron radiation sources.

In addition to structural integrity, the long-term management of HHBs needs to ensure their use. This in turn requires the improvement of energy performance through upgrade or retrofits (e.g. wall/roof insulation, upgrading windows and HVAC, replacing lighting, changing operational schedules) that properly protect the building fabric considering its own physical characteristics and significance through the conservation principles implementation (Webb, 2017). In term of solutions adopted to reduce energy consumptions, this means to primarily identify and retain the HHB inherent energy efficient features (e.g. porches, skylights, shutters, vents) (Franzen, 2014). Beside the envelope, the HVAC systems may be retrofitted too, and this may modify the HHB microclimate as well as the occupant behaviour causing offset on energy savings (e.g. through the rebound effect) (Ben and Steemers, 2014). Then, in times of climate change (e.g. higher T, extreme precipitation, sea level rise, floods risks) and energy poverty, the EU is increasing its climate ambition to become the first climate-neutral continent by 2050 (Green Deal, n.d), although with some concessions to protected buildings. Therefore, when selecting (renewable) energy production source and supply systems during upgrade or retrofit interventions in HHBs, potential visual impacts and damages on fabrics, high capital cost (e.g. global cost, lifecycle cost, payback period) and reduce retrofit lifespan need also to be considered (May and Griffiths, 2015; Kandt *et al.*, 2011; Franco *et al.*, 2015; Salata *et al.*, 2014]. Similarly, HHB that are highly vulnerable to the impact of climate changes are also those more prone to maladaptation triggered by inappropriate upgrade/retrofit interventions subsequently accelerating decay and energy consumption (Romão and Bertolin, 2022; Huijbregts *et al.*, 2014; De Wilde and Coley, 2012). In fact an inappropriate selection of thermal insulation materials during retrofit may alter the moisture balance and drying capacity of the HHB envelope with impacts that are exacerbated by global warming. These are: overheating in summertime, change in envelope moisture buffering with interstitial/surface condensation risks, decrease of walls drying potential, capillary rise, decay caused by low surface T and/or high moisture content as freezing thawing, mould decay and salts weathering respectively (Vereecken and Roels, 2014; Klõšeiko *et al.*, 2015). For example, the moisture content of historic walls with higher water absorption coefficients is more sensitive to wind-driven rain and radiation effects (Marincioni and Altamirano, 2014). Sometimes to cope with post upgrade/retrofit microclimate conditions, humidification/dehumidification is added with further alteration of the moisture balance. Looking at the HHB users, impacts result in a decrease of the indoor environmental quality with overheating, overloading of passive systems, an increase of HVAC systems inefficiency, an increase of cooling energy demand resulting in the growth of energy costs. To sum up, HHB envelopes outdoors as well as indoors undergo ageing and are vulnerable to climate-driven (natural or artificial by use of HVAC systems) deterioration mechanisms. Masonry, wood and stones respond to the variations in RH (and T) with changes in dimensions and mechanical properties (Mecklenburg *et al.*, 1998; Camuffo, 2019). To limit the arising of damage-favourable conditions, usually damage tolerant-like design approach (Grandt, 2003) or risk assessment tools (RATs) are implemented. These tools are especially used to preserve the collections housed inside HHBs that in addition to agents of deterioration as fire, theft are prone to risk linked to the microclimate. For example, to limit the fluctuations of T-RH in indoor environments, Standards of the technical committee CENT-TC 346

Conservation of Cultural Properties (ASHRAE, 2019; EN, 2010; ISO/TR 19815, 2018) establish allowable climatic variations ranges for art objects, which are susceptible not only to physical/structural damage (Bogaard and Whitmore, 2002), but even to chemical (Zhai and Soh, 2017; Michalski, 2022; Nishimura, 2011) and biological ones (Vereecken and Roels, 2012; Pinniger and Meyer, 2001). Results in literature (Burmester and Eibl, 2014; Johnsen, 2013; Erhardt and Mecklenburg, 1994; Erhardt *et al.*, 2007; Bratasz, 2010; Bertolin *et al.*, 2021a, 2021b; Verticchio *et al.*, 2021) have highlighted that the indoor environmental conditions in HHBs do not always meet these requirements through passive control. This means that active climate control (HVAC) systems need to be implemented to resolve the hygrothermal deficiencies or the potential conflict with human thermal comfort at cost of a certain budget availability that, as explained above, will become less economically sustainable for HHB owners and managers in time of climate change and/or not appropriate retrofit. Limiting the energy consumption is therefore a delicate issue.

After the introduction, the following section 1.1 briefly reviews the multidisciplinary findings of the SyMBoL project (2018–2022) that has partially faced some of the above-described research gaps and has led to the creation of this Special Issue (SI). Then, section 2 discusses the contributions printed in this SI emphasizing their novelty and finally section 3 concludes reporting what are the future research needs that still need to be investigated in depth.

### *1.1 The SyMBoL project (2018–2022)*

The International Project SyMBoL—Sustainable Management of Heritage Building in a Long-term Perspective (project N° 274,749, funded by the Norwegian research Council)—coordinated by the Norwegian University of Science and Technology (NTNU) had the opportunity to examine few of the Norwegian Medieval Stave Churches (SCs) to provide methodological practice for testing heritage materials not destructively and to understand some of the above reported research challenges with greater clarity.

While in recent buildings, physical properties of assets and materials are available from manufacturers or database, this is not the case of historic materials that are heterogeneous and/or traditionally done at local scale. This means that their properties need to be investigated *in situ* using NDT or in laboratory implementing the same techniques on mock-up samples resembling original materials. The micro-indentation technique, a micro-sensitive technique still not commonly used in heritage science (Lukomski *et al.*, 2020) was adopted in SyMBoL (coupled with dynamic water vapour sorption and X-ray microtomography too) to examine the physical properties of small volumes of distemper paint samples (DPS) for trying to scale-up such information at macro scale (Freeman *et al.*, 2021a). To this aim macro-sized mock-ups to be used in laboratory tests were prepared for mimicking physical behaviour of “real” distemper paints present in SCs based on existing knowledge from the Directorate of Cultural Heritage (Riksantikvaren), the Norwegian Institute for Cultural Heritage Research (NIKU, partner in SyMBoL) and on preparatory tests results conducted at NTNU. These tests, published in Freeman *et al.* (2021b), focused on (1) the process of selecting optimal indentation separation for proteinaceous adhesives derived from mammalian and fish sources: rabbit hide, bovine hide, bovine bone and swim bladder of fish; (2) the effect of indentation separation on the mechanical properties of proteinaceous adhesive films typically used by artists and conservators during consolidation of distemper paints. Freeman *et al.* (2021a) reports the method of analysis followed with the micro-indentation technique as well as the results from tests conducted on chalk-based ground samples and on micro-DPS taken from polychrome walls of the Eidsborg Stave Church, Norway. Beside nano-indentation tests, destructive/semi-destructive multitechniques (i.e. XRD, environmental scanning electron microscopy [ESEM], energy-dispersive X-ray spectroscopy [EDS], FTIR spectroscopy, enzyme-linked immunosorbent assay [ELISA], gas chromatography-mass spectrometry [GC–MS]) were applied to chemically characterize the above analysed 17th century DPS. Results published in Freeman *et al.* (2021c) identified red ochre as the main red pigment within the topcoat of DPS, confirmed the use of a chalk basecoat and permitted the recognition of alteration phases. In addition, the stratigraphic layers of micro-DPS collected in Heddal and Eidsborg SCs, detected the specie of the wood substrate (pine tree), markers of proteinaceous material attributed to the use of animal-based glues and spot areas with linseed oil. In Bridarolli *et al.* (2022), The Getty Conservation Institute (GCI, partner in SyMBoL) compared the mechanical properties of seven animal glues (adopted in conservation practice) within ranges of temperature (T) and relative humidity (RH) typical of uncontrolled environments. The performance of these materials was quantified on cast glue films using dynamic mechanical analysis (DMA) and tensile testing. The applied experimental protocol resulted in the identification of phase transitions between the glassy and rubbery states and the evaluation in those states of the stiffness, viscoelasticity, strength and strain at break of each tested adhesive. In conclusion this research has contributed to a better understanding of the current preservation state of Heddal and Eidsborg distemper paints, to a deeper comprehension and awareness of materials used in DPS, to an improved prediction of what are the environmental conditions at which specific glues may fail and ultimately to a more appropriate selection of adhesive which may last longer.

The acoustic emission macro-sensitive technique was selected as NDT responsive to the early onset of climate-induced mechanical decay on wood (i.e. crack initiation detection). Preliminary tests were conducted at the NTNU Fatigue laboratory (Boccacci *et al.*, 2021) with the combined use of AE system, Digital Image Correlation and Universal Testing Machine. Acoustic behaviour of Scots pine specimens undergoing an external tensile load was investigated to explore the early warning capability of the AE technique in detecting mode I and mixed mode fractures. Specimens were different for tree rings number (high and low) and grain angle (0–20–40–60°). The threshold value of 51.9 dB was found as an early warning indicator for Scots pine samples with mixed mode fractures; while in the case of Mode I fracture, as cracks occurred instantaneously, the oncoming fracture was not predicted. Then, the main experimental task at NTNU was the development of a novel Risk Assessment Tool (RAT) for determining the level of risk of mechanical decay on a cylindric Pine element resembling a stave (diameter of circa 16 cm) when subjected to (natural and artificial) environmental hygric change similar to those existing in the SCs of Ringebu and Heddal (Bertolin *et al.*, 2020a, 2020b; Bertolin *et al.*, 2021a, 2021b; Karvan *et al.*, 2021; Bartolucci *et al.*, 2020; Bartolucci *et al.*, 2021; Califano *et al.*, 2023).

Validation and application to Microclimate studies. Damage functions and RAT may closely link environmental monitored or simulated data with the condition of objects in collections or inside HHB. The potentiality in the use of this novel RAT (Bertolin *et al.*, 2021a) was tested using (1) real monitored microclimate data measured with thermo-hygrometers in Heddal and Ringebu (Califano *et al.*, 2022a, 2022b, 2023) and (2) machine learning algorithms applied to analyse climate-induced risk of mechanical decay on valuable heritage objects kept indoors. In this framework, NTNU contributed (Califano *et al.*, 2022a, 2022b) to analyse the several existing guidelines provided by standards and protocols about the optimal microclimatic conditions that should avoid decay. Criticalities of the existing protocols were pointed out, emphasizing the need for systematically and periodically updated specifications, tailorable to a given case study of concern, without forgetting the ever-present needs of energy- and money-saving approaches. Then, NTNU produced a novel simple strategy (Califano *et al.*, 2022c), named Median of Data Strategy, for identifying RH drops by scanning the RH time series. Afterwards it proposed a machine learning approach for predicting whether climatic fluctuations could have catastrophic effects on the historical wooden materials.

Indoors, these studies have contributed to estimate the risk induced by the use of different heating strategies, that is, the continuous mild heating, the sporadic intermittent heating, and the no heating strategy (i.e. keeping the climate as it is) and—recently—the risk induced by the impact of cyclic repetition of microclimatic patterns over long-term periods (Califano *et al.*, 2023]. The long-term reconstruction of the indoor temperature in the medieval SC of Ringebu was carried out using a building simulation approach and the T fluctuations indoors were analysed over three reference periods: far past (1948–1977), recent past (1981–2010) and far future (2071–2,100) to highlight the climate-induced fatigue—with a simplified approach—both for the natural and the artificial microclimate in time of climate change. Outdoors, a very recent study (Bertolin and Cavazzani, 2022) has developed an algorithm to assess the risk of Freeze-Thaw decay on the foundation stones of the whole group of the 28 Stave Churches highlighting the climate change impact over the last 70-year (1950–2020) using the land surface temperature variability extracted from the Global Land Data Assimilation System GLDAS. The outcome is useful to evaluate the climate change trend, the average lifetime (half-life time) of foundation stones as well as the number of interventions necessary to guarantee their long-term structural soundness.

Finite element modelling (FEM). In SyMBoL, numerical modelling was used to model the properties of the Scots pine wooden samples based on data retrieved during experimental results (Bertolin *et al.*, 2021b; Karvan *et al.*, 2021); in addition, the numerical approach allowed to extend experimental results validity thanks to the parametrization (Soboń and Bratasz, 2022).

The FEM was used by the Polish Academy of Science (PAS, partner in SyMBoL) to assess risk of fracture in massive wooden cultural heritage object and to model the risk due to idealized RH variation (Soboń and Bratasz, 2022). To replicate a common situation with dynamic T and RH variations in a Church during sporadic use of a HVAC system for comfort purposes, the risk of fracture was simulated assuming the object was not in hygrothermal equilibrium with the surrounding environment. The two-dimensional elastic model of such object was subjected to two types of RH variations: step and sinusoidal. The critical amplitude and duration of variations inducing crack propagation were determined for both the two. The modelling showed higher risk of fracture for sinusoidal variation than for sudden RH drops. These results were inserted in the existing Herie tool at PAS (link: https://herie.pl/Home/Info), integrated in the module for “incorrect relative humidity > mechanical decay” to elucidate general trends for both crack formation and propagation in case of Pine wood of cylindrical shape.

## 2. Contributions to the special issue

This SI presents several contributions related to the development of robust methods based on ML algorithms for studying and predicting the indoor microclimate into HHBs. Both the two contributions by Manara *et al.* (2022) and Miglioranza *et al.* (2022) focus on microclimate of the SyMBoL case studies in Ringebu and Heddal (Norway). Currently, microclimate monitoring in HHBs is often carried out for very limited periods of time—especially when no dedicated budgets are allocated—or for longer periods of time but with sensors that are not calibrated over the years or that do not receive the needed maintenance. Considering this, Manara *et al.* (2022) presents an unsupervised ML method for: simulating the microclimate variability in the SCs without monitoring it directly, that is, using existing weather stations data (outdoors); filling gaps in case the original monitored datasets are corrupted, incomplete, with sensors’ errors because of the HHB remoteness, the natural ageing of the sensors, the lack of continuous check during the downloading process. The work explores the potential of variational auto encoder (VAEs) ML tools compared to traditional ones in (1) filling missing data of many hours’ time span, up to some days; (2) calibrating the VAE through short-term monitored datasets in HHBs versus longer-term outdoor data from weather stations in proximity of the HHBs; (3) reconstructing long-tern time series inside HHBs. Results show that additionally it is possible to reconstruct a reference natural microclimate signal to be compared to an artificial time series (caused using a HVAC system). As a matter of fact, this would lead towards smarter choices for the management of the indoor microclimate for preventive conservation by limiting time and money in consuming on-the-field monitoring campaigns. The second contribution by Miglioranza *et al.* (2022) focuses on the study of microclimatic fluctuations caused by the presence of many visitors within the historic building. The work proposes a new algorithm for detecting events taking place in Ringebu and Heddal stave churches, by identifying the fluctuations in T and RH caused by the presence of people. Three methods have been tested: an unsupervised clustering algorithm termed “density peak”, a supervised deep learning model based on a standard convolutional neural network (CNN), and a novel *ad hoc* engineering feature approach named unexpected mixing ratio (UMR) peak. Results show the last method is promising in automatizing the detection of visitors impact for supporting the management of visitor’s access in HHBs.

On the topic of robust risk assessment tools (RATs) focused to HHBs exposed to extreme events and/or natural hazards, the contribution of Bertolin and Sesana (2023) presents a synthetic component-based modelling framework to analyse the vulnerability of the whole group of the 28 still existing SCs (including their contents) in terms of potential multihazard risk for flooding and earth landslide events. Input data for this framework were collected by existing danger maps from NVE (Norwegian Water Resources and Energy Directorate’s). Results show that few churches are subjected to high risk of both flooding and landslide (i.e. Øye, Torpo and Urnes) while Uvdal, Torpo, Ringebu are especially at high landslide risk and Flesberg Heddal and Høre at high flood risk. This paper informs decision makers on SCs in most danger highlighting what are the key indicators whose monitoring over time is crucial for increasing hazards awareness and preparedness. In addition, it contributes to a better understanding of place-based vulnerability with local mapping dimension also considering future threats posed by climate change.

A second contribution by Moreno *et al.* (2022a) investigates three past events over 2017–2021 in which rainfall caused damage and collapse to historic rammed Earth fortifications in Andalusia (Spain) with the aim of preventing similar situations from occurring in the future. The study presents a methodological framework based on the use of vulnerability indices, GIS and satellite resources. The Hazard level caused by rainfall is obtained from Art-Risk 3.0 (Moreno *et al.*, 2022b); while the vulnerability of the structures is assessed with the Art-Risk 1 model (Moreno *et al.*, 2022c). Then the workflow for the statistical use of Global Precipitation Measurement (GPM) and Global Satellite Mapping of Precipitation (GSMaP) satellite resources is validated and tested over three detected hazardous events to characterize the strength, duration and intensity of precipitation, while the strength of the winds is evaluated from data derived by ground-based weather stations. Results depict how damages occurred by non-intense rainfall (i.e. not exceeding 5 mm/hour) although in areas exposed to torrential rainfall hazard. The continuation of the rainfall for several days and the poor state of conservation of the walls are all factors that may trigger the collapse of restored mortars. The long-term sustainability of this contribution stays on the workflow applicability. In fact, satellite data nowadays offer a huge pool of data available for free through Copernicus (https://www.copernicus.eu/en) and/or Google Earth Engine (https://earthengine.google.com/) which are supportive in long-term affordable reanalysis.

For energy and carbon savings retrofit interventions on HHBs, Stellacci *et al.* (2022) presents an integrated computational approach for energy retrofit of historical buildings in extreme climate environments. They score different energy retrofitting solutions using energy simulation analysis within a virtual environment (i.e. long-term performance of identified retrofit over future extreme climate (2030–2,100)) testing the effectiveness of data from Grasshopper 3D with a multicriteria decision analysis technique (M-MACBETH). These energy retrofitting solutions are assessed both on performance-based (e.g. energy consumption, weight and carbon footprint), and preservation criteria (e.g. cultural, architectural value, spatial configuration) before and after the retrofitting interventions. Finally, the integrated computational approach is tested for predicting the performance of a traditional timber-framed dwelling in a historic parish in Lisbon.

The sustainable approach proposed by this contribution stays in the importance of conducting building energy simulation linking physical and digital environments and in identifying a set of evaluation criteria to detect the optimal retrofit (e.g. better performances with limited carbon footprint) that may be applied to other historic buildings considering different evaluation criteria and context-based priorities.

Menconi *et al.* (2023) propose a second framework for retrofitting interventions in Traditional Listed Dwellings (TLDs) to improve their energy performance utilizing Dynamic Energy Simulation (DES). They tested their framework on selected case studies in the city of Brighton and Hove (South-East England). Their methodological approach establishes a baseline scenario of heating energy consumption (HEC) to compare energy performance pre- and post-interventions and between different case studies. This analysis highlights some key physical determinants of the HEC which have considerable effects on the amount of energy and carbon savings achievable in retrofits. The novelty stays in the visualization of the results in terms of energy and carbon savings potential after standardization, normalization and comparison with a baseline scenario. This helps in selecting the suitable retrofit interventions on HHBs that usually are extremely variable and inhomogeneous.

The last contribution concerning interventions in HHBs (Agha and Hussein, 2023) aims to shed light on adaptive re-use in traditional buildings, that is, traditional cafés (TCs) in Erbil (Iraq). An inductive approach is used to clearly detect what are the solutions implemented over decades when reusing TCs. While a qualitative method is used to extract themes and issues from four case studies in the Erbil citadel's buffer zone through physical surveys and 18 semi-structured interviews with owners, servers and visitors of the TCs. The contribution highlights as the TCs in Erbil have spatial identity and architectural value that are worthy preservation because of the unique spirituality and significance TCs have for the community. In addition, it shows the high flexibility and adaptive reuse capability TCs have through space modifications (increasing visitors' capacity); addition of modern devices (comfort and management standards improvement); and addition of services (integration with the community). The concept of adaptive reuse intrinsically brings a long-term management vision. Notwithstanding positive and negative impacts triggered by adaptive reuse needs to be carefully correlated to level of changes or aesthetics and significance conservation needs.

Finally, regarding standardized approaches in testing mechanical properties of HHBs materials, this SI includes the contribution by Kourkoulis *et al.* (2022) which illustrates the determination of mode-I fracture toughness of a brittle structural materials as the marble. This has been done by means of the notched Brazilian disc configuration, taking advantage of a recently introduced analytical solution and, of data provided by an experimental protocol with notched marble specimens under diametral compression using the loading device suggested by International Society for Rock Mechanics and the 3D digital image correlation technique. The analytical solution highlights the role of geometrical factors (e.g. width of the notch) which are usually disregarded. The data of the experimental protocol are comparatively considered with those concerning the response of the specific material under uniaxial tensile load. This combined study provides interesting data concerning the exact crack initiation point and the level of the critical load causing crack initiation. Results show the crack initiation point is not known *a priori* (even for notched specimens) and that the maximum recorded load does not correspond by default to the critical load responsible for the onset of catastrophic macroscopic fracture. At a load equal to about 70% of the maximum one, a process zone of non-reversible phenomena is formed around the notch's crown, designating termination of the validity of any linear elastic solution used to determine the normalized stress intensity factors. Therefore, the experimental procedure must be monitored with additional NDT to give an overview of the displacement field developed during loading.

## 3. Future research needs

The contributions in this SI fall within the general needs for actions highlighted in section 1 as those requiring further development. Still, these contributions only address some of the detected challenges, thus supporting the need of continuing expanding the research in,

Long-term risk assessment: In terms of natural hazards, the multidimensional vulnerability concept with exposure, susceptibility, coping capacity aspects has been addressed to still a limited types of HHBs (e.g. religious buildings made of masonry). At landscape and multi-HHBs scale, more realistic risk models, capable of forecasting emergency situations in the future, should be achieved through the validation of the satellites data products with experimental/*in situ* monitored data to evaluate their precision-accuracy, reduce their uncertainty and understand parameters and thresholds of damage on objects/materials of interest. In terms of RAT, digital records of the status of conservation of HHBs must be carried out systematically over time to both correlate materials, building envelope, landscape variation with climate and hazard conditions and preserve significant information in case of HHB loss. RAT, danger maps as those reported in this SI and multidisciplinary information can be incorporated into HBIM tools for Disaster Risk Reduction, management and conservation plans at local scale. Research is still needed to highlight BIM and HBIM differences; improve existing LCA libraries and integrate notion of heritage significance for a better data collection/modelling; create HBIM prototypes that emphasize synergies between disciplines; develop methodological frameworks (collect, process and manage information of large size) that are standardized with an improved interoperability, reduced inherent complexity and that are exportable to HHB with similar characteristics possibly using the automation potentiality offered by the ML. This is essential to achieve a cost-effective methodology more attractive for the end users. Then, the case studies monitored over a long-term or used for validation should be disseminated as much as possible to support the stakeholders in decision making process (e.g. for selecting hierarchies in information, deterioration risks, priorities in conservation). Finally, to avoid the risk that HBIM will be rapidly forgotten in local database, it needs to be integrated with Internet of things or digital twin technologies to facilitate and extend the service life of the information (Jouan and Hallot, 2019). In terms of climate-induced decay, RATs are still adopted to alert in case of occurrence of past risky events. The research needs to update and reformulate these tools providing them with (real-time/future) predictive capabilities capacities taking advantage by ML algorithms. This requires improving the work on:

1. reanalysis of large datasets (e.g. past and present climate conditions) to warrantee their quality (e.g. filling gaps, reconstructing original climate signal by corrected time series) and to generate complete time series from few control parameters as input.
2. developing algorithms capable of detecting climate/microclimate periodicity, trends, underlying structure, or patterns of risk.
3. reanalysing existing RAT and standards on climate control in CEN-TC346 at the light of energy efficiency and sustainability goals. In this framework ML may be used to optimize decision processes. This will help in filling the knowledge gap left by regulatory exemptions related to HHBs upgrade/retrofit.

When dealing with energy retrofits in HHBs, comprehensive criteria, methods and processes for assessing and selecting sustainable retrofits or for identifying novel technologies with minimal visual impact and optimal reversibility in Renewable Energy Source (RES) are still lacking. Further knowledge is also required to report the effects triggered by incorrect interventions or exacerbated climate conditions (i.e. maladaptation risks) in particular on comfort, HVAC energy performance, HVAC systems inefficiency, links among occupants' expectations—microclimates character defining feature in HHBs—optimal conservation requirements.

Further research should advance the interoperability of software used in (energy) building simulation models to facilitate validation of simulation results with both *in situ* and laboratory data; to extend simulations to wider types of HHBs under retrofits scenarios that involve mechanical, environmental, economic aspects (e.g. fracture toughness, end-of-life, minimal cost-effectiveness). Similarly, more case studies of upgrading, retrofit and adaptive reuse in different types of HHBs in countries with similar social and climate conditions are required. These will support the assessment of the relationship between tangible (e.g. social, architectural, cultural values) and intangible significance/loss of value (e.g. local, traditional, societal values) and of how the interventions may affect it.

Additional experimental research is needed on mock up samples resembling as much as possible the characteristic of the original heritage material. In such framework, existing theoretical models, laboratory tests on mock ups and numerical studies resembling the geometries and properties of the tested samples are meaningful. Further studies on validation, besides the understanding on material properties, may provide interesting suggestions concerning experimental or *in situ* NDTs setups optimization or appropriate selection of techniques. Next steps ask for: use of multi-NDTs simultaneously over longer monitoring periods; integration of the two scales in *in situ* surveys to better depict material and techniques properties (at macro-scale) and material ageing (at micro-scale). Finally, the integration of data retrieved by material properties (through NDT implementation) and by indoor climate conditions will facilitate the development of novel method of detection of unique HHBs characteristic thus diminishing the discrepancy between actual HHBs/objects performances and simulated results.

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