Geotechnical Engineering for the Preservation of Monuments and Historic Sites III – Lancellotta, Viggiani, Flora, de Silva & Mele (Eds)

Rethinking preventive conservation: Recent examples

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ABSTRACT: The past few decades have seen an increasing awareness of the potential socio-economical and environmental impact of investment in Cultural Heritage (CH). Preserving CH is not only an obligation to sustain and transmit it to the future generation but is also a driver of sustainable growth. Here, recently concluded projects are taken in consideration for a reflective thinking on preventive conservation, as the only viable strategy towards a sustainable and cost-effective management of CH, to face unprecedented challenges posed by increasing natural and man-made threats. Here, the main open issues for a widespread implementation of preventive conservation are identified, moreover, standardised, integrated good practices, validated over significant case studies, are presented within a multi-level replicable framework.

1 INTRODUCTION

Over the past few decades, the awareness of Cultural Heritage (CH) potential and of the benefits brought by it to society as a whole is significantly grown, leading to a strong development of national and international policies. Several examples demonstrated the significant socio-economical and environmental impact of investing in CH. CH has been recognised not only as an irreplaceable asset, but also as a driver of sustainable development and a strategic resource to promote peace, diversity, inclusiveness and participation (Jagodzińska et al. 2015). In order to preserve CH, its intrinsic fragility and the growing threats that is facing are particularly worrying and are calling for the development and enforcement of good and validated practices. To this end, preventive conservation is likely to be the most cost-effective strategy, strongly recommended by international institutions involved in preservation, as the International Council on Monuments and Sites (ICOMOS). The 2003 charter (ICOMOS 2003), for instance, while setting an ensemble of principles for conservation, recognises preventive maintenance as the best therapy for built heritage.

According to preventive conservation philosophy, damage and decay are unavoidable, however they can be tolerated as long as the affected system is fit-for-purpose, namely it meets a set of requirements related, for instance, to structural capacity, aesthetic, comfort and safety of the user, economic and market values and, in the case of historic buildings, authenticity and heritage value. The probability of failing to meet one or more of such requirements is, therefore, reduced by scheduling maintenance and interventions according to prescribed criteria based on performance and/or parameter monitoring and the consequent analysis and prognosis (CEN 2010). This approach allows timely detection of anomalies, optimized long-term allocation of the resources and prioritisation of the required measures.

A preventive conservation framework is the effective integration of condition survey and monitoring with risk assessment (Taylor 2005), where condition survey and monitoring repeat over time

DOI 10.1201/9781003308867-4

the estimation of the building performance through qualitative and quantitative methods, whereas risk assessment forecasts the potential loss of performance due to specific hazardous events. Their integration allows the identification of the probable causes from the detected damage and the prediction of the remaining service life, based on the expected evolution of the degradation under given scenarios (Taylor 2005). This integration is boosted by the development of a reliable digital twin namely a duplicate of the asset, generated by a fusion of models and data and able to evolve replicating the physical twin evolution in time (Wagg et al. 2020). Documenting the CH asset condition and understanding its need in connection with its environment and its operation become fundamental pillars of conservation. Nonetheless, this asset investigation is complicated by several factors, as further described in the following sections. Such shortcomings should be tackled by validated, replicable and cost-effective strategies able to adapt to the specificity of each asset, without losing objectivity in the interpretation of the evidence.

Two recently concluded European projects led by the University of Minho, with an active involvement of the authors, have been an incredible opportunity to reflect further on CH preventive conservation, formulating a multi-level comprehensive methodology, built on standardised protocols and aimed at addressing the aforementioned shortcomings. These protocols were validated and tested on a large set of assets located in different context and geographical area. The main outcomes of the projects are described in the last part of this paper.

2 PREVENTIVE CONSERVATION: A MEDICAL ANALOGY

The similarities between the diagnostic process for human and building pathologies have led to a medical analogy, embraced by international recommendations and scientific literature. This analogy supports the identification of a standardised framework for conservation, drawing inspiration from a field that has theorised that prevention is better than cure, for a long time. Following this analogy, in (Della Torre 2010) and (Balen 2015), three levels of prevention were defined: (i) a primary level aimed at avoiding the causes; (ii) a second level aimed at an early detection of the symptoms; (iii) a third level aimed at preventing a further spread of the pathology and its side effects. First level encompasses mitigation strategies, ranging from simple measures (e.g. proper use of the asset and constant maintenance) to more systematic modifications of the level of hazard, exposure and/or vulnerability. Second level relies on a systematic screening. Third level consists in an urgent cure. It is clear the change of perspective: the remedial treatment (level 3) should not be the standard way, it is rather an ultimate solution when prevention (level 1 and 2) fails, namely it is a defeat of the conservation system (Balen 2015). Extending the medical analogy, preventive conservation can be, thus, seen as a process of early diagnosis and treatment, repeated across the asset lifespan, in which damage and defects are seen as symptoms of a pathology.

The diagnosis aims at defining with sufficient degree of certainty the most probable causes for these symptoms, following a differential diagnostic procedure, namely comparing multiple alternatives. These alternatives are reduced to the most likely based on the data collected by anamnesis (interview and search for medical history, presenting complaint and relevant data), examination (mainly qualitative and supported by simple tools) and testing (experimental quantitative evaluations). The causes are then tackled through a proper therapy, whose effects are object of control in time. Shifting from cure to prevention requires a change of mindset and the acquisition of a new awareness of its advantages that are often visible only in the long-term and, nowadays, are not always quantifiable yet. Moreover, such positive consequences are only achieved upon an initial investment in screening that may demand considerable economic and societal costs, especially when a proper planning and knowledge is lacking (Balen 2015). In this regard, the implementation of a preventive conservation strategy should be driven by a case-specific cost-benefit analysis, based on factors as time and resources required for a repeated assessment, costs of timely and delayed measures, significance of the asset and level of risk.

3 PREVENTIVE CONSERVATION: CONDITIONS FOR IMPLEMENTATION AND OPEN ISSUES

A wide-spread implementation of preventive conservation rests on (Balen 2015): (i) scientific knowledge; (ii) clear codes and guidelines; (iii) supportive policies; (iv) trained professionals; (v) a society aware of the importance of its heritage and the advantages of prevention. Nowadays, relevant examples for each of these factors exist in many countries, nonetheless, it is argued that there is no system with the compresence of all of them (Balen 2015).

Promoting education of society, making it aware of the benefit of regular control and maintenance and of the significance of heritage, is a paramount strategy to avoid neglection and vandalism and spread the responsibility of prevention among local communities (Balen 2015, Della Torre 2010). Increasing awareness requires consistent regulations and policies including financial supports but also the evidence of the preventive conservation benefit. This evidence consists of good examples that, in turn, requires trained professionals. The legal framework can rely on obligations and recommendations. The former are intended to enforce preventive measures, by indicating, for instance, when the assessment is mandatory or the periodicity of inspection and maintenance. The latter are indications of the steps to take and instructions, aiming at spreading good practices. In different countries, protection, conservation and actuation criteria are commonly defined at completely different scales (e.g. both national and local, only national or only local), with different levels of coordination between the involved entities. Intervention and management strategies may exist, although disperse, or lack completely (Masciotta et al. 2019). Such sparse and vague instructions induce a dangerous state of uncertainty regarding conservation policies and may result in a non-compliance.

The legal framework is also relevant in the field of testing. Lack of accreditations, regulations and guidelines jeopardise the reliability of the tests that are affected by the personal experience and judgment of the operator. Together with laws and regulations, supportive policies and financial investment through grants and incentives may play an essential role in promoting proactive conservation strategies. Indeed, most of the CH buildings and sites are financially non-self-sufficient and rely on public subsidies to invest in conservation, but recent financial crises have led to deep cuts to heritage sector funding (Marjanović 2014). Moreover, funding is mostly addressed to listed assets, neglecting a large number of historic buildings. Preventive habits may optimise resources allocation and management of the limited budget available, but many assets are already in a severe state of decay to a point where financial institutions are unwilling or unable to invest in urgent remedial measures that are preparatory to a preventive management (Marjanović 2014).

Finally, as already mentioned, the evidence of the preventive conservation benefit is essential to spread its practice. All the stages of conservation, including technical and practical activities, require expert professionals. Lack of training and education of the parties involved in conservation is likely the principal cause of inappropriate decision making. It results in interventions that do not address the causes, but just the symptoms, leading to negative consequences like a recurrence of the pathologies, a diffusion of the damage or an acceleration of the decay. Inadequate interventions, including use of incompatible materials or incompatible structural systems, is commonly driven by non-systematic documentation, limited testing, misinterpretation of the collected data and, in general, an excessive appeal to subjective judgment in the absence of conclusive evidence. Even good decision making may be hindered by the lack of skilled craftsmen to carry out the required activities (Balen 2015).

On the other hand, sometimes, the practitioners voluntarily avoid a detailed investigation claiming that it is expensive and time-consuming, reporting the dispersion of information and the inconsequential existing procedures (Gonçalves et al. 2017). This is likely due to the nature of the sought information, cumulative and dependent on the availability of time and sources. Significant data can be non-existent, unreliable or outdated. Documentation, thus, requires iterative and flexible procedures and adequate platforms to store and retrieve it. In this regard, digital technology may offer an unvaluable support to inspection and documentation. Recent advancement in software and hardware allows to collect, store, retrieve and process an unprecedented large amount of data. Potentially, advanced surveying techniques and structural health monitoring strategies are likely to reduce the time requirement to produce updated and precise information.

Nonetheless, purchasing and maintaining the required software and hardware components, including instrumentation, licences, storage platforms and processing systems, require a significant investment that should be considered in the cost-benefit analysis. More importantly, the information that is generated by such advanced tools, is indiscriminate and growing in size and complexity, is demanding in terms of data management and interrogation and requires a time-consuming processing to become significant and meaningful to the stakeholders. This not only increases the costs but also requires new expertise from fields that were not directly involved in conservation before. On the other hand, saving on the sources or on the post-processing of the data is likely leading to an insufficient level of knowledge. In both the cases, excess or lack of data, confusing and meaningless information is produced, contributing to the scepticism of the stakeholders regarding the diagnostic process.

A final issue, to be mentioned, is the multidisciplinary nature of heritage analysis and preservation that encompasses different approaches, each one with its own terms, methods and sources. A synergistic framework needs a coordination and unification that start from the terminology. Indeed, different disciplines currently use the same words with subtly different meanings or address similar concepts by means of completely different words.

4 RETHINKING PREVENTIVE CONSERVATION: HERITAGECARE METHODOLOGY

Addressing all the aforementioned open issues is not an easy task as they are strongly connected. A non-harmonised, sparse and vague legal framework, without uniform terminology and standardised methodologies for data collection and interpretation, leaves room to subjectivity, prevents interdisciplinary collaboration and hinders successful preventive conservation instances, leading, in some cases, to poor decision making that enhances decay and loss. The lack of good examples contributes to a diffuse scepticism regarding preventive strategies and building diagnosis considered inconclusive, expensive and time-consuming, therefore unworthy.

Unaware owners do not demand preventive conservation, since codes do not enforce it and policies do not provide financial support for it, moreover, they do not resort to expert professionals in case of need that, therefore, are not encouraged to invest in training and perform accurate diagnosis while assessing existing structures. Tackling such issues requires rethinking preventive conservation and the role of academia in disseminating good practices and boosting advancement in scientific knowledge. This process should lead to the development of a consistent and cost-effective preventive conservation framework, defined according to the following steps: (i) review of existing methodologies, documentation and management systems, standards and codes relevant to assessment and conservation; (ii) standardisation of terminology, protocols, recommendations and criteria, integrating the existing ones into a consistent unitary approach harmonised with the current regulations; (iii) identification of flaws or gaps in the overall process flow or in its tasks (e.g. outdated methodologies or conservation needs that are not properly addressed); (iv) development and validation of novel strategies, including testing techniques and diagnostic tools, to fill such gaps; (v) validation of the overall methodology in real scenarios.

A systematic literature review is of paramount importance. Indeed, beside policy-makers, other institutions and scholars have produced a large number of protocols, recommendations and testing strategies, often focused on specific goals within the field of documentation, inspection, diagnosis and conservation (Gonçalves et al. 2018, Kioussi et al. 2011, Pereira et al. 2021). A comparative analysis of these methods aimed at an integration and a harmonisation also with the existing codes is unavoidable. Moreover, the consistency of the framework should be improved by addressing built heritage conservation as a specific case of a wider existing building conservation discipline rather than a separated instance, allowing good practices to be generalised, irrespective of the original field of application. This beneficial integration of the methodologies should follow a holistic approach that includes in the assessment all the needs of the asset as a whole, thus related, not only to structural safety and material conservation, but also to user comfort, energy efficiency and sustainability among others. This requires a comprehensive and multidisciplinary process of harmonising the good practices towards a cost-effective management, in which any activity or intervention carried out on the building aims at fulfilling more of its needs at the same time or, at least, at minimising the negative impact in case of conflicting needs.

Upon this preliminary analysis, a set of basic requirements for a preventive conservation framework are defined as follows:

- The framework must use a clear and unified terminology. Glossaries of damages, activities, principles, concepts, assets typologies and components have been collected in national and international standards and guidelines, e.g. (EN 15898 2019, ICOMOS 2003). A standardised glossary should be built by harmonising such sources and it should be furnished with clear textual and graphical information for a univocal identification of each item.
- Informed decision-making must be supported by a set of relationship databases connecting at least: (i) symptoms and causes, defining also the most effective diagnostic tools to formulate a correct diagnosis; (ii) causes and remedial measures, based on the urgency of the intervention and the extent reached by the pathology. Such databases are built on scientific knowledge and previous experiences and should be updated upon advancement of research. Their correct use prevents the influence of subjective judgment and experience on the diagnostic process and the implementation of unnecessary or incorrect treatments. Moreover, they can help the stakeholders select the most appropriate equipment for their specific predictive conservation needs, based on ongoing and expected damage scenarios (Pereira et al. 2021).
- For each asset a database must be created to collect all the documentation produced. The database should allow a dynamic updating across the entire lifespan of the asset, adapting to the cumulative nature of information (Kioussi et al. 2011). The preventive conservation framework should aim at a comprehensive documentation of the whole investigated system, including the building envelope, the interior, the technical installations, the equipment and the integrated movable assets, as they all contribute to the value and the performance of the system.
- Documentation and data collection must be as free as possible of biases. In case of qualitative methods, especially visual inspection, subjectivity can be prevented by defining a standardised mean of recording the information, presenting clear requests through fields to be filled and unambiguous options for pre-set multiple choices, to be used according to a protocol for each method. In case of quantitative methods (e.g. on-site or lab tests) errors and uncertainties should be minimised by defining clear protocols including information as the equipment, the data storage and retrieval strategy and the tasks to be performed in preparation, during the execution and afterwards, namely, to plan the activities, apply the method and interpret its outcomes.
- Expert and trained professionals are the main actors of the diagnostic process. The protocol of each task of the framework should clearly specify the needed expertise and the accreditation when relevant. Owners and users, irrespective of their background and education, should contribute by correctly using the asset and its components and by monitoring the application of the technical recommendations. Moreover, they should participate in documentation, not only through interviews, but actively, carrying out non-expert regular inspections, aided by simple checklists or questionnaires, to report in a standardised way malfunctioning, damage and decay in the very early stage. This ensures an adequate level of maintenance and a timely identification of the anomalies, optimising the subsequent expert activity.
- To guarantee a flawless exchange of information, for each party involved (e.g. professionals, owners and managers, stakeholders, policy-makers, etc.), databases access and editing rights must be clear, defining type, amount and format of information that each category can query, produce and/or edit. This ensures the quality control and that each party interacts only with information that is meaningful for its purposes. A standard minimum quality and amount of information needed for each task of the framework should be defined, aiming at a good trade-off between costs and benefits of documentation.

– The framework must be flexible and multi-level, in order to be replicable and scalable, adapting to the expected variability and peculiarity of diverse geographical areas and target assets, with various complexity, level of performance, conservation needs, protection status, local environmental, social, economic and financial conditions. Such factors affect the extent of the information that can be collected and generated. Therefore, the granularity of information should be defined upon agreement among the parties involved, based on the pre-defined level needed for each task. A hierarchic and nested organisation of the levels, where the specific tasks of a lower level are included in the upper levels and complemented by additional activities, allows a dynamic adaptation of the service, over time, to new conditions, resources or needs. At least two levels for the assessment can be identified, in agreement with ISO 13822 standard (ISO 2010), namely a preliminary and a detailed assessment. An harmonisation of standard procedures can be attempted by integrating the preliminary inspection with the condition survey detailed in EN 16096 standard (EN 2012).
– The diagnosis should produce an indication of the recommended measures and their urgency for the asset as a whole, based on the condition grading, the risk and the recommended measures for its components (EN 2012). The criteria and the relevant features used to issue the grade should be clearly expressed as well as the aggregation formulas to estimate the overall score based on the component's values. Standardised criteria should be also defined to link condition and risk to the urgency and type of intervention needed. A colour-coded rating supports the interpretation by making reporting more user-friendly to non-technical users (Abbott et al. 2007).
– The preventive conservation framework should present a high level of digitisation. All the aforementioned relationship databases, glossary, protocols and previously generated documentation on the asset should allow online, real-time exploitation, especially to support on-site activities. This reduces the time invested by the operators in learning the methodology and performing the tasks, reduces the gap in technical knowledge between different operators and increases the accuracy of the inspection (Gonçalves et al. 2018). Moreover, a digital platform supports the definition of clear access and editing rights, automatically filtering the information and providing ad-hoc authorisations and restrictions to each category of user. The digitisation of the information is also essential to establish an effective interoperability between all the parties involved in the management and preservation of the assets. To this end, specific protocols should be defined to guarantee that the documentation is made available for other purposes, as analysing energy efficiency, managing activities within the spaces, estimating quantity take-off, allowing interactive and virtual engagement with the asset, etc.
– The databases created for each instance allow data collection and exploitation at the individual building level. However, a centralised management of the information allows the statistical analysis of an increasing group of assets, offering an invaluable tool for policy-makers to learn from experience and establishing good practices. This higher level analysis, indeed, provides a paramount insight into pathologies occurrence, reliability of the diagnostic techniques and effectiveness of remedial measures.

The recently concluded HeritageCare project (SOE1/P5/P0258) has significantly contributed to this ongoing process of rethinking preventive conservation. This multidisciplinary high-technological effort, involving eight beneficiary partners and eleven associated partners from three countries (Portugal, Spain and Southwestern France), coordinated by the University of Minho, has led to the development of a new validated methodology for heritage preventive conservation, according to the aforementioned requirements.

For a thorough description of the project and its outcomes refer to (Barontini et al. 2021; Masciotta et al. 2019, 2021). HeritageCare multi-level methodology encompasses a set of tasks organised according to a systematic workflow in three following stages, namely prior to, during and after inspection, each one with specific data categories to be collected and generated and activities to be carried out. The granularity of the documentation and information searched, stored and produced varies according to three Service Levels, SLs (Table 1).

Table 1. HeritageCare service level definition.

Service Level	Designation	Functionality
SL1	StandardCare	Provision of what is essential for the primary health and ordinary maintenance of the heritage building.
SL2	PlusCare	Provision of what is necessary for the primary health, ordinary maintenance and thorough screening of the heritage building along with its integrated and movable assets, including monitoring data to support decision making.
SL2	TotalCare	Provision of what is necessary for the primary health, ordinary maintenance, thorough screening and enhanced management of the heritage building along with its integrated and movable assets.

SL1 provides a low-cost and rapid, although complete, assessment of the historic building, harmonised with the methodology described by EN 16096 Standard (EN 2012). Prior to inspection, the off-site documentation is carried out, through historical survey and bibliographic search. The reliability of all the textual and graphical sources is assessed and all the relevant data is extrapolated and collected within the Building ID and management information, namely a series of descriptors, updated over time. These include univocal code, name, category, protection status, property, time of construction, original and current functions, localization, important historical information, architectural features, construction system, principal building materials, previous interventions, inspections, maintenance actions, test reports, number of integrated and movable assets of cultural interest with a description of their significance, age and main geometrical and material features. This documentation is furnished with bibliographic references, sketches and drawings of the main components and spaces. The inspection at SL1 is mainly qualitative and is performed by at least two experienced professionals, with complementary expertise, capable of grading the condition state of the building and its components. The main support on-site is the inspection app (Figure 1), with an e-form to be filled online, with a standardised checklist of items and sub-items to survey. During on-site activities, the surveyors have access to informative materials as the standardised glossary, the damage atlas with definitions and examples and a collection of most common damages and deterioration processes for each sub-item. Each damage affecting the sub-item is graded through a condition index and a risk index, according to a 4-point scale, from 0 to 3 (Figure 2). These indexes are then used to assess the sub-items, the items and the asset as a whole, in a bottom to top cascade. More details on the assessment criteria are provided in (Masciotta et al. 2019).

Upon completion of the inspection process the report for the asset managers and owners is automatically produced and stored on an online platform. The report encompasses an informative section on the overall condition of the building and its main components and a set of clear and schematic recommendations regarding remedial or preventive actions to undertake in the short/medium/long term based on the identified damages, their most likely causes and consequences (Figure 3). The asset managers or the owners are then invited to provide feedbacks, in order to document any following measure undertaken on the building. Building ID, management info and subsequent condition reports constitute a simple but informative attribute-based digital twin. Movable assets hosted within the building may deserve specific attention during the inspection. To this end an ad-hoc documentation protocol is defined, aimed at producing an Asset ID, namely a set of relevant data, similar to the Building ID, used to unambiguously identify any specific heritage object and allow its standardised inspection. This inspection is carried out by means of a dedicated form where damage, alteration and operational and environmental conditions that are likely to affect the asset conservation (e.g. temperature, relative humidity, illumination, etc.) are recorded.

SL2 complements and increases the level of information on the building and the integrated and movable assets, producing a virtual restitution and collecting quantitative information, through testing, monitoring and surveying techniques. Typology, location and number of tests are defined

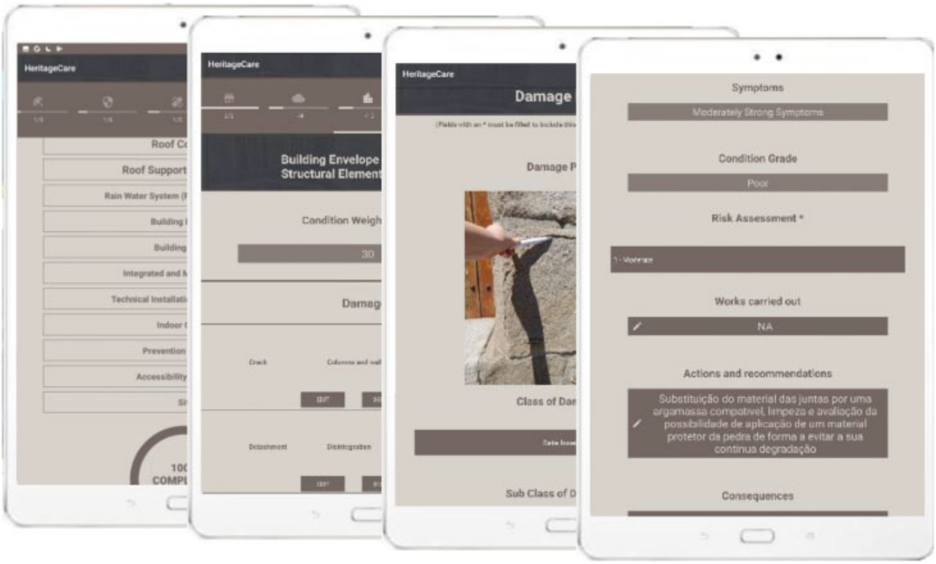


Figure 1. HeritageCare mobile inspection app.

Class N.	Condition index
0	Good – No symptoms
1	Fair – Minor symptoms
2	Poor – Moderately strong symptoms
3	Bad – Major symptoms
NA	Not (safely) accessible

Class N.	Risk index
0	Long term No actions | preventive monitoring
1	Medium term Non-urgent actions | Monitoring
2	Short term Timely repair or additional inspection and diagnosis
3	Urgent and immediate Urgent repair or additional inspection and diagnosis
NA	Not inspected Not safely accessible or not visible

Figure 2. Condition and risk rating indexes.

Figure 3. Excerpt from the Guimarães ducal palace inspection report.

prior to inspection, based on the condition assessment and upon agreement among the involved parties. Each test has a pre-set protocol defining the expertise requested to the operators, the equipment and the procedures for a correct execution. Testing and monitoring is intended to identify and track physical, mechanical and environmental parameters for a detailed assessment of the asset condition and the evolution of its performance. All the required techniques are summed up to build a service that is tailored to the specific asset needs and resources. This flexibility fosters an application of the methodology to any context, without requiring extra costs or specific expertise of the operators.

For instance, the methodology is independent of the surveying strategy, allowing the managers to decide whether to request a traditional metrical survey or a more advanced one, image-based (e.g. terrestrial or aerial photogrammetry) or range-based (e.g. static or dynamic laser scanning). For photogrammetry three protocols exist depending on the goal, namely reconstruction of planar objects, 360° reconstruction of movable assets or detailed reconstructions. The protocol determines the rules and the parameters of the acquisition (e.g. number of captured images, the shot overlap and path, the lens system, the focal length, the exposure triangle), based on the characteristics of the object to capture and the required level of detail. For laser scanners, protocols are more flexible. Nonetheless, essential practical rules are defined and strictly followed to optimize the outcome of the data acquisition. On-site, beside surveying and testing, the operators collect an ensemble of 360° panoramic photos of the whole buildings, recording all its main components and integrated movable assets.

The resulting digital twin integrates the alphanumerical information of SL1 with graphical information obtained by interlinking these 360° panoramic views. This simple, although clear 3D reconstruction allows a virtual tour inside and around the building and is enriched by the identification of hotspots (e.g. damage hotspot, asset hotspot, sensor hotspot, etc.), clearly recognisable through a predefined visual code. Each hotspot is a link to stored information, as SL1 condition reports, specific documents and images concerning the assets, alteration or damage detected during on-site inspections, real-time reading from the monitoring systems installed. When a point cloud is generated, this is also navigable for the stakeholders on the platform, contributing to the information content of the digital twin. Moreover, the platform allows important operations directly on the point cloud, such as slicing to produce 2D drawings (plans, sections and elevations) and segmentation to identify functional parts of the building (e.g. roof, façades and rooms).

Finally, SL3 produces a highly informative 3D model in a BIM environment. A protocol with a standardized workflow to develop and update the BIM model is further discussed in (Barontini et al. 2021). The protocol is based on a clear separation of roles and expertise, a standardisation of the documentation process and the interoperability with the e-form and other professional software. This ensures the exchange of information and its use for other preservation purposes, as for instance organising and performing an inspection, analysing the structural safety or the energy efficiency, designing interventions, managing activities within the spaces, etc., without requiring modelling expertise and holding software licence to any of the parties involved, except for the BIM modeller.

The protocol defines the extent and granularity of the information for each element of the BIM model according to the purpose of the model, to be defined in agreement by all the parties, and in compliance with EN 17412-1 standard (BS EN 2020), as a combination of geometrical data, alphanumerical data and documentation. Indeed, the model consists in an assembly of parametric objects representing the real components of the building with an acceptable level of geometrical detail. These objects are placed in their correct location in the three-dimensional space, as resulting from the existing documentation and the surveys. Accurate measurements and point clouds produced in service level 2 are a fundamental source for the model. The information related to each object is enriched by means of non-graphical attributes and linked documents as, for instance, the outcomes of the historical survey, the bibliographic research and the condition survey. Localised damage can be easily represented by patch-type objects. Similarly, in case of monitoring, the exact location of the sensors can be shown within the 3D model, enabling the real-time reading of their records.

The main purpose of the BIM model is to support on-site activities. Operators can navigate and interrogate it online by using mobile devices or even with the aid of augmented reality technology through mixed reality smart glasses. The availability on-site of an informative model that collects all the previous documentation on the assets is paramount, providing a continuous and timely interaction between virtual objects and physical counterparts. This approach allows a fast comparison of actual damages or alteration phenomena with a previously recorded condition, for a fast decision making regarding urgent measures or an optimisation of the inspection process towards the causes of the phenomena. Augmented reality is a further improvement, permitting a visualisation of the information collected in the BIM model directly on top of the real inspected objects. Smart devices allow also an efficient and rapid data collection by taking pictures or measuring distances. Beside purchasing the smart devices, the surveyors do not need to invest in licences, since navigation and query of the model can be done on free of licence model viewer software or directly on the online platform. No expertise in BIM modelling is demanded to the surveyors, since the manipulation of the model is carried out as back-office activity by an expert BIM modeller upon receiving the inspection forms and reports.

Increasing service level, from SL1 to SL3, implies an increment of the quantity and complexity of the information, requiring more advanced surveying and testing techniques, thus more sophisticated equipment, costs, time and expertise of the operators. It also demands advanced strategy to store, manage and visualise the produced documentation. The flexibility of a multi-level approach allows to provide a service tailored to the specific requirements and financial availability of the owners and the conservation needs and complexity of the specific asset. The adaptability and effectiveness of the methodology were tested over several typologies of heritage buildings (e.g. churches, chapels, palaces, castles, etc.) equally distributed over the three countries. In particular, sixty case-study buildings (twenty per country) were inspected and assessed according to the first service level. Fifteen out of these sixty (five per country) were selected for the implementation of the second service level. Finally, one case study per country was included in the third service level. Two selected case studies, namely São Torcato church and the Guimarães ducal palace, are discussed hereafter to show a complete SL2 and SL3 application, respectively.

4.1 *São Torcato church*

Located in the homonymous village, close to Guimarães, in the north of Portugal, São Torcato church's construction started in 1871, based on the original conception proposed in 1825, featuring a Neo-Manuelino, revival style, and continued in phases for more than 130 years (Ramos et al. 2013). Photos taken during the construction allow documenting the evolution of the work (Figure 4). In its actual configuration, the church has a Latin-cross plan, with a gallery entrance, a single nave (57.5 m long, 17.5 m wide and 26.5 m high) with side chapels and an apse at the north end. The transept is 37 m long and 11.5 m wide. Nave and transept are covered with barrel vaults and a dome with octagonal tambour stands at their crossing. Two towers are placed on the sides of the façade featuring a rectangular plan (7.5×6.5 m^2) and a height of 50 m. Wall thickness varies in the façade, from 2.5 m to 1.7 m. The thickness is 1.3 m in the lateral walls and 1.45 m in the towers (Ramos et al. 2013).

The succession of building phases determined the use of different materials, in particular three-leaf granite masonry for towers, nave and transept, and reinforced concrete for the dome and apse. The gabled roof is supported by timber trusses. Since 1970s the church has been subjected to inspections and regular control, due to a severe cracking in the front area of the church, especially the façade (Figure 5a), likely associated to their differential settlement and tilting, due to the poor mechanical characteristics of the soil. Between 2014 and 2015, the church underwent a structural intervention aimed at eliminating the differential settlement and restoring material continuity, by means of micro-piles, post-stressed tie rods and crack injection (Masciotta et al. 2017). To assess the impact of the construction activities on the church and validate the intervention, a monitoring system was installed and was active before, during and after the works (Masciotta et al. 2017).

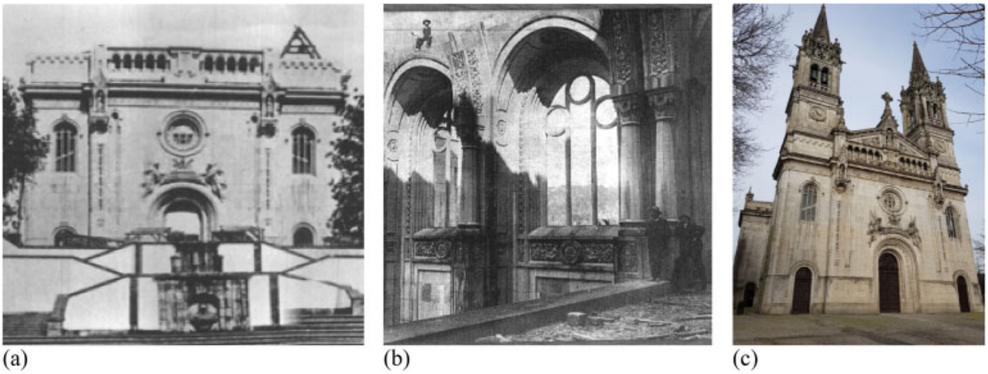


Figure 4. São Torcato church, building phases: (a) exterior view; (b) interior view; (c) actual aspect.

After few years, HeritageCare SL2 protocol was applied to the church. The large number of existing documents was collected and used to constitute the Building ID and management information. In this case, dealing with a quite recent asset that underwent several investigations and a significant intervention, the material available encompasses previous surveys, photos taken during the construction and interventions and test reports. The inspection carried out by the HeritageCare team identified several forms of degradation and damage, such as discolouration, efflorescence, biological growth and bird infestation (Masciotta et al. 2021). Most of the problems were related to water infiltration through roof, walls and openings. After the intervention, a permanent deformation was still evident in the choir, whereas new cracks appeared on the triumphal arch and along the lateral walls of the nave.

3D documentation consisted in a laser scanner survey, by means of a Leica ScanStation P20 (Figure 5). A 3D point cloud with about 3 billion of points, then reduced by processing and filtering to 17 million, was generated over 174 scan stations. The generation of the model required 3 weeks of work to two technicians. Contextually, a photographic survey was carried out in 110 minutes by means of a 360° camera Ricoh theta V at 42 locations, capturing inside and outside. The enriched virtual tour model was generated through the proprietary software Pano2VR®and ad-hoc developed plugins. A more detailed report on this case study can be found in (Masciotta et al. 2021).

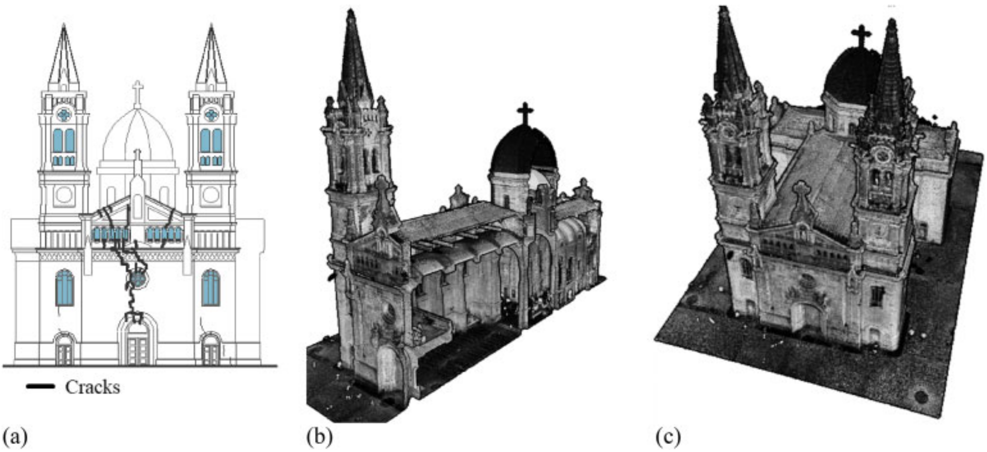


Figure 5. São Torcato church: (a) crack survey before intervention; (b) point cloud of the interior; (c) point cloud of the exterior.

4.2 *Guimãraes ducal palace*

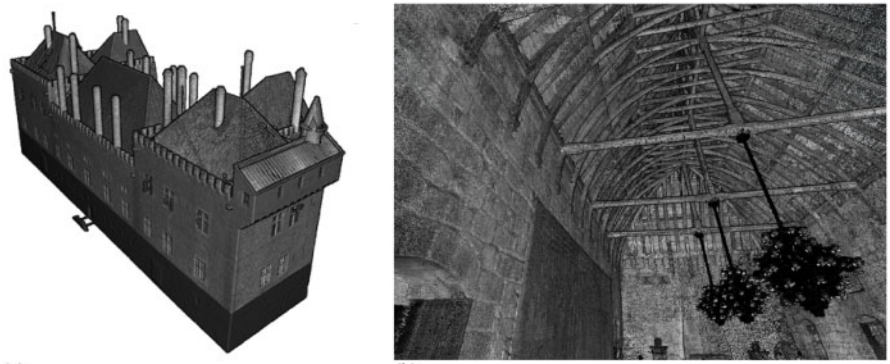
The construction of the ducal palace of Bragança, located in Guimarães, Portugal, was more articulated than the previous case study and was affected by several vicissitudes. The construction, begun in 1420, under the first Duke of Bragança, suffered a first stop after his death. In 1478, the construction continued under the third Duke. In this period, the actual organisation of the spaces was defined. However, the palace remained incomplete, abandoned and subjected to dismantling and reuse of the materials, since the beginning of the 16th century, once the court was moved to another town. The alteration of the building continued during the 19th century, when it was turned into a military barrack. Finally, after the acknowledgment of its importance and the inclusion in the national monument list in 1910, the palace underwent a series of strong interventions, with demolition of the changes occurred in the previous century and addition and reconstruction of several of its parts, aiming at the supposed original aspect of the building. During the repair, an extensive use of reinforced concrete beams was made in the floors and roof. The actual building features a rectangular plan around a central courtyard, surrounded by a colonnade at the two lower storeys. Thirty-nine brick chimneys, among which only four are original, constitute a landmark of the city, as well as the timber trusses of the main rooms are one of the most precious features of the building. These elements are also a major concern for preservation, significantly contributing to the overall vulnerability of the palace.

The diagnosis was based on a detailed inspection that involved more than two professionals to reduce the time-requirement. The staff was interviewed providing a series of relevant information to complement the main findings of the inspection. Degradation and alteration likely due to moisture and water penetration, fostered by the inadequate and poorly maintained drainage system, were identified. Loss of material in the walls is also present, likely due to the incompatibility between the granite blocks and the mortar used in recent repointing works. Finally, superficial cracks are found at the ground floor in load bearing walls. The building features several integrated movable assets, including hundreds of art pieces dating back to the 17th and 18th centuries. The inventory and condition survey of the most significant ones were carried out. Few pieces showing an unsatisfactory conservation state were closely inspected by the HeritageCare team.

Based on the criticalities emerged from this condition survey and according to SL2 protocols, an ad-hoc monitoring system was installed in October 2018 to track structural and environmental parameters. The goals and demands of the monitoring system were defined upon agreement with the directions of the DRCN (Northern Regional Directorate of Culture), aiming at a trade-off between costs, visual impact of the sensors and quality of the collected information for the conservation purpose. The network, still operating, is composed of: (i) 12 temperature and relative humidity sensors (7 surface and 5 ambient sensors) and 5 combined sensors measuring surface temperature, relative humidity and luminosity; (ii) 3 xylophagous sensors at the timber roofing of main room and chapel; (iii) 1 carbon dioxide sensor; (iv) 2 biaxial clinometers on the outer wall; (v) 1 external meteo station recording air temperature, humidity, barometric pressure, wind direction and velocity, precipitations, rain duration, hail, solar radiation and carbon dioxide.

SL2 protocols adopted included a laser scanner survey, carried out, using a Leica ScanStation P20 (Figure 6). Four full working days on-site were necessary for the survey. 360° panoramic views ware taken, concurrently. All these sources of information contributed to the generation of the digital twin of the palace hosted on the HeritageCare platform. This is composed, at SL2, of the 360° panoramic views based virtual tour, enriched by a set of hotspots. Asset hotspots identify the significant movable assets inspected and assessed with more detail, providing the results of the on-site survey (Figure 7).

Damage hotspots locate the anomalies found during previous inspection on-site. Sensor hotspots allow reading the most recent instrumental acquisitions (Figure 8). Here, samples are updated hourly. Based on pre-set threshold values, the acquisition presents a colour-based warning so that the manager can easily identify parameters that are deviating from the acceptable condition. The results of the laser scanner survey are also navigable on the platform.



(a) (b)

Figure 6. Guimãraes ducal palace point cloud: (a) external view; (b) detail of the interior.

Figure 7. Virtual tour enriched with asset hotspots, linked to condition survey report.

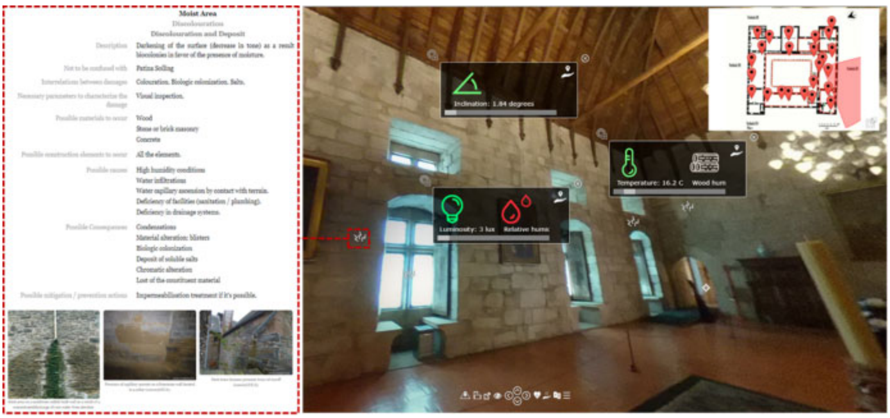


Figure 8. Virtual tour enriched with sensors and damage hotspots, linked to recent acquisition and damage report, respectively.

Finally, SL3 protocol was applied, by building a BIM model of the palace, enriched with all the aforementioned data (Figure 9). The model was generated first resorting to traditional survey techniques and existing documentation, then it was validated through the laser scanner acquisition. The purpose of the model, namely supporting an effective exchange of information between asset manager and surveyors regarding assets condition and ongoing or emerging anomalies is fulfilled by a wise trade-off between graphical and non-graphical information. This allows a reduction in time and costs to generate the model, ensuring a sufficient level of geometrical detail to correctly localise, within the building and its components, damage, movable assets or sensors. An augmented reality aided inspection was carried out by means of a pair of HoloLens and a smart glass inspection app. More information on this case study are provided in (Masciotta et al. 2019).

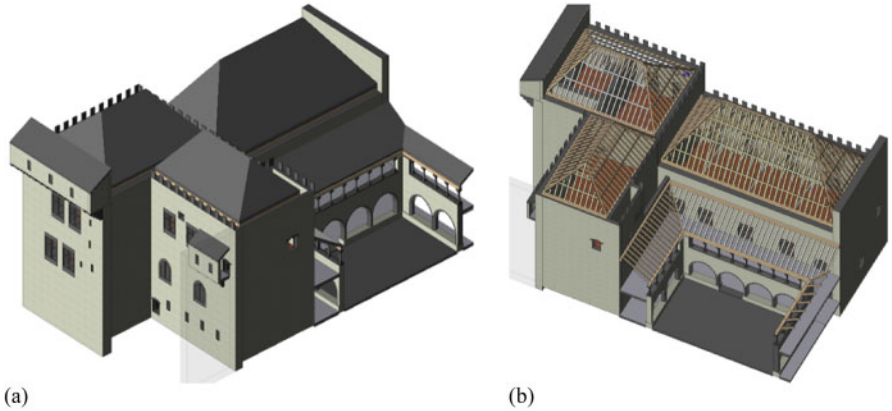


Figure 9. Guimãraes ducal palace BIM model: (a) global view; (b) detail of the roofing system.

5 NEW TECHNIQUES FOR THE INSPECTION AND PRESENTATION OF THE NON-VISIBLE PARTS OF THE BUILT HERITAGE: HWITHIN METHOLODOGY

The Heritage Within (HWITHN) European Research Project (Ortega Heras et al. 2021) aimed to develop new technologies to produce an innovative visualization of the cultural heritage by showing nonvisible features of buildings and archaeological assets. 3D surveying and modelling techniques (e.g. photogrammetry and laser scanning) have greatly evolved in the recent years but they can only reconstruct the exterior surfaces of the elements.

The project aimed to go beyond this barrier to image also relevant information of the interior of its constructive elements and other non-visible data. To this end, the project not only resorted to existing techniques (Ground Penetrating Radar) but also developed new ones, namely a system to perform on-site ultrasonic acoustic tomography of complex architectural elements in an automatized way. As a result, the inner hidden morphology of several columns could be reconstructed, on an almost stone-by-stone basis, and the inner damage and state of conservation of the material could be evaluated.

The final 3D model and associated information was implemented into a Virtual Reality (VR) application to offer an interactive visualization of our heritage, on-site and remotely. The approach proposes to relate the visible with the invisible, looking beyond the surface of the object, which facilitates the identification of inner morphology, cavities, hidden objects or damage. The action proposed as a pilot case study the Archaeological Museum of Carmo, in Lisbon (Portugal), which occupies the ruins of the old church of the Carmo Convent, destroyed during the 1755 Lisbon earthquake.

The Carmo Convent was commissioned in 1389. After two attempts, failed due to local subsoil conditions, the construction works started in the last decade of 14th century and continued until

1423, with alternate vicissitudes, including structural problems still related to subsoil capacity. In the following centuries, further addition and works embellished the church that was also populated with various pieces of art, until 1755 when a catastrophic earthquake caused the collapse of most of the structure. Although in ruin, the building was preserved due to its emblematic value and today is a museum.

All the activities of the Heritage Within project relied on the synergistic contribution of a multidisciplinary team of architects, civil engineers, telecommunication engineers, archaeologists, art historians, and geophysicists, driven by a collaborative definition of goals and demands. The project took advantage of the wide expertise of this team and generated layers of specialized information of the case study (e.g. virtual reconstruction of the original aspect of the church, structural analysis results, thermography studies or location of old art pieces), inserted within the VR platform with two main objectives: (i) make the public more aware of the essential role of professionals in the field of conservation (from art historians to engineers and architects), showing the importance of surveying, diagnostic and analysis activities for the conservation of built heritage; (ii) help specialists in the interpretation of their own results related to other specialists outcomes, by means of novel visualization tools and integration of the results of diagnostic investigations from different sources into a single VR platform.

The use of virtual reality for the dissemination and storytelling of complex results is expected to enhance accessibility to cultural heritage and enrich the visitor's experience. Moreover, it is likely to support technical activities, allowing an easy and informative visualisation on-site instead of at their desks on their computer.

Knowledge of the monument is a key aspect of conservation activities. The HWITHIN project essentially explores the use of VR as a work environment to read and visualize multiparametric information, facilitating the interpretation of technical inspection and analysis results (obtained from non-invasive inspections or structural analysis). The use of such platforms to interrelate heterogeneous data can help to understand cause-effect mechanisms between constructive characteristics, damage and structural behaviour. Nevertheless, beside the primary preservation purpose, the project set as primary objective an enhancement of the visitors' engagement with the building, for example, through the virtual reconstruction of the original aspect of the church. To this end, the multi-layered digital twin created was enriched with technical information, but also made suitable for the implementation of a virtual reality visit of the church in the actual condition and in the reconstructed aspect before its collapse. Based on the goal and the intended user, the complexity of the model can range from a virtual tour based on interlinked 360° panoramas to an advanced 3D photorealistic restitution (Figure 10).

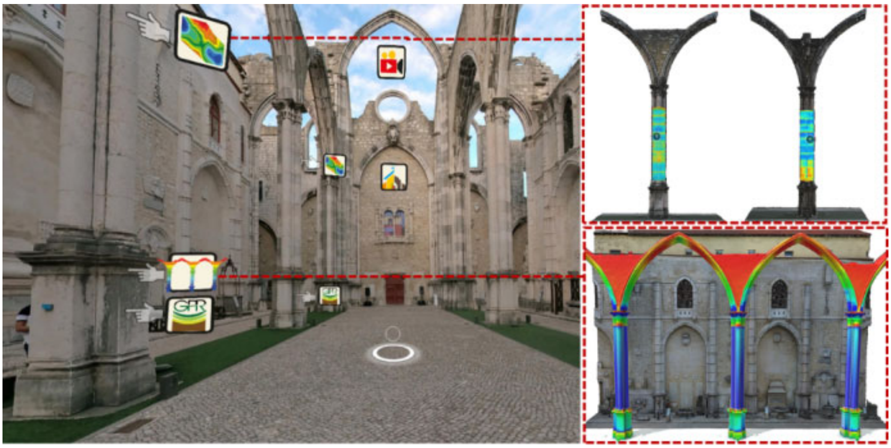


Figure 10. Virtual tour and linked layers: photorealistic 3D restitution, ultrasonic acoustic tomography (above) and structural analysis results (below).

The proposed approach constitutes an effective system for storing and analysing heterogeneous data. The future challenging goal is to integrate the virtual scenarios proposed with an Internet of Things (IoT) system to be used with a digital twin perspective. The Carmo Convent can be equipped with sensors measuring in real time environmental and structural health monitoring parameters. Results can be evaluated on the digital twin and possible interventions can be assessed and managed remotely. The association between physical object and virtual reality makes it possible to activate data analysis and monitoring of the monuments in such a way that it is possible to operate in predictive mode, identifying problems even before they occur. A digital model continuously connected with its physical counterpart and capable to be managed in an interactive form can highly optimize conservation activities.

6 CONCLUSIONS

Although preventive conservation is recognised as the potentially most cost-effective strategy for cultural heritage preservation, its widespread application is complicated by several factors, as its multidisciplinary nature, the sparsity and case-specificity of the available information, the lack of effective guidelines or standards, the limited expertise of the professionals and the lack of awareness of users, owners and managers. Here, a list of essential requirements in the field of preventive conservation is presented, within an ongoing process of rethinking this discipline towards the definition of a comprehensive and cost-effective framework. Moreover, innovative practices developed and validated, with an active involvement of the authors within two European Projects, are presented.

ACKNOWLEDGEMENTS

This work was financed by ERDF funds through the V Interreg Sudoe program within the framework of the project "HeritageCare - Monitoring and preventive conservation of historic and cultural heritage" (Ref. SOE1/P5/P0258). The Heritage Within research project was co-funded by the Creative Europe Programme of the European Union, under the Cross-sectorial subprogramme, Bridging culture and audiovisual content through digital action (Project 614719-CREA-1-2019-1-PT-CROSS-SECT-INNOVLAB). Moreover, this work was partly financed by FCT/MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB/04029/2020.

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