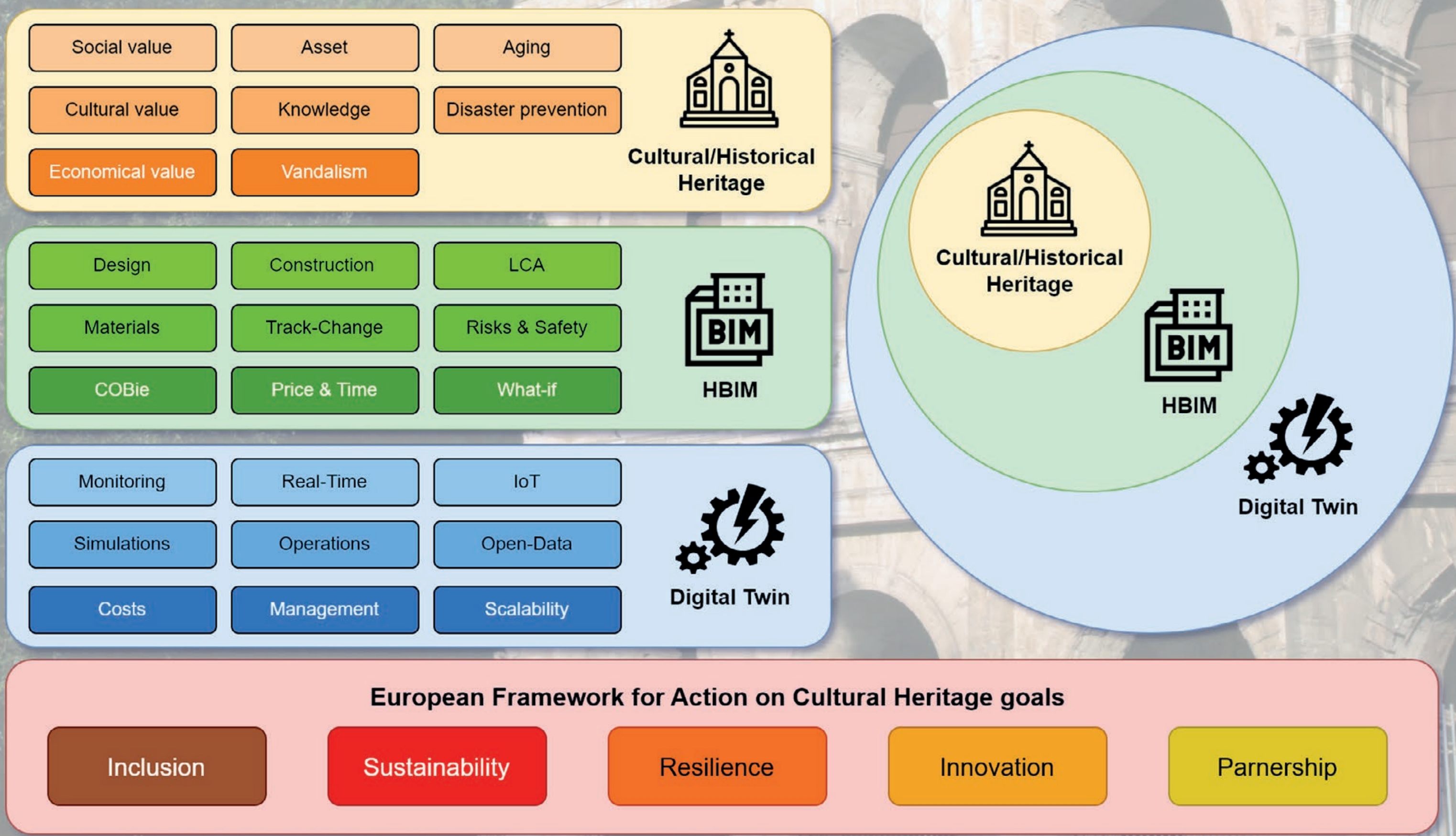
# Framework for Sustainability of Cultural Heritage




*Picture of the Colosseum in Rome (Royalty free image)*

# Sustainable Restoration of Cultural Heritage in the digital era

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Abstract: The reprocessing, preservation, and maintenance of Italy's extensive historical architectural heritage, represent a relevant challenge for digitalization, considering that it is not only among the oldest in Europe but is also widespread across the country, encompassing both urban and rural areas. The care of such an aging-built environment needs a carefully planned approach that can take advantage of new technologies such as Historical/Heritage Building Information Modelling (H-BIM) and Digital Twin (DT). The final goal is to promote a long-term sustainable restoration, implying high qualitative standards. The topic of sustainability is often focused on new constructions, where it is of fundamental importance to save materials, energy, and land use, as well as decrease the carbon footprint. However, it is important to apply innovative digital management technologies to historical buildings in Italy, which are way more fragile if compared to modern ones. Cultural heritage is in general subject to specific challenges that need to be addressed, especially considering extreme events such as the earthquake that occurred in the L'Aquila Region in 2019, or in the area of Amatrice in 2016 affecting Marche and Umbria Regions. Digital technologies can be used to prevent or at least mitigate the effects of those kinds of catastrophic events, limiting damages and saving human lives, but also providing valuable information, and creating tools to be shared among stakeholders, to restore the physical and cultural value of a historical building, even in case of extreme events.

Keywords: Historical Building Restoration; Historical Building Information Modelling (H-BIM); Digital Twin for Built Environment; Sustainability.

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## 1. Introduction

Preserving cultural heritage is a complex topic that requires a vision encompassing both the past and the future, integrating technological advancements with a significant commitment to safeguarding past architectural treasures. This process extends beyond perpetuating the peculiarities of a site but must also consider its temporal and cultural relevance (Martinsson-Wallin, 2016). This paper aims to investigate the correlation among various topics related to the preservation of historical buildings, including conservation, maintenance, sustainability, resilience, and asset revitalization. The goal is to counter the regression of environmental, sociocultural, and economic components. The ultimate goal of these protective efforts is to foster more eco-sustainable and liveable urban settlements, while ensuring the preservation of the historical-cultural context (Chen et al., 2022).

This process requires a holistic and multifaceted approach involving coordinated actions developed by national and local authorities, stakeholders, and users (Wang, 2012).

Cultural heritage protection is a global concern, as underlined since the World Heritage UNESCO Convention of 1972, focused on the definition of a framework to define, protect, preserve, and disseminate cultural and natural heritage to future generations, assigning urban planning and national directives aimed at cultural asset safeguarding (Vestheim, 2019).

The European Union (EU) also has developed its framework for preserving cultural heritage, which encompasses tangible, intangible, and digital aspects of heritage, including remembrance, understanding, identity, dialogue, cohesion, and creativity (European Parliament, 2018). The European Framework for Action on Cultural Heritage, announced in the new European Agenda for Culture, aligns with the Council of Europe's European Heritage Strategy and comprises five main strands:

- Inclusion: participation and access for all.
- Sustainability: smart solutions for a cohesive and sustainable future.
- Resilience: safeguarding endangered heritage.
- Innovation: mobilizing knowledge and research.
- Partnership: reinforcing international cooperation.

Therefore, international commitment is evident in developing innovative and collaborative strategies to preserve cultural heritage. However, the EU's policy is primarily the responsibility of Member States regional and local authorities that are demanded to adopt and adapt the framework to their needs.

The topic is highly relevant for Italy, where there are 4,026 museums, galleries, and collections, 293 archaeological areas and parks, and 570 monuments and monumental complexes (Arosio & Federici, 2019) and UNESCO recognizes 53 Italian sites on the World Cultural Heritage list (UNESCO, 2023).

Within this framework, digital technologies assume a crucial role to be used as a tool for supporting restoration and protection, also implying advanced techniques such as satellite technologies (Figure 1), three-dimensional scanning, architectural studies, knowledge of ancient materials, cataloguing strategies, and the collection of semantic and survey data (Cinquepalmi et al., 2023; D'Angelo et al., 2018; De Gregorio et al., 2020). Recently, sophisticated innovations like Historical/Heritage Building Information Modelling (H-BIM) and Digital Twin (DT) have established a revolution in the architectural and engineering domain (Cinquepalmi & Cumo, 2022). Although initially designed to support new construction buildings, these tools also have demonstrated all their potential for preservation, protection and restoration of historical structures. BIM facilitates the management during design and building phases, developing an actual site state that can be used in the future. Digital Twin, on the other hand, relying on ground and satellite data, allows for uninterrupted monitoring of the performance of historical structures, proposing a comprehensive and synchronous vision of their current and future condition using sensor data and simulation algorithms. Therefore, a shared and integrated approach is fundamental to tailoring such solutions for preserving the historical built environment.

## 2. The use of BIM in Restoration of Historical Buildings

In recent years, the Italian construction sector has undergone a significant transformation thanks to the progressive integration of BIM in the construction processes. The digital-based approach takes advantage of computerised modelling and data-driven collaboration, condensing all built information inside a 3D model with advanced capabilities, fully virtualizing the construction processes, and following the building lifecycle. In most nations, directives regarding

BIM were primarily conceived with a focus on new construction projects. However, recently, some regulations have expanded their range to include the restoration of historical buildings. In Italy, BIM has recorded an ascending trend thanks to the national regulation (Ministerial Decree 560/2017), that requires its mandatory use for public utility buildings.

Despite recent advancements in BIM for architectural restoration, a substantial misalignment remains regarding how to properly integrate this methodology into conservation processes. In the context of the renovation of historical constructions, there are various approaches often correlated to the “scan to BIM” methodology (Bosché et al., 2015). However, it resolves only the geometric modelling aspect, omitting the information relative to the physical and mechanical properties of the building components. In the case of architectural valuable assets, data capture and management are as important as geometric modelling. Informative layers can contain important details that are useful not only for the conservation and restoration process but also for maintaining the knowledge of how an element was built and with which techniques and materials. This is particularly relevant for archaeological studies and to maintain coherence or differentiate the various interventions that were developed during the building history (Bruno et al., 2021).This leads to the creation of a “unified digital database” with specific classes and ontology, encompassing all data related to the physical and operational characteristics of infrastructure, with a targeted focus on historic preservation and the characterization of construction materials. Therefore, a substantial step forward has been represented by the introduction of H-BIM for addressing the complex modelling challenges of Cultural Heritage. It uses commercial BIM software, including specific tools for Heritage modelling, pursuing full digital restitution of the historical architectural heritage elements according to artistic, historical, and constructive typologies. In addition, H-BIM is an emerging technology that enables us to understand, document, advertise, and virtually reconstruct the built environment (López et al., 2018). Although such an advanced tool exists, the topic requires further deepening to develop a common approach to the matter. For historical buildings, the collection of archives and historical information and the respect for genuine architectural details require a tailored approach to develop computer-based modelling, capable of providing a clear picture of historical significance, also considering archaeological issues where required, extending and complementing the architectural approach of BIM.

## 3. BIM limitations for cultural heritage

BIM incorporates data obtained from material and component manufacturers as a standard for new construction projects. However, in the context of restoration, especially of ancient buildings, this strategy meets with considerable obstacles. Often, the needed specification of architectural elements is not directly accessible, but must be acquired through subsequent diagnoses and studies (Moyano et al., 2022).

The validity of a BIM model is tied to the depth and integrity of the information that can be embedded in its geometric features. In an object-based modelling approach, most of the information originates from manufacturers, which is also why the digital resources of BIM objects are so valuable (Bastem & Cekmis, 2022). However, this methodology could face substantial limitations within restoration projects, where architectural details can be retrieved only after the use of diagnostic techniques. Consequently, the limits of the current BIM approach towards restauration sites could be summarised as follow:

- Integrate into BIM a track change of the material and interventions received by the asset for tracing the restoration processes.
- Inclusion of diagnostic data, instrumentation used and analysis results in BIM metadata to increase the reliability of modelling.
- Inclusion in the Levels of Development (LOD) of BIM, that is a classification focused on restoration processes, as already proposed by the Italian UNI 11337 standard.
- Using standards, such as the Construction Operations Building information exchange (COBie), to structure the data format, allowing the organisation and sharing of relevant information on components, equipment and systems.
- Using standardised formats in order to facilitate the sharing process among different stakeholders (archaeologists, restorers, owners and users), enabling a coordinated effort of the different parties involved in the restoration and management process.

The information coming from diagnostic tools and studies needs personalised BIM strategies. This is possible only by modifying and adapting the structure of BIM to the historical context, respecting the peculiarities of the ancient construction work and the specifications of the current conditions. The safeguarding of historical characteristics

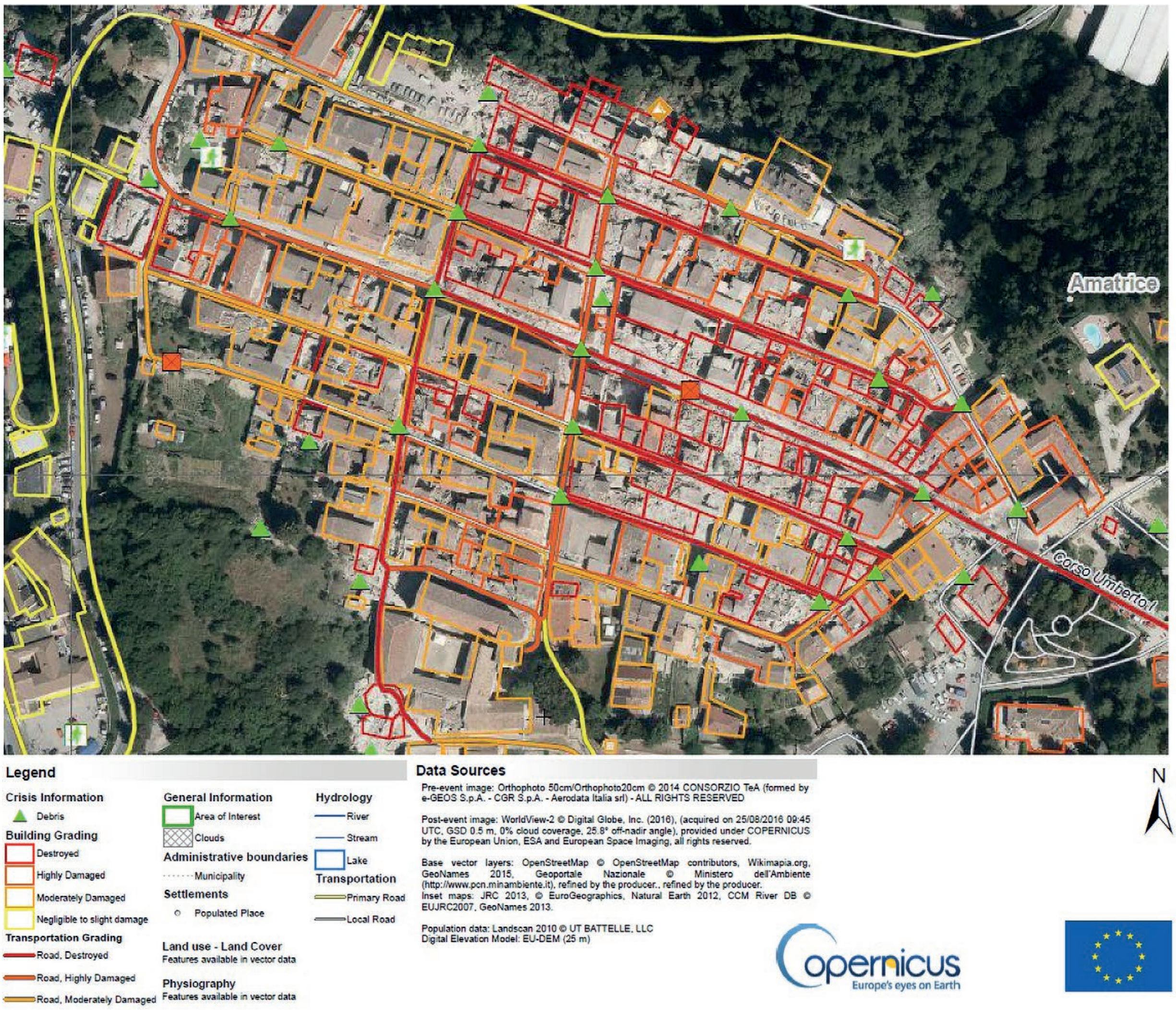


Figure 1 | Satellite technologies in support to the restoration process of the totally destroyed historical centre of Amatrice (central Italy) The parts identified in red represent destroyed buildings: dark orange highly damaged, light orange moderately damaged and yellow negligible to slightly damaged (severity scales with colour) (Cinquepalmi & Cumo, 2022). Courtesy of the Italian Space Agency (ASI) and the EU Copernicus programme © 2016 (Free of use).

shall be integrated at the initial phase of the BIM process, considering the requirements that can be both building and cultural-oriented.

Because the main standards imposed by the BIM methodology are oriented to the physical properties of the structure, it could be somehow difficult to fit other data inside the models. This is particularly evident in Industry Foundation Classes (IFC) files, as defined in ISO 10303-21 and ISO 10303-28, that do not include definitions and ontologies that are proper for restoration work (Oostwegel et al., 2022), requiring a deep understanding of the architectural work, its details, and traditional construction methodologies that often are more common knowledge among archaeologists than architects or engineers. Therefore, new methodologies are required for the use of BIM to safeguard the historical attributes of historical buildings. The application computerised 3D models facilitate the management and supervision of a building, but some aspect, such as the model resolution (in terms of pix/$m^2$ for textures or points/$m^2$ for meshes), needs to be investigated based on the specific value of every physical element (such as masonry, woodworks, roofs, and other traditional construction techniques). Sometimes, it is also possible to obtain metadata from specific diagnostic techniques such as multispectral imaging, stratigraphy, thermography and X-rays. These data are not always foreseen by BIM and must with difficulty be placed within its environment. Once intervening within a conservative restoration process, it is extremely important to retrieve all the available historical, archivist and archaeological information on the asset, in order not only to trace as far as possible the changes that time has brought to the building, but also how these interventions were executed (in terms of technological processes), for the sake of the conservation of the asset itself.

All these data must find an appropriate place within the BIM architecture and in most cases of historic buildings analysed, they are largely predominant over the already known and classified geometric and material information. Furthermore, it can also be used for the evaluation of alternative restoration scenarios, developing coherent and accurate *what-if* scenarios, especially for assets located in areas prone to the risk of extreme events that may lead to the damage or complete destruction of an asset, as in the cited cases of L'Aquila (Figure 2) and Amatrice (Figure 1) earthquakes, not to mention, the potential life-saving benefit of a restoration that ensures a better resilience of the building in the event of a disaster. In fact, this cognitive approach to restoration produces an increase in resilience and sustainability because it allows for the evaluation of each element during the preliminary phases of the restoration, reducing all typical incertitude of inadequate restoration information.

## 4. Methodologies and Regulations

The restoration and preservation of a historic building requires a rigorous and detailed methodological approach to ensure the quality of the result, preserving the original formal and aesthetic characteristics of the asset. In the presence of more recent architectural or decorative elements that could disfigure the overall nature of the historic building or induce structural disharmonies, the choice can be made not to preserve them, as highlighted during the restoration work developed for the reconstruction in the cases of both earthquakes in the central Emilia region in 2012 and in the city of L'Aquila in Italy. (Tatangelo et al., 2022).

A generalised methodological approach for the restoration and conservation of a historical building includes: 1# building survey, 2# diagnosis of degradation phenomena, 3# historical study, 4# analysis of construction techniques and materials, 5# design of restoration and recovery interventions, 6# execution of restoration interventions, and 7# final documentation and restoration monitoring.

As evidenced by Cesare Brandi, Italian art historian and critic, founder of Italian's restoration theory, it is important to carefully consider the use of innovative methodologies, because they can have severe theoretical and practical implications on historical buildings (Kühl, 2023). Restoration and conservation are multidisciplinary domains that shall embrace both traditional and innovative restoration methodologies. Focusing only on digital technologies and practices without a proper consideration of the historical values of an asset could be limiting. An element that emerged during the works related to the RECIPE project (founded by European Space Agency and aimed at the development of low-cost 3D models generation using crowdsourced and earth observation data) is the fundamental lack of information related to the asset's historical and cultural value, as well as the knowledge of the past interventions (D'Angelo et al., 2018).

The *Codice dei Beni Culturali e del Paesaggio* (President of the Republic, 2004) defines restoration as a set of activities oriented towards the historical assets, aimed at maintaining its material integrity, protection and transmission of cultural values. Current Italian regulations ranges from approaches that emphasise a careful understanding of the historical artefact, with the aim of preserving every historical layer, gathering all possible information related, for the requalification of missing parts in order to restore what is supposed to be an ideal form of the asset (Casiello, 2009).

Italy recognizing the importance of a general approach towards digitalization of cultural and artistic assets as a fundamental tool for conservation also in light of an extensive BIM application approach, adopted in 2009 the EU framework for Digital Libraries (EUDL) with Ministerial Decree 2008 "Service for the digitization of cultural heritage - Digital Library" and its modifications (D.M. 2008 Service for the Digitization of Cultural Heritage - Digital Library, 2008). Therefore, despite its current low-adoption and due to the enormous effort necessary to develop a complete catalogue of the extremely high number of registered Italian cultural assets, a consistent process of digitization of all Italian cultural assets seems to be yet a long undergoing process, and is part of the National Plan for Digitization of Cultural Heritage supported by EU funds within the National Recovery and Resilience Plan (NRRP).

## 5. Life Cycle Phases in H-BIM

In the construction field the Building process is described by Life Cycle Phases (LCPs). These phases encompass pre- and post-construction activities, such as design, economic management, utilisation, and maintenance. These phases can be schematically summarised as a) Design Phase; b) Construction Phase: c) Operational Phase.

Considering historical building, LCPs shall be adapted to the restoration process, as in Figure 3:

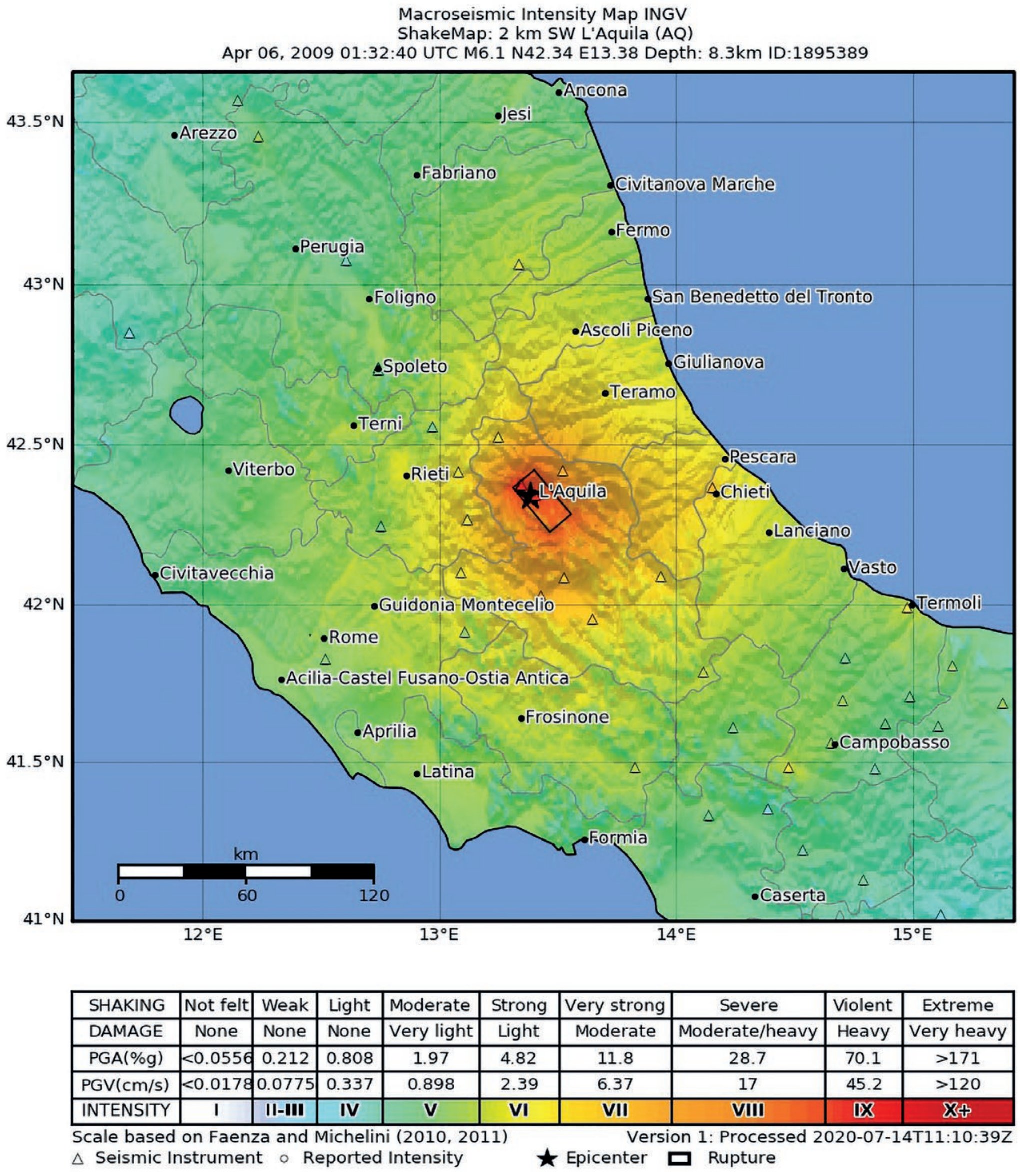


**Figure 2** | Localization of L'Aquila Earthquake (2009) with the darkest red indicating the damage intensity (Source: INGV 2006).

- Design and Diagnostic Phase: This stage requires a deep examination of the building to assess its conservation status, integrating a historical-evolutionary analysis to define specific preservation objectives. This phase shall be carried out in collaboration with the stakeholders in order to share the best way to preserve the historical, cultural, and economical value.

- Intervention Phase: Planned restoration actions are developed, emphasising heritage protection. This phase shall be implemented in agreement with the same stakeholders included during the design phase.

- Maintenance Phase: This phase concerns a long-term management of the historical built environment, ensuring periodical maintenance, in order to guarantee its integrity over time.

For Management of the historical Built environment, from the digital point of view it is intended the application of digital technologies to asset knowledge, and the use of subsequent data and information in order to optimise the restoration process, and establish a permanent monitoring mechanism for ensuring better preservation, thus reducing the management related risks, for safety and security of

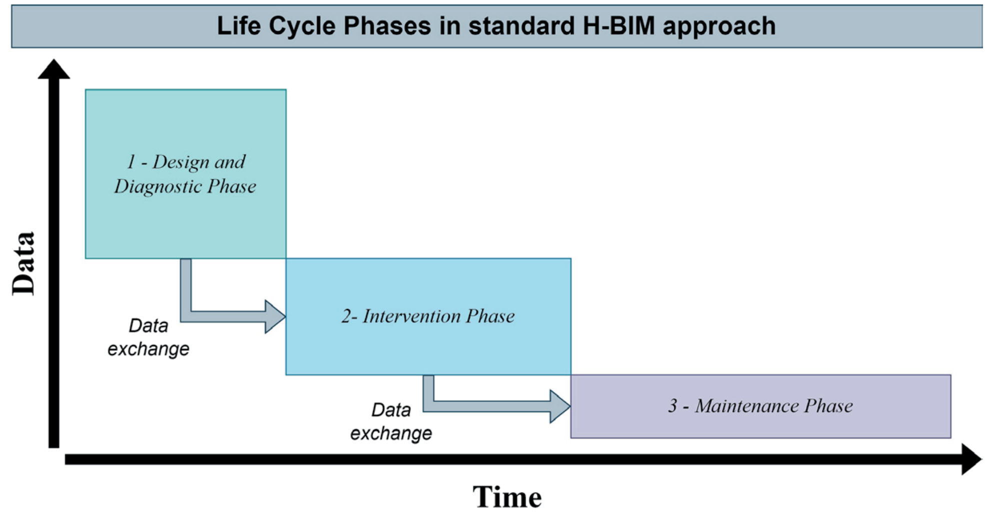


**Figure 3** | Phases and Data Flow in standard H-BIM.

both stakeholders and cultural values. Moreover, the first two phases can be integrated with digital technologies through various methodological paradigms:

- H-BIM leans towards the creation of 3D models that embody both the physical form and the other information related to the building.
- Cloud data emphasises the importance of a shared collaboration among the parties involved, promoting efficient communication and early identification of possible inconsistencies.
- Advanced Diagnostic Technologies to gather all information about the building and its state of conservation, not necessarily evident at first sight. This implies the use of laser scanners, hyperspectral imaging or photogrammetry.

Collectively, these methodological paradigms are required to work synergically, ensuring a holistic and efficient H-BIM approach, enhancing the effectiveness of the restoration process, and ensuring a consistent long-term preservation. As discussed further in the present work, the third phase of management and maintenance can take the advantage of DTs technology.

## 6. H-BIM development and integration

There is a clear synergic interaction between the first two LCPs, design phase and construction sites are connected by a tight schedule. As the project evolves, restoration experts who adopt H-BIM perceive the importance of collaborating with other professionals' experts in other disciplines, both from the historical and building sectors. Figure 3 clearly displays LCPs sequence for a standard H-BIM approach. Design and Diagnostic Phase (1) is characterised by a high level of informational detail and usually shorter than the Intervention Phase (2) often source of large amounts of further information and data to be gathered, for improving maintenance. The Maintenance Phase (3), on the other hand, while generally prolonged over time, presents less dense informational content. Among the phases mentioned above, there is a consequential exchange of information, to ensure fluidity and continuity in data management throughout the building life cycle. The Design and Diagnostic Phase is the starting point, laying down the foundation through the design activities for a detailed historical analysis of the asset to be restored

In conclusion, the maintenance phase ensures that the interventions have been correctly executed, with a continuous recording, and tracking of the results. The arrows between the phases represent the constant flow of information and activities, emphasising the interconnection and the sequence of the entire process.

### 6.1 H-BIM in web-based cloud environment

The H-BIM approach can be expanded considering the more recent advancements in Information and Communication Technologies (ICT) for the creation of web-based shared and collaborative environments. This can result in the adoption of cloud applications for the H-BIM environment, where specialists involved in the restoration process can establish effective collaboration with stakeholders and experts. Such collaboration can manifest through various technological approaches, depending on

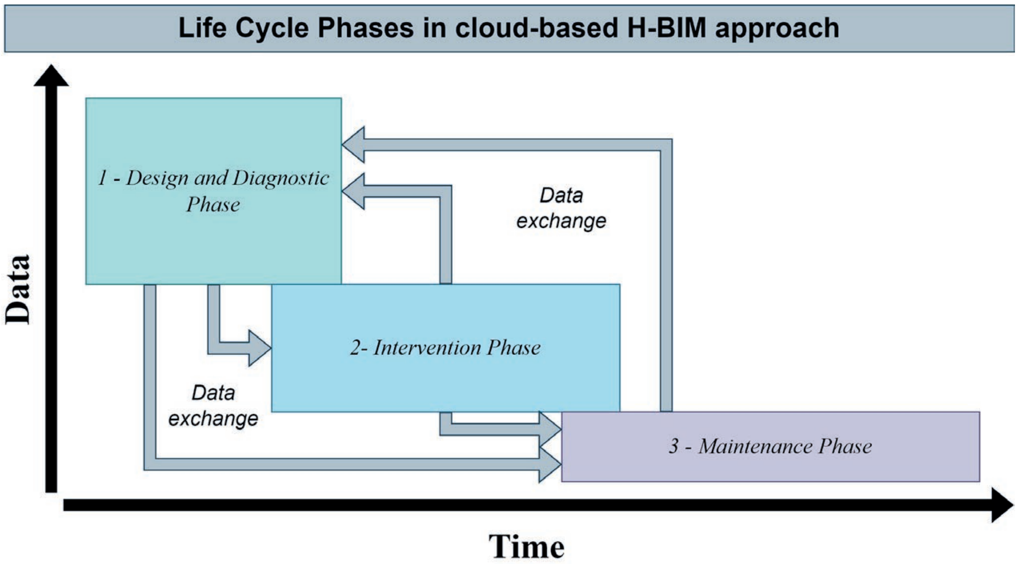


**Figure 4** | Phases and Data Flow in Cloud-based H-BIM.

the BIM software used. However, thanks to the adoption of a web collaborative approach, it is possible to share building information models between architectural and structural design, connecting the design and intervention phases, or the architectural design and the maintenance models for building monitoring. In Figure 4 it is highlighted how a cloud-based approach leads to an efficient tracking of interventions. The process, which is usually oriented at the design phase, therefore can be widened to incorporate further detailed information coming from other LCPs. This leads to an increased value of the global process that reduces the global efforts, increasing the sustainability and integrating all phases in a single shared workflow.

Within this scenario, there is partial overlap between the three LCPs sharing information during the process. possible bidirectional connections between different phases highlights a feedback mechanism, indicating that information can circulate in both directions.

## 7. Digital Twin as a future proof tool

One of the most promising digital technologies for the new era of built environment is the application of Digital Twin (DT) (Cinquepalmi & Cumo, 2023). On the basis of M. Grieves definition: "[...] *a digital twin is a digital model of an intended or actual real-world physical product, system, or process (a physical twin) that serves as the effectively indistinguishable digital counterpart of it.*" (Grieves, 2019), the definition is clearly applicable also to historical buildings. DTs can monitor and simulate in real time an asset, producing data and information through Machine Learning algorithms. Digital Twin, represents not only a virtual replica of the physical asset but a complex and interconnected system needs to be carefully planned from the design phase to be effective. Such development is achievable only through the adoption of the last ICTs advancements like distributed ledger (i.e., cryptocurrency for security reasons), fog/edge computing (to share the computational loads across the network and to increase system resiliency), cloud database (to safety storage and share data), federal and/or SaaS (Software as a Service) solutions certified and ready to market services, and Internet of Things (where sensors and actuators devices support the monitoring activities and human operations at affordable costs).

The appropriate choice of sensor and actuators is essential for the effective and efficient implementation of a DT model: operative difficulties connected with ancient materials and construction must be carefully considered and agreed among all experts involved including digital professionals. Temperature and humidity sensors are a good example: they can be used to evaluate the presence of moulds and contaminants but even better results can be obtained using hyperspectral imaging.

One of the potential risks related to the use of advanced digital technologies for the management of the historical built environment, especially in the case of Digital Twins, may be the lack of IT technicians able to dialogue effectively with conservators, archaeologists and historians and architects. In the lack of an effective dialogue between all stakeholders, the risk is that of an increase in entropy on the construction site, which could jeopardise the preservation of the property as in many recent cases

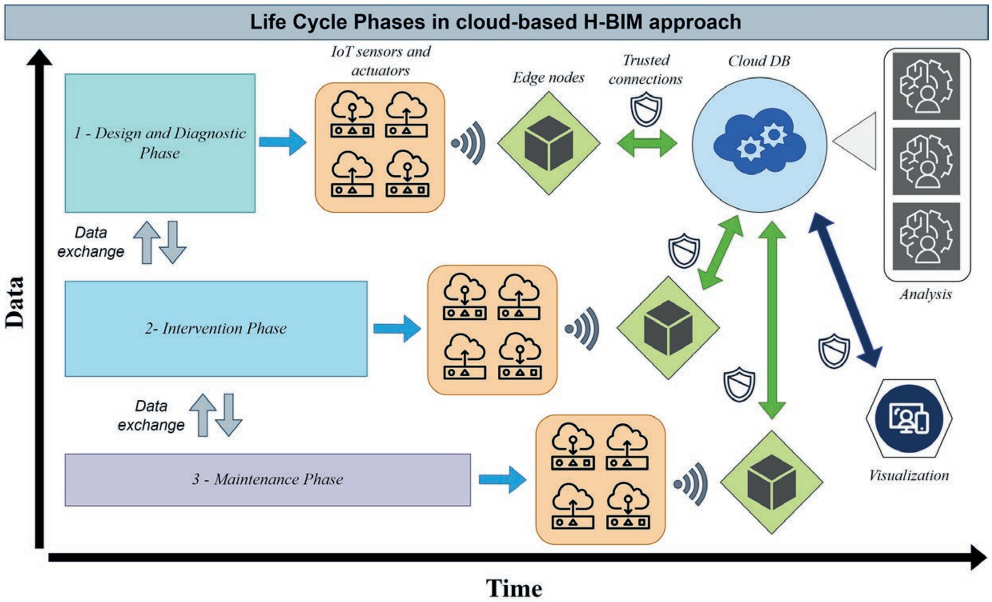


**Figure 5** | Digital Twin integration within the LCPs.

(Cinquepalmi & Cumo, 2023). Moving to a schematic representation of DT implementation on LCPs (Figure 5) we can assume that the restoration process is evolving towards "integrated construction", a concept referring to the overall integration between different phases and disciplines (Čustović et al., 2023). Every aspect, from design to historical analysis, intervention, monitoring, and documentation are planned in parallel, for maximising the functional value of the process while optimising operational capacities, ensuring the safety and continuous maintenance of the historical built environment. The data paths start from sensors and actuators (that can be different for every LCPs) and go through edge nodes for data collection and pre-processing. Then, they are stored and elaborated on a cloud service with secured connections, only accessible by trusted users, both for the security of the asset and for stakeholders.

Moreover, the use of DT increases safety and security, enhancing the capability of detecting in real time any issue potentially rising during the restoration process (Cinquepalmi & Cumo, 2023). The monitoring and prevention capability of DTs goes through the entire life cycle of a building, representing a key factor for better management. There are also other important advantages in using DTs.

Thanks to sensor data it is possible to assess the energy balance over time, revealing valuable information about building energy performances and the opportunities to save energy (Teng et al., 2021). Moreover, it is possible to identify waste production, heat losses, water management and other critical aspects to increase building sustainability. It would be possible to identify what upgrades a building requires to increase resource efficiency and waste reduction with automatic what-if scenarios (Yang et al., 2022).

This leads to a real time tracking and evaluation of the carbon footprint. Using data coming from cameras it is also possible to monitor the conservation state of the structures (Ai et al., 2023). It is possible to lower operational costs by optimising resource distribution, developing failure assessments and even preventive maintenance intervention (Salem & Dragomir, 2022). In light of this, DTs represents one of the most promising tools for historical building management, where the value of the building can be way more elevated if compared to the cost related for the development of the infrastructure.

Nowadays, the integration of DT and BIM is one of the main challenges where the international scientific community is focusing.

## 8. Conclusions

Historical buildings are a cornerstone of the cultural heritage of each Nation, embodying collective memory through architectural forms and stories. The safeguarding and recovery of such monuments are necessary to keep collective memories alive. In this framework, the introduction of digital technologies such as H-BIM and DTs manifests as cutting-edge advancement, proposing optimised methodologies for recovery and maintaining cultural heritage, and representing a new horizon for those kinds of building processes.

If H-BIM is more focused on the construction phase, DT can be applied across the whole restoration process up to the maintenance phase, making this technology a fundamental tool for the preservation of cultural heritage. However, there are many challenges associated with the introduction of these tools. The main one is the development of a shared and collaborative approach that can take the advantages of cloud-based BIM, to develop a common framework, where the different experts can communicate to develop the best solutions to address the restoration process. Therefore, it is necessary a careful approach that sees the participation of digital experts since the preliminary design phase, to evaluate the best technologies to be used, avoiding data redundancy or the acquisition of useless information, and selecting the most cost-effective solutions. Although the challenges are clear, so are the benefits, in terms of sustainability, conservation, and monitoring. The current Building management culture is requiring a major effort in order to consider the new approach of H-BIM towards historical and cultural values.

Professional and academic courses are strongly required to build a widespread shared awareness in this regard. The more promising path seems to be a strong collaboration between researchers, local/central administrations, and professionals, as already in place in some universities in Italy such as the faculty of Architecture at La Sapienza in Rome and the Civil, Construction-Architectural and Environmental Engineering Department of L'Aquila University, both engaged in professional postgraduate courses in this specific field. However, to ensure that H-BIM and, especially, Digital Twin approach, would be truly effective and shared, it seems necessary from the Ministry of Culture in Italy to come up with a specific regulatory proposal, to require such instruments, since the beginning of any restoration work. Anticipate as far as possible the risk assessments of a restoration site for a historical property, seems to be the more secure approach, considering that it is often during such restoration processes that most serious damages occurs, as in the cases of Windsor Castle in UK (1992), Chapel of the Holy Shroud in Turin (1997) and Notre Dame de Paris (2019) (Cinquepalmi & Cumo, 2023). Therefore, a common effort is mandatory to address the new opportunities of digitalization especially in a sensible sector such as the preservation of the historical built environment.

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