Chapter 5
The Role of Documentation in Risk Assessment

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Abstract This chapter aims at providing a protocol for the comprehensive documentation of cultural heritage: it addresses the need for standardized procedures by targeting cultural heritage operators broadly, emphasizing generalizable methodologies over technical specifics. The outcome of this study aligns with the European approaches to digitalization, and focuses on the clarity, quality requirements, result evaluation, and data management plans. Aligned with a vision of digitalization for cultural heritage preservation, the protocol complements risk management efforts by integrating ongoing monitoring, restoration, and structural integrity assessments. This approach underscores sustainability and economic viability, encapsulated in the guidelines for Documentation Techniques and illustrated through Case Studies.

Keywords 3D digitization · Built environment · Conservation · Data management · Guidelines · Digital models · Documentation · Metadata · Paradata · Risk impact

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5.1 Introduction

In the field of cultural heritage preservation and conservation, documentation stands as a crucial foundation for comprehending, protecting, and transmitting our shared heritage to future generations. Comprehensive and accurate documentation not only provides a detailed record of cultural heritage sites, but also plays a key role in identifying and mitigating risks that may compromise their integrity and survival (Kioussi et al., 2013). Historically, cultural heritage sites have been exposed to a wide range of threats, including natural disasters such as earthquakes, floods, and wildfires, as well as human-induced challenges like urbanization, pollution, and armed conflict. The development of effective risk management strategies requires a deep understanding of the vulnerabilities of cultural heritage sites, which can be attained through careful and systematic documentation (Ramalhinho & Macedo, 2019).

In the field of 3D documentation, methodologies have continuously evolved to address the shifting needs of heritage preservation and the new risks it faces (Alessandri et al., 2019). Traditionally, cultural heritage documentation relied on conventional surveying and mapping methods, which, while effective for their time, offered limited accuracy and scope. With the advent of advanced digital technologies, the field has undergone a transformative shift, providing unprecedented accuracy and detail even in challenging environments (Martínez-Espejo Zaragoza et al., 2017). Laser scanning, for instance, has become an indispensable tool for capturing detailed three-dimensional data of heritage sites, enabling not only accuracy measurements but also the creation of highly accurate digital reconstructions (Alessandri et al., 2020; Del Pizzo et al., 2024).

Photogrammetry, which converts overlapping images into detailed 3D models, offers a scalable and cost-effective approach to documentation (Bitelli et al., 2019). These digital models have revolutionized the way cultural heritage sites are visualized and analyzed, allowing researchers and conservators to explore and interact with heritage assets within virtual environments. This capability facilitates more thorough analysis, deeper interpretation, and more informed conservation planning. Moreover, in recent years, Virtual Reality (VR) and Augmented Reality (AR) have emerged as powerful tools that offer immersive and interactive experiences of cultural heritage. VR enables users to virtually explore heritage sites in fully immersive, digital environments, fostering engaging and educational experiences. Meanwhile, AR enriches physical site visits by overlaying contextual information, digital reconstructions, and interactive elements onto the real-world environment, thereby deepening the visitor's understanding and engagement (Barrado-Timón & Hidalgo-Giralt, 2019). The integration of these technologies not only enhances documentation and analysis but also creates new opportunities for public engagement, education, and the promotion of cultural heritage in innovative, accessible ways. By merging the physical and digital branches, these tools represent a new frontier in cultural heritage preservation, ensuring that the understanding and appreciation of heritage assets can reach broader audiences and be preserved for future generations.

The importance of documentation in cultural heritage preservation extends far beyond mere visualization and immersive experiences. It plays a critical and multifaceted role in enabling effective risk assessment and disaster preparedness. By capturing detailed records of physical characteristics, structural details, historical data, and other pertinent information, documentation equips stakeholders with the tools necessary to perform comprehensive risk assessments. This enables the identification of potential threats and an evaluation of their likely impacts, contributing to more informed and proactive conservation efforts (Khodeir et al., 2016).

Over the past two decades, there has been significant progress in research related to risk assessment and its implications for cultural heritage. However, these advancements have not yet been fully translated into practical applications, nor sufficiently integrated into policy and decision-making processes. One possible explanation for this gap lies in the incomplete transfer of quantitative data, which is essential for developing effective strategies for risk mitigation and impact reduction (Bonazza & Sardella, 2023). Without robust data, the formulation of preventative measures and long-term planning remains hindered, preventing the full realization of these research advancements in protecting cultural heritage.

The integration of this data with 3D documentation is expected to significantly enhance the ability to develop proactive conservation strategies, thereby improving the resilience and long-term protection of cultural heritage assets. By facilitating this integration, stakeholders will be better equipped to anticipate, mitigate, and respond to emerging threats in a timely and effective manner. Moreover, robust documentation will play a critical role in disaster preparedness and response by supporting the development of conservation strategies and contingency plans tailored to the specific needs of each site (Wilson et al., 2018).

Within this type of documentation, a discipline that undoubtedly plays a pivotal role is geomatics. Specifically, when dealing with small to medium-scale geospatial data, cartography emerges as a crucial component. In contemporary contexts, this form of documentation should be understood as a dynamic digital tool that facilitates the creation of layered, multi-dimensional representations of the territory. These representations are not limited to morphological data but also incorporate a wide array of information from different fields, such as temperature variations, atmospheric precipitation, traffic patterns, and much more. The primary advantages of this type of digital mapping are manifold. First, it allows for the rapid and frequent updating of data, ensuring that the information remains current and relevant. Second, it transcends the traditional concept of fixed map scales, enabling seamless transitions between highly detailed maps and broader, more generalised representations. This flexibility makes it an invaluable resource for a range of applications.

The thematic elements to be represented in such maps are numerous, especially when aiming for a comprehensive territorial analysis in relation to the risks it may encounter. These thematic layers are often interconnected, providing a multi-faceted understanding of the environment. Many of the thematic maps developed for these purposes—such as altitude maps, slope maps, land use maps, and hydrographic network maps—can be applied across a variety of contexts and adapted to address different types of risks. These versatile maps can be useful for general risk mitigation, regardless of the specific hazard being analyzed. Conversely, other maps may be highly specialized, focusing on particular risks such as wildfires, landslides, or seismic events, which are relevant only within the context of specific vulnerabilities. In this context, the dimension of time plays a crucial role. The ability to compile historical data that tracks the evolution of certain phenomena allows for the creation of temporal maps that illustrate how risks have developed over time within a given area. This temporal perspective is essential for understanding patterns and forecasting future risks, especially for those hazards that have a clear cyclical or historical precedent.

It is also important to emphasize that such documentation does not necessarily need to be created exclusively for the purposes of risk mitigation or territorial analysis. Often, these data sets already exist within administrative or institutional records, having been generated for various other uses. These pre-existing resources can be updated and repurposed for risk assessment, thereby reducing both time and costs associated with generating new data sets from scratch. Moreover, the integration of existing data allows for more efficient and comprehensive analyses, contributing to more effective planning and intervention strategies.

5.2 The European and National Landscape on Digitising Cultural Heritage at Risk from Climate Change

As previously mentioned, the digitisation of built heritage poses particular challenges. Architectures are functional assets. They are susceptible to the effects of wear and tear, rehabilitation, maintenance and conservation over time, so the digitisation process (which is inherently more complex than for museum assets) must also provide stakeholders with tools for management and informed decision-making.

"Managing a changing historic environment" (Wijesuriya et al., 2013) requires a high density of information content, including both geometric and non-geometric data, broader than that required for conservation alone.

The high cost and rapid obsolescence of plans for 3D digitisation of architectural heritage means that producing information to support decision making and management may be a more sustainable approach, as the data can be reused in other contexts, such as for valorisation and communication. The European Community has significantly promoted innovation in the cultural heritage sector, focusing on documentation, preservation, and sharing of Europe's legacy. This has been achieved through directives, studies, and guidelines, alongside supporting major research projects like Europeana, the key digital infrastructure for European cultural heritage. The roots of this effort trace back to the Lisbon Strategy of 2000 (Hervás Soriano & Mulatero, 2010), which emphasized the role of digitalization in promoting European culture while also driving economic growth, employment, and social cohesion. In 2020, the Creative Europe programme should continue to support cultural sectors, including cultural heritage, in seizing the opportunities of the digital transition. Cultural institutions were encouraged to embrace digital tools and technologies to preserve and promote European heritage in an evolving digital landscape. The 2019 Green Deal, aimed at achieving climate neutrality by 2050, did not initially target cultural heritage but in 2022 (Directorate-General for Education, Youth, Sport and Culture (European Commission), 2022) identified the threats posed by climate change to cultural heritage and emphasized the role that heritage can play in the broader environmental goals of the Green Deal. The document called for interdisciplinary research into the impact of climate change on cultural heritage materials and the mitigation of risks. To monitor and protect heritage assets, it recommended studies on the behaviour of materials under environmental stress, using advanced technologies such as modelling, AI and 3D documentation. Additionally, the European Commission introduced a recommendation for a common European data space, which encourages member states to digitize their cultural heritage between 2025 and 2030. This aims to improve the preservation of at-risk heritage using technologies like 3D scanning, AI, virtual and augmented reality, and cloud computing. Such tools allow for non-invasive analysis and visualization of heritage damages, facilitating restoration and conservation efforts while also gathering knowledge on climate-related impacts and resilience strategies. In response to the COVID-19 pandemic, the European Council approved the Next Generation EU fund in 2020, amounting to EUR 750 billion to support the recovery of member states. In Italy, the National Recovery and Resilience Plan (PNRR) was introduced in 2021 to also use these funds to address some structural deficiencies in the Italian economy, particularly through the digital and environmental transitions. The plan has 16 components, including 'Digitalisation, Innovation, Competitiveness and Culture' and 'Education and Research', which specifically address the digital and environmental challenges for cultural heritage. This approach ties cultural preservation to wider economic and environmental reforms, ensuring that Europe's heritage continues to thrive in a digitally driven and climate-conscious future.

The National Digitisation Plan[1] has been created by the Central Institute for the Digitisation of Cultural Heritage—Digital Library to promote the digital transformation between 2022 and 2026. It aims to preserve the cultural heritage, to make it more accessible and to promote new professional actors and services, contributing to the achievement of the United Nations' 2030 Sustainable Development Goals,[2] namely quality education, decent work, economic growth, business innovation and infrastructure, and sustainable cities and communities.

The target groups are public and private GLAMs and cultural institutions, as well as professionals, academics, artists and other stakeholders.

PND has three sections: vision, strategy and guidelines.

[1] https://digitallibrary.cultura.gov.it/il-piano/

[2] https://sdgs.un.org/2030agenda

The goal is to move from digital conversion to digital transformation. This shift is a challenge for technology and culture. It involves creating a digital ecosystem (Sotirova-Valkova, 2024) based on the relationships between objects and between objects and people (Rovelli, 2018).

Cultural institutions should not consider digitalisation as a stand-alone initiative, but as an integral activity closely linked to all the decisions and actions. According to the Istituto Centrale per la Digitalizzazione del Patrimonio Culturale,[3] a digital copy correctly acquired for documentation purposes has an informative and cognitive value comparable to that of the object itself, since it represents its material characteristics and state of preservation. It can be used for simulations and monitoring if replicated over time. After the 2013 European Adaptation Strategy,[4] Italy adopted the "National Climate Change Adaptation Plan",[5] which include a section on heritage and landscape. Strategies for protection, control and prevention are based on vulnerability and risk assessment, as well as the study of heritage building materials and environmental degradation. Intense and increasingly frequent rainfall is damaging buildings and accelerating deterioration. In the Firenze area, rainwater leaches the calcium carbonate in the calcite veins of the typical 'pietraforte' stone, increasing the risk of blocks falling, potentially causing injury and loss of decorative elements. Prediction models suggest that in the near future, rainfall and increased atmospheric CO2 concentrations will increase the dissolution of carbonate rock materials (Bonazza et al., 2009). Research on the impact of climate change on cultural heritage is still limited, particularly on the correlation between material degradation and climatic variables and to deepen research from the territory and the city to individual objects.

The Extraordinary National Plan for Monitoring and Preservation of Immovable Cultural Heritage[6] defines the criteria for selecting artefacts to be monitored and the conservation interventions and control priorities. The level of risk is defined on territorial danger and buildings vulnerability indices and on monitoring and protection implementation systems. In order to assess the risks to a heritage property, a thorough knowledge of its condition and location is essential. A holistic approach is required, from the global to the particular, and from the context to the artefact. High-resolution diagnostics need to assess the structure or element, integrating technologies such as remote sensing, drones, photogrammetry and sensors to monitor the evolution of deterioration.

At present, the Cultural Heritage Risk Map[7] is the only available (and sometimes not updated) tool for planning interventions according to the concept of "level of risk".

[3] https://docs.italia.it/italia/icdp/icdp-pnd-digitalizzazione-docs/it/v1.0-giugno-2022/index.html

[4] https://climate.ec.europa.eu/eu-action/adaptation-climate-change/eu-adaptation-strategy_en

[5] https://www.mase.gov.it/pagina/piano-nazionale-di-adattamento-ai-cambiamenti-climatici-pnacc

[6] https://dgspatrimonioculturale.beniculturali.it/attivita-direzione-generale-sicurezza-del--patrimonio-culturale/bozza-automaticapiano-straordinario-di-monitoraggio-e-conservazione-dei-beni-culturali-immobili/

[7] https://dgspatrimonioculturale.beniculturali.it/attivita-direzione-generale-sicurezza-del--patrimonio-culturale/il-sistema-informativo-della-carta-del-rischio/

All the Italian documents cited introduce these themes without any operational reference.

However, it is important to remember that raw data must be interpreted and evaluated. Processing is what turns data into information, and this requires a critical approach.

Documentation and monitoring must be carried out by experts with interdisciplinary skills. The data must be accompanied by metadata and paradata to ensure its correct use, quality and accuracy, and to trace the collection and processing steps (Wetzel et al., 2024).

The topic aligns with the Italian National Research Plan 2021–2027 (Programma Nazionale per La Ricerca|Ministero Dell'Università e Della Ricerca) in which 'Humanistic Culture, Creativity, Social Transformation, Society of Inclusion' are among the key research and innovation areas for Italy. The first research area is "Digitisation of Protection, Conservation and Valorisation Processes", focused on quantifying deterioration and calculating damage indices to prioritise conservation works (Randazzo et al., 2020).

5.2.1 Current EU Guidelines and Documents on 3D Digitisation of CH

As mentioned above, the European Union has supported 3D digitisation of cultural heritage over the years, funding projects, studies, research infrastructures and aggregators that have produced publications, dissemination events, guidelines, white papers, software and so on.

In summary, most of these documents present the state of the art in 3D digitisation and guidelines for the acquisition of artefacts for long-term preservation. While starting from the objective of conservation, an essential role is given to the use of 3D models in valorisation, education and communication projects. This leads to the transfer to the built heritage of workflows tailored to the content typical of GLAMs.

Conversely, buildings, archaeological sites, gardens, urban areas and other large assets not typically housed in a museum have similar needs for protection and valorisation, but their digitalisation requires a different approach, clearly linked to the tradition of architectural surveying as an operational tool for knowledge, design, and management.

A heritage digitisation project for preservation and management requires different techniques, is more expensive and time-consuming, but could be more sustainable by extracting contents for dissemination.

Although the first projects on 3D digitisation of cultural heritage[8] emphasised the need to develop repositories for archiving digital models by addressing critical

[8] https://digital-strategy.ec.europa.eu/en/library/study-quality-3d-digitisation-tangible-cultural-heritage

issues related to formats, visualisation, sharing, etc., the initial focus was strongly on describing tools and techniques for 3D digitisation, i.e. ‘how to do it’. Over time, the focus gradually shifted to the sharing of semantically enriched digital data, emphasising the need to define standards, ensure data quality, ensure process transparency, manage data ownership and establish efficient ways of sharing.

The advent of digital technologies has prompted a re-evaluation of the concept of digitalisation, with insights emerging from diverse contexts, particularly within the European scholarly community. Two notable contributions to this discourse were published in 2020:

1. Basic principles and tips for 3D digitisation of cultural heritage[9]
2. Study on quality in 3D digitisation of tangible cultural heritage—Mapping parameters, formats, standards, benchmarks, methodologies, and guidelines (European Commission, 2022)

The documents, which vary considerably in form, style and length, direct attention away from digitisation tools and techniques and towards issues related to the complexity and quality of the digitalisation process, and thus the sharing of digital data. Therefore, digitalisation is embedded in a broader, preservation-oriented strategy that cannot afford to lower standards of preservation. This strategy encompasses the semantic enrichment of models, the generation of a broad spectrum of data and metadata, and the provision for long-term preservation, with proper planning and management of digital archives to ensure FAIRness (Findable, Accessible, Interoperable, Reusable).

5.3 Digital Documentation of Tangible Cultural Heritage

The European Commission has highlighted a crucial paradigm shift driven by digitisation and new governance models (Brunet et al., 2022). Over time, the concept of ‘cultural heritage’ has been progressively broadened to include not only tangible and intangible assets, but also digital resources, in the dual sense of native digital and products and services derived from digitisation processes.

Cultural heritage digitalisation has been underway since the 1990s, but here is no overall data on the extent of this work by numerous institutions. The National Plan for the Digitisation of the Cultural Heritage 2022–2023 reports that the central institutes’ information systems contain over 37 million catalogue descriptions and 26 million images. It is impossible to give a precise estimate, but it is likely that significantly fewer objects have been digitised in 3D.

The reasons include, but are not limited to:

- Less technological maturity
- Less standardisation
- Higher production costs

[9] https://digital-strategy.ec.europa.eu/en/library/basic-principles-and-tips-3d-digitisation-cultural-heritage

- More recent standardisation of digital data
- Higher storage requirements

Although progress has narrowed many gaps, major differences still exist, particularly between the digitisation of immovable and movable assets and especially those in museum collections.

Technological advances have made 3D digitisation more extensive. However, the focus has shifted from the practical aspects of digital reference production to broader policies and strategies, including data management, process sustainability, communication and sharing, and the digital services that can be derived from them.

Classification of digitised cultural heritage is incomplete and approximate due to the diversity of objects and contexts. The Europeana Network Association Task Force on 3D Content (Europeana, 2020) has defined five categories of 3D content, based partly on the techniques used and partly on the intended use. Italy's PND distinguishes between movable and immovable works, as proposed in the UNESCO Conventions on the Hague discussing "cultural property" (UNESCO, 1954).

Some preliminary considerations on the concepts of complexity and quality, which are generally applicable to a wide range of situations and objects, are presented below. A classification of these concepts is also proposed, that synergistically (but not bi-univocally) considering the dimension of the object and the level of detail of the description to be obtained, suggesting the adoption of a multi-scale and multi-source approach. Finally, the most up- to-date declination of digital models is proposed, no longer understood merely as numerical replication but as a Digital Twin of the cultural heritage under analysis.

Some preliminary thoughts on complexity and quality are presented below. A classification of these concepts is proposed that synergistically (but not univocally) considers the dimension of the object and the level of detail considered. A multi-scale, multi-source approach is also suggested, and the digital twin is proposed as an evolved form of digital model.

5.3.1 The Concepts of "Quality" and "Complexity"

The "quality" of a digitisation project depends on the ability to handle different aspects of complexity; therefore, it is important to define the concepts of "complexity" and "quality" in this context.

Complexity
Factors of complexity can be identified:

- in the process
- in the object and context of the survey
- in the management of the data produced.

Reality-based models, which are at least the potential geometric support for a digital twin, transforms surveying from a one-off operation into a workflow that recursively produces, maintains, updates and enhances 3D spatial data.

The digitisation process goes beyond creating a digital copy. It addresses digital transformation, involving the collection, organisation and extraction of not only geometric information. Thus, being at the convergence of economic, technical and scientific resources, it constitutes an effective support for decision-making.

Cultural, historical, economic, and technological aspects of cultural heritage can be viewed as a "system" (Ripp & Rodwell, 2018), a concept applicable to other domains of knowledge.

Systems (Cilliers, 1998; Grieves & Vickers, 2017) can be distinguished into:

- simple, when they present evident cause-effect relationships between a few components, therefore being completely understandable and predictable.
- complicated, composed by many more components, linearly and straightforwardly connected.
- complexes, made by a multiplicity of interacting components, many-to-many connections, often producing surprises (generally unwelcome).

The layering of aspects that characterise a cultural property (history, artistic value, conservation of materials, current and past use, etc.) leads to the recognition of complexity in the process itself. It is also possible to highlight elements of complexity in the management of the results of the digitisation process (Martin, 2012), because of the multiplicity of investigations and data.

Current research topics concern how the now widely shared FAIR principles can be put into practice. Many projects are under development to define shared infrastructures, in Europe they include ARIADNE Research Infrastructure AISBL (ARIADNE RI), the European research infrastructure on Heritage Science (E-RIHS) and the Digital Research Infrastructure for the Arts and Humanities (DARIAH). Their main objective must be to overcome the fragmentation of digitisation experiences defining a real digital ecosystem, to enable the use of digital tools and methods of data analysis. In Italy, the National Plan for Cultural Heritage Digitization (PND) aims to define a strategic vision to promote and organise the digital transformation process up to 2026.

The open questions concern transforming a multidisciplinary approach into a deep interaction between studies with different competences. The practical obstacles include:

- the still unsatisfactory interoperability of data.
- medium and long-term data archiving strategies and sustainability.
- the methods of scientific validation, also due to the lack of reference standards.

Quality

Data quality assessment generally relates to compliance with standards and criteria, which the cultural heritage digitisation field lacks.

Any digitisation process involves sampling, and this inevitably leads to an approximation of geometric or other values to the analogue original, with an analogue/digital dualism becoming an integration (Levy, 1998). Furthermore, quality assessment can be subjective (Zhou et al., 2024) or objective (Javaheri et al., 2021), depending on the role of human observers. Most literature (Di Filippo et al., 2023), with a few exceptions (Zhang et al., 2022), refers to comparison with a reference model obtained separately.

5.3.2 Evaluation of the Digitisation Process

There are no standardised methods for producing digital documentation and most projects begin without prior agreement on procedures or results. Technological innovation and the variety of software and hardware favour a performance-based approach rather than a prescriptive one, as happened in the past in the sporadic technical specifications prepared (Monti et al., 2000). However, the approach used in classical topography and photogrammetry, where roles and competences are better defined, could also be applied to architecture and archaeology. The specifications, which translate the customer's requirements into technical language, are the operational reference for the contractor, and the inspector checks the processes and the end products. However, the drafting of specifications and final inspections are sacrificed due to limited resources in the heritage sector.

In terms of specifications, one solution might be to establish common guidelines for similar built heritage assests, as the Digital Library is doing for movable ones. (Istituto Centrale per la Digitalizzazione del Patrimonio Culturale, 2022).

5.3.3 Evaluation of the Digitisation Product (Reality-Based 3D Models)

To quantify quality, it is necessary to identify the geometric and semantic relevant aspects of a reality-based 3D model, in particular:

resolution, considered as the level of detail in both geometry and texture, which contains information on materials and conservation.

completeness, which refers to the complete coverage of all surfaces of the object and the integrity of thematic attributes in a specific domain.

The concept of accuracy comes from metrology and is applied to geometric aspects, considering that texture projection errors are almost negligible (for example, due to poor calibration between the image acquisition sensor and the one used for shape digitisation). The correct evaluation of this statistical parameter requires a set of error-free reference measurements, i.e. much more accurate than those to be evaluated. On the other hand, the term precision refers to the repeatability of results obtained using different methods of measuring.

In summary, in addition to the aspects mentioned above, it is essential to consider the suitability of 3D models for reuse, as intended by the FAIR principles. So, it is proposed to add to the FAIR principles the concept of "suitability", which plays a key role in facilitating data reuse. This addition will refer to the parameters that define which reuses are suitable for a given 3D model, in order to overcome the idea of the documentation process as a one-off. Encouraging data reuse increases sustainability, so the suitability parameters will facilitate reuse itself and the overall "FAIRification" process of reality-based 3D models. Suitability therefore suggests the application of objective methods of process assessment, while preserving flexibility in the evaluation of the product, for which specific characteristics must be rated but considering, each time, compatibility and performance aspects of 3D models with respect to the users, the goal, the framework of use. Supporting suitability assessment helps data producers, clients and all stakeholders to speed up the production of digital deliverables, promoting the sustainability of the documentation, preservation and valorisation of cultural heritage.

5.3.4 Multi-scale and Multi-sensors Approach

In the digital documentation of tangible cultural heritage, a multi-scale approach is crucial for capturing the diverse aspects of both large-scale urban environments and the fine details of individual artefacts or buildings. Traditional analogue designs, such as orthogonal projections, were always linked to a fixed scale. However, with the advent of digital tools, users can zoom in and out freely, breaking the rigid connection between graphic scale and the level of detail. Nevertheless, the need for maintaining consistency in the level of detail remains. Concepts like Level of Detail (LoD) and Level of Development (LOD), familiar from Building Information Modelling (BIM), are increasingly being applied to heritage documentation. Specifically, in the field of built heritage, frameworks such as Level of Geometry and Grade of Accuracy help ensure precision across different scales.

At the urban scale, large-scale cartography has shifted towards 3D city models, which depict the built environment and natural elements in detail. Geographic Information Systems (GIS) are often employed in these models to study the relationships between different urban features. Such systems are essential for understanding the broader spatial contexts in urban heritage studies, as well as in archaeology, where documentation typically starts with large-scale territorial analyses before moving into more detailed investigations of smaller sites or artefacts.

When digitizing individual artefacts or collections, the approach differs from that of buildings, particularly because georeferencing is not always necessary for movable objects. Institutions like museums, galleries, and libraries play a central role in this field. For example, the Smithsonian Museum has developed a comprehensive digitization program and metadata model, while the British Museum has recently committed to digitizing its entire collection within 5 years. These large-scale digitization efforts are not only about preservation but also have economic and cultural tourism benefits. The European Union's Europeana platform promotes access to digital cultural resources, with the ambition of digitizing millions of objects.

Photogrammetry and 3D scanning are the most commonly used techniques for digitizing artefacts, offering high-resolution, detailed representations. However, these processes require specialized equipment and expertise, especially when dealing with delicate or valuable objects. Handling, supports, and rotation systems must be carefully managed to ensure the accuracy of the final digital models.

For the documentation of historic buildings, Historic Building Information Modelling (HBIM) is gaining popularity. It typically integrates data from photogrammetry and 3D scanning to create comprehensive digital models of heritage structures. Georeferencing and accurate control networks play a fundamental role in ensuring the precision of these models, especially when aligning scans or incorporating data from multiple sources. Though HBIM is still evolving, it shows great potential in supporting the conservation and management of historical buildings. Alternative approaches focus on integrating building data into GIS systems, which allow spatial information to be managed and visualized, with greater flexibility for exploring detailed data.

At the urban scale, documentation and monitoring efforts address both natural and human-induced risks, which require a combination of aerial and ground-based technologies. UAVs (Unmanned Aerial Vehicles) equipped with RTK modules and SLAM (Simultaneous Localization and Mapping) technology are essential tools for surveying and documenting urban environments. These devices can provide both aerial and ground-level data, offering a comprehensive view of historic sites. For example, the historical centres of cities like L'Aquila and Firenze, a UNESCO World Heritage Site, have been extensively studied to monitor their transformations over time and to mitigate risks from natural disasters and human activities.

On a broader territorial scale, documentation must consider both natural landscapes and the transformations brought about by human activity. The European Landscape Convention defines landscapes as key elements within territories, shaped by the interactions between natural and human factors. Documenting these areas often requires a multi-sensor approach. UAVs equipped with LiDAR, thermal, and multi-spectral cameras are particularly useful for capturing data in large, complex, or high-risk areas, such as those prone to landslides, floods, or fires. Submerged or aquatic areas require specialized surveys, such as bathymetric mapping, often conducted using autonomous vessels that can simultaneously gather data above and below the water surface.

The digital documentation of cultural heritage demands the integration of multiple data sources and technologies. This multi-source and multi-sensor approach helps in understanding the structural behaviour, identifying damage, and evaluating the overall performance of heritage sites. Monitoring technologies, including satellites, drones, and ground-based sensors, are essential for creating a holistic view of these sites. By combining such tools with historical research, databases, and visual documentation, conservationists can ensure the long-term preservation and management of cultural heritage.

5.4 Georeferencing of Geometric and Thematic Data

Georeferencing is a fundamental aspect of this documentation process. Integrating and consolidating significant information and data of a territory is feasible if their geospatial coordinates are expressed within the same reference system.

The datums listed in the EPSG (European Petroleum Survey Group Geodetic Parameter Dataset), which collects the set of geodetic parameters that define the geographic reference systems and coordinates used to represent the Earth's surface on maps and in navigation systems, are commonly used when considering large study areas where relationships with the territorial context are critical.

The EPSG dataset, developed in 1986, has become a widely used standard for the management of geospatial data and geodesy. It contains a wide range of coordinate systems, geodetic datums, and other information related to map projection and coordinate transformation. The combinations of these elements are identified by numerical codes that uniquely identify the coordinate systems and geodetic parameters. This encoding type is extensively used within Geographic Information Systems (GIS). Within a single nation, such as Italy, maps may reference different geodetic datums and projections., because if the temporal evolution of the territory and the advancements in scientific knowledge (Istituto Geografico Militare, 2022). Currently using the ETRF2000 system as of epoch 2008.0 is mandatory for the public administration in Italy (D.M. November 10, 2011), as also indicated in the European INSPIRE directive.

Local reference systems may also be used, depending on the extent of the area and the purpose of the study. However, at least approximate referencing is always desirable to allow multi-scale measurements. In the case of large complexes, typically cartographic aspects must be considered, such as the choice of the projection surface to be adopted and its characteristics, in order to ensure the best congruence between field measurements and their graphic restitution (Bonora et al., 2021).

In the case of details of a building or movable objects, referencing has a different meaning, and it is more helpful to specify their location in a larger context than to define their absolute position. Proto-spatial referencing systems such as the Raumbuch (Bonora et al., 2023), which consists of the progressive breakdown and coding of the building into increasingly simple portions, can be useful for this. An essential feature of the Raumbuch is a progressive and unambiguous identification of the spaces and surfaces of a building. The identification codes, which form the master strings, allow the link to the thematic data relating to the different scales in which the buildings are articulated. In this way is possible to capillary describe the building and constitute a structured container capable of collecting and returning the various cognitive contributions, facilitating their progressive implementation.

Also, thematic information can be referenced, such as materials, state of preservation, presence of sensors/installations, etc. This can be realised with many solutions including point clouds annotated with uncontrolled textual descriptions or 3D enriched models in which thematic information is organised with controlled and standardised data structures.

Machine and deep learning can support the extraction of semantic information from geometric information (Matrone et al., 2020), but this field requires further investigation because of the amount of data produced by photogrammetric and laser scanning surveys and the high number of semantic classes to be identified.

5.5 Metadata and Paradata

In the case of built heritage, conservation and valorisation are inextricably linked to fruition. So the issue is not only generating a 3D model for visualisation, but also of developing tools that simultaneously address the knowledge, conservation and management. We are at the crossroads of a digital and ecological transition (Münster et al., 2021), where the pressures of climate change and natural hazards need to be responded to with a new cognitive approach that innovates digital documentation processes (Bosone et al., 2021).

The Digital Twin paradigm is emerging (Jouan & Hallot, 2020) as a multiscalar information model continuously enriched in time and space. This includes all types of information, from geometric and archival information to real-time data collected by monitoring sensor networks. BIM-GIS domains are examples of the integration of heterogeneous data into a geometric model of buildings and environment.

Within the workflow for the digitisation of the built heritage attention has been mainly focused on the model and its information content, neglecting the part related to the documentation of the survey process.

Surveying a heritage building is a complex and expensive task and, in the past, their documentation has been episodic.

Digital documentation of the built heritage is not an automated process but still requires an error-prone interpretation of acquired data, so monitoring of the workflow is necessary to validate, integrate and possibly correct the information as soon as possible. A scientific approach requires that the methods and paths adopted are verifiable and repeatable.

There are no standards to check is the documentation of a building is complete. At the national level, the most detailed checklist (focussed on structural analysis) is the "path of knowledge" contained in the "Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale".[10]

Often the survey of large buildings takes a long time, so it is advisable to systematically archive data, metadata and paradata related to (i) previous information, (ii) new acquisitions and (iii) data processing.

A BIM model of a new building, without information on masonry stratigraphies, construction characteristics, LODs, etc., is just a silent geometry. At the same time, the metadata and paradata are the information that certify the reliability of a digital

[10] https://cultura.gov.it/comunicato/linee-guida-per-la-valutazione-e-riduzione-del-rischio-sismico-del-patrimonio-culturale-allineate-alle-nuove-norme-tecniche-per-le-costruzioni-d-m-14-gennaio-2008

survey of an existing building. HBIM systems link building information to geometries, but they do not link information about the survey. Storing the survey data would help to update the geometry.

To date, this information is not consistently recorded by surveyors, except from annotations on sketches and collection of raw data according to unspecified criteria, usually in proprietary formats. Data collected in different workflows (topography, laser scanner, photogrammetry, etc.) are usually recorded separately, in non-standard formats, so survey data are often dispersed.

Some commercial proposals go in the direction of integrating different information, but these are strictly hardware and software dependent applications and not fully usable for complex projects. In principle, metadata cannot be efficiently found and stored.

The documentation of the workflow and metadata related with processing and production of the final outputs is even less common and standardised. Especially when the processing is not only a plot or a 3D model, as in the case of HBIM, it is essential to preserve the raw data on which the information content is based for possible corrections or additions.

Other issues are related with the use of machine and deep learning for data analysis and processing (Pellis et al., 2022) because the final results may depend on unsupervised processes. Nowadays, workflows are used by operators without specific training, making it even more important to retain the procedures and metadata to validate the results.

There is no universally accepted metadata system (Pamart & de Luca, 2020). It should be noted that many diffused metadata profiles (including Simple Dubin Core Metadata structure) do not include 3D file descriptors.

5.6 Open Challenges and Future Trends

Digitisation projects often face problems sharing data and results due to unclear Digital Rights Management laws. Despite the increasing diffusion of the FAIR principles, in Italy, reference is made to copyright law, whose regulatory framework is still referable to Law 633 of 22 April 1941, while in the digital context, the EU Directive 790/2019 and Legislative Decree 177/2021 have recently intervened. The creator of the digital model is considered the sole owner of all rights and economic exploitation. This is in contrast to the multiple actors in multidisciplinary processes, who are often only associated for the duration of the project, without paying attention to the maintenance of the result.

Many projects are frustrated by underestimating copyright and data protection issues, underestimating the cost of hosting services, publication rights or penalties, or making verbal agreements without written specifications. Bureaucracy and approval processes can also affect the timing of a project by hindering planning. Ineffective communication between team members leads to misunderstandings and delays. Uncontrolled changes to the project scope can lead to scope creep, affecting schedules, budgets and resources.

Budgeting for digitisation projects is challenging. Each project must also consider contributions to the expansion of the infrastructure and its needs, so that long-term valorisation results must be highlighted to potential funders.

Budgeting for digitisation projects is challenging. Each project must consider contributions to infrastructure and its specific needs. Long-term benefits must be emphasised to potential funders.

Future trends can be traced back to:

- Data acquisition methods, both in the sense of multi-sensor integration and the use of faster mobile sensors.
- The use of AI for the integration of semantic content into geometry.
- The definition (from a theoretical and regulatory as well as practical and operational point of view) how to share and use, especially online.
- The definition of de facto or regulatory standards.
- The creation of digital contents, i.e. the process of freeing pieces of a collection from the limits of their physical materiality and enabling them to exist in a virtual space.
- To open access aspects, making digitised cultural resources available for everyone to use without restriction.

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