TECHNICAL REPORT

IIT TR-02/2025

Information Technologies for Cultural Heritage

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June 2025 - Version 1.1

Abstract

Cultural heritage, which includes tangible assets such as works of art and historical sites, and intangible assets such as traditions, languages and knowledge, is essential for the collective memory and identity of communities. However, its conservation and valorization requires innovative approaches and advanced technologies to address challenges such as physical deterioration and global accessibility. In this technical report, opportunities and challenges related to the usage of information technologies in cultural heritage will be illustrated, outlining a panorama that combines innovation, creativity and responsibility.

1 Introduction

Information Technologies (IT) have revolutionised many sectors of society, including cultural heritage (CH). Thanks to digitisation, it is now possible to preserve digital copies of cultural goods and to exploit innovative tools for their valorisation, use and protection. Large-scale projects, such as Europeana (https://www.europeana.eu/it) [49], which offers access to millions of digitised cultural goods, and Google Arts & Culture (https://artsandculture.google.com/) for the digital valorization of cultural heritage, have demonstrated the potential of IT to make cultural heritage more accessible and usable for all.

A significant example of this transformation is represented by 3D printers, which allow to create physical replicas of three-dimensional artefacts starting from digital models. This technology expands the opportunities for restoration and study, for instance through the use of digital twins, but also opens up new issues related to copyright management and the prevention of fraudulent uses of an asset.

Cultural heritage, which includes tangible assets such as works of art and historical sites, and intangible assets such as traditions, languages and knowledge, is essential for the collective memory and identity of communities. However, its conservation and valorization requires innovative approaches and advanced technologies to address challenges such as physical deterioration and global accessibility. Figure 1 illustrates information technologies that can be used for cultural heritage, once created a digital copy of the asset.

In the following, opportunities and challenges related to the usage of IT in cultural heritage will be illustrated, outlining a panorama that combines innovation, creativity and responsibility. This paper is organized in eight sections:

- Background information (Section 2)

Figure 1: The digital revolution of cultural heritage.

- Main IT research and application areas for CH (Section 3)
- Examples of vertical domains related to CH, such as cultural tourism, education, scientific research and entertainment (Section 4)
- Information Technologies for CH (Section 5)
- Cross-cutting aspects, such as accessibility and security (Section 6)
- Examples of Major Projects for CH (Section 7)
- Discussion and conclusion (Section 8).

2 Background

Cultural Heritage, represented by both tangible and intangible assets, preserves the collective identity and historical memory of communities. UNESCO (United Nations Educational, Scientific and Cultural Organization) has played a key role in defining the categories of CH, protecting it through international conventions and globally recognized registers of sites. As societies have evolved, the concept of cultural heritage has expanded to include, for example, traditions, languages and digital assets, leading to new challenges for their conservation. This section explores in detail the various categories of cultural heritage, illustrating their specificity and the current challenges related to their management and protection.

2.1 Cultural Heritage

When talking about CH, it is important to highlight what is actually meant by this expression. The term heritage generally refers to the set of goods (Cultural Assets) that represent a certain community and that are inherited (heritage) or better transferred from previous generations to future ones. Normally in the heritage of a community we find language, behaviors, religion, cuisine, arts, social habits, beliefs, etc., i.e., all those things that portray the way of life of the community. These goods are normally divided into:

- tangible or material goods such as works of art, historical artifacts, archaeological sites, etc.
- intangible or immaterial assets such as oral traditions, languages, traditional knowledge, etc.

UNESCO played a crucial role in formalizing and spreading the term "Cultural Heritage" with the Convention Concerning the Protection of the World Cultural and Natural Heritage of 16 November 1972 [1], which provided an official definition and established criteria for the inclusion of sites in the World Heritage. Indeed, UNESCO since then has begun to draw up a list of World Heritage sites[2] dividing them into 3 categories: cultural, natural and mixed. It has therefore defined a list of World Heritage Sites in Danger[3] and a list of Intangible Cultural Heritage, since, as anticipated, the concept of cultural heritage has evolved over time, also extending to traditions, languages, social practices, knowledge and skills transmitted from generation to generation[4]. These lists are dynamic, since new sites can be added from time to time.

The definition of Cultural Heritage by the European Commission is "CH consists of cultural and creative resources of a tangible or intangible nature, with a value for society that has been publicly recognised in order to preserve it for future generations"[5].

Tangible cultural heritage assets can be divided in many ways. For example, the General Catalogue of Cultural Heritage[6] proposes 9 sectors:

1. Historic and artistic assets, that present a historical and artistic interest together, such as churches, palaces, monumental complexes
2. Archaeological assets: remains of ancient civilizations, such as archaeological sites, archaeological finds and archaeological monuments
3. Architectural and landscape assets: buildings, monumental complexes, historic centers, historic agricultural landscapes, historic gardens
4. Demo-ethno-anthropological assets: objects and artefacts of popular culture, such as traditional costumes, work tools, household objects
5. Naturalistic assets
6. Photographic assets
7. Numismatic assets

[1] Convention Concerning The Protection of the World Cultural and Natural Heritage https://whc.unesco.org/archive/convention-en.pdf

[2] https://whc.unesco.org/en/list/

[3] https://whc.unesco.org/en/danger

[4] https://ich.unesco.org/en/lists

[5] https://ec.europa.eu/commission/presscorner/detail/en/memo_17_5066

[6] https://catalogo.beniculturali.it/

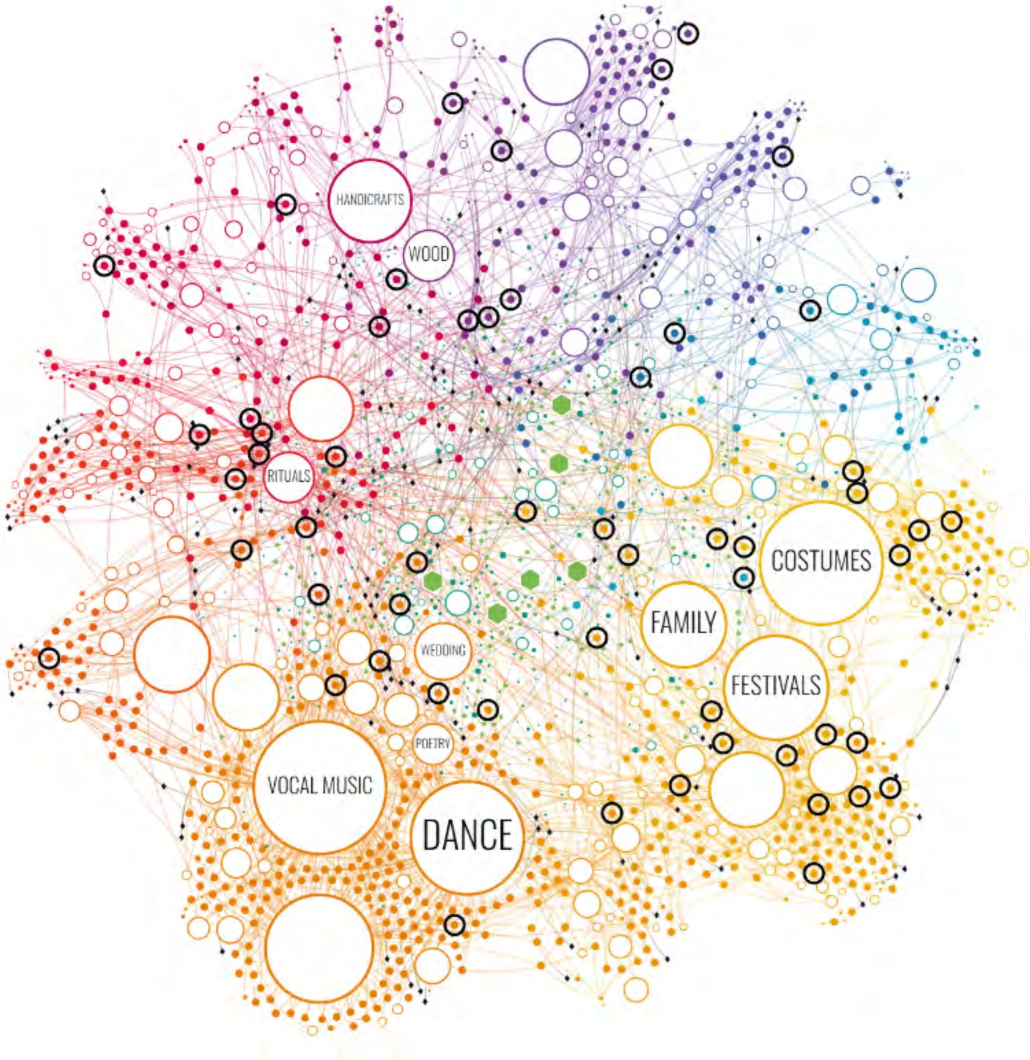

Figure 2: Unesco Intangible Cultural Heritage (2024-07-24)

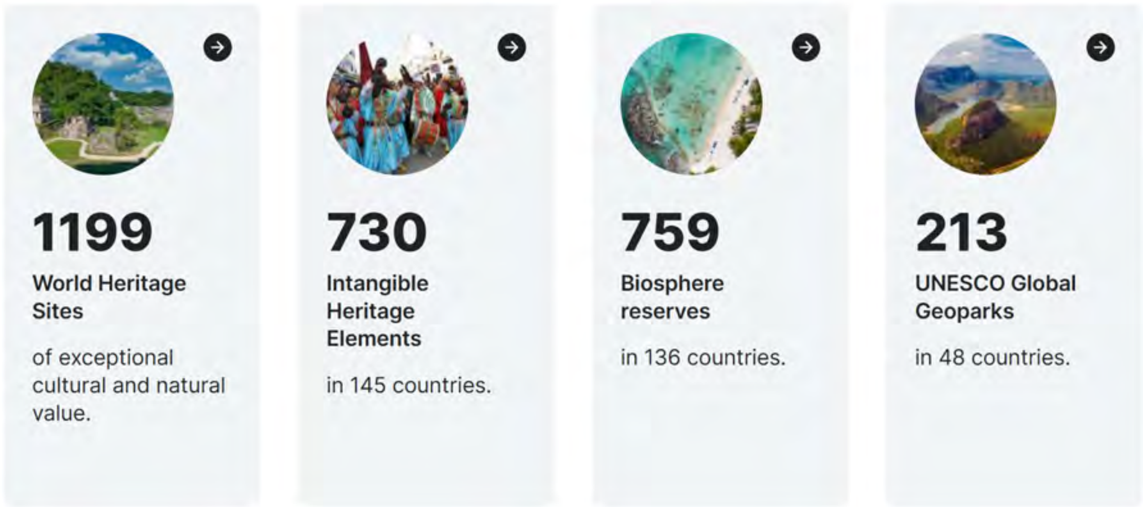

Figure 3: Unesco sites (2024-07-24)

8. Scientific and technological assets
9. Musical assets.

Other sectors are: Artistic goods (paintings, sculptures, applied art objects, installations, contemporary works of art), Book goods (manuscripts, incunabula, ancient and rare books, prints, geographical maps) and Archival goods (historical documents preserved in archives, such as government acts, private papers, account books).

Finally, it is also worth mentioning Digital Heritage, for example in the UNESCO definition: "Digital heritage consists of digital materials of enduring value that should be preserved for future generations. Digital heritage comes from different communities, industries, sectors and regions. Not all digital materials have enduring value, but those that do require active preservation approaches to maintain the continuity of the digital heritage".

2.2 Information Technologies and Human-Computer Interaction

In the modern sense of the definition, Information Technologies include computer systems, software, programming languages, processing and storage of data and information. When talking about Information Technologies aimed at use by users, it must be taken into account that they must be designed in a way that allows people to understand and interact with them in a simple, intuitive and effective way. Human-computer interaction (HCI) is a research area related to the design of information systems that focuses on the interfaces between people (users) and technological devices, such as computers, mobile devices, website, ATM interfaces or information kiosks. Important aspects of human-computer interaction are accessibility, which aims to allow interaction to users with disabilities, and usability, which defines guidelines and methodologies to make the interaction more natural, easy, intuitive and simple for all users. Cultural heritage is a much-investigated application field of new information technologies. Visualization plays an important role in enhancing the user experience, both on-site and online. The range of possible visualization devices is wide and heterogeneous: from small screens of smartwatches, to large screens located on-site, to the latest generation of immersive head-mounted displays, together with the increasing availability of real-time 3D rendering technologies for online and mobile devices and, recently, Internet of Things (IoT) and Social Robotics approaches [70]. Physical objects in a museum or other cultural venue are often augmented with sensors that detect when they are moved and manipulated, allowing descriptive information to be presented to users as they look at them, fostering their engagement. For example, a 2019 study built and tested with real users an interactive pedestal for artifacts related to World War I relics. The results showed that visitors positively appreciate this type of tangible interaction with the objects in the collection, as it allows them to discover details and learn about aspects that normally go unnoticed [92].

3 Application Areas of Technologies for Cultural Heritage

Information technologies are often used in the field of cultural heritage to create a wide range of applications to improve its management, protection and fruition. The digitization of cultural heritage has seen exponential growth, with tools to achieve it ranging from microfilms to 3D scanners. In the field of protection, the Internet of Things (IoT) allows to monitor the conditions of the assets to prevent their deterioration. In the field of restoration, advanced technologies such as 3D lasers and photogrammetry help to preserve monuments and works of art. The fruition and valorization of heritage have expanded thanks to the web, mobile apps, social media and the use of augmented reality (AR) or virtual reality (VR), which make the experience of cultural heritage more accessible and engaging. Each area will be illustrated in detail in the following.

3.1 Digitalization

The digitization of Cultural Heritage is a process that has significantly accelerated in recent decades, revolutionizing the way we preserve, study and share our CH. The possibility of preserving a digital copy of so many cultural assets has created a digitization fever driven by the anxiety of saving this enormous heritage from all possible threats.

3.1.1 The origins

One of the first techniques used in a widespread way to obtain a copy of cultural heritage was microfilming [15] which allowed the reproduction of paper documents on analog media by reducing the dimensions from 15 to 48 times compared to the original materials. The main disadvantage of this technique is the difficulty of access: to read the information stored on a microfilm, it is necessary to use special readers (see figure 4) or consult them on site. Subsequently, microfilms also became the object of digitization both to overcome the problem of access and because microfilms were also becoming an obsolete technology. The first attempts to digitize cultural heritage date back to the 1960s and 1970s, with pilot projects that used still rudimentary technologies to create digital databases and catalogs.

3.1.2 The advent of digital

In the 1990s, with the development of personal computers and the Internet, the digitization of cultural heritage accelerated. The first large-scale digitization projects were born, focused on the creation of **digital libraries** and online archives. Among these projects, we can mention the Gutenberg project [73] started in 1971 by Michael Hart with the aim of creating a digital library of books no longer covered by copyright. The introduction of high-resolution scanners, image processing

Figure 4: Indus 4601-11 Microfilm Reader. Source: `https://worldmicrographics.com/roll-film-readers/`

software and 3D technologies has made it possible to create high-quality digitizations, increasingly detailed and accurate.

3.1.3 Digitalization today

Digitization of cultural heritage is still a very active field of research and development. Today, it is mainly used to preserve fragile cultural assets, create immersive visitor experiences, facilitate scientific research, and promote culture globally. Despite progresses, digitization of cultural heritage still presents many challenges, such as ensuring the long-term preservation of digital data and addressing issues related to copyright and access to information.

3.1.4 Digitization of texts

The digitization of works such as parchments, tombstones and ancient sheets of paper focuses primarily on the creation of a digital copy of the original, usually achieved through tools such as scanners or high-resolution cameras. This process produces a digital image of the work, but does not automatically include the extraction of the text contained within. In fact, text extraction is considered a distinct activity, which can be done separately or as part of a larger project.

When you want to extract text from a digitized work, you can use two main approaches. The first is the use of optical character recognition (OCR) software, which automates the conversion of the text in the image into an editable digital format. The second, often used for complex or ancient texts, is manual transcription by experts. However, not all digitization projects include this step. In many cases, digitization is aimed solely at preserving or archiving the images, without further processing.

For particularly ancient or deteriorated works, such as parchments or tombstones, text extraction may require advanced tools, such as machine learning algorithms or the involvement of specialists in paleography, to overcome the difficulties related to the readability of the content.

3.2 Safeguard

The preservation of cultural and historical heritage is crucial for the continuity of our ancestors' cultural traditions. In this context, a 2023 study investigated whether serious games could have the potential to effectively maintain and communicate tacit knowledge associated with cultural heritage. The authors developed a serious game to increase tourists' engagement with the cultural and historical tradition of a place by revisiting historical events contextualized in the game. The results of user tests seem to confirm the feasibility and effectiveness of the [32] approach. Historical monuments that are part of cultural heritage can be in danger due to natural disasters, wars, climate change, uncontrolled construction, pollution, and mass tourism [63]. Some studies have investigated how information technologies can help in the field of preservation. For example, the work of Masciotta [84] describes a digital methodology developed in the HeritageCare project for the preventive conservation of cultural heritage. The method is based on standardized inspection protocols and digital tools to document the state of conservation of cultural assets, monitoring them over time, and allowing informed decisions on restoration. A 2020 work analyzes IoT architectures used for real-time monitoring and conservation of historical buildings, identifying the prevalent areas of use in the Valorization and Preventive Conservation [5]. Finally, a 2023 review focused on the technological elements that have enabled the conservation, promotion and dissemination of tangible and intangible cultural heritage in the period from 2018 to 2022. Of the 146 articles identified by the authors, 70% present a technological approach to preserve cultural heritage with a prevalence of 3D digital technologies (44% of those with technological approaches), followed by augmented reality or virtual reality (15%) [88].

3.3 Restoration

Over the past 50 years, there have been many restoration interventions on famous cultural assets such as the Sistine Chapel and the Notre Dame Cathedral, damaged by a fire. In the following table, we report some of these interventions specifying the period in which they were carried out, the reason for the intervention, an estimate of the costs and the information technologies that were used to support the operation.

From the causes of deterioration identified in the table, some recurring factors emerge that can be grouped into main clusters:

1. **Air pollution and environmental degradation**:
    - Air pollution (5 occurrences)
    - Environmental degradation
2. **Erosion and natural agents**:
    - Natural erosion (4 occurrences)
    - Wind and water erosion
    - Exposure to the elements
    - Adverse climate
    - Landslides
    - Invasive vegetation
3. **Humidity and climatic agents**:

Bene Culturale	Intervento di Restauro	Cause del Deterioramento	Coordinate	Costo	Tecnologie IT utilizzate
Cappella Sistina, Vaticano	1980-1994: Rimozione di secoli di sporcizia e fumo, recupero dei colori originali	Inquinamento atmosferico, fumo di candele, accumulo di polvere e umidità	41.9029° N, 12.4534° E	$4,2 milioni	Scanner ottici ad alta risoluzione, database digitali, analisi spettroscopiche
Cenacolo di Leonardo da Vinci, Milano, Italia	1978-1999: Pulizia, consolidamento della pittura e integrazione delle parti mancanti	Deterioramento naturale, interventi precedenti non adeguati, umidità, luce e inquinamento	45.4668° N, 9.1705° E	$8 milioni	Imaging multispettrale, software di monitoraggio ambientale
Grande Muraglia Cinese, Cina	2000 in poi: Consolidamento e restauro delle sezioni deteriorate	Erosione naturale, degrado ambientale, vandalismo, abbandono	40.4319° N, 116.5704° E	Diversi miliardi di yuan	Droni per mappatura, modelli 3D per valutazione strutturale
Notre-Dame, Parigi, Francia	2019 in corso: Consolidamento strutturale, restauro delle vetrate e ricostruzione del tetto	Incendio, degrado causato da inquinamento atmosferico e usura	48.8530° N, 2.3499° E	$865 milioni	Scanner laser 3D, modelli BIM, analisi termografica
Palmira, Siria	post-2015: Restauro e ricostruzione del sito archeologico distrutto durante il conflitto siriano	Distruzione durante la guerra civile siriana	34.5551° N, 38.2768° E	Decine di milioni di dollari	Modelli 3D, fotogrammetria, droni
Buddha di Bamiyan, Afghanistan	anni 2000 in corso: Ricostruzione e restauro delle statue distrutte dai talebani	Distruzione intenzionale da parte dei talebani	34.8261° N, 67.8266° E	$30 milioni	Ricostruzione 3D, fotogrammetria e modellazione laser
Sfinge di Giza, Egitto	1989-1998: Stabilizzazione delle zampe, restauro della struttura, pulizia	Erosione naturale, inquinamento atmosferico, sabbia	29.9753° N, 31.1376° E	$2,5 milioni	Analisi spettroscopica, modelli 3D
Machu Picchu, Perù	2000 in poi: Conservazione delle strutture in pietra e gestione del turismo	Erosione, turismo, frane, clima avverso	13.1631° S, 72.5450° W	$10 milioni	Sensori ambientali, modelli 3D
Taj Mahal, India	2015-2018: Pulizia delle superfici marmoree, restauro delle strutture e giardini	Inquinamento atmosferico, umidità, usura	27.1751° N, 78.0421° E	$5 milioni	Scanner laser 3D, software per analisi dell'inquinamento
Statua della Libertà, Stati Uniti	1984-1986: Restauro della struttura interna, pulizia e sostituzione della torcia	Corrosione, esposizione agli agenti atmosferici	40.6892° N, 74.0445° W	$87 milioni	Modelli CAD, sensori per il monitoraggio della corrosione
Templi di Angkor Wat, Cambogia	2000 in poi: Restauro dei bassorilievi e consolidamento delle strutture	Erosione naturale, vegetazione invasiva, umidità, saccheggio	13.4125° N, 103.8667° E	$20 milioni	Modelli 3D, software di mappatura per monitoraggio
Colosseo, Roma, Italia	2013-2016: Pulizia e consolidamento delle superfici, restauro delle arcate	Inquinamento atmosferico, traffico urbano, usura	41.8902° N, 12.4922° E	€25 milioni	Scanner laser 3D, software per monitoraggio vibrazioni
Moai, Isola di Pasqua, Cile	anni 1990: Consolidamento delle statue, ripristino delle teste cadute	Erosione da vento e acqua, esposizione agli elementi, vandalismo	27.1167° S, 109.3667° W	$10 milioni	Fotogrammetria, software di monitoraggio dell'erosione
Biblioteca di Alessandria, Egitto (Nuova Biblioteca)	inizi anni 2000: Ricostruzione e modernizzazione della biblioteca	Distruzione nell'antichità da guerre e incendi	31.2089° N, 29.9092° E	$220 milioni	Sistemi digitali per conservazione e accesso, database per gestione collezioni
Museo Nazionale del Brasile, Rio de Janeiro	2018 in corso: Restauro e ricostruzione dopo l'incendio	Incendio devastante, manutenzione insufficiente	22.9050° S, 43.2286° W	$35 milioni	Scanner 3D, software di archiviazione digitale, monitoraggio sicurezza
Pietà di Michelangelo, Roma, Italia	1972 in corso: Restauro a seguito di attacco vandalico	Attacco vandalico	41.9029° N, 12.4534° E	Non disponibile	Scanner laser, sistemi di imaging per analisi danni
Pompei, Italia	In corso: Conservazione del sito archeologico	Agenti atmosferici, turismo di massa	40.7469° N, 14.4989° E	€105 milioni	Scanner 3D, software GIS, sensori ambientali
Partenone, Atene, Grecia	In corso: Restauro e consolidamento	Inquinamento atmosferico, erosione naturale, danni da conflitti storici	37.9715° N, 23.7267° E	€5 milioni	Scanner laser, modelli BIM, software di monitoraggio strutturale
Stonehenge, Inghilterra	In corso: Restauro e protezione delle pietre	Erosione naturale, turismo, inquinamento, traffico	51.1789° N, 1.8262° W	£10 milioni	Scanner laser, sensori per monitoraggio vibrazioni

Table 1: Main Restorations

- Humidity (3 occurrences)
- Dust and moisture accumulation
- Corrosion

4. **Vandalism and conflicts**:
   - Vandalism
   - Vandalism attack
   - Damage from historical conflicts
   - Looting
5. **Tourism and wear and tear**:
   - Tourism (2 occurrences)
   - Mass tourism
   - Wear and tear
6. **Fires and other disasters**:
7. **Poor maintenance, inadequate previous restorations**

From the list of the 7 main causes, five (1, 4, 5, 6, 7) depend largely on human activity and only two (2, 3) on natural factors. The main Information Technologies used in the restoration interventions were the following:

1. **Drones and sensors for monitoring**:
   - Mapping Drones
   - Environmental Sensors
   - Corrosion and Vibration Monitoring Sensors
2. **Monitoring and analysis software**:
   - Structural, Environmental, Erosion and Vibration Monitoring Software
   - Safety and Pollution Monitoring Systems
3. **Scanners and 3D models**:
   - 3D Laser Scanners (3 occurrences)
   - 3D Models (2 occurrences)
   - 3D Scanners (2 occurrences)
   - High Resolution Optical Scanners
4. **Digital modeling and BIM software**:
   - BIM Models (2 occurrences)
   - CAD Models
5. **Imaging and photogrammetry techniques**:

- Multispectral Imaging
- Photogrammetry
- Thermographic Analysis
- Spectroscopic Analysis

The first 2 techniques are used to perform a preventive analysis on the state of a cultural asset before the intervention, while the remaining ones can be used both in the preparation phase and during the intervention itself.

Virtual or digital restoration is a set of integrated two-dimensional or three-dimensional computer graphics methodologies that allow you to visualize the work as it was supposed to be, or to pre-visualize the restoration intervention with a hypothesis of reconstruction of an artistic, archaeological or architectural asset. The development of digital intervention models, without resorting to non-reversible interventions on the original, is particularly useful when the asset cannot be restored in a traditional way, for example due to the physical impossibility of the intervention, the lack of adequate technical solutions or the lack of accurate documentation to follow for the reconstruction of the work.

3.4 Fruition

Web, **mobile applications**, **social media**, **gamification** and **crowdsourcing** technologies have transformed access to cultural heritage, making it more accessible and accessible to a wider audience. In the following, we provide more details.

3.4.1 World Wide Web

The Web has revolutionized the way in which information on cultural heritage is distributed and consumed. Museums, galleries and archaeological sites offer virtual tours, digital catalogues and interactive resources that allow users to explore works of art and historical monuments directly from home. Platforms such as Google Arts & Culture[7] allow access from anywhere in the world to millions of digitized works and cultural documents, making the enjoyment of heritage more democratic and global.

3.4.2 Mobile Applications

Smartphone apps have facilitated direct and personalized interaction with cultural heritage. Many apps include augmented reality (AR) and geolocation features, allowing users to explore many cultural heritage sites with additional information directly from their mobile device. An example is the Vatican Museums app that provides interactive maps and multimedia audio guides to enhance the visitor experience.

3.4.3 Social Media

Social media, like the web but in an even more amplified way, have played a crucial role in the dissemination of cultural heritage, offering platforms to share visual content and stories. Museums and cultural institutions use Facebook, Instagram and YouTube to promote events, share images and videos of exhibitions, and engage the public through interactive posts, polls and live streaming. This approach helps to reach and raise awareness of a global community, encouraging real-time interaction.

[7] `https://artsandculture.google.com/explore`

3.4.4 Gamification

Gamification has made the cultural heritage experience more engaging, by transforming educational content into interactive games. Examples include apps that invite users to solve puzzles, explore historical sites through quests, or compete with other users to discover information. These approaches, often used in museums, make learning fun and engaging, especially for young people.

3.4.5 Crowdsourcing

Crowdsourcing allows the public to be involved in the preservation and valorization of cultural heritage. Users can contribute data, images or even funding for cultural projects. Platforms such as Europeana or Wiki Loves Monuments encourage active participation, allowing users to upload photographs or descriptions of local monuments, expanding the cultural archive available online. These technologies have therefore brought the general public closer to cultural heritage, improving accessibility, interaction and the level of participation.

3.5 Valorization

Information technologies are also often used to promote cultural heritage. Some examples are given below. The game AVARUM Lands relies on local culture for its plot, using the physical space of the city as a play area and involving visitors/tourists and inhabitants in an immersive experience with the urban space in order to promote the cultural heritage of the territory [43].

Several studies exploit the potential of virtual and/or augmented reality. The Innovative Cultural Experience (ICE) is an Augmented Reality system that combines cutting-edge technologies such as an interactive transparent screen, motion sensors, multimedia material and interactive games to offer a personalized experience using information based on tangible and intangible cultural heritage. When a user/visitor approaches the place where the system is located, multimedia information is displayed on the transparent screen and allows to interact with the content (text, images, videos including 3D and immersive, and games). This technology can also be used for education, business or tourism [68]. A 2023 study uses virtual reality to replicate the experience of group visits to museums, allowing multi-user interaction through discussions that occur around cultural heritage objects, with the aim of promoting them and CH in general [29]. In Italy, a 2021 study aimed to support the enhancement, enjoyment and understanding of monuments had utilized both Spatial Augmented Reality, to enhance the monument and narrate its history through images and sounds, and Augmented Reality, to facilitate the reading and interpretation of the most important frescoes of a basilica[31]. The European Pa.C.E. Project (Heritage, Culture, Economy[8]) had promoted recovery strategies and good practices to enhance the tangible and intangible heritage, promoting the economic development and tourist attractiveness of the Alcotra region.

If we extend the boundaries of cultural heritage to craftsmanship, considering that artisans play a fundamental role in preserving cultural heritage and promoting economic sustainability in many communities, we can find several projects supporting the marketing of local products. For example, the "E-commerce for Artisans" project has proposed a digital eCommerce platform that provides artisans with tools and resources to create online showcases, manage inventory and orders, receive payments securely, etc., in order to allow them to face larger and more global markets [104].

[8] https://www.interreg-alcotra.eu/it/pace-patrimonio-cultura-economia

4 Examples of Vertical Application Domains

The application of IT to Cultural Heritage extends to various vertical sectors that benefit from them, such as cultural tourism, education, scientific research and entertainment. This section presents examples of how IT support each of the domains mentioned.

4.1 Cultural Tourism

Scientific and reasonable tourism development has become one of the most effective ways for the protection and sustainable development of cultural heritages. A 2020 study conducted a bibliometric analysis based on 535 articles from the Web of Science database on publishing trends, major publication topics and keywords. The research results seem to confirm that the tourism industry has become the main carrier of the digital transformation of cultural heritage management. Digital tools such as 3D technology, laser, geographic information technology, database modeling, etc., have supported the visualization, management, risk monitoring and planning of cultural heritages. Such digital transformation is driven by the tourism industry in the spirit of sustainable development, and therefore, the tourism industry has become the main driving force for the sustainable development of cultural heritages [133]. Examples of the application of information technology for tourism promotion are given below.

Footprints of Travel is a game that enhances cultural attraction experiences for tourism and space management using augmented reality (AR) and artificial intelligence of things (AIoT). This approach creates personalized experiences throughout the city such as navigation in cultural sites, recognition of the amount of people present, and dynamic data processing within the context management framework. The application also improves the safety of sites and comfort of people through temperature control, smoke detection, automatic fans, and artifact protection [72].

Technology can also support the travel planning phase. For example, the Cityzen platform supports cultural heritage-focused travel planning by providing a semantic web-oriented data model that can be used by tourists to accurately and efficiently plan their sightseeing visits. The platform also manages cases of incorrect and incomplete information by using the social web as a possibility to actively involve users in information management [93].

4.2 Education and training

Technological advances have provided cultural heritage with new learning environments, reconfiguring the ways in which information is transmitted and received. Many interventions exploit serious games, for example in [131] is proposed a game that uses 3D modeling to strengthen people's active construction of knowledge of cultural heritage. A recent study from 2023 presented and analyzed the state of the art on game-based learning on mobile devices in cultural heritage education [19]. Virtual and augmented reality are also often used to promote accessibility and understanding of culture and to propose new ways of interacting with cultural heritage. In a 2020 study, the authors identified and evaluated only in Spain 197 cultural heritage education programs that integrate the use of virtual environments and/or augmented reality to promote user learning [65]. In the same year, Vargas et al. investigated whether the use of augmented reality improves students' motivation to learn topics related to cultural heritage, evaluating studies from different databases and specific journals regarding technological systems [119].

An example of experimentation of a set of immersive, team-based and whole-body activities for cultural heritage education for primary school children is MagicMuseum, which exploits the interactive and multisensory capacity of a smart indoor space equipped with IoT-enriched components, such as floor and wall projections, smart lighting, music and sound, motion and gesture sensors and smart objects [57].

Technologies used to promote learning and interaction with cultural heritage also include robots. A 2020 study investigated whether social robots can be used for the cultural and tourism industry as a new tool to engage students in designing new edutainment applications in museums. The results confirm that the use of the social robot captures new age groups favoring the involvement of young audiences [38].

The great interest about new learning methodologies in the field of cultural heritage is confirmed by the increase of publications related to e-learning methods in CH, especially after the Covid-19 pandemic, during which many academic institutions have switched to e-learning platforms for managing the teaching process. A 2023 study performed on Scopus a bibliometric analysis of the literature on "e-learning in cultural heritage" from 2000 to February 2023 available , identifying 308 papers. Among the most frequently used keywords are "Virtual Reality" and "Augmented Reality" which seem thus confirmed as the main technological fields for teaching in the field of Cultural Heritage [85].

4.3 Scientific Research

Information technologies support research and analysis in the field of cultural heritage through advanced visualization tools, data analysis, computational modeling and other techniques to better explore, interpret and understand historical and cultural contexts. Advanced analysis technologies and machine learning algorithms allow to identify patterns or hidden details that may escape the human eye. The analysis of patterns on archaeological finds uses several advanced technologies, such as shape recognition, artificial intelligence (AI), and computer vision. These approaches support archaeologists in identifying cultural and technical traces through the details of wear or decoration in artifacts. The diversity of studies ranges from clustering algorithms to identify similarities in finds, to 3D software for the analysis and accurate documentation of geometric details, to the use of spectroscopy techniques to determine the provenance of materials. For example [116] Troiano et al. explore machine learning algorithms to identify cultural groups, using quantitative data to detect technological patterns on archaeological finds, with a study of European sites to identify homogeneities between processing phases.

3D reconstructions allow us to virtually recreate historic buildings or damaged objects, offering an immersive experience to researchers and the public. In fact, virtual reality can be used to study and visualize historical environments that are now lost, providing a deeper understanding of the original context of archaeological works and sites. [55] Forte et al. illustrate the use of VR to create collaborative 3D environments, allowing archaeologists to explore and interact with historic sites in a new and immersive way.

Computer science allows us to manage large amounts of data relating to cultural heritage, centralizing and organizing information in databases accessible to scholars. Through these systems, it is possible to catalog, monitor and cross-reference information, such as images, descriptions, chemical analyses, and historical documentation, making research more efficient and complete. An example is provided by the Pelagios project[9], an open network that links geospatial data from multiple sources. Isaksen et al. [66] examine the data collected by this project confirming their benefits.

GIS technology, together with remote sensing by airplanes, drones or satellites, allows to explore vast areas and to map the cultural heritage in a detailed way, optimizing the planning of conservation or excavation activities, for instance detecting archaeological sites (not yet excavated) by identifying anomalies in the ground or hidden remains under the surface. The GeoMemories [1] project has

[9] `https://pelagios.org/`

reconstructed the 1943-1944 landscape of some Italian areas (Pisa, Liguria, Rome, Florence, ...) using aerial photos taken by the Allies during the Second World War and superimposing them with current satellite images. The platform created has allowed to recognize patterns of Roman roads in places where now entire residential neighborhoods arise.

4.4 Entertainment

Cultural heritage, understood as the traditions, works of art, monuments and customs passed down from previous generations, represents a rich source of inspiration for the entertainment industry. This heritage offers a glimpse into the past that not only educates but also entertains, by revisiting stories, legends and cultures in new and engaging ways. Below are some significant examples of how cultural heritage is used in this sector.

Film and TV series widely exploit cultural heritage to set stories that capture the imagination of the public. An example is the series "Game of Thrones", which, despite being set in a fantasy world, draws inspiration from historical events such as the War of the Roses in England. Even films like "Gladiator", which revisits ancient Rome, or "Braveheart", which recounts the exploits of William Wallace and the wars for Scottish independence, offer narratives that intertwine historical events and cultures with a strong component of spectacle.

The European Project Interreg Pa.C.E., Heritage, Culture, Economy[10] has promoted recovery strategies and good practices to enhance the tangible and intangible heritage, promoting economic development and the tourist attractiveness of the Alcotra region.

If we extend the boundaries of cultural heritage to crafts, considering that artisans play a fundamental role in preserving cultural heritage and promoting economic sustainability in many communities, we find several projects supporting the commercialization of local products. For example, the project "E-commerce for Artisans" proposed a digital eCommerce platform that provides artisans with tools and resources to create online storefronts, manage inventory and orders, receive secure payments, etc., to allow them to access larger and more global markets [104]

Video games have made innovative use of cultural heritage to create interactive worlds. The "Assassin's Creed" video game series is one of the most famous examples: each title is set in a different historical era, such as the Italian Renaissance, Ancient Egypt or the French Revolution. These games offer the player the opportunity to explore cities and historical places reconstructed in detail, indirectly educating the public through gameplay. Other games, such as "Tomb Raider", include explorations of archaeological sites and references to ancient myths and legends.

Digitalization and new technologies have made it possible to bring cultural heritage into entertainment through immersive experiences. Museums and cultural institutions, such as the Louvre Museum or the British Museum, offer virtual tours that allow you to explore historical collections directly from home. Similarly, immersive exhibitions such as "Van Gogh Alive", where the audience is immersed in an interactive digital representation of Van Gogh's works, combine art, culture and entertainment.

Theater and music are other channels where cultural heritage finds space in entertainment. Historical musicals such as "Hamilton", which tells the life of Alexander Hamilton, one of the founding fathers of the United States, combine historical narration with modern forms of entertainment, such as rap and musical theater, to engage the audience in a cultural and educational experience. Theatrical performances of classical works, such as Greek tragedies or Shakespeare's plays, also rework cultural heritage in forms adapted to contemporary audiences.

Documentaries and historical television series are another important tool for bringing cultural heritage to the general public. Platforms such as Netflix, Prime, BBC and National Geographic

[10] `https://www.interreg-alcotra.eu/it/pace-patrimonio-cultura-economia`

produce content that explores ancient civilizations, historical periods or legendary figures. A notable example is the series "The Crown", which narrates the life of Queen Elizabeth II, combining real historical events with dramatic narration to entertain and inform.

Historical reenactments, often considered a form of live entertainment, are another way in which cultural heritage is used. Events such as medieval or Roman battle reenactments (e.g. the Gladiators of the Colosseum in Rome) offer the public the chance to experience fragments of the past first-hand, combining elements of entertainment, culture and history.

5 Information Technologies for Cultural Heritage

For cultural heritage management, there are several IT technologies useful within different application areas. In this section we list and describe the main technologies, their application in CH and some practical examples.

5.1 Internet of Things

Within current technologies, the Internet of Things (IoT) paradigm represents one of the most effective ways to monitor the "things" that surround us [5]. By exploiting physical devices such as environmental sensors, surveillance cameras, cultural heritage condition monitoring devices, etc., it is possible to monitor and collect data in real time, using it not only for monitoring but for proactive management and conservation of cultural heritage. A 2020 work analyzes the IoT architectures used for monitoring and conservation of historic buildings, identifying the prevalent areas of use (Enhancement and Preventive Conservation) and the issues to be managed such as limited connectivity, energy efficiency and operational difficulties in distribution, configuration and maintenance.

The use of IoT technology to improve access to cultural heritage sites and increase visitor engagement has become increasingly popular. For example, EFESTO-5W is a platform for defining IoT-enhanced personalized visits to cultural heritage sites that allows different stakeholders to configure the behavior of smart objects to create more engaging visitor experiences [4]. A recently published exploratory study investigated if and how an IoT-based game affects the experience of museum visitors. The study involved a total of 18 participants who took a guided tour of the Natural Science Museum of the University of Bari and played the game afterwards. The results show that playing the IoT-based game positively affects the visitor experience and, in particular, their emotions [7]. Another example of applying IoT to cultural heritage education, in this case for primary school children, is the creation of a space equipped with IoT components such as floor and wall projections, lights, music, sound, motion and gesture sensors and intelligent objects in order to favor learning [57].

An example of using IOT to preserve intangible cultural heritage is I-BASA, an IoT and Edge cloud-based platform that offers audiences an easier way and deeper engagement with traditional Gamelan music, created by an indigenous Indonesian metal and wood percussion orchestra. I-Basa is designed to provide an interactive and community-based medium for people to explore and compose Gamelan music together [114].

A specific application of IoT is Edge Computing. In literature, different definitions of the concept of Edge Computing have been provided [21]. At the base of each definition there is the same concept, that is, bringing data processing close to the generation source, reducing latency and response time. This is particularly important for applications where the timeliness of the data is critical. Edge Computing finds practical application for example in smart sensors, which are devices that combine sensing with processing capabilities. They can collect data from the environment (such as temperature, pressure or movement) and perform a first local processing that can include filtering, conversions and some basic decisions. Smart sensors often have communication capabilities to send the processed data to other systems or devices.

These sensors can be used to monitor cultural sites, such as museums, buildings, archaeological sites, etc. providing a constant monitoring that allows identifying potential problems and taking preventive action for their conservation. For example, Tse et al. describe CANARIN II, a low-cost platform for monitoring temperature, air pressure, humidity, and other parameters in the Joanina Library of the University of Coimbra [117].

5.2 Blockchain

Blockchain is an implementation of a distributed ledger maintained by many participants, who do not necessarily trust each other, and that uses a distributed consensus algorithm. Updates to the ledger (called transactions) are grouped into blocks, and blocks are added one after the other in chronological order. Since data is only added and never deleted, the chain is continuously growing and constitutes a complete record of all transactions since the first block. Thanks to the use of cryptography, each block depends on the contents of all previous blocks, making it impossible to change the data contained in old blocks without also rewriting the new ones. Executable code, so-called smart contracts, can also be stored within the blockchain. A smart contract is not necessarily tied to a real contract, it is simply code executed by all nodes in the blockchain network, and the result of the calculation is stored after a consensus has been reached. The great advantages of a blockchain as a data store are that it is immutable, distributed, always available, secure and publicly accessible. The main problems with implementing blockchain in distributed ledgers are scalability and efficiency: often, the consensus algorithms used to ensure consistency are expensive in terms of time and resources, but in some cases, the assumptions of trust can be relaxed, so that simpler consensus algorithms can be used.

Although it was initially designed for financial transactions, blockchain technology can be used to record anything of value. In particular, in the context of cultural heritage it can have at least two fields of application: certifying provenance and authenticity, tokenization and profit sharing [118]. As for certifying authenticity, an immutable register can be created with blockchain that includes various characteristics of the registered goods, along with all the activities that are performed on those goods and who is authorized to perform them [3]. This can be particularly useful for safeguarding data regarding minor or less famous goods, especially in cases where there is a risk of them being stolen or destroyed due to natural disasters or conflicts [6]. Consequently, if the legal ownership and movements of an art object are recorded in an immutable and decentralized way, the provenance will also be easier (faster and cheaper) to trace [126] and misappropriation will be countered. Tokenization consists of converting a right on an asset that is owned into a digital token, which can then be exchanged on a blockchain platform. In this way, the asset remains permanently connected to the blockchain, all exchanges are recorded, and this can make the trade of rare and ancient artifacts fair and traceable [128]. Furthermore, the ownership of the digital asset could be shared among multiple users who divide the profits from loans and exchanges, and the creation of donation and fundraising systems for the protection of the physical asset can be facilitated [48].

An innovative use of technology, related to intangible resources, concerns the protection of food culture through the creation of a database of culinary resources and a "museum" of national foods [77].

In an optimistic view, blockchain technology democratizes access to art and stimulates conversations about the role of art in society, favoring innovation and investment, while, in a pessimistic view, it is absorbed by large platforms owned by companies that regulate and effectively recentralize it. At the same time, there remain great uncertainties related to the loss of private keys and the need for the majority of the population to rely on infrastructure and technologies that they do not understand and designed by others, creating great questions related to governance [127].

5.3 Artificial intelligence

Artificial Intelligence (AI) can be defined as the theory and development of computer systems that can perform tasks normally requiring human intelligence, such as visual perception, speech recognition, translation between languages, and decision making. Often, such systems are based on the optimization of mathematical functions.

AI can be used to analyze large amounts of data from sensors, images, and other inputs to identify patterns, anomalies, or trends that can help in the conservation and management of cultural heritage. In particular, AI, together with computer vision and machine learning, has been used to solve problems related to history and interpretation in the field of fine art, for example in the analysis of the composition of landscapes in paintings [74], of brush strokes [76], of canvases [79], of style in general [46], of facial poses in portraits [132, 27]. Scholars and experts have also used image analysis capabilities as tools to resolve controversies that were difficult to resolve using traditional art historian methods, such as the debate over whether or not some painters in the 1400s used optical devices to enhance the realism of their works [34, 113]. Another important field of use concerns the reconstruction of damaged works [47] or parts of them [33, 103] thanks to the analysis of other works by the artist in question. Also very significant is the application to the arduous task of authenticating certain works [45, 107], even if these methods are not always accepted as valid by the expert community, since authentication not only requires information deriving from the image, but also depends on the study of the materials (pigments, canvas, etc.), documents certifying the ownership of the works, knowledge of the iconography. Therefore, there are still many open challenges and great research opportunities in the field of applying AI to the study of figurative arts [112]. Generative AI refers to artificial intelligence systems that can create new content, such as text, images, or music, by learning patterns from existing data, requiring the user to just provide a prompt written in natural language. Image-generating models have rapidly become famous for being used to quickly create sketches, digital art, and even stock photos. AI models for image generation have also been embedded into interactive artifacts, as an experiential way for designers to engage with such models. In particular, in interactive picture frame allows users to manipulate image content through physical controls like knobs and buttons, transforming prompt engineering into a tangible experience[71]. As the models became more and more sophisticated, though, controversies arose about generative AI, mainly around the fact that those algorithms can imitate the styles of works that have been used to train them, and that artists where not asked for permission to use their work. For this reason, some researchers are now working on defense techniques for content owners against unwanted web scrapers: the digital artwork is "poisoned" in a way that is invisible for a viewer but creates an unexpected behavior of the model if included in a training set [110, 111].

The adoption of AI in the cultural heritage sector signifies major advancement but also introduces ethical and practical challenges, including capturing diverse histories accurately and avoiding biases from incomplete datasets. Additionally, the opacity of many advanced AI systems contrasts with the cultural heritage sector's focus on data curation and provenance, driving demand for tailored AI solutions.

5.4 Virtual Reality and Augmented Reality

Virtual reality (VR) involves creating a completely digital environment in which the user can immerse themselves. Using special headsets, sensors that track head and body movements, and motion controllers, the user is isolated from the real world and has the illusion of being in a three-dimensional computer-generated world. With augmented reality (AR), on the other hand, digital elements are superimposed onto the real world. Using devices such as smartphones, tablets, or special glasses, the user can see digital information integrated into the surrounding environment. These technologies can be used to create immersive and interactive experiences for users who want to explore or learn more about cultural heritage, or they can be used for digital preservation and reconstruction of damaged historical sites.

Many papers have described their use in the field of cultural heritage, for example the systematic reviews of the works of the last decade presented in [9], [26] and in [106] that provide an overview of the use of virtual, augmented and mixed reality for the management and conservation of cultural heritage. In particular, in [26] eight important application fields are identified: 3D reconstruction of cultural artefacts, digital heritage, virtual museums, user experience, education, tourism, intangible cultural heritage and gamification. An interesting use case concerns the use of virtual and augmented reality for the visualization and interaction with the reconstruction of underwater archaeological sites [61]. In another study authors analyse opportunities and challenges in the design of exhibition spaces in the Metaverse (i.e. a virtual space that allows users to interact inside a customizable, highly interactive environment) [23].

5.5 Big Data Analytics

The concept of Big Data was first coined in the fields of astronomy and genomics in the 2000s, to indicate the explosion of data that those sectors were experiencing. Then it slowly spread to other sectors so much so that it became a term of common use. There is no univocal definition of Big Data. Initially the term was coined to indicate a very large quantity of data, both structured and unstructured, that could not be contained in the memory of a computer [86]. Today the technology for managing Big Data has evolved so much that systems such as Map Reduce [28] can manage them quickly and scalably. Even the consultation of these large quantities of data is possible thanks to search engines such as Presto [81]. Analyzing Big Data (or Big Data Analytics in English) means examining large volumes of data to extract patterns, correlations, trends, user preferences and other useful information [53].

The field of Cultural Heritage has also experienced the advent of Big Data [125]. In recent years, a large amount of cultural data has been digitized and transcribed. These cultural data include on the one hand catalogs of digital objects, such as digital archives, and on the other texts, such as the contents of books and articles, and images, such as digitizations of documents or photos of monuments. The availability of cultural data is so huge that even in the field of cultural heritage we can talk about Big Data. For example, Europeana, the largest aggregator of digital objects at European level, contains more than 31 million images and 24 million texts [49] and the number of digital objects is constantly increasing. Compared to other research fields, in Cultural Heritage, therefore, we talk about two types of cultural data: the digital object (texts, images, etc.), which is usually unstructured, and the metadata associated with it, which are usually structured [129]. However, simple data storage is not enough to talk about Big Data Analytics. Data must be analyzed to extract knowledge. Compared to other research areas, in the Cultural Heritage sector, Big Data analysis is particularly crucial because it allows to extract opinions, perceptions and interpretations of the past and present [125]. Analyzing Big Data in the cultural sector therefore means extracting knowledge derived from human history. The results of this analysis can be exploited in different areas, such as education and entertainment [124]. In the education sector, the results of Big Data analysis can be used to stimulate student interest and promote learning performance [120]. In the entertainment sector, they can be used for the development of computer games, to promote the preservation of cultural heritage [42]. In tourism sector, Big Data does not only concern cultural data but also tourist data, such as tourist flows to a given destination or tourist preferences for the construction of tourist destination recommendation systems [64].

5.6 Semantic Web

The term Semantic Web was first used by Tim Berners Lee in 2001 in an article published in Scientific American to underline the transition from the classic document-based Web to a new form of Web based on data and their relationships [11]. According to Berners Lee, the Semantic Web should have facilitated the interconnection between the various entities and ensure faster research of topics of interest. Through the use of markup languages such as RDF (Resource Description Framework) [8], OWL (Web Ontology Language) [87] and SPARQL (SPARQL Protocol and RDF Query Language) [44], the Semantic Web allows the creation of a network of interconnected data (via a graph structure) that can be queried and analyzed semantically. As a result of this graph organization, data is published in the form of Linked Data [12], easily navigable through SPARQL queries. Connected to the concept of Semantic Web is that of ontology. An ontology is a formal and structured representation of a set of concepts within a domain and the relationships between them [60].

Many criticisms have been leveled at the concept of Semantic Web, mainly based on its difficulty in implementation due to scalability issues, reliability of sources, and high implementation costs [62]. However, in the field of Cultural Heritage, the Semantic Web has been and is continuously applied in the organization of data. In fact, given their nature often organized in the form of catalogs, cultural data are easily describable through ontologies and Linked Data. Numerous more or less standardized ontologies have been developed in the field of Cultural Heritage such as CIDOC CRM (Conceptual Reference Model) [40], EDM (Europeana Data Model) [41], SKOS (Simple Knowledge Organization System) [89] and FRBRoo (Functional Requirements for Bibliographic Records - Object-Oriented) [95]. Furthermore, many digital archives are available in the form of Linked Data, navigable via SPARQL queries [37]. The data organized as Linked Data can then be used to build applications, such as LOD4Culture, which provides a map for the navigation of cultural resources [122].

5.7 Satellite images

Satellite images can be acquired in different bands of the electromagnetic spectrum, such as visible, infrared and radar, allowing to obtain detailed information on various aspects of the Earth's surface. Optical images capture visible light, similar to traditional photography; Infrared and thermal images detect the temperature of the Earth's surface; SAR (Synthetic Aperture Radar) technology uses radar waves to create high-resolution images of the Earth's surface; Multispectral and hyperspectral images capture data in different bands of the electromagnetic spectrum providing data on the composition of the soil or the physical and chemical composition of the objects observed.

These images can be used for a wide range of cultural heritage applications. They are crucial for assessing potential damage to sites caused by natural disasters, conflicts or human activities. For example, UNESCO and UNITAR (United Nations Institute for Training and Research) have used satellite imagery to assess damage in conflict zones such as Iraq and Syria [36], and after natural disasters such as the 2015 Nepal earthquake[11]. SAR images from COSMO-SkyMed (the

[11] urlhttps://www.unesco.org/en/articles/satellite-imagery-helping-monitor-cultural-heritage-sites-under-threat

Italian Space Agency's satellite constellation) are used to monitor the structural integrity and ground deformation of monuments and historical sites, including the Colosseum archaeological park. This helps in planning conservation efforts and preventing further damage [123]. By combining images from the European Space Agency's Copernicus Sentinel satellites with machine learning algorithms, previously unknown cultural heritage sites can be discovered [115]. Examples include the Cultural Landscapes Scanner[12] [108] and OPTIMAL[13] projects. This approach is particularly useful in remote or inaccessible areas such as the Cholistan Desert in Pakistan, opening up new opportunities for archaeological research [94]. Satellite imagery can also be used to detect, quantify the extent and monitor illegal activities such as looting or unauthorised excavation at archaeological sites. An example is the work to document the looting damage reported due to war at 1200 archaeological sites in Syria [22]. Finally, satellite data can help assess the impact of environmental changes, such as urban development or climate change, on cultural heritage sites.

5.8 3D Modeling

3D modeling is the process of creating a three-dimensional representation of an object or surface in a virtual space using specialized software. Building Information Modeling (BIM) is a process for generating and managing digital representations of the physical and functional characteristics of buildings. A variant applied to historic buildings and cultural heritage is HBIM (Historic Building Information Modeling). This process involves the creation of detailed three-dimensional models that faithfully represent the architectural, structural and historical characteristics of existing buildings, integrating geometric data with information on materials, colors and construction techniques. Data from terrestrial laser scanning, drone photogrammetry and portable laser scanning are combined to obtain detailed 3D models along with historical information, text, images, videos and URLs. The goal of this procedure is to create a model that documents the entire history of a building, from construction to modifications and maintenance. This approach takes full advantage of the fourth dimension of BIM, namely time, to trace the evolution of the building over the years and facilitate its conservation, management and documentation.

In [83], authors review the application of BIM to cultural heritage, establishing that current research areas can be grouped in Geometric Data Collection and Modeling, BIM for Information Management and Augmented reality and Virtual reality. They also point out that there is minimal evaluation of real case studies, as well as that current limitations in HBIM implementation stem from the absence of a standardized methodology.

5.9 Digital Storytelling

Digital storytelling for cultural heritage is the use of digital tools to tell stories related to cultural heritage. It combines multimedia technologies with historical, artistic, and cultural content to create immersive narrative experiences and requires collaboration between experts from different domains [67]. Digital storytelling for cultural heritage aims to enhance it, facilitate understanding, and promote interest in the past and traditions, making cultural experiences more interactive and accessible to a wide range of audiences. Examples are immersive exhibitions and documentary films, that use technologies such as virtual reality, augmented reality, video projections and sound to create a multisensory experience that engages the visitor, allowing viewers to "immerse" themselves in the historical or artistic context, creating a deeper connection with the content. Examples of immersive exhibitions are Inside Van Gogh [25] and Inside Klimt [24], both held at the Cattedrale

[12] https://activities.esa.int/4000132058

[13] https://www.journalchc.com/2022/08/29/contrasto-agli-scavi-clandestini-il-progetto-optimal/

dell'Immagine in Florence. Docufilms are documentaries narrated through a creative and cinematic approach. They use a combination of interviews, reconstructions, archival images, and narration to tell real stories. Examples are documentaries about Bosch [100] or an animated film about the life of Van Gogh [101]. A variant of docufilms are interactive documentaries, which allow the user to interact with the story and decide what to explore further [98]. Some studies, however, criticize interactive documentaries, as they risk losing the thread of the story and therefore its persuasive power [54]. Another relevant example is provided by the study by Elisa Bonacini, who explores how to exploit digital storytelling to involve local communities in the preservation and enhancement of cultural heritage [14]. Specifically, the project described in the article encourages communities to actively participate in the narration and documentation of their local traditions and stories.

5.10 Optical Character Recognition

Optical character recognition (OCR) technology converts text from an image, such as a scan or photograph, into an editable, searchable digital format. This process is essential for turning physical documents, such as books, newspapers, or contracts, into easily manageable digital files. OCR works by analyzing the image pixel by pixel, recognizing characters based on their shape, and comparing them to predefined templates. Newer systems use advanced artificial intelligence and machine learning algorithms to improve accuracy, especially with complex or poor-quality text. The process begins with the acquisition of an image of the document, which is then enhanced through pre-processing techniques to optimize readability. Once the characters have been identified, OCR uses dictionaries and linguistic rules to better interpret the text and correct any errors. This technology has applications in many areas, such as digitizing documents for archiving, creating accessible content for people with visual impairments, and managing data in computer systems.

Handwritten text recognition, known as HTR (Handwritten Text Recognition), is an evolution of OCR (Optical Character Recognition) technology. While OCR was designed to recognize and digitize printed text, HTR addresses the much more complex challenge of interpreting handwriting, which varies significantly in style, slant, and readability. This advancement has been made possible by recent developments in artificial intelligence, particularly the use of advanced neural networks and machine learning models. HTR stands out for its ability to decode handwritten texts even in complex situations, such as historical documents or non-standard handwriting. Unlike OCR, which relies primarily on the recognition of predefined shapes, HTR integrates a contextual analysis, using dictionaries and linguistic models to interpret the meaning of the text and resolve ambiguities. This approach allows for the accurate transcription of documents that in the past would have required long and laborious manual transcriptions. This technology is particularly useful in the digitization of historical archives, diaries and manuscripts, but also finds applications in modern areas, such as the interpretation of handwritten notes or manually filled out forms. Although HTR still faces significant challenges, such as the variability of human handwriting and the quality of original documents, its continued development promises to further expand the possibilities offered by digitization, making an ever greater part of our written heritage accessible and searchable.

6 Cross-cutting Aspects

In addition to specific application areas, cultural heritage management also requires special attention to cross-cutting aspects that cut across all areas of intervention. These include issues such as accessibility, management and security of digital data. In the following paragraphs we will present these aspects referring to the CH.

6.1 Accessibility and inclusion

Cultural Heritage belongs to all peoples, and its conservation is aimed at cultural growth and human promotion, therefore it must be available to all citizens [10]. As described above, IT technologies are increasingly pervasive and can bring benefits in many areas, including the protection, conservation and enhancement of cultural heritage, enabling new intelligent services that, for fairness and inclusion, must be easy to use for everyone, including people with disabilities. Information technologies can therefore be exploited to provide people with disabilities with alternative, complementary or augmented ways to perceive, understand or interact with cultural heritage assets through accessible solutions such as audio descriptions, subtitling, conceptual maps or 3D representations. Designing and creating a museum accessible to all is a much investigated area of research and development; to confirm this, since 2008 a specific international conference has been organised, the International Conference on the Inclusive Museum which took place in Zaragoza in 2025[14].

To provide an enjoyable entertainment and learning experience for all visitors, including people with disabilities, the virtual museum must not only be accessible, but also inclusive: it must offer greater equality and learning opportunities for all social groups. To achieve the goal of creating accessible immersive solutions and environments, it is necessary to think in an accessible and universal way from the early design stages (Universal Design). The approach must be user-centric, involving people in the co-design of the virtual cultural experience [17].

Museums have often been involved in accessibility assessments (e.g. in [80]) and in the development of technological solutions offered to improve the inclusion and accessibility of exhibits (e.g. [121], [16], [18], [39]). Visual arts, by their very nature, are generally inaccessible to people with visual impairments. One of the most widespread solutions to allow blind visitors to enjoy the works is to make available an audio guide, a program that provides a description of the main works of art in the collection in audio format. However, the audio guide generally only describes what is seen, making it difficult for people with visual impairments to create an accurate mental reproduction of the images of the artefacts. A project that has attempted to address this gap with a solution for 2D artworks is Eyes-Free Art which explores the use of proxemic audio to create an interactive audio experience to go along with the verbal description. The proxemic audio interface allows the user to move closer and further away from a painting to experience background music, sound effects and a detailed verbal description to help them better understand the content and structure of the artwork [121]. In the work of Li et al. from 2023 [75] instead, the potential of data sonification for improving the accessibility of oceanographic data in museums for blind and visually impaired students was explored. The results showed that the developed audio visualization prototypes support the effective transmission of oceanographic concepts and data.

Many studies aimed at improving the fruition and accessibility of museum works for users with visual impairments use multimodal approaches. A 2020 review article identified the most frequent areas of intervention: Atypical devices for exploring virtual copies, Digitally augmented touch replicas, Interactive tactile surveys based on gestures, Assisted navigation for self-guided tours, and hybrid solutions, such as mobile apps with multi-touch pads to interact with the audio interface via gestures [102]. A very ambitious project in this field funded by the European community is ARCHES ("Accessible Resources for Cultural Heritage EcoSystems") which has developed cutting-edge technological solutions, such as 3D tactile reliefs, accessible apps and games for smartphones and tablets, together with avatars that use sign language, to help European museums become barrier-free. The technologies have been co-designed and tested by more than 200 disabled people in Spain, Austria and the United Kingdom[15]. Virtual reality has also been used to increase the enjoyment and ac-

[14] `https://onmuseums.com/2025-conference`
[15] `https://www.arches-project.eu/`

cessibility of museum works. For example, the University of Salerno has designed a virtual museum of archaeological finds from three local museums. This virtual museum uses virtual reality to allow everyone to access and explore the different rooms of the museum [18].

Another way to make museum artifacts more accessible is to use sensors or radio frequency identification (RFID) technologies. RFID technology enables the automatic identification of objects and has been successfully applied in museums to improve the visitor experience. For example, Museum4All is a project that aimed to organize the description of the contents of the artifacts present in a museum with accessible information provided according to the user's capabilities, in order to offer a level of knowledge suitable for each person [16]. An RFID tag is applied to each artifact to allow the description of its characteristics and historical details in a personalized way: when the user is in proximity to the artifact, the content is provided through a mobile application via one or more channels (visual, auditory, tactile, etc.).

Recently, Artificial Intelligence has also been used to improve the accessibility of cultural heritage. A 2021 review examines the literature on technology used to create and deliver accessible experiences in museums and cultural heritage sites, presenting a conceptual framework that incorporates key elements (and interrelationships between them) of online experiences in museums and cultural heritage and leverages artificial intelligence (AI) to enhance and expand online and in situ accessibility [96].

Many studies present guidelines to improve the accessibility and inclusiveness of museums, for example [39], [99], [30]. General suggestions refer to exploit multicanality, customization and adaptation, and provide tactile replicas (or alternative ways of perceiving and enjoying) of the artefacts to compensate for sensory deficits.

Public bodies have also dealt with the drafting of guidelines for museum accessibility. For example, the General Directorate of Museums of the Italian Ministry of Culture in 2018 published the Guidelines for the drafting of the Plan for the elimination of architectural barriers (P.E.B.A) in monumental complexes, archaeological areas and parks. Indications are provided for overcoming architectural, cultural, cognitive and psychosensorial barriers in places of culture under the jurisdiction of the Ministry.

The cultural heritage field does not only include museums. A 2021 review [97] examined the literature on technology used to create and provide accessible experiences in cultural heritage sites, especially by exploiting recent and future developments in artificial intelligence to improve and extend online and in situ accessibility. A 2020 work explored the potential impact of social computing systems to improve people's access to cultural heritage, focusing in particular on deaf and physically impaired users [69]. The cultural heritage taken into consideration also ranges among less traditional ones. For example, in [59] an approach is presented to rediscover three-dimensional botanical models as accessible teaching aids using 3D printing, multimedia content, sensors and microcontrollers. Finally, it is worth to mention an article related to the preservation of intangible cultural heritage: a 2020 paper investigated whether 360° videos presented through virtual reality can foster user immersion for the preservation of intangible cultural heritage, specifically the traditional diving from the Stari Most bridge, an old bridge in Mostar, Bosnia [109].

6.2 Digital data management

The digitization of cultural heritage is the process of converting physical objects, such as works of art, historical documents and monuments, into digital formats, and involves various information technologies related to the processing of digital data. It begins with the creation of a digital copy through the use of 2D and 3D scanners, which allow you to capture details of works of art or create three-dimensional models of monuments. High-resolution digital photography is used to acquire detailed images of documents and paintings, while multispectral imaging technologies allow you to obtain information that is not visible to the naked eye, such as details hidden under the surface of a work.

Once the data has been acquired, processing technologies come into play, such as 3D rendering and modeling software, which allow you to virtually reconstruct monuments and archaeological sites. Image processing is also crucial to improve visual quality and correct any defects. This digitized data is then stored and managed through databases and digital archives, which allow the data to be organized and made accessible efficiently. cloud storage solutions are often used to store large amounts of data, ensuring remote access and security. In some cases, blockchain is used to authenticate and trace the origin of digital data, ensuring their integrity.

Data processing involves the use of advanced algorithms, such as machine learning and artificial intelligence, which allow for the automatic analysis of large amounts of cultural data. These tools are capable, for example, of recognizing patterns or styles in works of art, or of reconstructing damaged historical texts. Data mining and semantic analysis techniques allow for the extraction of significant information from the data, facilitating the understanding of large historical or archaeological collections.

Digitized data must then be made accessible. Websites and digital platforms such as Google Arts & Culture, allow the public to explore digitized cultural heritage, while APIs allow developers and researchers to access this data to integrate it into other applications. Mobile apps and augmented reality allow for the interactive visualization of digital content, enriching the visitor experience even in physical sites.

The digitalization of cultural heritage is often used also to improve its management, for example recently a framework based on ontology has been proposed to support the conservation and restoration of cultural heritage both in the information organization phase and in the determination of requirements and criteria for the intervention in order to provide a decision support tool to identify more suitable intervention options with greater chances of success [90].

6.3 Digital data security

The main objective of digital data security related to cultural heritage is the protection and preservation of digital information related to cultural heritage. It is essential to maintain the integrity of the data, protecting it from external threats, such as malware, hacking or ransomware cyber attacks, thus ensuring that it is not altered or damaged over time: this allows the authenticity and historical accuracy of cultural resources to be preserved, avoiding unauthorized or accidental modifications.

Another crucial aspect is confidentiality, with access limited to authorized users only, so as to prevent theft, manipulation or abuse of information. Some data, in fact, could contain sensitive details that, if disclosed, would compromise the security of the heritage.

At the same time, it is essential to guarantee the availability and continuity of digital data to make it accessible and usable when necessary, reducing the risk of permanent losses due to technical failures, human errors or catastrophic events. From this perspective, maintaining backups and rapid recovery systems becomes essential.

Data security also deals with ensuring the authenticity and traceability of information, so as to confirm its origin and make any interventions or modifications transparent. This is particularly important to maintain the historical credibility of digital content.

Furthermore, the protection and long-term preservation of digital data related to cultural heritage is essential to ensure their accessibility also in the future. Digital preservation techniques, through periodic migration to new formats and media, ensure that cultural information remains usable despite technological evolution. In other words, this approach allows to overcome technological obsolescence, preserving cultural heritage for future generations.

Finally, with the development of digital technologies, an important issue is that of protecting information from unauthorized distribution. Research in this area exploits the management via blockchain, already presented above, or investigates effective methods to embed marks, serial numbers, etc. in the original data to prove its origin. Among these, the use of digital watermarks that can be visible or preferably invisible but permanently embedded in the digital data. A 2010 paper presented two methods for digital watermarking: in the first one, the watermark is embedded directly into the original image. The main advantage is that no precondition transformations are needed. The method is robust to filtering, JPEG compression and geometric transformations. The second one involves encoding the text via line offsets: the text lines are moved vertically so that the document can be uniquely encoded [13].

7 Examples of Major Projects for Cultural Heritage

Over the years, several initiatives for the digitalization of Cultural Heritage have been carried out. Europeana [49], the Library of Congress [78], Canadiana [20] and CulturaItalia [35] are just some of the most representative examples. All these projects are large catalogs that aggregate resources from different sources. They manage not only the digitized data, but also their metadata and allow their research, use, and in some cases even their valorization. For example, in Europeana it is possible to access curated collections that organize the resources under a single theme. These collections can then be used for scientific research, in the educational field or as simple use by the generic user.

In the field of the valorization of Cultural Heritage, there are many projects that allow access to the various resources through virtual tours. Most of the projects concern major museums, which allow you to navigate the various galleries and rooms through virtual visits. The National Gallery in London [56], the Louvre in Paris [82], the Vatican Museums [91], the Rijksmuseum in Amsterdam [105] are just a few examples of museums that offer virtual visits. There are also outdoor projects that allow you to navigate their sites, such as the Acropolis in Athens [2] and large natural parks, such as Yosemite [130] in Nevada. A broader initiative is Google Earth [58], which allows you to navigate many locations around the world, as well as offering educational and didactic itineraries. Among the various features offered by the virtual visit is the possibility of accessing audio guides, walking through the rooms of the museum or the areas of the site, selecting from various guided itineraries, and reading or listening to the card associated with a cultural resource.

In the following, we present a list of projects that have been milestones in the use of information technologies for the protection and enhancement of Cultural Heritage.

- **Google Arts & Culture**
  Created in **2011** and continuously evolving, it is one of Google's initiatives for the digital valorization of cultural heritage.

- **Europeana**
  Launched in **2008**, it is a European project for the digitisation and accessibility of the continent's cultural heritage.

- **CyArk**
  Founded in **2003**, it is one of the first projects to use 3D scanning for the digital preservation of historical sites.

- **ReACH (Reproducing Art and Cultural Heritage)**
  Launched in **2017**, it focuses on the use of 3D printing for the reproduction of works and

monuments.

- **TIME MACHINE (EU)**
  Started in **2019**, it is a long-term European project to create historical simulations in 4D.

- **Smithsonian 3D Digitization**
  Officially launched in **2013**, this program of the Smithsonian Institution is dedicated to the 3D digitization of cultural and scientific heritage.

- **The Met Unframed**
  Introduced in **2021**, during the COVID-19 pandemic, to deliver immersive experiences remotely.

- **CHESS (Cultural Heritage Experiences through Socio-personal interactions and Storytelling)**
  Created between **2011 and 2014**, it is a European project that combines artificial intelligence and interactive storytelling.

- **Scan the World**
  Founded in **2014**, it is a global platform for 3D scanning of artworks and sculptures.

- **Heritage Building Information Modelling (HBIM)**
  Conceptualized in the early **2000s** and actively developed since **2010**, it is a digital method for managing architectural heritage.

- **MUSING (Museum User Scenarios Innovation and Gamification)**
  Developed between **2015 and 2018**, it introduced elements of gamification into museums.

- **iHERITAGE (ICT Mediterranean Platform for UNESCO Cultural Heritage)**
  Launched in **2020**, it focuses on the use of immersive technologies for the cultural heritage of the Mediterranean.

- **The Perseus Digital Library**
  Born in **1987**, it is one of the first academic projects of digitization and analysis of classical texts, in continuous expansion.

- **Digital Atlas of the Roman Empire**
  Created in the 2010s, it integrates interactive maps based on archaeological and historical data.

- **MonArch (Monitoring Heritage Buildings with IoT)**
  Designed from **2017** onwards, it uses IoT sensors to monitor the status of cultural assets in real time.

In the following, we report few representative projects. It is worth noting that some cultural sites appear to be real open-air laboratories, as numerous projects are concentrated there, probably due to the high mass-media interest that invests them and makes easier funding from sponsors, contrary to what happens for the majority of sites for which public resources are often insufficient. Examples of laboratories are the archaeological excavations of Pompeii, the Buddhas of Bamiyan and the arch of Palmyra.

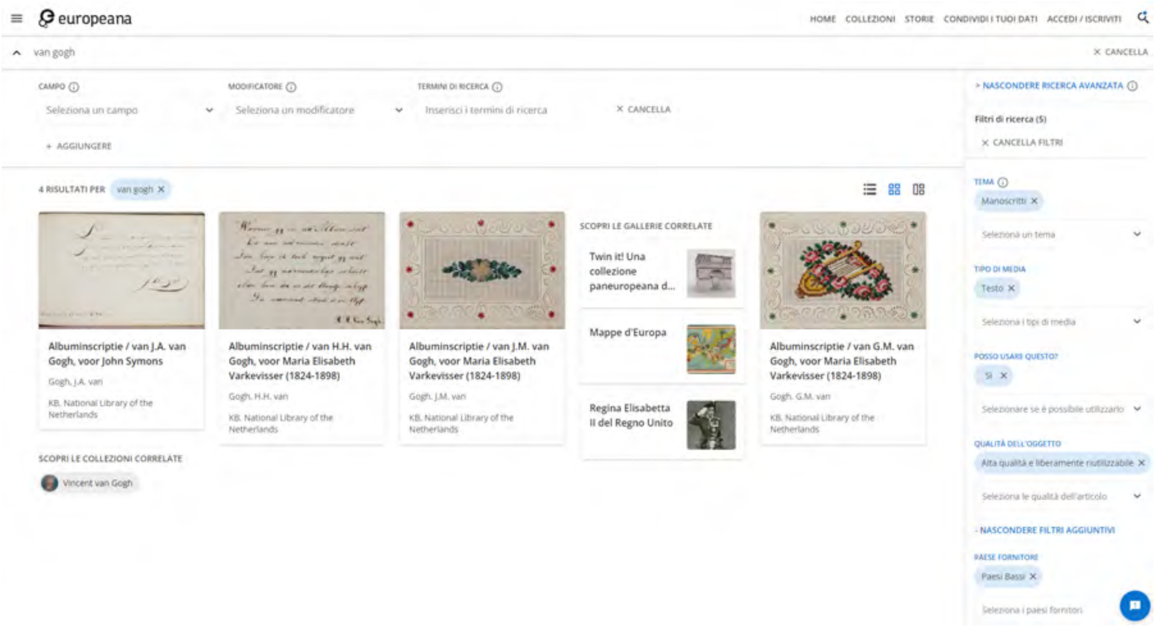

Figure 5: An example of filtered results in Europeana

7.1 Europeana

Europeana is a digital platform that brings together and makes accessible millions of cultural resources from across Europe [49]. Founded in 2008, Europeana works with over 3,000 cultural institutions, including museums, libraries and archives, to digitise and share Europe's cultural heritage. The platform provides access to a wide range of content, including images, text, video and audio, fostering research, education and innovation. Europeana also supports digitisation projects and provides tools and guidelines for cultural data management, helping to preserve and valorise cultural heritage in a digital context.

Europeana offers several navigation modes to facilitate access to its vast digital archives. Users can explore content through keyword searches, advanced filters, and thematic categories. Europeana allows you to filter search results by the following modes: theme, media type, license, provider country, language, aggregator, content provider, color, image orientation, image size, and file format. Figure 5 shows an example of keyword search results filtered by some criteria in Europeana. The example is based on a search for the keyword *Van Gogh* (top left in the figure) and applies several filters (on the right). By selecting a specific object, you can view its card, with a preview of the digital object (Figure 6) and its metadata, any related collections and objects, and the possibility to download it, if available (Figure 7).

Europeana also offers the possibility to browse content by theme. Currently, the supported themes are Archaeology, Art, Photography, Newspapers, Manuscripts, Maps and Geography, Migrations, Fashion, Music, Industrial Heritage, World War I, Sports, and Natural History. For example, selecting the Migrations theme takes you to a dedicated page [51], which not only shows the theme definition, but also offers various content, including famous migrants, associated virtual galleries, stories, and various migration elements, as shown in Figure 8.

Europeana offers a wide range of stories and galleries that allow users to explore Europe's cultural

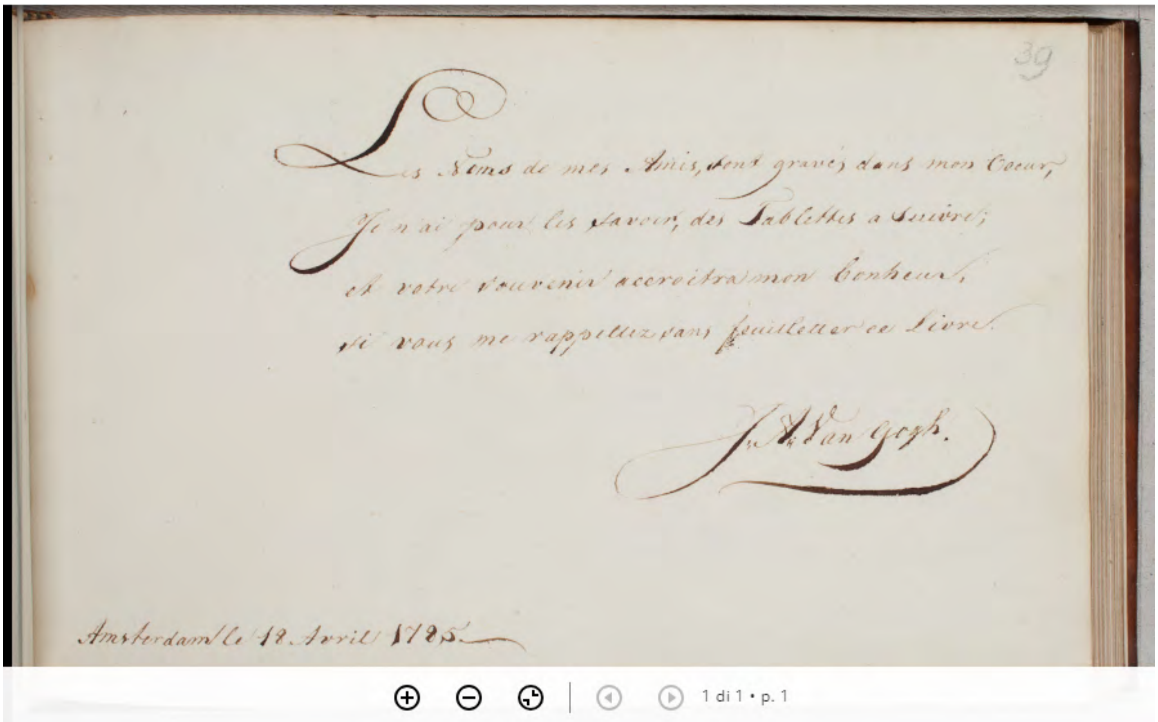

Figure 6: An example of a digital object preview in Europeana

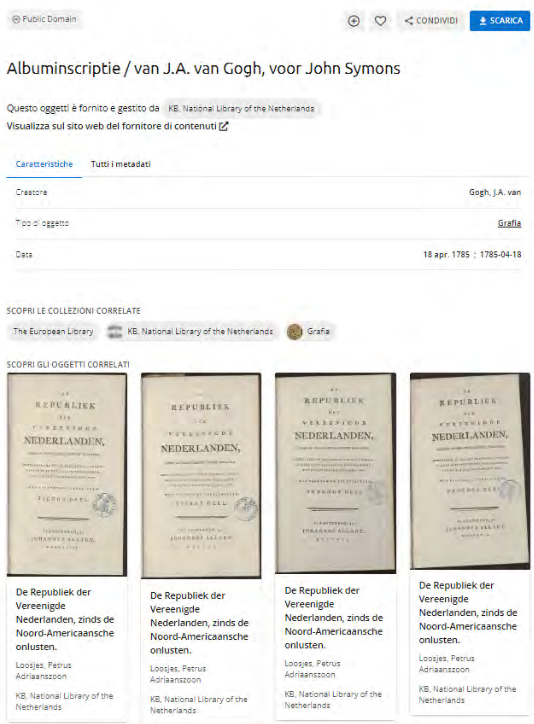

Figure 7: An example of a card associated with a digital object in Europeana

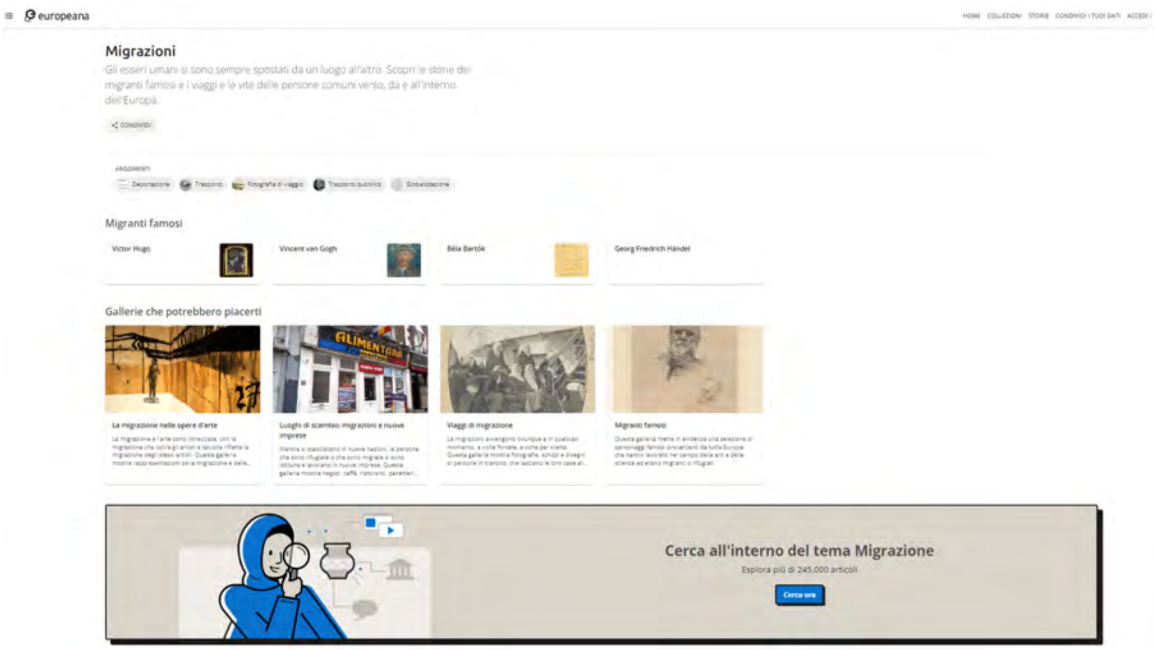

Figure 8: The Migration page on Europeana (updated 4 June 2025)

heritage in an engaging and interactive way. Stories on Europeana tell the story of inspiring people, extraordinary places, and revolutionary ideas through the cultural heritage [52]. These stories cover a wide range of themes, such as European migration, the history of democracy, and the lives of famous artists and writers. The stories are enriched with images, videos and historical documents, offering an immersive and educational experience.

Europeana Galleries present curated collections of images, artefacts and documents on specific themes [50]. For example, there are galleries dedicated to historical figures such as Julius Caesar, artistic movements such as Impressionism, and iconic objects such as the teddy bear. Galleries allow users to explore cultural heritage in a visual and thematic way, making it easier to discover new content.

7.2 National Gallery

The National Gallery in London is an art museum located in Trafalgar Square. It houses a large collection of European paintings from the 13th to the 19th century, with works by artists such as Van Gogh, Botticelli, and Turner. The National Gallery website offers the possibility of taking a virtual tour from the comfort of your own home. The tour can be accessed via desktop, phone, or VR headset, offering an immersive and detailed experience. The virtual tour of the National Gallery in London offers several features. First of all, the virtual tour offers thematic paths that guide the user through specific collections or artistic movements, as shown in Figure 9. Once you have chosen your thematic itinerary, you can directly access a 3D reconstruction of the rooms, as shown in Figure 10.

For almost all the objects in the room, there is a card with informative details, both in text and audio form (Figure 11). It is also possible to zoom in on the images.

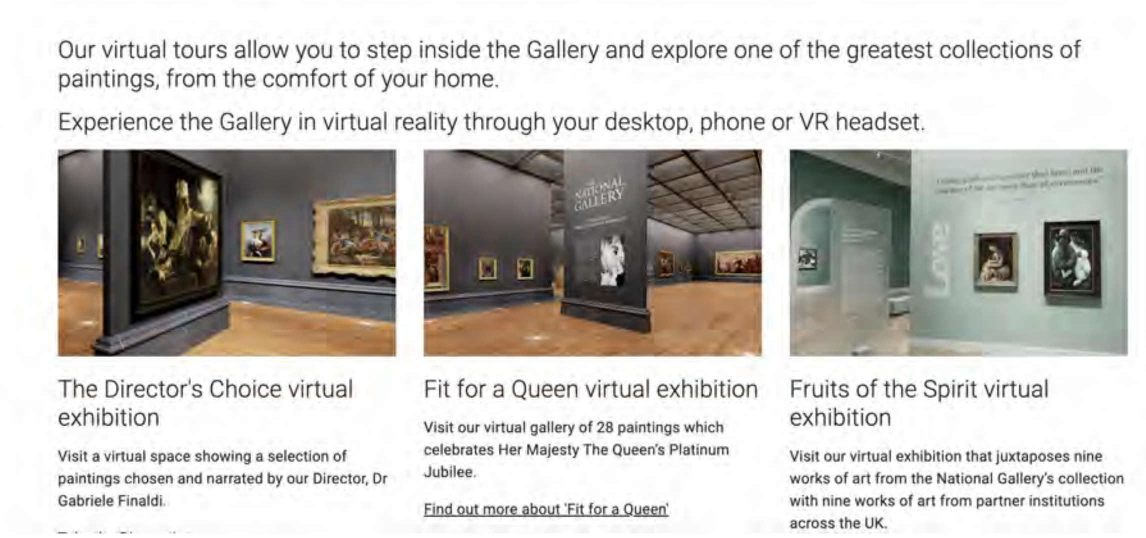

Figure 9: Page to choose a thematic route from those offered by the virtual tour of the National Gallery (updated 4 June 2025)

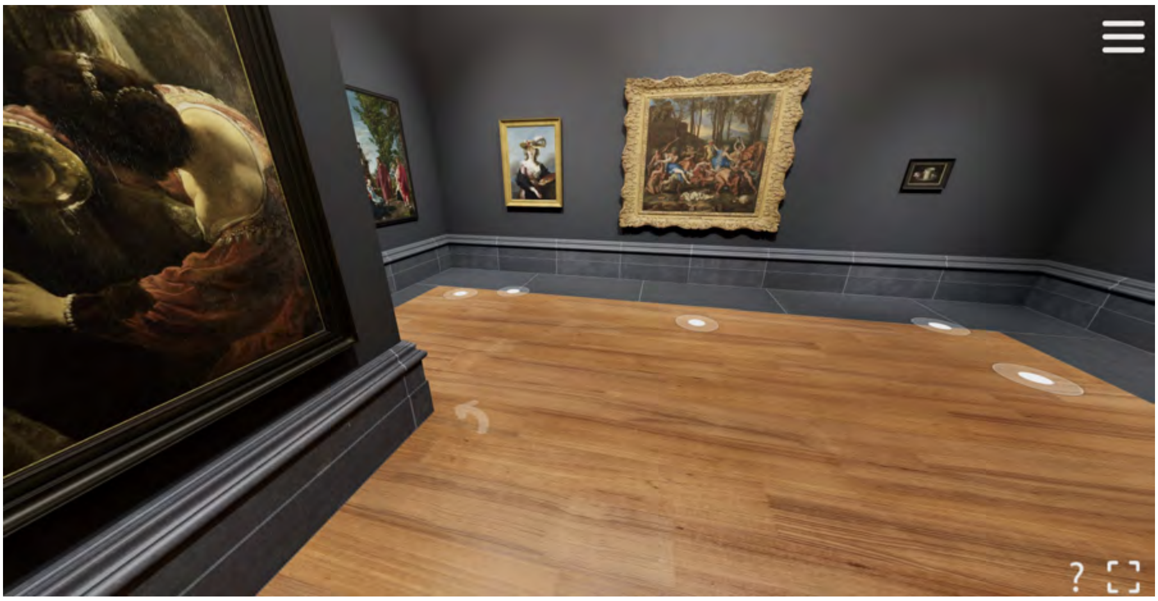

Figure 10: 3D reconstruction of a room from the National Gallery virtual tour (updated 29 August 2024)

Figure 11: 3D reconstruction of a room from the National Gallery virtual tour (updated 29 August 2024)

8 Discussion and Conclusions

Today, the integration of information technologies in the cultural heritage sector represents a radical change, which profoundly transforms the way we preserve, study and make our heritage accessible. The digitalization of cultural heritage has undergone a great acceleration, allowing not only to preserve, but also to replicate works and monuments with unprecedented fidelity. Thanks to 3D technologies and advanced printing, it is now possible to create highly detailed copies, usable for both restoration and exhibition. The management of large quantities of digital data, made increasingly efficient by the cloud and Edge Computing, facilitates archiving and continuous monitoring, allowing targeted and timely interventions. Artificial intelligence, together with machine learning, plays a key role in the analysis of complex data and in supporting conservation. These technologies, in fact, allow us to identify patterns and anomalies in artifacts, and are already used to solve challenges related to the history and authenticity of works. The possibilities are wide and include the prediction of deterioration risks and the authentication of works, making it easier to preserve what could otherwise be lost. Virtual and augmented reality are also changing the way we enjoy cultural heritage. Through immersive experiences, visitors can explore digital environments that enrich their understanding of places and works. As these technologies progress, scenarios of multi-user visits in digital environments will open up, simulating group interaction and offering experiences that bring together an increasingly large and diverse audience. We cannot, moreover, overlook the potential of blockchain in the management of cultural heritage, useful for safely and transparently recording the provenance and authenticity of works. Blockchain could revolutionize the art market, facilitating the traceability of transactions and reducing the risk of forgeries. This technology has also opened the way to new forms of digital collecting and shared ownership through the tokenization of works. Monitoring cultural heritage through the Internet of Things (IoT) and Big Data analytics allows real-time data collection on the state of conservation of cultural heritage, increasing the reactivity of sensor networks and allowing immediate and targeted interventions. This integration of technologies, therefore, represents a significant transformation, which offers endless possibilities to enhance and protect cultural heritage in the long term.

Alongside these prospects, however, significant ethical issues emerge. The digitization of cultural heritage raises questions about intellectual property and copyright: a digital copy can in fact be replicated infinitely, and it becomes crucial to maintain control over reproduction rights to protect artists and cultural institutions. Added to this are issues of privacy and security, as IoT technologies in cultural sites collect data on visitors and staff, creating a potential breach of confidentiality.

Furthermore, while advanced technologies promise to make cultural heritage more accessible, they risk widening the digital divide, as some cultural content may become accessible only to those with the necessary technological resources. There is therefore an urgent need to ensure equitable and inclusive access for all segments of the population.

Finally, the environmental impact related to the energy consumption of these technologies is not negligible: managing large amounts of data requires considerable resources, and it will be important to develop more sustainable solutions. The growing dependence on digital infrastructures also poses governance issues. There is a risk that digitized cultural heritage will be regulated by private entities that could limit access, control and transparency, raising concerns about possible commercial exploitation.

Information technologies therefore offer exciting prospects for the preservation and valorization of cultural heritage. However, their adoption requires a careful balance between benefits and ethical implications, so that cultural heritage remains inclusive, respectful and sustainable for future generations.

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