USING DIGITAL TWIN MODELS (DTM) FOR MANAGING, PROTECTING AND RESTORING HISTORICAL BUILDINGS

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1. Introduction

In Italy, historical buildings are particularly vulnerable to extreme events, such as earthquakes, floods, and landslides often connected with extreme climatic events, without mentioning all the risks connected with vandalism, wars, and acts of terrorism [1-3]. Fragility is due in part to the age of most of these buildings, as well as to their construction materials and techniques [4]. Most of the historical buildings in Italy were built using unreinforced masonry, which can be prone to collapse or severe damage in the event of an earthquake [5-7]. In addition, some buildings may have been constructed on unstable ground or in flood-prone areas such as the case of the Leaning Tower of Pisa, which further increases their vulnerability to natural disasters.

Such vulnerability requires the use of all the most advanced technologies, both for monitoring and management, and the most promising one is currently the use of Digital Twin Models (DTM). Digital Twins are defined as virtual replicas of physical objects, systems, or processes that are used to simulate, monitor, and optimise their real-world counterparts [8]. They have become increasingly important in various industries, including the built environment, because of the numerous benefits they offer [9]. In general, Digital Twins allow for better understanding and management of complex systems, as they provide real-time data and insights that can help identify and address issues before they become significant problems. This can result in improved efficiency, reduced downtime, and cost savings. Additionally, Digital Twins can facilitate collaboration among different stakeholders and enable more informed decision-making.

In the context of the built environment, Digital Twins can have a significant impact on the design, construction, operation, and maintenance of buildings and infrastructure. By creating a Digital Twin of a building or infrastructure project, architects, engineers, and contractors can visualise and test different design options, evaluate energy and resource usage, and identify potential safety hazards before construction begins [10–12]. DTMs can also be used to facilitate the restitution of a historical building after

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an extreme event. By providing a detailed virtual representation of the building, experts can better plan and provide for the restoration process, ensuring that the building is restored to its original conditions as quickly and effectively as possible. Overall, using DTMs for managing historical buildings offers a range of benefits, from improved maintenance and preservation strategies to more effective emergency response and restoration efforts. As such, it is likely to become an increasingly important tool for the preservation of the vast cultural heritage of Italy in the years to come [13–15][1].

1.1. A fragile heritage to be preserved: the Italian case study

To address the challenges of vulnerability of built heritage, experts in Italy are increasingly turning to DTM to better understand the potential risks historical buildings face and so develop more effective strategies for their preservation and restoration. By creating virtual replicas of these buildings, experts can simulate the effects of extreme events and test different restoration and preservation scenarios, helping to ensure that these important cultural assets are protected for future generations. Overall, the fragility of historical buildings in Italy underscores the importance of taking a proactive and collaborative approach to their preservation and restoration. By leveraging the latest technology and expertise, it is possible to protect these buildings from the risks posed by extreme events and ensure that they continue to inspire and educate for years to come. The fragility of these buildings has been highlighted by several recent events in Italy (Figure 1).

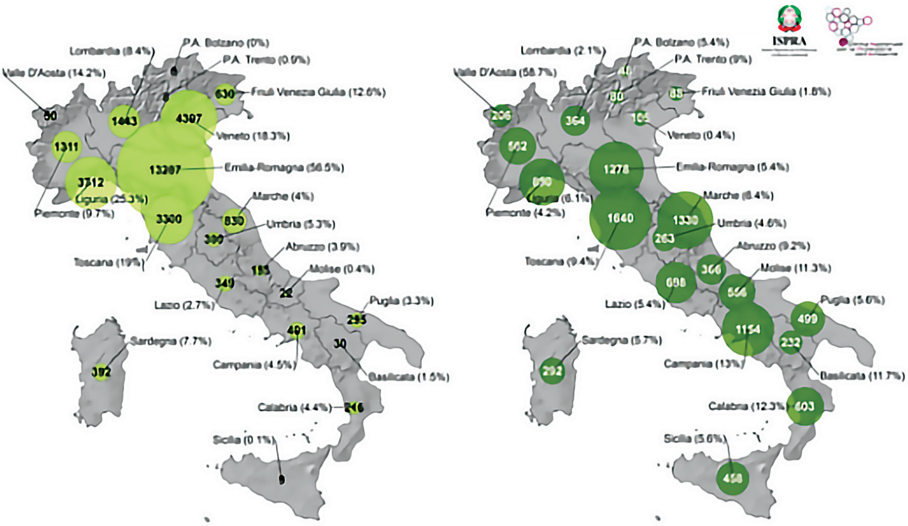

Figure 1. Maps of flooding (left) and landslide (right) risks, threatening cultural heritage features in Italy as evaluated by the Italian National Agency for environmental protection and research, the number in the coloured circles is the number of assets at risk [16].

In 2016, a series of earthquakes struck central Italy, causing widespread damage to historic towns and villages[2]. Many buildings, including churches, palaces, and other landmarks, were either partially or completely destroyed. Similarly, in 2018, heavy rainfall and flooding caused significant damage to historical buildings in Venice, including St. Mark's Basilica, which suffered extensive water damage[3]. The flooding also highlighted the challenges of preserving historical buildings in a historical city that is increasingly susceptible to rising sea levels and extreme climatic events, stressing the importance of employing the best available technologies to improve risk management and the response to such events (Figure 2). The 2016 earthquake in central Italy, which struck on August 24, caused significant damage to many historic monuments and buildings in the region; it had a magnitude of 6.2 and though centred in the area surrounding the town of Amatrice (Figure 3), it was felt throughout the region. Some of the most severely affected monuments included the Basilica of *San Benedetto in Norcia*, the Cathedral of *Santa Maria Argentea in Amatrice*, and the Church of *San Salvatore in Campi*. In many cases, entire sections of these buildings were destroyed or severely damaged, and in some other cases, entire structures collapsed[4].

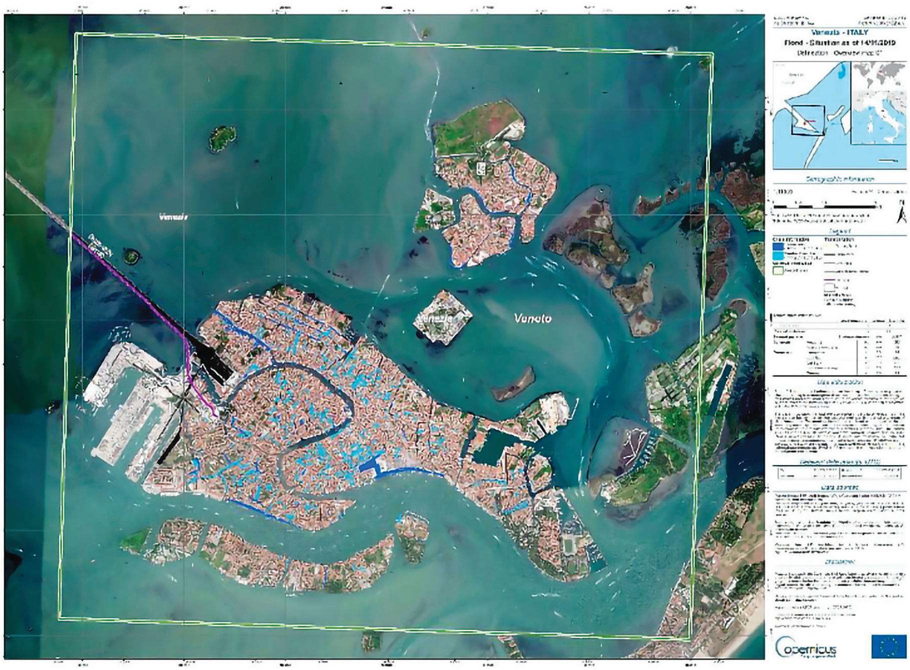

Figure 2. Satellite image of the flooding in Venice on November 19, 2019. The high tide levels of flooding are measured by satellite altimetry sensors and graphically represented with blues of different intensity (darkest blue = deepest water) [17].

The earthquake also had a significant impact on smaller towns and villages throughout the Abruzzo region, where many historic buildings and monuments were highly damaged or destroyed. The Italian government and international organisations have been working to assess the damage and develop plans for the restoration and preservation of these cultural heritage sites; the earthquake has had a profound impact on central Italy's heritage, highlighting its fragility as well as the need for ongoing efforts to protect and preserve these important monuments and buildings.

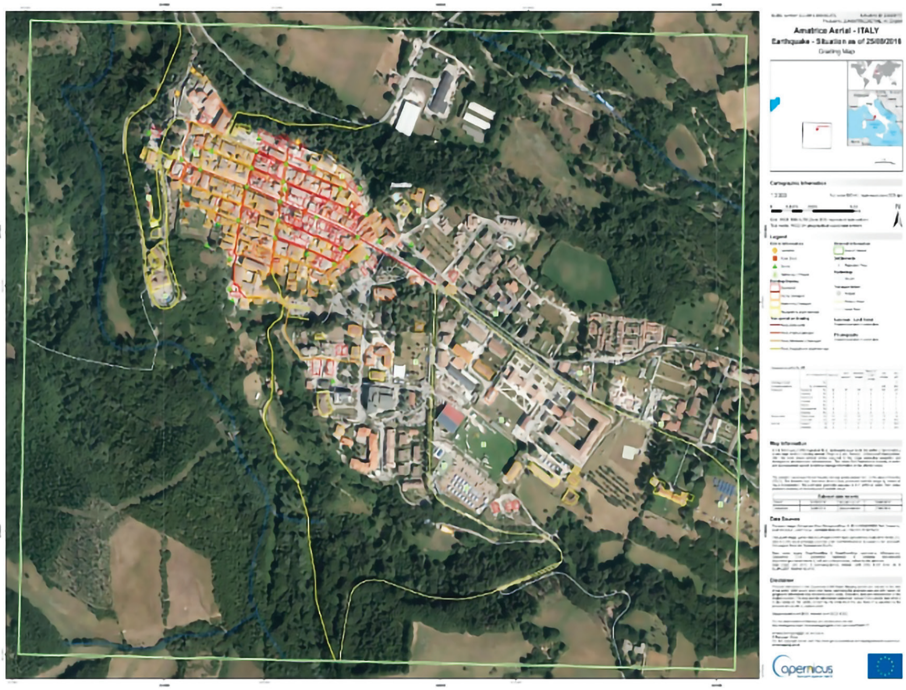

Figure 3. Map of Amatrice (Italy) after the 2016 earthquake, showing damage assessment, based on Copernicus Satellite images and data. The parts identified in red represent destroyed buildings: dark orange highly damaged, light orange moderately damaged and yellow negligible to slightly damaged (severity scales with colour) [17].

Several organisations, including UNESCO[5] and the Italian Ministry of Culture [18], have launched a number of initiatives to support the recovery and restoration of these monuments[6]. In some cases, Digital Twin technology has been used to create virtual models of damaged structures, allowing experts to assess the extent of the damage and develop restoration plans. One example is the Church of *SS Apostoli e Biagio* where a digital representation of the asset has been created using common user-friendly 360° cameras and photogrammetry with LiDAR to capture geographic data from the site [19]. However, the work on the Church of *SS Apostoli e Biagio* lacks the control capability typical of a Digital Twin application and is nearer to a digital model without real-time monitoring. It is a common problem for Digital Twin applications that can only reach an early stage of development due to a lack of funds and a proper framework able to define all the parameters and digital requirements in real time that a Digital Twin should have. Another example is the Digital Twin developed for the *Quadriportico* of the Cathedral of *San Matteo in Salerno,* in Italy, where the authors proposed an automated analysis for the state of degradation by exploiting a solution that combines a graphical database and a dynamic Digital Model [20]; the Gothic Cathedral of Milan was also investigated using Digital Twins for the monitoring and study of the structural response of the building, as preventive maintenance and strengthening operations [21].

1.2. Using Digital Twins for heritage management and preservation

The topic of Digital Twin technology for cultural heritage has been studied in detail for museums where the already existing infrastructure can be integrated with ease in Digital Twin applications for both the fruition of content and the monitoring of digital data [22], asset and people monitoring [23], light control [24] and virtual reality visits [25-26]. Digital Twins rely on a variety of enabling technologies, as shown in Table 1.

Table 1. Enabling technologies needed to a Digital Twin in order to accurately replicate physical systems in real-time, allowing for analysis, optimization, and decision-making.

TECHNOLOGY	DESCRIPTION
Internet of Things (IoT) Sensors:	These sensors collect data on physical objects, such as machinery or equipment, and transmit it to the Digital Twin.
Cloud Platforms:	Digital Twins require large amounts of storage and the possibility to develop aggregated metrics for analysis and control. Cloud platforms are very suitable to achieve this goal, making it possible to access and store data from everywhere at low latency.
Machine Learning (ML) and Artificial Intelligence (AI)	AI and ML algorithms can analyse data collected by the Digital Twin providing valuable insights into how to optimise performance or predict future behaviour.
Augmented, Mixed and Virtual Reality (AR, MR, and VR):	AR, MR, and VR can provide a visual representation of the Digital Twin, allowing users to interact with it in real time. The difference between VR and AR is the type of environment, where AR adds virtual assets/ elements to the real-world and VR creates a virtual world to inspect a site. Instead, MR is a trade-off between the two, where the virtual and the real world combine and interact with each other.
Security:	Security in digital assets is a topic of fundamental importance to avoid tampering and thefts. Nowadays the most discussed security technologies to support DTM are based on distributed ledger technology (such as for Blockchain), quantum encryption and traditional security methods based on authorizations and encryption.
Simulation software:	This software is used to create and simulate the Digital Twin's behaviour in various scenarios, allowing for analysis and optimization.
Fog Computing:	Fog computing can be used to process data in real-time, receiving and processing sensor data on site before their transmission to the cloud platform. This leads to reduced latency, lower computational power and improving responsiveness.
5G and 6E wireless networks:	5G and wireless networks provide high-speed, low-latency, and a high number of connected devices, which are essential features for real-time data processing and communication between Digital Twins and physical systems.

As far as the application of DT to cultural heritage management is concerned, thus, beginning with a point-cloud model, both AI-based technology for automatic object recognition, and ML models for system automations are used and the building must be modelled in IFC (Industry Foundation Classes) file format. Within the model, all information relating to the installation, maintenance and management of the individual components must then be digitised, including the sensors and IoT instruments that are physically placed inside the building to continuously monitor its condition and act on HVAC, lighting, hydraulic related systems, etc.

A suitable platform must then be identified to manage the data coming from the physical reality; this platform will not only visualise the data in an advanced manner but will also contain simulation models and predictive algorithms, able to analyse the situation in real time and plan automatic or ‘human in the loop’ strategies to deal with normal usage, abnormal situations, or accidental events. The visualisation of the Digital Twin can be made more usable by using specific gaming technologies and/or augmented reality systems, which can also be used for training non-specialised workers for maintenance interventions in critical areas. It is worth mentioning that a digital model alone, should not be considered as a Digital Twin, because it lacks the real-time monitoring and control capabilities typical of a Digital Twin.

Digital technologies have played a significant role in the reconstruction of damaged buildings in Italy following natural disasters such as earthquakes, using UAV and 5G networks [27-28]. These technologies have been used for various purposes, including damage assessment, documentation, and restoration planning. Among the most promising technologies for risk assessment and response[7], satellite technologies have also been applied to aid in the reconstruction of damaged buildings in Italy. Satellites can provide high-resolution imagery and data that can be used for damage assessment, monitoring, and planning.

A pertinent example of the use of satellite technology is the Copernicus Emergency Management Service (EMS)[8] in operation since April 2012. It provides near-real-time satellite imagery and maps, on demand, of disaster areas, to support emergency response and reconstruction efforts for selected emergency situations that arise from natural or man-made disasters anywhere in the world. This service was used extensively following the 2016 earthquake in central Italy, providing valuable information about the extent of the damage and the condition of the affected buildings. Satellite technology can also be used to monitor and assess the ongoing stability of damaged buildings.

For example, synthetic aperture radar (SAR) can be used to detect changes in the shape and movement of buildings over time, providing valuable information about their stability and potential risks. In addition, satellite technology can aid in the identification of new risks, such as landslides or changes in soil moisture, that may affect the stability of damaged buildings. This information can be used to inform restoration plans and prioritise reconstruction efforts. Overall, satellite technologies have been an important tool in the reconstruction efforts following natural disasters in Italy, providing valuable information about the extent of the damage, ongoing stability of damaged buildings, and potential risks, in order to aid restoration planning and prioritization[9].

2. The application of digital technologies for the restoration of historical buildings: two success stories – The Basilica of Saint Francis in Assisi (Italy) and Notre Dame of Paris (France).

The Basilica of Saint Francis in Assisi, Italy, is a UNESCO World Heritage site and an important symbol of Christian spirituality. In 1997, the Basilica suffered significant damage in an earthquake which caused the collapse of several vaults and the destruction of many frescoes and other works of art (Figure 4).

Figure 4. The collapse of the fresco ceiling in the Basilica of Saint Francis in Assisi following the 1997 earthquake [29].

The digital model developed for the Basilica is a comprehensive 3D model that includes detailed information about the building's structure, materials, and historical features. Based on data collected before the 1997 earthquake that caused significant damage to the building and especially to the frescoed vaults, the model was developed using a combination of laser scanning, photogrammetry, and other digital imaging technologies to create an accurate 3D model of the building's structure, materials, and historical features [30][10].

To restore the basilica, experts initially employed only digital scans, moving only later towards a true digital twin technology which allowed them to create a virtual replica of the building and simulate different restoration scenarios. Using this DTM, experts were able to test different restoration strategies and evaluate their impact on the building's structural integrity and aesthetic value. They were also able to identify potential risks and issues that could arise during the restoration process, such as the need to reinforce certain sections of the building or the risk of damage to the surviving delicate frescoes and other works of art.

Furthermore, after the introduction of digital technologies, the restoration process was able to ensure that the construction site of the Basilica of San Francesco was carried out in a safe, efficient, and effective manner [31-33]. The digital model was used to simulate the effects of various restoration strategies, allowing researchers to evaluate the potential outcome of different interventions before being implemented. This approach can help to reduce the risk of unintended consequences and ensure that restoration efforts are targeted and effective, enabling experts to preserve and protect the building's cultural heritage: DT technology holds many promises for the future management of these valuable assets.

The Assisi Basilica construction site for restoration has been integrated with Internet of Everything (IoE) technologies, which are able to monitor internal conditions by means of wireless sensors placed throughout the site. The Basilica has specific needs in terms of security, safety, management, and visitors' services. Therefore, a specific infrastructure has been designed, characterised by high reliability and resilience and is able to operate in both critical and ordinary conditions. The infrastructure can ensure:

- an adequate level of security and safety to people and assets
- the maximum ease of utilisation, using automation systems
- an adequate level of reliability, resilience, and flexibility
- a good modularity and expandability for future upgrades, such as new services and sensors.

On the other hand, the digital infrastructure contributes to reducing energy consumption and maintenance costs, transforming the digital management of the construction site for restoration into a permanent tool for the ordinary management of the Basilica, continuously powered by data and information coming from the building sensors and in line with the principles of a Digital Twin.

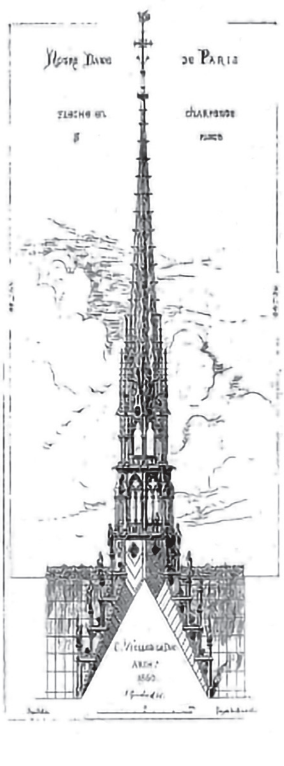

Figure 5. La Fleche (the Spire) of Notre Dame, original drawing by Eugene Viollet le Duc for the great restoration project of the Cathedral (1860). The wooden Spire was destroyed in the fire of 2019 [34].

The comparative construction site we decided to analyse is the reconstruction of Notre Dame Cathedral in Paris. On April 15, 2019, a fire broke out in the church, causing significant damage to the historic structure. The fire is believed to have started in the attic of the cathedral, which housed a complex network of wooden beams and trusses known as "the forest"[11], the result of the restoration project led by Eugene Emmanuel Viollet le Duc [34] and was surmounted by a tall wooden spire (Figure 5). The fire burnt the antique masonry and caused the spire to collapse. Firefighters worked for several hours to contain the blaze and prevent its spreading to the cathedral's bell towers and other parts of the building[12] and surroundings.

The use of Digital Twin technology for the Notre Dame Cathedral is expected to dramatically improve management of the construction site during the restoration process. Several research activities have been developed based on the collected materials resulting from the debris, mainly stones and timber, and were heavily polluted due to the strong presence of lead from the ancient roof covering which had dissolved completely as a result of the high temperatures of the fire and were highly toxic. In particular, the timber that had partially survived the fire allowed for a very interesting study on the paleo climatic condition of Europe during the Middle Ages [35].

The cause of the fire was initially unclear, but investigators later determined that it was likely the result of an electrical short-circuit, caused by a combination of factors, including the age of the electrical wiring in the attic of the church and the presence of inflammable materials such as sawdust and debris that could have contributed to the quick spread of the fire through the cathedral's wooden roof (Figure 6) [37][13]. The main positive results of the extensive application of Digital Twin technology for the construction site management at Notre Dame is summarised in Table 2.

Figure 6. The collapse of the spire of Notre Dame Cathedral during the fire that broke out in 2019, occurred during an extensive restoration programmed for the church [36].

Table 2. Construction site management phases for the Notre Dame restoration

ACTION	RESPONSE
Scanning the existing situation	The effectiveness of the DTM is linked to an in-depth knowledge of the existing state of a building, as an optimal precondition for the restoration site, aimed at the creation of a Building Information Model (BIM). The acquisition of photographs and historical materials is also crucial for the creation of a database to support the Digital Twin aimed at restoration.
Planning and scheduling	The DTM is used to create a detailed plan and schedule for the restoration work, considering the various components of the building, the extent of the damage and the available resources. The model is also used to identify critical paths, optimise work sequences, and allocate resources more efficiently. This can help to reduce errors, rework, and waste, ultimately saving time and funds, and increasing the overall quality and the cost/effectiveness of the results.
Quality control	The DTM monitors the quality of the restoration work, ensuring-consistency with the design and specifications. The model also compares the actual work to the planned work, identifying any deviations or discrepancies that need to be addressed. This can help to reduce errors, rework, and waste, ultimately saving time and funds, increasing the overall quality and the cost/effectiveness of the results.

Track-change	The DTM is used to document the restoration process, thus producing a detailed record of the work that has been done and the materials that have been used and providing the opportunity to catalogue the damaged assets, and to store all the information in a database for tracking and preservation purposes. This can be useful for future maintenance and restoration work, as well as for research and education purposes.
Safety and security management	With DTM it is possible to identify potential hazards and challenges, allowing the construction team to plan and execute the restoration work in state-of-the-art safety conditions. This will lead to a reduction of the accident and injury risks, ultimately improving the overall safety of the construction site. Moreover, Digital Twins are an effective method to reduce risks connected with vandalism, as they continuously monitor the security inside the site.
Communication and collaboration	DTM facilitates communication and collaboration among the various stakeholders involved in the restoration project. The model also shares information and updates, tracking progress, and coordinating the work of different teams and contractors. This can lead to a reduction in the duration of the work, saving time and funds.
Virtual walkthroughs	The DTM creates a virtual walkthrough of the building, allowing the construction team to familiarise themselves with the building and plan the restoration work more effectively. The model also identifies potential hazards and challenges, such as difficult-to-reach areas or structural weaknesses.

3. Extensive application of the Digital Twin Models (DTM) to construction site management for heritage preservation

The construction site management of Notre Dame and the Assisi Basilica differed in several ways due to the unique circumstances surrounding each restoration project. For Notre Dame, the use of Digital Twin technology was instrumental in facilitating the restoration process, allowing a very accurate mapping of the damage caused by the fire and helping in the development of a detailed plan for reconstruction.

In addition, the DTM was used to manage the complex logistics of the construction site, including the movement of workers and materials, and to monitor the safety of the workers, as well as the detailed classification and registration of all historical damaged assets, during the restoration process. However, it is worth noting that the restoration of the Assisi Basilica did involve the use of advanced technologies such as laser scanning and 3D modelling to accurately document the existing structure and help in the restoration process. These technologies were used to create a 3D model of the basilica that allowed for accurate measurement and analysis of the damage caused by the earthquake [38].

On the other hand, the restoration of the Assisi Basilica did not involve the use of Digital Twin technology from the initial phases. The restoration in Assisi was carried out through a combination of traditional building techniques and modern restoration methodologies. The restoration team relied on their expertise and experience to assess the damage to the basilica and to develop a restoration plan.

In addition to restoration efforts, the Notre Dame Restoration Project also highlights the importance of preserving cultural heritage through digital means. By creating DTMs of the cathedral, experts were able to capture and preserve its unique characteristics and historical significance, even in the face of significant damage. Figure 7 shows a digital reconstruction of the cathedral [39] made by the *Centre National de la Recherche Scientifique* (CNRS), where the parts of the cathedral destroyed by fire are clearly marked in red.

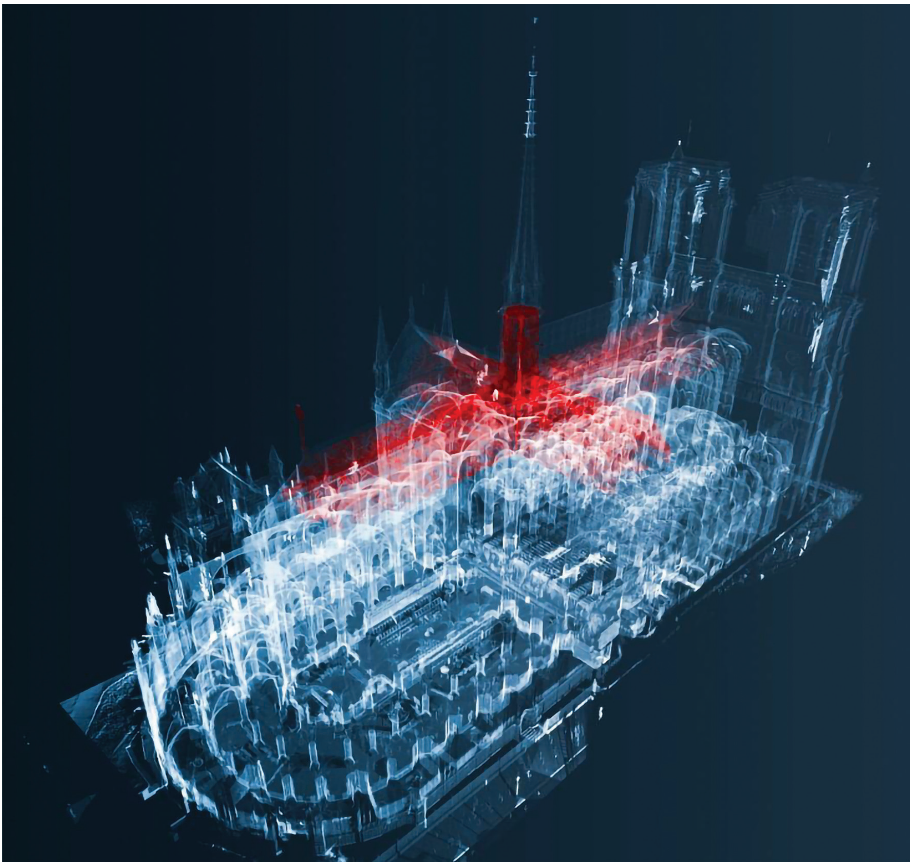

Figure 7. Notre Dame digital model realised by the French Centre National de la Recherche Scientifique (CNRS) to manage the construction site of the cathedral restoration (© V. ABERGEL / L. DE LUCA/MAP / Vassar College / GEA / Chantier scientifique Notre-Dame de Paris / Ministère de la Culture / CNRS)» [39].

3.1. Risk evaluation processes in the construction sites for restoration

The fire that destroyed the Cathedral of Notre-Dame in Paris in 2019 also stresses a very relevant issue related to safety management on construction sites, especially when associated with restoration processes within historical buildings. Fire seems to be one of the most common causes of damage for restoration construction sites, but there are also other types of damage, both direct and indirect, which are a constant field of study for safety experts, as well as insurance companies and forensic engineers [40].

Even if today, there is increased social awareness about heritage conservation and reinforced legislation on the safety and security of construction sites in place throughout almost all of Europe, the kind of disasters like the fire of Notre Dame and many others, seem to prove that we are not yet at the point where the risks can be rightly balanced. The task of finding the right balance between opening a construction site within a cultural heritage site and the needs of preservation, often overlooking the equally dangerous extraordinary activities of maintenance, as well as simple interior renovations or temporary installations related to exhibitions, which are sometimes equally dangerous in terms of temporary electrical equipment, as in the case of Notre Dame, is not an easy one.

Almost everywhere in the world, governments are increasingly aware of the need to protect historical buildings where high vulnerabilities to fire are combined with the presence of inestimable works of art, but they sometimes underestimate the potential risk of all those transitional phases connected with temporary works within the buildings, which often involve the temporary deactivation of full firefighting, or other security procedures or measures[14].

An impressive but not exhaustive list of disasters connected with the opening of construction sites related to restoration processes could be recalled as an example of the risk threatening any historical building during the mentioned delicate phase of intervention for conservation during the last decade of the twentieth century and the first decade of the twenty-first, as seen in Table 3.

Table 3. Non-exhaustive list of the most prominent fire outbreaks in historical buildings during restoration processes (1989-2008) [40].

Date	Historical building	Place
1989	Palazzina di caccia di Stupinigi	Turin (Italy)
1992	Windsor Castle	Windsor (UK)
1996	Teatro La Fenice	Venice (Italy)
1997	Cappella della Sacra Sindone	Turin (Italy)
1998	Chiesa Santi Geremia e Lucia	Venice (Italy)
2003	Molino Stucky Isola della Giudecca	Venice (Italy)
2006	Troitsky Cathedral	Saint Petersburg (Russia)
2008	Castello di Moncalieri	Turin (Italy)

All the buildings included in Table 3 are of great historical and artistic value for their respective countries and worldwide, often listed in the UNESCO world heritage site list, and therefore it is unthinkable that the restoration work could have been conceived without the utmost attention to safety aspects; yet whether the accident was accidental or intentional, a clear lack of attention to possible risk factors that were not initially taken into account, led, in all these cases, to serious damage to property and sometimes also to individuals involved in procedures to extinguish the fire, not to mention the consequent effects, both in social and economic terms, from the loss of use of the property for several years. The frequency of those accidents involving Italian sites seems related more to the very high concentration of historical and artistic assets in the country than to the lack of attention from Italian authorities towards the heritage in question, which, on the contrary, is protected by very advanced laws and is a model for restoration procedures globally. Research conducted by the National Observatory of the National Fire Brigade Corps in collaboration with the IUAV University of Venice shows that the risk of fire outbreak during restoration procedures seems to be sensibly higher than in any construction site, and that incidents occur more often during lunchtime or between the end of the working day and the beginning of the night surveillance shift [41][15].

The application of digital procedures and techniques needs forward-thinking and should begin ahead of the planning of a construction site for the restoration of historical buildings, as was the case with Notre Dame, as it presents several advantages to be considered broadly, such as the possibility of simulating the effects of the future construction site on the building to be restored. A prior and accurate scanning of the building using the point-cloud methodology, in association with the creation of a Building Information Model (BIM), therefore, seems to be a very valuable starting point for both the restoration process, and in the event of an accident for possible reconstruction, as in the case of Notre Dame. Only the in-depth knowledge of the building, thanks to a very accurate preventive digital model, made it possible to proceed immediately with the production of the stone and wood parts that will replace those destroyed by the fire and, at the same time, clear the church of the debris produced by the fire, paving the way for the complete implementation of a Digital Twin model of the construction site, that will give back the cathedral to the Parisians before the end of 2025.

4. Conclusions

In conclusion, both the restoration projects for the Notre Dame Cathedral and the Assisi Basilica have demonstrated the importance of utilising advanced digital technologies for the preservation, restoration and, ultimately, the management of historical buildings. The use of Digital Twin technology in the restoration of Notre Dame is presently providing a level of accuracy and precision that is hardly feasible with traditional construction site techniques, allowing for a very efficient restoration process. On the other hand, the restoration of the Assisi Basilica relied more on traditional building techniques, mainly based on experience, but still utilising advanced technologies such as laser scanning and 3D modelling to document the existing structure. The comparative experiences of the two mentioned restoration projects, combining cutting-edge technology with expert knowledge and careful planning, make it possible to restore and protect these important cultural assets.

The use of advanced technologies, including Digital Twins, has transformed the field of historic preservation, allowing for a more comprehensive understanding of historical buildings leading to more effective restoration and maintenance practices, as well as research and studies connected to traditional masonry and timber construction techniques and materials, further developing the historical knowledge of the construction processes.

High-resolution scanning of buildings, using the point cloud technique, even before the planning of a restoration site, appears to be an excellent preventive response to the risks physiologically associated with the opening of a construction site, and their translation into a BIM, a perfect complement to the legal obligations on construction sites currently in force. However, it is the massive use of DTM that seems to be the real future answer to the seemingly unpredictable risks arising from building heritage construction sites, but which almost always turn out to be the causes of the worst disasters.

Acknowledgements

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Notes

[1] According to the 1972 United Nations Convention Concerning the Protection of the World Cultural and Natural Heritage, Italy has one of the largest concentrations of historical and artistic patrimony in the World. As of 2021, Italy has 58 listed sites and 31 sites in the tentative list, making it the state party of the convention with the most World Heritage Sites [42].

[2] The 2016-2017 Central Italy earthquake sequence, defined by the Italian National Geo-Vulcanologic Institute (INGV) as the Amatrice-Norcia-Visso seismic sequence, began in August 2016. On 30 October 2016, the strongest tremor was recorded, at a magnitude of 6.5, with its epicentre between the municipalities of Norcia and Preci, in the province of Perugia. On 18 January 2017, a new sequence of four strong tremors of magnitude greater than 5 occurred, with a maximum of 5.5, and epicentres located between the L'Aquila municipalities of Montereale, Capitignano and Cagnano Amiterno. This set of events caused a total of about 41,000 displaced persons, 388 injured and 303 dead, of whom 4 died indirectly, as well as incalculable damage to the region's built-heritage and the complete destruction of the historical centre of the village of Amatrice. The total estimated damage amounts to 26.5 billion euros, Amatrice being the most damaged municipality with over 1.3 billion euros in damages, followed by Camerino with 1.2 billion euros, and by Norcia, with 1.1 billion euros [43].

[3] On 12 November 2019, an exceptional high tide wave occurred in the northern Adriatic Sea also affecting Venice and its lagoon. Although an exceptional high tide (>140 cm) had been predicted by the numerical models in use, during the course of the evening, sudden gusts of wind at over 100 km/hr caused a further local intensification of this phenomenon. The maximum level of 187 cm resulting from those concomitant circumstances was recorded at Venice – Punta della Salute and occurred at 22:50 with a delay of about one hour after the peak of 182 cm, recorded in the open sea by the *Acqua Alta* Platform causing the complete flooding of the entire historic centre with enormous damage to people and properties. The historical city of Venice has been protected under the UNESCO World Heritage Convention since 1987, and after the almost two-metre-high tide flood occurred in 2019, a continuous monitoring of the city by the EU Copernicus satellite programme has been in place, also considering the recurrence of the phenomenon.

[4] In Amatrice, the facade of the Church of San Francesco, dating back to the fourteenth century, has collapsed, and has also lost its oculus. There was also a great deal of damage to the Church of Sant'Agostino near the ancient walls of Amatrice, with its typical Gothic portal, and the "Cola Filotesio Civic Museum". The ancient gates of Accumoli, dating back to the first decades of the year 1000, have been devastated. The damage involved the medieval walls and gates, remains of the bastions, medieval churches and palaces, and some Baroque ornaments. In Arquata del Tronto, one of the rare point-

ed-arch doors dating back to the 1600s was damaged. Camerino was the most affected city which saw the collapse of one of the Santa Chiara monastery walls and some damage to the cathedral clock. In Tolentino, the church of Santissimo Crocifisso ai Cappuccini, formerly known as the Church of Peace, collapsed. In San Ginesio, the convent of San Francesco, the convent of the Benedictine Sisters and the Collegiate Church are unusable. Also, in Macerata there was damage to the Galleria delle Fonti and the façade of the Church of San Giovanni. Furthermore, some cracks have also appeared inside the building that houses the Mozzi Borgetti Library. The monuments of Norcia, in the province of Perugia, suffered significant damage, such as the Church of San Benedetto and the Benedictine walls. Small cracks were reported on the outside of the Cathedral of Urbino, which had already undergone restoration following the 1997 earthquake.

[5] The creation at the University of Udine, in Italy, of the UNESCO Chair for Intersectoral safety for disaster risk reduction and resilience is a significant scientific response to the natural disasters that have occurred in Italy since 2016 and represents a world-class centre of excellence on issues related to security, disaster risk reduction and resilience.

[6] Article 1 of Law no. 229 of 15 December 2016, “Conversion into law, with amendments, of Decree Law no. 189 of 17 October 2016 – Urgent interventions in favour of the populations affected by the earthquake of 24 August 2016” extended tax exemptions for supporting cultural activities in Italy (the so called Art Bonus) to donations in favour of the Ministry of Culture (MIC), for maintenance, protection and restoration interventions also of cultural assets of religious interest (entities and institutions of the Catholic Church or other professions) present in the municipalities affected by earthquake events since 2016. The interventions on built heritage are co-financed by the Commissioner of the Government for the 2016 earthquake reconstruction.

[7] The most relevant technologies used to monitor and assess damage in historical buildings can use remote or local observations to achieve their goal. Some of them are installed onboard autonomous robots of different types such as UAVs (Unmanned Aerial Vehicle), rovers and submarines. Other tools are used to inspect the sites from space, such as earth observation satellites, or from high altitudes, as in aerial surveys, or they are placed on fixed or mobile sensors, as is the case for environmental sensors, Radio-Frequency Identification (RFId) beacons and distance sensors. Moreover, the monitoring devices can analyse single or multiple physical properties at the same time. One example is the environmental sensors that can monitor temperature, pollutants and humidity, at the same time or multispectral/hyperspectral cameras that can be used to inspect the pollutants and moulds on surfaces and measure surface temperatures, as well as radar sensors to inspect heights and displacements. There is quite a high number of possible technologies available, and they should be adopted specifically for any site, taking into account what the focus of the monitoring action is, in addition to the sensors’ location and the category of the site.

[8] The Copernicus Emergency Management Service supports actors dealing with natural disasters, man-made emergency situations, and humanitarian crises as well as those involved in preparedness and recovery activities. The service improves people’s safety and helps to prevent loss of lives and/or property before, during, and after disasters by providing information, for example, on the type and magnitude of risks, the extent of a flooded area, the spread of a forest fire, the damage caused by an earthquake or the progress of recovery and reconstruction efforts (European Commission: Emergency management Service, service overview).

[9] Starting in August 2016, a sequence of strong earthquakes struck Central Italy, causing several casualties among the local population: over 300 people were killed,

360 injured and over 2000 were left homeless. During the long seismic sequence, Italian Civil Protection authorities asked for the activation of the Copernicus Emergency Management service, which produced about 120 maps of the affected zones, with the aim of supporting the national authorities' decisions in the activities of rescuing populations and securing as much as possible of the built environment, infrastructures and cultural heritage. (Released date: Mer, 02/11/2016 - 13:00 Copyright: Copernicus EU Programme ® EU Commission, 2016)

[10] The Digital Twin model was used to aid in the restoration and conservation efforts for the basilica. For example, it was used to develop a detailed map of the building's surface cracks, which are a major concern for the building's stability. This information can be used to develop targeted restoration plans that address specific areas of concern, rather than adopting a more generalised approach.

[11] The complex timber structure supporting the lead roof tiles of Notre Dame cathedral was technically well described by Eugene Viollet Le Duc (1814-1879) who was entrusted by the French government with the Cathedral's restoration, which involved the entire timber architecture supporting the gothic roof and the reconstruction of a wooden Gothic spire at the transept intersection, rebuilt employing the same carpentry techniques as those employed in the Middle Ages.

[12] Despite the significant damage caused by the fire, many of the cathedral's most precious artefacts and works of art were saved, thanks in part to the heroic efforts of firefighters and other emergency responders. The fire also spurred an outpouring of support from around the world, as people donated money and resources to help with the restoration and rebuilding of this iconic symbol of French history and culture.

[13] The Notre Dame fire started in the attic, above the gothic stone arches of the cathedral vaults. The current hypothesis is that the fire may have been caused by short-circuited cables from the six electronic bells installed in the spire, which were intended to be temporarily operating during the original construction site. The fire spread through most of the wooden carpentry supporting the lead roof (the so called "forest") reaching the cathedral's 300-foot wooden spire. Several parts of the gothic arches collapsed, and some of the upper walls of the cathedral were also damaged. However, the vaulted stone ceiling of the cathedral prevented extensive damage. According to authorities, a nine-hour battle against the fire was necessary to extinguish it. The fire started at around 6:50 p.m. on Monday, April 15, 2019, and was finally extinguished by early Tuesday morning.

[14] The topic of the preservation of historical buildings and fire safety in restoration work was dealt with in Siena at a major international congress in 2008, and more recently in Bergamo during Safety Expo 2016, in Turin at PREVINTO 2018 and at many other conferences. Despite this, fire safety on restoration sites is still not greatly discussed and therefore not properly implemented by those responsible for such activities [39].

[15] The construction site for restoration procedures seems to be among the primary causes of fires in listed buildings together with short circuits in electrical systems and vandalism. Research conducted by the engineer, Stefano Zanut of the National Observatory of the National Fire Brigade Corps and Prof. Piero Michieletto of the IUAV University of Venice, shows that the working conditions in a restoration site are more insidious than those in an ordinary building site: in the city of Venice, where new constructions are not allowed and, only the reuse and conservation of existing buildings is permitted, fires were found to be six times more frequent than in building sites in the nearby region of Friuli (12% compared to 1.8%). Most fires within construction sites occur in the time slots between 12.00 a.m. and 1.00 p.m. and between 5.00 p.m.

and 7.00 p.m., i.e. in the absence of workers and before the start of post-work surveillance. The analysis of the causes makes us reflect on the importance of the management aspect as an indispensable support for the safety of cultural property [40].

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Summary

Historical buildings are essential cultural assets to be preserved and maintained for the sake of future generations. However, they are also highly vulnerable to natural disasters and other extreme events, which can cause irreparable damage or even their total loss. To manage these risks, a growing number of experts are turning to Digital Twin Models (DTM), conceived as more than a mere virtual replica of physical objects or systems. They can be used to monitor, inspect, and simulate the functioning and behaviour of a building in real-world scenarios. In the context of reconstruction, DTM can be used to create virtual models of damaged buildings, allowing experts to assess the extent of the damage and plan restoration.

By creating a DTM of a historical building, experts can gain valuable insights into its construction technique, structural integrity, maintenance needs, and potential vulnerabilities in real time. This can help to extend the lifespan of the historical building and ensure that it remains in good condition for future generations. In case of an extreme event, such as a natural disaster or terrorist attack, war or vandalism, a DTM, together with all related enabling digital technologies, can be used to plan for and respond to the crisis, also simulating the effects of a disaster to develop emergency response plans accordingly. Therefore, the use of DTM can enhance the current vision of a historical building thus helping it to increase its resiliency to potential damaging, preserving, and maintaining its historical and cultural value and characteristics through time.

Riassunto

Gli edifici storici sono beni culturali essenziali da mantenere e preservare per il bene delle generazioni future. Tuttavia, data la loro natura, sono anche molto vulnerabili alle calamità naturali e ad altri eventi estremi, che possono causare danni irreparabili o addirittura la loro distruzione. Per gestire questi rischi, un numero di esperti sempre maggiore si rivolge ai Digital Twin Models (DTM), in grado di andare oltre ad una semplice replica virtuale di oggetti o sistemi fisici. Questa tecnologia può infatti essere utilizzata per monitorare, gestire e simulare il funzionamento interno ed il comportamento

di un edificio posto nell'ambito di scenari reali. Nel contesto di processi di ricostruzione, il DTM può essere utilizzato per creare modelli virtuali di edifici danneggiati, consentendo agli esperti di valutare l'entità del danno e pianificarne il ripristino.

Creando il DTM di un edificio storico, gli esperti possono ottenere preziose informazioni sulla sua tecnica di costruzione, sulla sua integrità strutturale, e sulle sue esigenze di manutenzione e potenziali vulnerabilità, il tutto in tempo reale. Ciò può aiutare a prolungare la vita degli edifici storici ed a garantire che restino in buone condizioni il più a lungo possibile. In caso di eventi estremi, come disastri naturali o attacchi terroristici, guerra, incidenti di cantiere e vandalismo, un DTM insieme a tutte le tecnologie digitali abilitanti correlate, può essere utilizzato per pianificare e rispondere alle crisi, simulando anche preventivamente gli effetti di un disastro, permettendo lo sviluppo di piani di risposta alle emergenze. Pertanto, l'uso del DTM può migliorare la nostra visione attuale di un edificio storico consentendo di aumentarne la resilienza ai danneggiamenti, preservando e mantenendo il suo valore storico e culturale e le sue caratteristiche nel tempo.