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CONSTRUCTION AND BUILDING PERFORMANCE

BUILDING AND DESIGN TECHNOLOGIES

DIGITAL TWINNING PROCESSES FOR THE BUILT HERITAGE CONSTRUCTION SITE: OPPORTUNITIES AND IMPLEMENTATION SCENARIOS

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Abstract

This work investigates the introduction of concepts, processes, and methods of digital twinning to construction sites in the field of built heritage construction sites, analyzing the related opportunities and proposing an initial applicative framework. The presented architecture is conceived to face both the complexity of the artefact – in terms of its historical evolution, its configuration, the presence of values related to traditional construction methods, etc. – and of the activities and operations performed on its construction site, including the production, elaboration, and use of information in the different decision processes.

This paper aims to provide a theoretical, methodological, and technical base to support the design and implementation of a digital twin for a construction site within the built heritage field.

Keywords

Digital twin, Built heritage, Construction site, Building recovery.

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1. INTRODUCTION

Since the mid-1990s, the digital evolution of construction has shown – and in some cases suffered – a continuous, although delayed, technological transfer of paradigms, methodologies, and tools from the world of the manufacturing industry, usually to improve the efficiency and profitability of the entire construction process, from design to construction and management of the building or infrastructure. In this phenomenon, a pivotal moment is represented by the inauguration, in 1997, of the Guggenheim in Bilbao, when Building Information Modeling (BIM) emerged as a new paradigm for the management of architectural design complexity forms and performances. Today, almost thirty years after the Bilbao effect, another industrial digital paradigm – the Digital Twin (DT) – is revolutionizing the construction process, especially in the construction and management phases. In its broadest sense, a DT is a virtual representation – in real-time (or slightly deferred) – of a real system, entity or phenomenon, whose main objective is to organize the information necessary for its monitoring and effective management [1]. In the manufacturing world, the DT is nowadays a consolidated practice in the implementation of monitoring systems of production plants. It not only traces the operation of the system but also supports the direct intervention, through special actuators, on the various components of the system.

In the building process, thanks also to the diffusion of the BIM and the Internet of Things (IoT) paradigms, the concept of the DT is currently having rapid diffusion, in particular in the management phase of complex buildings such as hospitals, where the monitoring of well-structured functional requirements can be advantageous from managerial and economic perspectives. In this context, some researchers are currently investigating the possible extension of the DT approach to the construction site – meant as a complex and dynamic system that involves many physical and human resources [2] – to improve the critical aspect of real-time control of operations, aimed at reducing waste of time and resources as well as improve the overall safety level of operators, even allowing faster actions to guide behavior and on-site operations.

The DT capabilities in real-time monitoring, control and management of a building, highlighted by some recent European funding calls, seem not fully exploited in the context of historical-architectural heritage, where often the DT concept is associated with a model of a state of the building, present or past, often for documentary or communication purposes. At the same time, no applications or studies have emerged regarding the definition of a DT scheme aimed at controlling and managing a recovery site. The state of the art presented in the following section shows that there is less research in this area of intervention that reveals the adoption of digital approaches to the recovery site.

One of the main characteristics of a recovery site of the historical-architectural heritage lies in the awareness that the knowledge acquisition phase is continuous and does not end with the design, which, however accurate, cannot collect the full knowledge of the building. Inevitably, this knowledge is deepened during the construction phase, both in terms of recognition of the historical phases of modification of the building and concerning the materials and traditional construction techniques. The recovery site is also remarkably complex, with peculiar planning and organization characteristics aimed at obtaining a flexible and articulated structure based on the nature of the existing ones. Its peculiarity originates in some intrinsic characteristics of the system. These conditions strongly influence the entire construction process, such as the limited availability of spaces that causes difficulties in the management of material procurement flows, as well as in the movement of human resources and vehicles. Another essential aspect is the high complexity of the processing cycles, which often require integrating new and traditional construction techniques. Finally, further issues to be considered arise when the building is located in an urban center. In this case, a deep impact is produced by obstacles caused by the contiguous buildings, the difficulties of access and transit of heavy vehicles, and the presence of provisional, safety, and service works. In such a system, in which the context is constantly changing as updates and modifications are frequent, there could be a loss of control of the construction process, leading to an extension of the contractual time, execution errors, and absence of safety conditions. Therefore, it is necessary to adopt strategies and best practices to support the process, also using digital technologies. In this context, the present work defines a framework for the DT of a building recovery site, outlining its features and proposing an initial configuration that supports its practical implementation on site. The article also intends to illustrate operational scenarios that frequently occur in the recovery construction site whose issues could be mitigated thanks to the use of the DT.

2. BACKGROUND

This section presents an overview of the primary research about the application of digital approaches to construction sites from 2009 to today. As noted by Perrier [3], such research focuses primarily on how to achieve greater productivity and safety during construction. The main experiences analyzed (Tabs. 1 and 2) are related to the monitoring of materials, equipment, and workers [4–6], the optimization of safety on-site [7–10], the DT [11, 12, 13–17] and the automation of the entire construction process [18, 12]. Among these, only a few have specifically focused on operations and sites related to recovering the historical-architectural heritage. In terms of flexibility and simplification of complexity using models, HBIM has revealed a strong potential, also considering the interest shown by much research [7] that highlighted its usefulness in the construction site processes, especially in terms of time optimization in the presence of variants and for preventive maintenance purposes [18]. At the same time, Perrier [3] underlined the potential of BIM to facilitate the estimation of waste generated by demolition and renovation activities during recovery operations.

An additional element derived from the literature review relates to the evolution in the use of digital approach-

Reference, year	*Aim of the research*	*Results*	*Search area*	*Application*
[4], 2009	To describe a warning system to prevent construction site accidents involving workers and heavy equipment	An experimental prototype was realized. It allows creating wireless communication from a server to a smartphone	Workers, equipment	All the construction sites
[5], 2012	To develop a concrete monitoring system through wireless signal transmission	A new technique has been developed that allows constant monitoring of the temperature and humidity of the concrete	Building materials	All the construction sites
[7], 2013	To prevent falling object accidents through a proactive approach	An integrated information management model has been proposed using a network of RFID sensors	Security	All the construction sites
[6], 2014	To solve the problem regarding the need for power cables and data transmission to monitor building materials	An integrated RFID sensor system is useful to monitor temperature, humidity and corrosion rate data of a concrete structure	Building materials	All the construction sites
[8], 2019	Propose the digitalization of the building process and construction management both for the organization of work and for safety on site	Integration of a plug-in into the software for design and safety planning	Time optimization, safety	Recovery construction site
[18], 2019	To connect the contents of Industry 4.0 and the sharing of information with BIM design, creating a network of sensors for monitoring on-site	Design of a single data container (black box) for data collection and storage of the entire construction process, obtaining the detailed history of the building	Construction process	Recovery construction site
[9], 2019	To define a methodology that supports the development of the reconstruction program of a historical urban centre hit by a seismic event; to prevent problems, interference and criticalities	UAV photogrammetry helped to inspect the real situation in a post-earthquake scenario, to plan the reconstruction phases	Construction process, safety	Recovery construction site
[10], 2019	To improve efficiency and productivity in the construction sites	Analysis of the case studies realized, with real-time monitoring	Construction process, safety	All the construction sites

Tab. 1. *Brief review of digital approaches to construction sites in the built heritage context.*

es to the construction site: the research, initially studying specific aspects such as the monitoring of flows and auxiliary factors, today tends to move towards the digitization of the entire construction process causing an increasing interest in the DT principles and methodologies.

As already happened with BIM, the origins of the DT are also to be found in the aeronautical industry. The first DT is identified in the virtual prototype, which, in 1970, helped NASA diagnose, manage, and solve the famous accident of Apollo 13 (known for the phrase “Houston, we have a problem”) directly from the ground [21]. The first explicit formalization of the concept of DT dates back to 2002, when Grieves introduced it (and published it, albeit later) as a digital support model for managing the life cycle of a product [22].

In the AEC world, the adoption of the DT approach – and consequently of this definition – has been much more nuanced, even if it is possible to identify its first applications in the management of operations and maintenance of plants and machinery, especially in complex buildings [23, 24]. More recent research works focusing on the DT support to construction and intervention phases aim at various aspects such as safety, optimization of activities and planning, quality control, construction site monitoring, procurement, machinery, and equipment use. Boje [11] investigated the possibility of integrating different approaches and technologies from different manufacturing sectors to manage the complexity of construction, providing a general framework based on the semantic web, while Sacks introduced the definition of

Reference, year	*Aim of the research*	*Results*	*Search area*	*Application*
[11], 2020	State of the art and considerations on dimensions of DT	DT framework including semantic representation through linked data	DT	All construction sites
[2], 2020	DT definition in the context of construction project management	Definition of a functional schema for DT within AEC processes	DT	All construction sites
[12], 2021	Defining the interaction between DT and IoT for project management	IoT-based data extraction and integration in a 4D model for project management	DT	All construction sites
[19], 2021	Digitally Facing complex problems related to safety and management of construction sites, management of materials, garbage and works progression monitoring	Fog computing paradigm to integrate IoT, AI and Blockchain technologies to facilitate the development of construction smart APIs.	Construction Process	All construction sites
[20], 2021	Analysis of the state of the art in the adoption of Industry 4.0 in construction sites	Results show how connectivity is a key aspect, ensuring the link between different purpose-specific technologies	Construction Process	All construction sites
[13], 2021	DT to assess materials distribution on-site, for disaster preparedness assessment	Integrating DT and deep learning provide an effective way to represent materials distribution on site.	DT, Materials management	All construction sites
[14], 2021	DT and simulation for excavation contaminated material management and disposal	DT and simulation can be integrated to improve construction management decisions that rely on continuous updates from the site	DT, Materials management	All construction sites
[15], 2021	DT for assembly of smart modular integrated construction systems	DT for tracking and monitoring of transportation and installation of prefabricated elements.	DT, Construction Site	All construction sites
[16], 2021	DT to support the prediction of safety issues according to the construction plan	DT integration with 4D modelling to identify potential hazards as per regulations and construction planning	DT, Safety	All construction sites
[17], 2021	DT to monitor the safety of pre-stressed structures	DT coupling with simulation to predict updated behaviours of structures, based on monitoring data.	DT, Materials	All construction sites

Tab. 2. *A summary of major works focusing on DT application to construction sites and existing buildings.*

DT Construction (DTC), outlining its relationships with other paradigms such as the IoT, automation on-site and BIM [2]. Some recent research has also focused on using digital twinning technologies to monitor specific issues such as materials distribution using images analysis [13], for management of assembly of modular elements [18] or excavation material disposal, considering soil contamination [14]. The link between DT and BIM is still apparent when the integration is applied to 4D models as a database to be updated through sensors, and that provides a set of data to perform predictive analysis [16].

In order to complete this brief analysis of the state of art related to the DT approach in the world of construction, it is necessary to mention that the world of software houses is now placing on the market some new platforms designed to support its implementation, such as iTwin (Bentley Systems), Tandem (Autodesk), as well as ad hoc applications from Microsoft and Unity3D.

3. INFORMATION REQUIREMENTS FOR THE MANAGEMENT OF BUILT HERITAGE RECOVERY SITES: ARTEFACT KNOWLEDGE AND OPERATIVE ISSUES

The recovery construction site of the built heritage is strongly linked to a traditional type of executive practice based on a series of processes carried out mainly on-site. Furthermore, it is burdened by variations and interferences where the executive project is often elaborated contextually to the implementation phase [25], leading to errors, risky conditions, and a lack of rationality. Therefore, it was hypothesized to break down the complexity of this area into individual topics aimed at highlighting the specificities and main criticalities that occur while intervening on existing built heritage. The artefact knowledge criticality is particularly important since the building life is frequently not accompanied by any documentation. In this regard, the relevant issues can be summarized below:

- historical reconstruction. There is often no information regarding the growth and modification phases of the building, which are also valuable for ensuring static safety during the intervention. In such cases, the technician must rely on his/her sensitivity and experience to detect the main information from the "reading" of the building;
- presence of complex geometries and irregularities that often do not allow the creation of digital models that perfectly match reality;
- recognition of constructive elements belonging to tradition, result of the material culture that determined them. For instance, the thermal and structural performances of these elements are unknown, nor are the features of the materials nor the execution techniques. Current and advanced survey methods cannot automatically define the characteristics of the building components, limiting themselves to documenting only what the instrument captures on the surface. These could determine a wrong choice of intervention techniques or incompatible materials, causing problems in the post-intervention as well as risks from the conservation point of view;
- presence of the so-called "test projects", which contemplates the execution of investigations of different levels of invasiveness to mitigate the lack of knowledge of the artefact;
- absence of documentation concerning the building (survey, stacking, origin documents, etc.);
- state of damage that makes the operations linked to the survey and the execution of the cognitive investigations of the architectural work complex and dangerous. This criticality occurs in post-disaster scenarios or when the building is in a condition of ancientness.

Entering the context of construction operations of the recovery project, the main criticalities are:

- executive practice in which single operations and processes are planned in sequence and do not show any principle of interoperability, determining complexity in the organization and planning of activities;
- off-site operations, provisions and processes are rarely considered, increasing the need for suitable spaces and organizational difficulties;
- the occurrence of specific environmental conditions on-site, such as temperature and humidity, which are essential to carry out works based mostly on traditional processes;
- small dimensions of the spaces available. This often causes difficulties in managing logistics, supplies and auxiliary factors (Fig. 1);
- obstacles caused by adjacent buildings, difficulties for access and transit of heavy vehicles, and the presence of provisional, safety, and service works. Typically these criticalities occur in particular conditions, for instance, when the building is in an urban centre or a post-disaster reconstruction context (Fig. 1);
- management of finds. In the presence of historical buildings, it is common to find elements of decorative, architectural, historical, technical-constructive value hidden by the historical, determining the suspension of works and the preparation of a variant that often requires authorization from the competent authorities.

4. DIGITAL TWIN FOR THE ARCHITECTURAL HERITAGE RECOVERY SITE

These criticalities and issues indicate that the recovery site of the historical-architectural heritage is complex and includes both intrinsic issues of the system and external factors which determine a lack of quality control of the construction process and workers' safety. In conceiving a DT that can support both the management of the recovery site and the intervention choices on the artefact, the need for an integrated approach also emerges at an information level. It consists, on the one hand, of the model of the artefact, progressively updated during the investigation and analysis activities, and on the other hand, the dynamic model of the construction site (Fig. 2), able to formalize in real time the information received from the various operations on the construction site (both monitored by sensors or manually for-

Fig. 1. *Logistics criticalities in a built heritage recovery site. Top: Storage areas located in internal courtyards or on scaffolding due to limited availability of space (Construction site after the 2009 earthquake of the E. De Amicis school – L'Aquila). Down: Auxiliary factors management in post-earthquake reconstruction (Fossa, AQ), such as installing cranes using telescopic legs or material storage tailored to reduce interferences with public pedestrian walkways.*

malized by the operators). Unlike a construction site for new construction, the process of continuous acquisition of information relating to the state of the artefact produces a significant amount of information that must immediately be coordinated with the already available knowledge regarding the artefact and its history.

Under the different proposed frameworks for the DT, in the context of building renovation sites, it is helpful to define the fundamental elements that contribute to its existence and functioning:

- the real, physical system;
- its virtual representation;
- the information flow from the real system to the virtual system;
- the information and implementation flow from the virtual system to the real system.

In our specific case, the physical system to be monitored can be discretized into two domains, the artefact itself and the renovation site that acts on it, considered as a structured and dynamic system of operators, activities carried out, equipment and resources used, materials, supply chain, preparations and temporary works, logistics, flows and paths for provision and disposal of materials. This physical system is mirrored by the virtual representation, usually identified with the term DT, which in our proposal is divided into two models, interconnected and interacting:

- the knowledge model of the building, based on the HBIM approach and enriched with the information generated by the analysis and investigation activities performed during the construction site or generated by active monitoring systems;

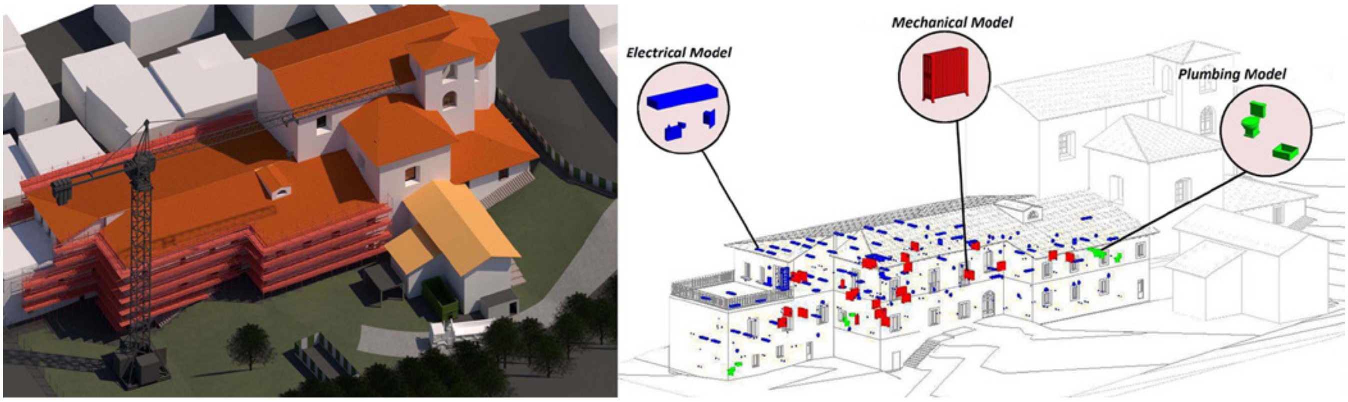

Fig. 2. *Recovery site information modeling. A dynamic model of the construction site (on the left) and management model (on the right) of the same historic aggregate in Montereale (AQ).*

- the site monitoring model, based on a BIM model that integrates the site model with the planning of activities and their progress and that formalizes the data generated in real-time by the physical site, using different approaches such as the Internet of Things, machine data produced by the equipment, and monitoring data collected by operators.

The information flows from the physical system to the DT, as indicated in Figure 3, to close the information cycle by ensuring that the information produced or extracted from the construction site, from the survey and the building monitoring can be processed in the DT. They can then support on-site activities both through actuators and automation (for example, in the monitoring of machines and systems) and provide information to on-site operators to better manage and coordinate their activities.

In a context such as the intervention on the historical-architectural heritage, the DT is part of an information process that describes not only the current state of the building but also different key aspects such as the temporal evolution, the characteristics and construction techniques associated with the survey models or previous states of the building. This information provides the

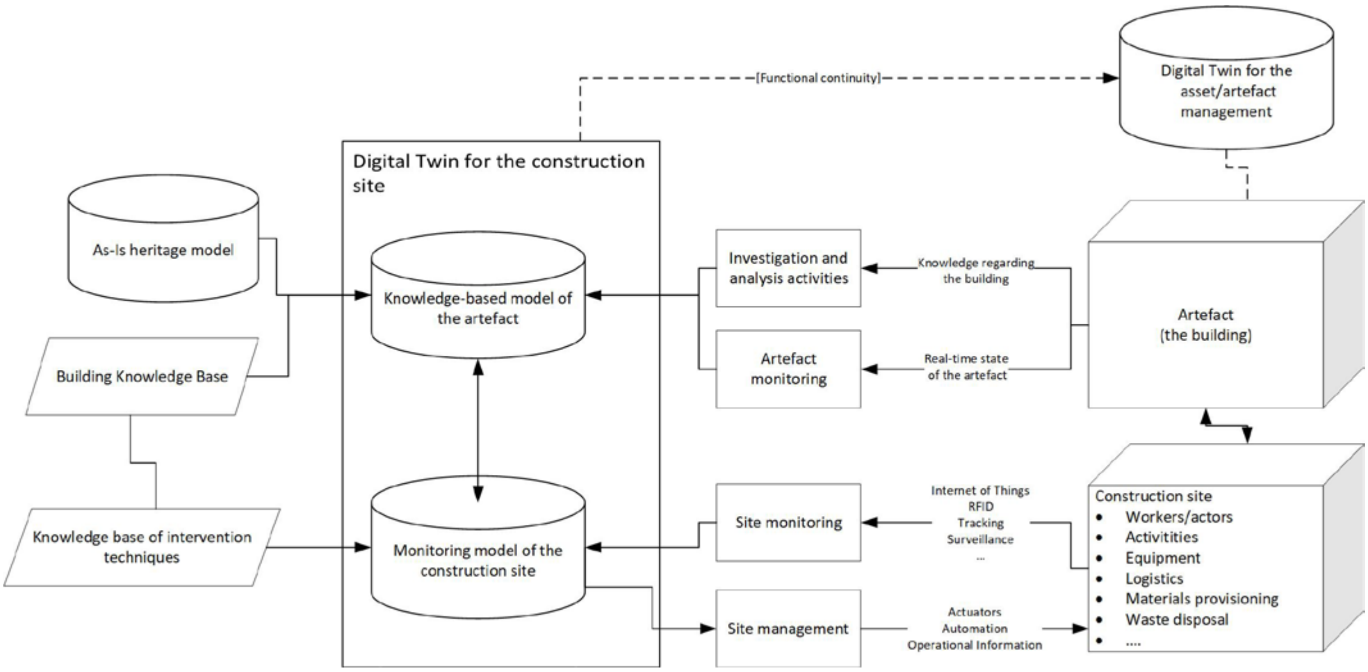

Fig. 3. *Relational Schema of the DT for built heritage recovery. Artefact knowledge and construction site monitoring models, integrated as part of the built heritage information system.*

base for decisions and actions in the recovery site, such as the choice of intervention and/or recovery techniques according to historic construction techniques. The DT of the recovery site is one of the components of a complex digital information system that accompanies the entire process, and that sees its natural completion in the DT for the building management, accompanying it after the conclusion of works. This highlights the real impact of this transformation of the information process, which sees the transition from the traditional concepts of "as-built" and "logbook" to a dynamic information system, a sort of on-board computer that supports management operational works and maintenance activities, also in predictive mode. The DT of the recovery site emerges as an integrator of the various specialized disciplines that contribute to the intervention on a historical building, overcoming the well-known problem of the separation of competencies and favouring collaborative solutions that are attentive to the various instances of the building, balancing conservation needs and functional requirements with the perspective of possible reuse. For implementing a DT for a recovery site, technology and process levels are identified, which must be designed and balanced about the complexity of both the site and the building (Fig. 4).

The process level focuses on the activities, phenomena and, more generally, those disciplines that produce information – obtained through investigations or intervention on the artefact – that can be collected, integrated into

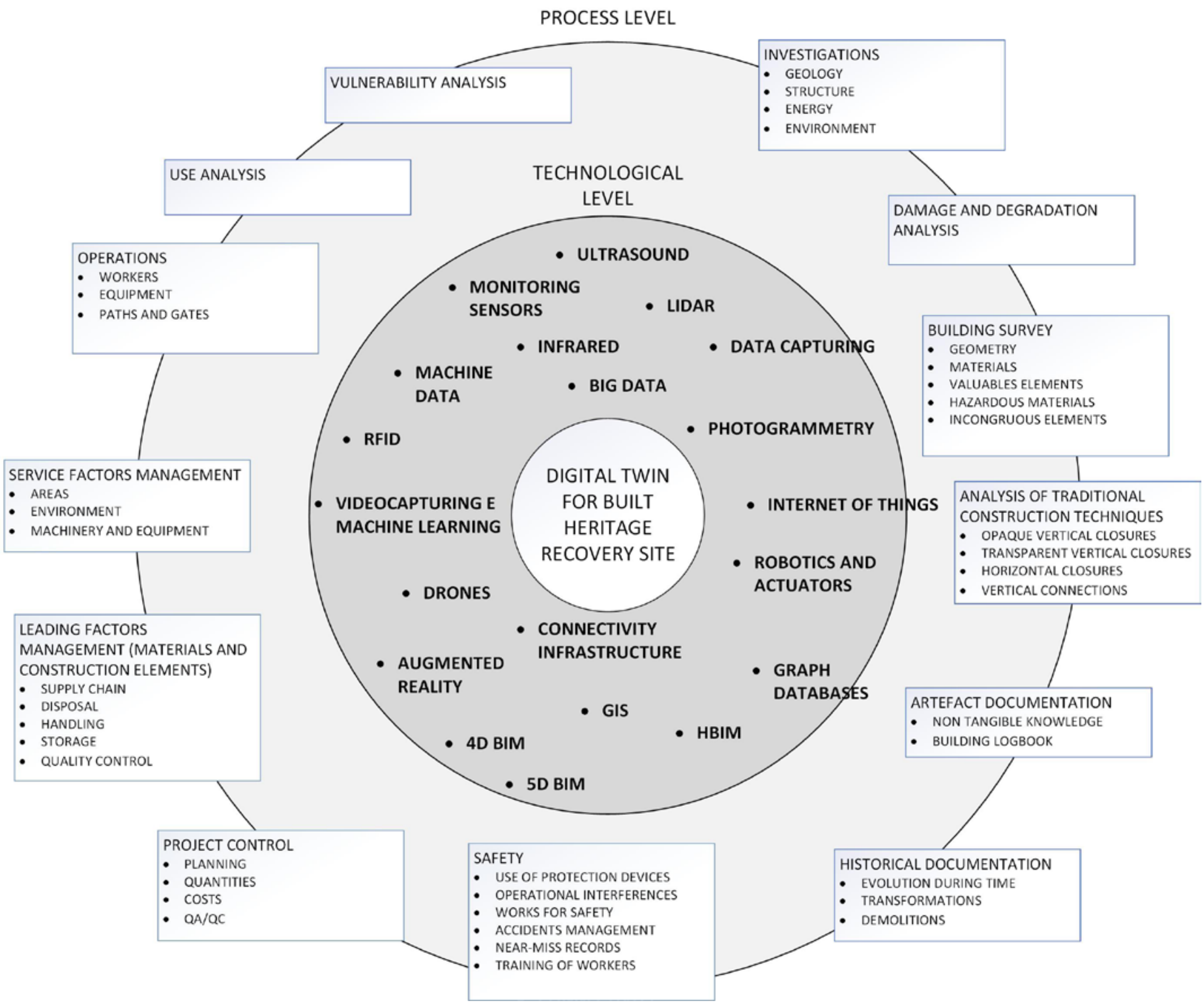

Fig. 4. *Process and technological levels of DT for a built heritage recovery site. Many technologies and digital approaches can be integrated to respond to information requirements related to different key processes in the built heritage practice.*

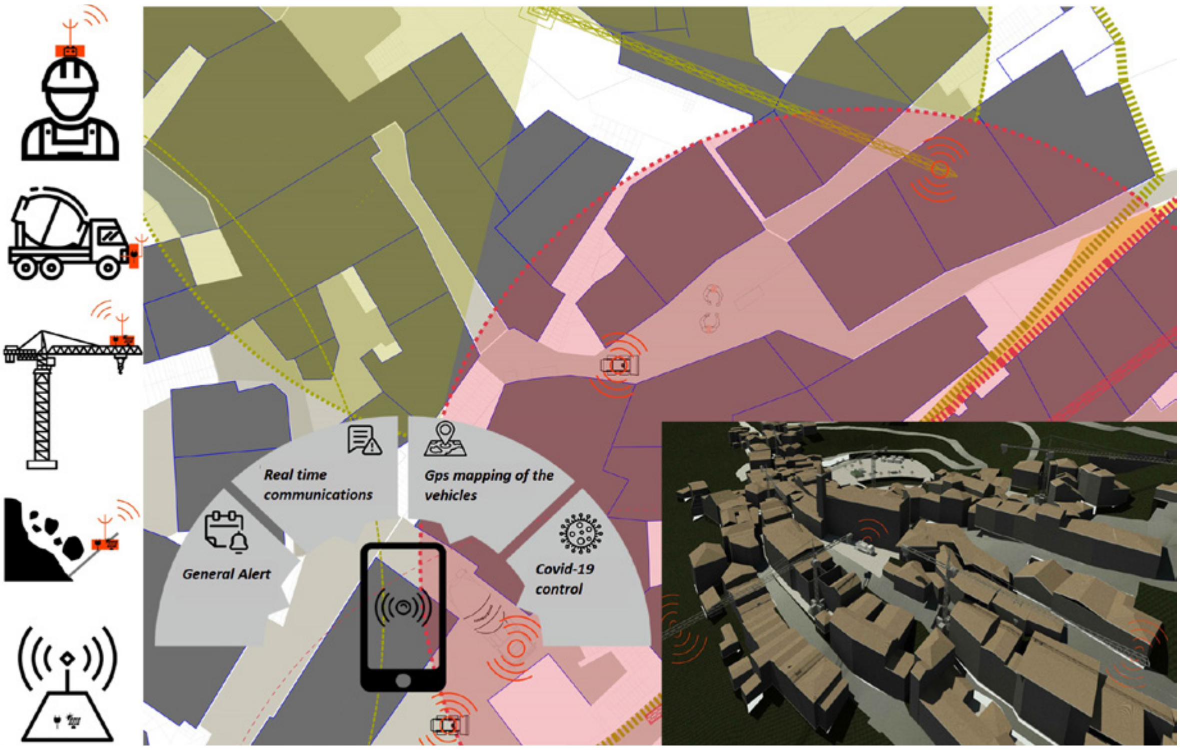

Fig. 5. *Remote control plan for the construction site management of the small city of Fossa.*

the DT and support the management of the recovery site. Activities and recovery site domains contribute to the definition of this level – such as the project control, safety, material management and site operations domains –, as well as specific activities aimed at gaining in-depth knowledge of the historic building, such as surveys, historical documentation, analysis of construction techniques, or damage and decay studies. The technological level focuses on the methodologies and digital approaches that will be used to collect data and information from the construction site and the building itself, organizing them within the DT model and allowing their re-elaboration to support the different decision-making processes both during the intervention phases and throughout the entire life cycle.

A pivotal role at the technological level is played by BIM, which in its various articulations (4D, 5D, HBIM, integration with GIS), provides a way to three-dimensionally represent objects structured in a relational semantically extended database. Other recognizable areas at the technological level are reality capture, which implies different methods of acquiring information (such as Lidar, photogrammetry), or the IoT and sensors domain, usually adopted for operations monitoring in the construction site (Fig. 5). Other areas include data formalization and processing, for example, through technologies such as Big Data or graph databases, and the one related to the return data to the construction site, through actuators or augmented reality interfaces.

5. ADVANTAGES AND CRITICALITIES

Adopting the DT to recover the built heritage brings many advantages in this specific area. Among the most disruptive and impacting ones, there is undoubtedly the transition from the traditional construction industry to a digitized one, the benefits of which are measured in terms of optimizing the management of flows and implementing the control and quality system. Furthermore, the adoption of the DT allows the creation of a logbook of the building, which, if generalized to the building fabric in its entirety, would allow the definition of a database helpful to catalogue and better comprehend the historical and architectural heritage. The usefulness of this tool is not only for cognitive purposes but also from the point of view of maintenance activities, end-of-life manage-

	Strengths - Advantages	*Weaknesses - Disadvantages*
Adoption of the DT for the recovery of the historical-architectural heritage	- Creation of an "identity card" of the historical construction	- Need for a transition phase for all actors in the process to adopt the DT
	- Optimization in the management of all flows, tangible and intangible	- Professional training of all actors according to the different levels of specialization
	- Determination of process innovation to define new professional skills	- Guarantee of privacy in the implementation of the approach according to the digital model
	- Transparency of the process (particularly important in the case of public works)	- Cost of infrastructure and connection systems
	- Implementation of attendance control and training/updating of workers	- Significant initial investment in terms of time and resources
	- Optimization of the control concerning the progress of the work	- Need for specific sector regulations
	- Quality improvement thanks to the reduction of errors and omissions	- Interoperability issues between software and systems
	- Building site security	- Change of the workflow
	- Rationalization of the control system concerning the maintenance process	- Difficulty in real-time access to data external to the building site
	- Automation in the cataloguing of materials with a view to their management at the end of their life	
	- Transition from the traditional construction industry to a digitized one	
	- Creation of a database to catalogue and to know the historical-architectural heritage, if the DT were generalized to the urban fabric	
	- Active collaboration between all the actors of the construction process	
	- Overcoming the limits of BIM in the graphic representation of irregular geometries thanks to the integration of other survey systems	

Tab. 3. *Critical analysis of the main advantages and disadvantages linked to the adoption of the DT for the recovery of the historical and architectural heritage.*

ment of materials and long-term compatibility analysis. Lastly, it would also be useful in case of natural disasters that frequently result in the loss of paper archives. The adoption of DT will also provide transparency of the construction process in its entirety and favour the selection of integrated technological solutions to better exploit data and information.

As with every process innovation, the adoption of the original twin requires a transition phase in which to invest time and resources. The change in the workflow and the adaptation of the professional training of all the actors in the process could lead to delays in its adoption, as well as the need for specific regulations and interoperability problems between software. Additional aspects of significant criticality are inherent data protection, also in terms of privacy and vital investment in infrastructure and connectivity, which are essential to ensure the intangible flow of data. Table 3 summarizes the main advantages and difficulties related to adopting the DT for the recovery of the historical-architectural heritage.

6. APPLICATION SCENARIOS AND ENABLING TECHNOLOGIES

Considering the discussed advantages and limits of DT application to the built heritage activities, it is possible to identify some application scenarios related both to a single building or a system of multiple buildings. As previously discussed, one of the key points regards embedding knowledge related to the artefact within the DT. For instance, studying an architectural heritage artefact involves a set of location-discrete investigations that do not fully represent all the stratifications and materials that compose a masonry wall and its evolution over time. Often the actual configuration of a wall is discovered only during the intervention activities when the plaster's superficial layer is removed. In the same way, often dangerous materials (i.e. asbestos) are discovered in the building or the area. All these emerging issues lead to design revisions, with a consequent increase in costs and delays. The application of a DT in this domain can enhance the data collected during the site operations, provide an immediate update of the artefact's state and configuration, and support faster decisions and actions.

A continuous application of DT during the management and operation of the building heritage could also help in tracing the interventions on its components, as well as shifting from planned – and often inefficient – maintenance to an "on-demand" approach, where is the building itself communicating the required maintenance actions. These two application scenarios highlight the advantages related to building investigation, documentation, and management. Similarly, the DT also generates relevant impacts in the construction site domain, such as real-time monitoring and management, safety control and materials management. The monitoring of works (Fig. 6) allows the real-time management of operational interferences not considered during the planning phase or caused by variations during the project execution. This provides additional benefits in terms of safety because it generates a contextual update of preventive actions. Safety is the field where DTs are now showing major efficiency and impacts. During the removal of supporting structures during recovery interventions caused by earthquakes, real-time structural monitoring ensures the warranty of safe operational conditions, avoiding quick collapses or accidents. Similarly, DTs allow for the coordination of vehicles in the construction site areas that, in the case of built heritage in historic cities, are usually relatively small, crowded and congested.

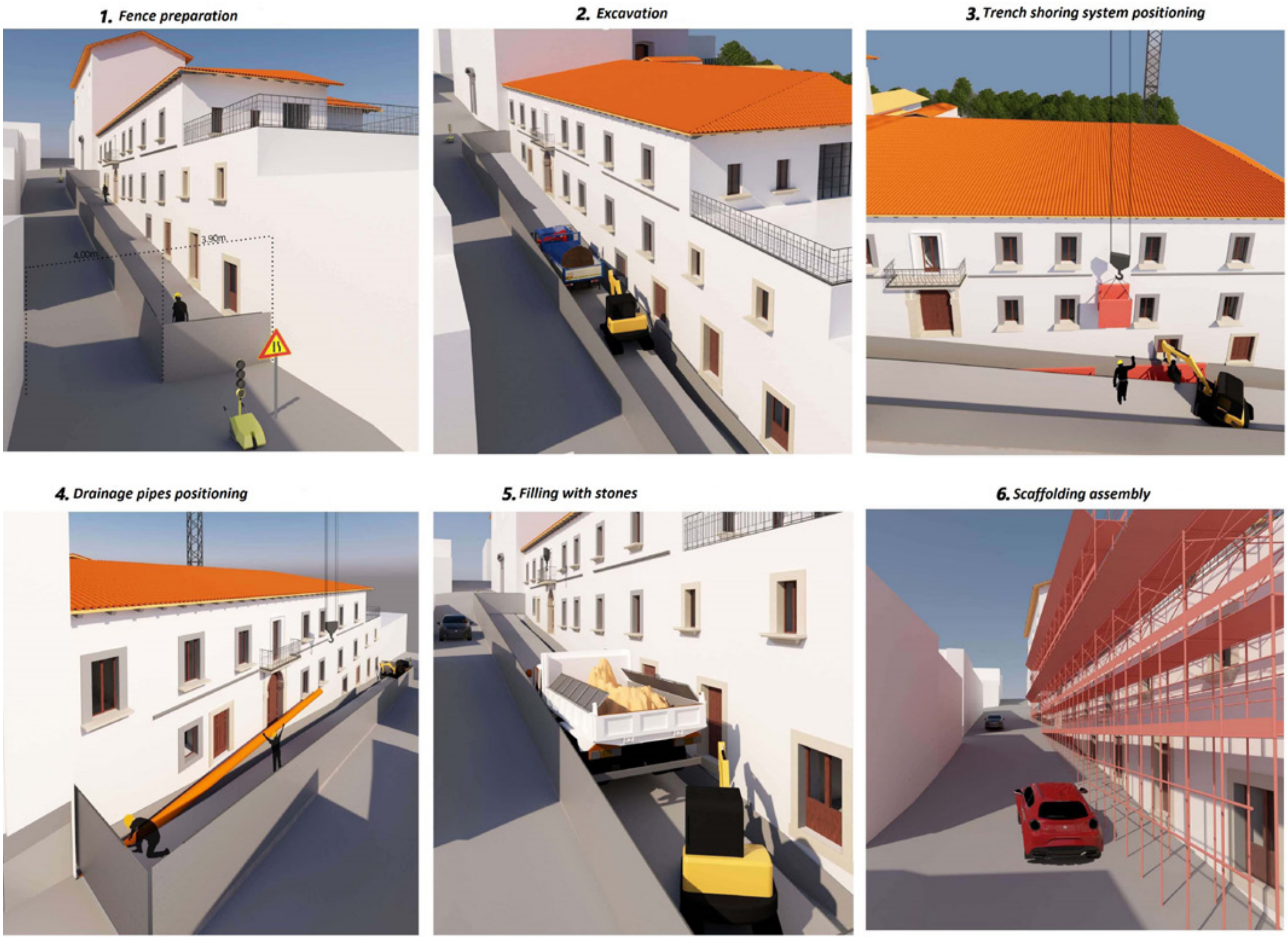

Fig. 6. *Operational models. Information models are used to support operational planning and real-time monitoring of works execution, including machinery and temporary works.*

Another application scenario relates to the construction materials management in the perspective of tracing its handling and favouring its reuse, also in terms of compatibility with the traditional construction techniques. DTs can then support the classification of those materials discovered on site (for instance, in terms of colors, weight, composition, quantity, origin, and location), reducing their transformation into waste.

In implementing a DT to construction sites, and specifically to those focusing on existing buildings, the technologies deeply influence the information collection and representation. They can be applied "vertically" to control some specific site phenomena or "horizontally" to formalize and control data related to different aspects. Other technologies are then considered to represent the information collected and organized in information models, usually based on BIM approaches. To complete the framework, it is also essential to conceive an efficient infrastructure that allows the information to flow from the site to the information model and vice-versa.

The technologies necessary for the application of DT techniques to the built heritage recovery site are already well-consolidated in the architecture and construction practices. Instead, what we consider as a shifting point is their integration to allow an extended and enriched control of a complex, dynamic system such as a recovery or construction site. Under these five scenarios, some use cases have been identified (Tab. 4).

7. CONCLUSIONS

This work investigates the possibility to extend DT concepts and approaches to the construction site within the built heritage scope, discussing criticalities and features

DT areas of application	*Use cases*	*Enabling Technologies*
Update of the artefact state and configuration	Representation of discovered states of the artefact different from the assumed ones. Presence of valuable elements to be preserved. Management of dangerous materials initially not detected in surveys and inspections.	Virtual reality Cloud and big data analytics Augmented Reality HBIM RFID systems Reality Capturing
Continuous monitoring of the site and works progression	Detailed monitoring and steering of operations on site. Real-time tracking of works progression.	4D BIM Video capturing
Maintenance monitoring	Automatic tracking of maintenance activities often performed without sufficient documentation or only in case of systems failure.	Machine learning BIM Augmented/mixed reality
Safety	Monitoring of structural elements during demolitions [26]. Monitoring of environmental factors (dust, pollution, asbestos, etc.). Support to the removal of temporary works and structures placed during earthquake emergencies to detect potential collapses. Control of machinery and vehicles, in particular in urban works where areas limited availability may increase collision risks. Management of site accesses in presence of limited road networks. Works in confined environments or underground spaces: monitoring of workers' conditions.	Sensors / IoT Wearable devices Image Capturing + deep learning Black boxes Acoustic actuators RFID systems e NFC Early warning
Materials management	Classification of materials recovered from demolitions and removals to favour their reuse. Real-time management of stocking areas, material provisions, materials handling and disposal.	RFID Systems Reality Capturing BIM Beacons GIS Vehicle tracking

Tab 4. *Areas of application, use cases and related enabling technologies for the DT implementation on built heritage recovery sites.*

of built heritage recovery sites, providing a solution based on two interconnected DTs, one dedicated to the knowledge representation related to the artefact and one dedicated to the construction site sensing and monitoring. In order to support further implementation of DT in this field, a process level and a technological level are presented and connected, and significant advantages and criticalities are discussed.

The study has shown how digital twinning processes have great potential in their application within the complexity of a construction site dedicated to the recovery of built heritage. In fact, to the well-known contribution of DT to real-time management of construction sites (in terms of logistics coordination, safety monitoring, material handling, etc.), some additional benefits emerge with the specific occurrences and issues that arise in the investigation, intervention and recovery activities performed in a built heritage construction site. The main advantages also relate to the continuous update and monitoring of the state of artefact from different perspectives such as historical layering, structural behaviour, and ancient materials tracking. The possibility of sensing both the artefact and the construction site allows for real-time steering of operations and activities, optimizing resources (humans and/or machinery) and reducing delays and inefficiencies related to the decision processes required in the presence of unexpected emergencies or discoveries. In this scope, it is important to state that the impact of digital twinning applications increases as per their ability to generate an immediate or at least near-real-time reaction. For this reason, further development of this research will focus on the development of methods and algorithms to enhance the responses of the DT, balancing predictive analytics and responsiveness to emerging phenomena. Machine learning algorithms and statistical analysis represent promising techniques to close the sensing-reasoning-acting cycle, especially if integrated with the adoption of actuators, robotics, and autonomous systems.

Authors contributions

The authors' names are listed in alphabetical order. Both authors equally contributed to the conceptualization of the paper. Author 1 investigated the requirements, role, and adherence of DT application to built heritage construction site domain, while Author 2 focused on the platform's conceptualization and the definition of its layers. Both authors contributed to the discussion of various scenarios and the writing of the paper.

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