URBAN CENTERS MANAGEMENT: A DIGITAL TWIN APPROACH

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ABSTRACT: *The management of the built environment is a topic that requires reference to the management of complex systems. In fact, the variety of domains involved means that the management of urban centers is not only complicated, and therefore it is not enough to model a set of rules that are representative of phenomena related to the real environment. Not only that, but what is evident is that emergency management lacks the ability to access real-time information that could be decisive. Having tools that provide real-time data, that reprocess it, and that are able to provide an enriched and slightly predictive view of what is happening offers the possibility of having a real impact in the management of the built environment. In this sense, digital twins are a valuable approach to achieving the desired results. Digital twins through the integration of technologies such as Internet of Things (IoT), simulators, Artificial Intelligence (AI), and Augmented Reality (AR) technologies make it possible to develop systems capable of exploiting the concept of collective intelligence, in a digital version, through a large number of heterogeneous agents working according to stigmergic mechanisms. This research work aims to propose its own architecture of digital twins for the management of resilient urban centers, with particular reference to the management of post-earthquake reconstruction scenarios.*

KEYWORDS: *Digital twin, urban environment management, urban centers, smart cities, emergency management, BIM.*

1. INTRODUCTION

The 2030 Agenda for Sustainable Development (Agenda, 2030) has set 17 Goals among which Goal 11 is defined as follows "Make cities and human settlements inclusive, safe, resilient and sustainable." In addition, there is a recent trend that identifies an increasing population shift to urban centers. According to the United Nations, over 55 percent of the world population inhabited cities in 2008, with the percentage expected to rise to 68 percent by 2050 (UN 2019). All of this implies the need to rethink cities focusing not only on the sustainability of these centers of aggregation but also with the intention of making them resilient to change and responsive to unexpected events.

It should be noted that urban centers, cities are complex organisms (De Toni et al., 2013). This implies that it is impossible to manage the processes affecting them through rules, but a holistic and integrated approach is needed. One approach that has been pursued for years to the problem of managing urban centers is the development of smart cities. The term smart city is said to have first appeared in the middle of the 1990s, when the cities promoted themselves after introducing new information and communication technology (ICT) infrastructure or e-governance services, or when attracting technology companies to provide new economic growth to the region (Hollands, 2008). Anyway, a smart city should go beyond the mere use of ICT systems. It is expected that a smart city should improve the quality of life of its citizens, while simultaneously simplifying the management of the city. In some cases of developing smart cities the term "smart" was referred to an automated mechanism introduced to perform the desired activity within a given domain (Ahad et al., 2020). Other smart city paradigms relate technology more directly with innovation and human capital development, based on the concept that technology can give a city's constituents the power to innovate, create, participate in society and solve problems collectively for the common good (Angelidou, 2015). In any case the current research on smart city does not fully address the complex nature, conflicts and interdependencies of the smart city objectives (Shamsuzzoha et al., 2021).

Meanwhile in recent years we assist the rise of Building Information Modelling (BIM) approach in a wider way than the one that wants it to represent but a small part (a narrow building-level view) within the wider environmental context. BIM's massive introduction into the processes of the built environment has led to a higher level of digitization of all kinds of information, as this approach allows the achievement of high performance only when embedded in digital systems and platforms. This evolution of BIM should be carefully framed within a paradigm that factors in people, processes and new emerging technologies in an increasingly interconnected world (Boje et al., 2020).

In this scenario it is expected that residents of future smart cities will be exposed to unprecedented amounts of

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real-time information on a daily basis (Du et al., 2020). This data also coming directly from people and equipment and assets can contribute to the development of a stigmergic system. Stigmergy is a communication method used in decentralized systems by which individuals in the system communicate with each other by modifying their surroundings and leaving traces (Debreu Netto et al., 2015). Indeed, the scenario of the 21st century is increasingly characterized by interactions between the physical and virtual worlds, thanks to the progressive creation of a global connective space with a high intensity of information flows, the potential of Information Communication Technology (ICT), as well as the Internet of Things (IoT), of Big Data, Virtual and Augmented Reality, and the spread of progressively more powerful computational devices, whose high processing capabilities, albeit without discretion, are being defined, namely the so-called Artificial Intelligence and Machine Learning, and related predictive algorithms (Cinquepalmi and Pennacchia, 2020). All this leads to a currently emerging paradigm and that is the Digital Twin (DT) paradigm. Other industrial sectors than construction have been developing digital twin-based concepts over the past decade, but this approach has made its first appearances in the AECO sector only over the past few years. Digital twins are a digital replica of their real counterparts. A DT is always a representation and for this reason unlike its physical counterparts, it is not an all-or-nothing proposition. DTs can be tailored so as to choose to collect information only about features that have value for the stakeholders involved or for the aim it is developed for. There is a crucial aspect in DT that differs them from simulation models and even common smart cities paradigm (Fig. 1) and it is prediction. Numerous examples have shown how digital twins can continuously monitor operations and identify abnormal behaviors, allowing human operators to react promptly and reduce downtime (Arup, 2019). In any case in the longer-term, it is evident that no single DT will be sufficient for modern complex cities: in a smart city scenario, independent DTs of various assets will need to communicate and cooperate, providing feedback to a central decision making "hub" or city-level decision makers (Pregnolato et al., 2022).

This paper presents a framework for implementing digital twins in urban centers. Building on what DA (Silva et al., 2018) showed as a technology for the smart city, our proposal is to include a reasoning layer through real-time data, which is one of the aspects that differentiates DT from the rest: short- to medium-term forecasting to provide decision support to the decision makers involved. The scenario that is particularly referred to is that of emergency management. Since city management requires dealing with complexity the digital twin is the ideal method to take into account different data and analysis in an integrated way. Starting with an analysis of the scientific bibliography concerning the digital twin and smart cities illustrated in the next section, the article aims to focus on real-time management and the insights that DTs can offer to support the management of the unexpected. Case study on which to implement the proposed framework will be presented.

2. LITERATURE REVIEW

Performing a search on the Web of Science, using the keywords "digital AND twin* AND "urban" AND "cit*" in

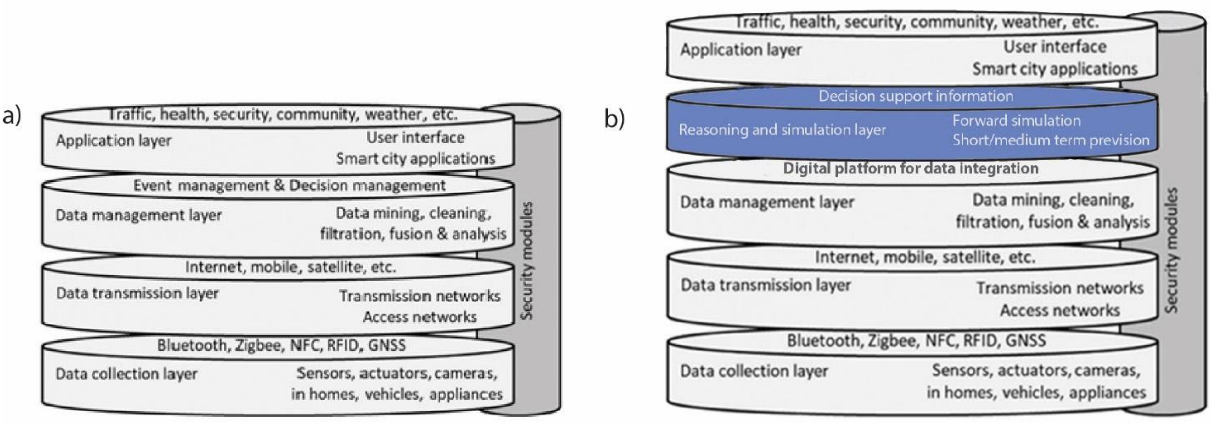

Fig. 1: a) Smart city architecture proposed by Silva et al., 2018; b) DT architecture whose fundamental layer that differentiates this from Smart Cities is the Reasoning and simulation layer that allow for short/medium term previsions supporting prompt decision-making particularly significant during emergencies.

a time range from 2006 to the present, yielded a total of 379 articles, most of them in the area of Computer Science (21.1%) and Engineering (17.8%)(Fig. 2). Particularly in relation to the latter area, there were only 153 papers in total (Fig.2). Furthermore, the metric analysis showed that most of the publications are concentrated in the last

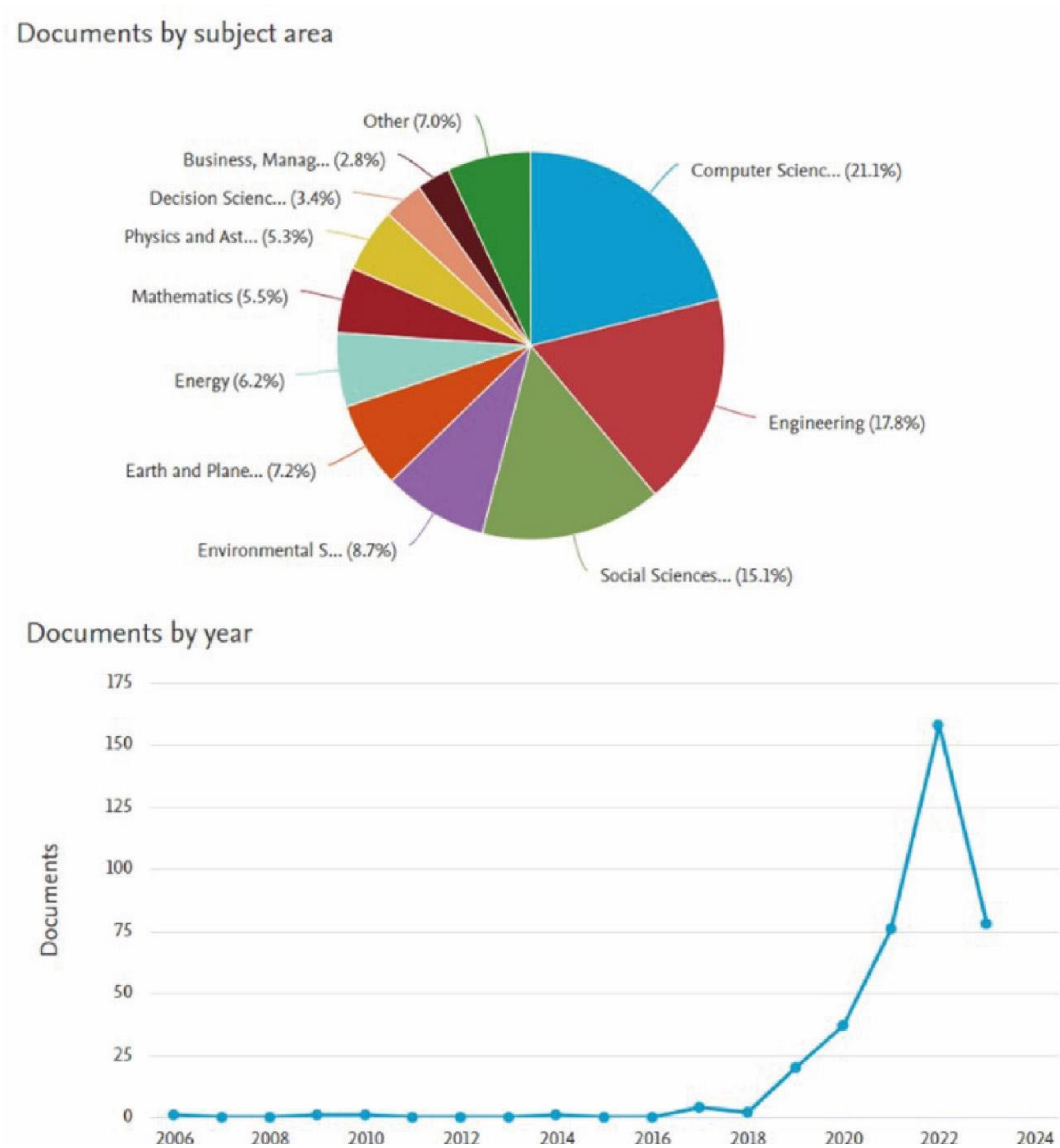

Fig. 2: The graph above shows the number of papers containing the terms "digital", "twin" and "urban" in the period from 2006 to 2023 divided by subject area. The graph below instead shows the trend (referred to the same period of time) of papers with the same key words comprised in the area of Engineering. The spike in the adoption of certain terms from the years 2021-2022 is evident.

five years, i.e. from 2018 to the present (Fig. 2). This data highlights how the topic is of recent interest in the international scientific community. From the 153 articles identified, a screening was first carried out by reading the titles of the articles and discarding those of no interest. Subsequently, the abstracts were read and the search areas were identified. These ranged from the topic of infrastructure and urban mobility to that of the construction and built environment. For each area, an article of particular interest to the study was identified, argued below and summarized in Table 1.

Gang Yu et al. (2021) focus on urban infrastructure, proposing a digital twin framework for the operation and maintenance of tunnels. Haishan Xia et al. (2022) analyze the BIM GIS relationship within the digital twin framework used to support smart city development. The study is also conducted in the area of infrastructure, in relation to rail transport. Salem and Dragomir (2022), on the other hand, develop a literature analysis of the construction project management using digital twin approach. Lv et al. (2022), Corrado et al. (2022) and Nica et al. (2023) carry out their research in the field of urban planning, also from a sustainable perspective (Corrado et al., 2022; Nica et al. 2023). In particular, Lv et al. reflect on the importance of using DTs urban platform to improve the future planning vision. Yu et al. (2023) analyze the support that new digital technologies can offer in the creation of smart cities, as does Wenhua Huang et al. (2022) in relation to the Internet. Other areas of interest are those concerning the use of the Digital Twin for the management of the built environment (Rotilio et al., 2023) and urban mobility (Yeon et al., 2023).

The research performed showed that the topic of DT in support of smart cities is an area of study of recent interest within the international scientific community and that it is addressed in specific areas, lacking a global and multidisciplinary approach. This research gap highlights how further research is needed, which this article aims to help bridge. Indeed, the main objective of the research presented here is to provide a framework that, based on a DT approach, supports the management of the complex contexts typical of post-disaster reconstruction in which many issues and disciplines converge. A demonstrator will be presented for framework validation.

Table 1: Summary of the main references analyzed

Reference, year	Aim of the research	Results	Search area	Case study
Gang et al., 2021	To propose a digital twin-based decision analysis framework for the O&M of tunnels	Results show that the framework can provide efficient and automatic decision analysis support for the O&M of tunnels	Urban infrastructure maintenance, operation and evaluation	Fault cause analysis of fans in Wenyi Road Tunnel in Hangzhou, China
Haishan et al., 2022	To study the combination BIM and GIS for the urban digital twin to support sustainable smart city design	A professional disconnect and fragmented composition pose challenges in the field of GIS and BIM integration. Future research should focus on smart city planning, updating, management; ontology-based GIS and BIM data integration platform; and operation; and the collaborative management of urban rail transportation engineering	Rail trasportation	-
Salem and Dragomir, 2022	To review the literature on construction project management through the lens of digital twins	Authors propose a framework for analyzing and supervising the development of digital twins that uses three main stages: the BIM; the existing monitoring and actuation digital twins; the artificial intelligence	Construction area	-
LV et al., 2022	To promote the expansion and adoption of Digital Twins (DTs) in Smart Cities (SCs)	The construction of DTs urban platform can improve the city's perception and decision-making ability and bring a broader vision for future planning and progression.	Urban planning	-
Corrado et al., 2022	To propose a comprehensive approach that takes the multiple facets of sustainable urban planning into consideration	A metric-driven framework for sustainability planning that understands a city as a sociotechnical complex system was proposed	Sustainable urban planning	Buildings in the Technical University of Crete campus
Nica et al., 2023	To inspect the recently published literature on digital twin simulation tools, spatial cognition algorithms, and multi-sensor fusion technology	Internet-of-Things-based smart city environments integrate 3D virtual simulation technology, intelligent sensing devices, and digital twin modeling	Sustainable urban governance networks	-
Yu et al., 2023	To study whether and how current practices based on digital twin technology can help the development of smart cities in China	The research provide suggestions for the development of digital twin technology-based ecosystems in emerging economies	Smart cities	China
Wenhua et al., 2022	To propose a basic concept of digital twin, and gives the construction method and possible applications of the energy internet digital twin	The key problems solved by digital twin technology are detailed and CloudIEPS, an energy internet planning platform based on digital twin, is introduced	Urban infrastructure	-
Rotilio et	To realize a first extended	Digital Twin is exploited as an adaptive	Built environment	DT

al., 2023	framework enabling the implementation of digital twins in the built environment	system for the built environment, as a support to optimize post-disaster reconstruction processes with a focus on reactive security management		demonstrators in the laboratory
Yeon et al., 2023	To introduce DTUMOS, a digital twin framework for urban mobility operating systems	DTUMOS is a versatile, open-source framework that can be flexibly and adaptably integrated into various urban mobility systems. His novel architecture combines an AI-based estimated time of arrival model and vehicle routing algorithm	Urban mobility	Large metropolitan cities including Seoul, New York City, and Chicago

3. RESEARCH METHODOLOGY

The proposed application framework for the development of DTs to support the management of urban centers begins with the identification of needs. It should be kept in mind that a DT however comprehensive is always a representation of certain components of reality. For this reason starting from the identification of needs or we could say critical issues for which decision support is desired can begin to design the digitization of the real world. This analysis can only start from the dialogue with the stakeholders concerned, the administrators of the territory (Public Administrations) and the decision makers who will then be the end users of the product.

The critical issues and needs thus identified lead to a second analysis concerning which aspects, parameters or agents need to be monitored in order to collect data useful for managing the identified issue. The connection in fact between the real world and the digital world is given by the Data Integration Layer (that will be better explained in the next section) which collects data through the use of the most suitable technologies. The choice of the latter also comes from a thorough analysis not only of what data needs to be collected but also of the context, the instrumentation possibilities of the environment, the data transmission technologies themselves, etc. Once the data have been collected and integrated with each other, we move on to the use phase.

As previously mentioned what makes a digital twin different from simulation systems is the ability to make short- and medium-term predictions by exploiting collective intelligence. To do this, it becomes necessary to identify the best tools for this intelligence to emerge and be recognizable and interpretable. Artificial intelligence tools, Bayesian networks, and game engine-type agent simulators are some of the possible means of interpreting data by highlighting patterns or recognizing behaviors, applying multifactor interaction knowledge on problems, or performing high repetitions of random simulations to probe all possible scenarios. Depending on the data collection method, the subsequent possible processing also varies and thus the choice of the two components of the DT is strongly influenced.

Finally, the last aspect that profoundly affects the system is how the information resulting from the processing can be transmitted to the relevant stakeholders. The first choice to be made is whether it will be information used in the back office or directly on site. In both cases, the solution involving the implementation of a cloud platform is the best since it allows more immediate access to the data even from smartphones. In the case of information displayed directly on site in addition to the previously mentioned smartphones, solutions involving augmented, diminished or mixed reality can also be used. Although tools for displaying information as holograms are not yet widespread on a large scale, the power of superimposed visualization is for many applications of extreme importance. However, it should be kept in mind that recently registration techniques are being developed such that overlay visualization can be achieved even with the much more common smartphones.

In the following paragraph the application of what was introduced in the methodology will be translated into the architecture of the proposed system.

4. A FRAMEWORK FOR THE IMPLEMENTATION OF DIGITAL TWIN IN URBAN ENVIRONMENT

We are sometimes faced with some confusion in differentiating simulation systems from actual digital twins. There are two main characteristics that put together determine and differentiate a DT from the rest: real time and short- and medium-term prediction. The forecasting capability that is the one that most characterizes a DT is achieved by an intelligence component that can predict unexpected situations and propose optimized solutions based on data from the physical layer in real time. The proposed integration methodology for an optimal DT implementation involves the development of a framework architecture that consists of four layers added to the physical one: the data acquisition layer, the data integration layer, the digital twin modeling layer and finally the user interface layer renamed the presentation and service layer (Fig. 3).

The physical layer refers, in this case, to the urban environment that is the object of the digital twin. Buildings, roads and facilities of cities are all considered since this will enable a valuable support to decision. The different level of scale of assets covered and the multi-domain visualization of information integrated with each other will provide a look at all crucial aspects at once.

Data acquisition layer (Data collection layer in Fig.1-b) is a functional representation of the interface between the physical layer and the framework and is aimed to fetch data to digital models. In this layer are managed gathering technologies and transportation data protocol parsing. Data can be divided into two distinct categories: static and dynamic data. Static data are related to the configuration of context, thus not changing continuously. It includes preliminary survey data and characterization of physical asset (e.g. BIM and GIS models, Point Cloud models, etc.). The purpose of collecting these data on an urban scale is to report a representation of the built environment as built and in its current state of preservation. Given the heterogeneity of the type of constructions objects of the representation (buildings, roads, bridges, infrastructure) data will also have heterogeneous formats and sizes, as well as different scales of representation of the data. Dynamic data on the other hand are related to observations about relevant aspects for the behavior simulation of the physical system. Dynamic data are typically transported in XML or JSON format. Cameras, wireless sensors, citizens' smartphones can all contribute to the acquisition of

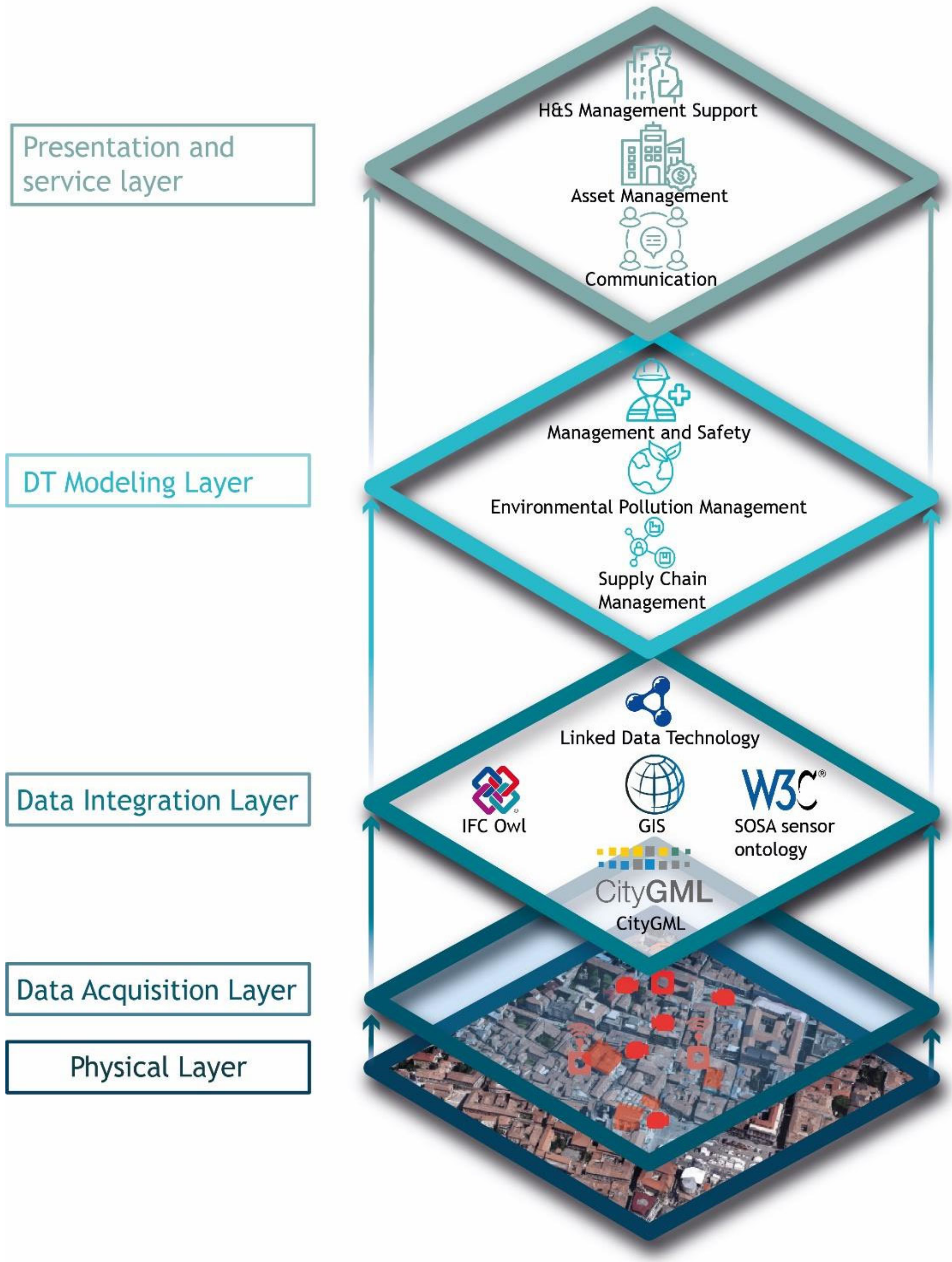

Fig. 3: DT for uban centres proposed architecture.

dynamic data, and by wisely choosing their placement these help create a stigmergic environment in which it is the assets, equipment, and people themselves (whether workers or citizens) that supply the DT with data.

Representation could be solved with the adoption of the Semantic Sensor Network Ontology (SOSA). SOSA ontology is recommended by the World Wide Web Consortium (W3C) for describing sensors and their observations, the involved procedures, the studied features of interest, the samples used to do so, and the observed properties, as well as actuators. Procedure for data acquisition optimization are fundamentals so as to avoid huge amounts of useless gathered data to analyze and improve the efficiency of the system.

Data Integration Layer will be in charge of integration of data at different scales (such as BIM and GIS representations), of different formats, and multidisciplinary. Beside this first task of data integration layer it has to be taken into consideration that most of popular data models (e.g. IFC, CityGML) do not claim to be based upon a formal Top Level Ontology since they have been developed pragmatically over years, and have been validated by practice. After the definition of the industrial exchange format IFC (Industry Foundation Classes), an important step in the direction of extending the scope of building data models is the recent introduction of IfcOWL ontology standard which is the Web Ontology Language format of IFC. This advance goes towards the embracement of Web of Data technologies to model the context of interest (buildings and assets). On the same line, research methodological approach is inspired by the expected benefits obtainable with Web of Data technologies such as the ability to granularly link data from different models. Web of Data consists of two technologies that are built upon the basic Web then relying on Universal Resource Identifiers (URIs) and Hypertext Transfer Protocol (HTTP): Semantic Web: RDF (Resource Description Framework) for graph-based data representation, and OWL (Web Ontology Language) for specification for shared conceptual models; Linked Data: Principles for specifying the interrelations and access across different datasets.

Both technologies contribute to the specification of the shared meaning of entities, one of the crucial problems in interoperability. This approach allows to support the integration of BIM models represented in IfcOWL with other building data referred to various ontologies directly in RDF; so many XML-based formats will also be supported such as CityGML-based format (for city scale representation) or sensor and observations data ontologies.

Then there remains the issue of data that are unstructured or do not have their own ontologies. This aspect for what concerns DT at the urban scale is extremely relevant since the vastness and heterogeneity of the elements taken into account makes the possibility of interfacing with multidisciplinary and multiscale data very realistic. A powerful framework therefore having to take this into account should contain the possibility of including new ontologies for both data and semantic links between structured and unstructured data. The framework proposed envisages the possibility of sharing data stored in RDF repository on the Web so that users can access them in a granular manner. Besides graph-based data model, schema/ontology languages, serialization formats, and query/reasoning languages, should provide a RESTful API technology for clients to interact with data.

Data Integration Layer can be mapped to Data Transmission Layer in Fig. 1-b because they methods shown also provide the means by which to communicate some of the data itself.

DT modeling layer (Data management layer plus Reasoning and simulation layer Fig. 1-b) is a virtual layer ideally containing the Digital Twin model or models. These differ according to the purposes for which they are implemented (e.g. in Fig.3 one DT for supply chain management, one for environmental pollution management and the last for H&S management). This layer contains the digital copy of the asset and the simulation tools for behavior forecasting. In the framework here proposed DTs are thought to be distributed over the cloud and connected to the framework via the internet. Different DTs are implemented by using domain specific algorithms and tools and are fed by Data Integration Layer through the REST Interface. Any DT internal structure is highly dependent on its specific domain and scope. Nevertheless, it must have a normalized external interface to link itself into the framework. Such interface is minimal and includes following data flows (usually in XML/JSON format): first configuration parameters and variables, time synchronizing clock, input and output streaming and exposed variables shared with the framework.

Finally, the presentation and service layer (Application layer Fig. 1-b) is a virtual layer on top of the framework that enables interaction with people/stakeholders. It corresponds to the RESTful API interface for retrieving information from the model integration bus. This layer is designed as a layer for distributing information to external management systems and specific user interfaces. This layer allows interaction with the population, thus also defining the DT as a tool for improving communication with and active participation of the citizenry. On the other hand, this layer is also the one that allows customers or decision makers to visualize data and possible suggested corrective actions. Again, the services toward which one can strive are diverse: three possible outputs of DTs are shown in Fig.3, namely support for site safety management, support for decision makers involved in real estate asset management, and communication with the public. It is at this level that the services that the digital twin will take care of are defined in detail, and so in a reverse engineering effort we start from here to understand at the root what data will need to be collected to meet certain set purposes.

5. CASE STUDY: L'AQUILA

The application for the proposed framework is the municipality of L'Aquila, in Abruzzo region, Italy. L'Aquila is a municipality that well represents the previously mentioned concept of complexity. First of all, it is a city that is located in an earthquake zone and periodically subjected to earthquakes that then result in subsequent states of emergency. L'Aquila is a historic city, and this entails two fundamental aspects: on the one hand, the city's housing stock is likely to be more fragile, less resilient to change, and with historical and artistic value to be preserved at the same time. On the other hand, its being an ancient city means that some infrastructure especially in the city center has drawbacks: narrow streets, uneven paving. All these aspects put together make the DT paradigm a very efficient and comprehensive method for dealing with problems.

The case we wanted to focus on is the implementation of a digital twin for safety support at construction sites and more specifically with regard to prop removal operations. In the most common post-earthquake scenarios, there is a frequent need to realize temporary shoring mainly for safety purposes, related to the use of the buildings themselves and of the adjacent public spaces (Fig. 4). Despite being conceived as temporary, the shoring is frequently intended to last more than a decade, often without undergoing revision or maintenance. Frequently they also create hindrance to the viability and free road travel because they occupy portions of public land. It is for this reason that their removal for the execution of recovery operations is a particularly delicate phase. This first demonstrator aims to test the ability of the proposed framework to integrate urban impact models of a construction site taking into account criticalities related to the removal of temporary shoring. The dismantling of this system is of great interest because it determines significant impacts in reconstruction sites, both in terms of operators' safety and organization and management.

The proposed DT will work by projecting short- and medium-term forecasts based on data streams generated by monitoring networks. These networks enable early warning strategies based on real-time predictive analysis of collected data, while also performing high-speed and qualitative simulations to assess specific risks and behaviors. The sensor network defines a fourth-level monitoring system, that is, a system that can estimate the location and extent of damage and use this data to determine the state of the overall structure, and thus its level of safety. The reference models are a simplified version of the FEM model simulator, linked to the HBIM model of the building aggregate, or structurally connected set of buildings. The DT thus implemented will work on three types of data sources: [a] sensor data from a network of sensors installed in the building aggregate and on temporary shoring, with the intent of monitoring relative displacements of structural elements, subsidence, and deformations, and [b] data communicated in real time through the sensors, arising from neighboring construction sites related to ongoing activities and positioning, vehicles and thus additional vibrations generated, and [c] contextual data communicated in real time related to urban processes that may interfere with or be jeopardized by the simple execution of temporary shoring removals or collapses.

This will enable the DT to provide valuable support during the reconstruction phase when the dismantling of temporary shoring may lead to the definition of deformation close to sudden collapse conditions. At the same time, the DT will integrate and interpret the data from the sensor network based on the three previously identified sources and generate an early warning if the limit values are exceeded. In this way, the decision maker will be informed and will be able to activate the necessary measures: stop work, if necessary, and evacuate the surrounding area. In addition to this, the DT integrated in a communication platform with the population will provide information about the works in progress so as to provide support to the citizen. Indeed, the latter could change his or her route by car if the site's workings block the passage or his or her walking route also in relation to the possible dust emissions reported by the DT. Finally, the continuous application of DT during the management and operation of the building stock could facilitate the transition from scheduled maintenance to an "on-demand" approach, in which the building itself communicates the necessary maintenance actions. Specifically, during the execution of consolidation work, the building aggregate will be equipped with a network of sensors aimed at conducting structural monitoring. The collected data are exploited to verify the performance of the buildings over time, allowing a continuous assessment of their safety and the opportunity to plan appropriate rehabilitation activities to reduce their vulnerability. The results in terms of process innovation introduced by the proposed research will support actors involved in the reconstruction and management of smaller historic centers, particularly site safety coordinators to coordinate and plan removal work.

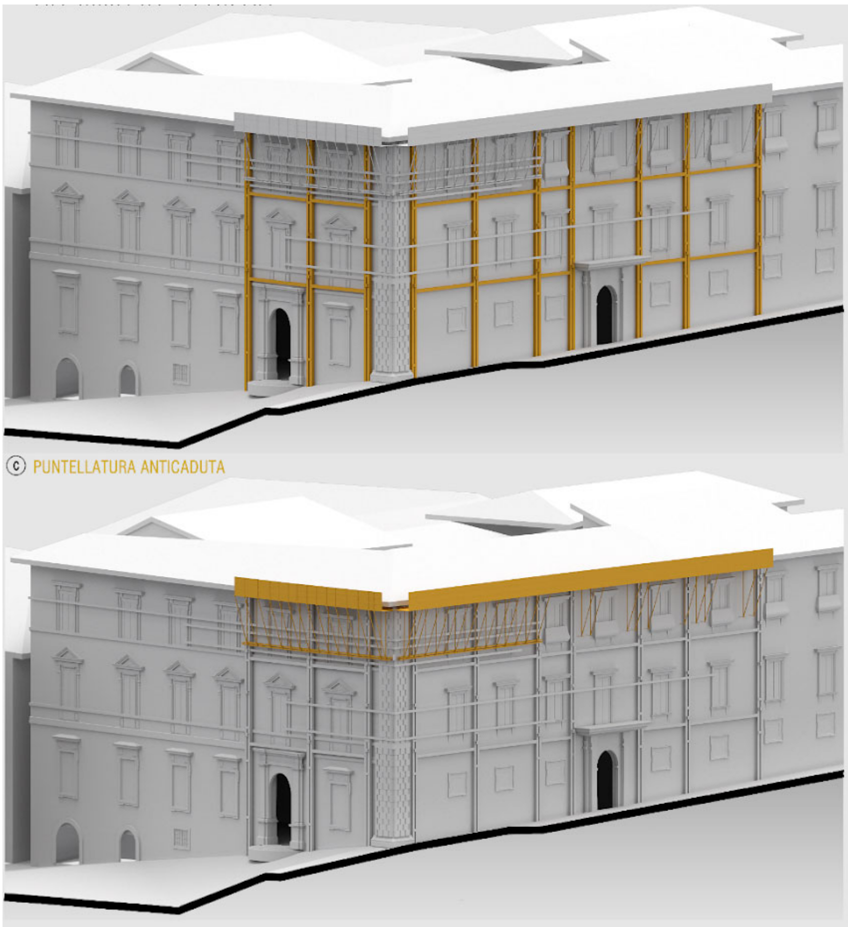

Fig. 4: Examples of shoring in HBIM for a historic building.

6. CONCLUSION

This paper presents a framework for implementing a digital twin in an urban environment that by its definition is characterized by complexity. The scenario chosen is that of post-earthquake emergency management and subsequent reconstruction phases. The configuration of an integrated system such as DTs that collect real-time data directly from the physical context allows for stigmergic systems. These imply that it is directly the environment, or rather the agents within it, that leave information on the ground for other agents. Inolte the DT through real-time simulation systems and data analysis is able to provide short- and medium-term forecasts that ensure decision support, both for stakeholders involved in land management, for those responsible for the construction and repair phases, and for the community.

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