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COGNITIVE DIGITAL TWIN FOR BUILDING MANAGEMENT SYSTEMS: A CASE STUDY IN ROME

The concept of "digital twin" is moving beyond manufacturing and industrial sectors configuring virtual models and ICT (Information Comunication Technology) systems for improved real-time data-driven management of physical assets, developing data-centric[2] processes to support the design, construction, and operation phases.

The configuration of Digital Twins is gradually becoming useful even in the AEC (Architecture, Engineering, Construction) sector, connecting physical objects such as buildings and their digital equivalent through ICT systems. In fact, thanks to the so-called Key Enabling Technologies (KET)[3] of Industry 4.0 and their progressive

[1] CITERA Interdepartmental Research Centre for Territory, Construction, Restoration and Environment - Sapienza University of Rome.

[2] According to B. Combemale, et al. data-centric approaches refer to the implementation of digital processes where data are collected and processed by predictive and prescriptive models in order to adapt the system handling the evolving data.

[3] According to the definition given by the European Commission, Key Enabling Technologies are "knowledge-intensive technologies associated with high R&D intensity, rapid innovation cycles, substantial investment costs and highly qualified employments". They have systemic relevance as they feed the value chain of the production system by

evolution (i.e. Cloud, BIM, GIS, Big Data, Internet of Things, High-speed Networking, Advanced Analytics, Robotics and Automation, Artificial Intelligence, Cybersecurity, Augmented and Mixed Reality etc.), the effective exchange of data from virtual to physical assets becomes possible.

In particular, the configuration of digital ecosystems for the built environment leads to the creation of three-dimensional information models with BIM (Building Information Modeling) approaches aiming at real-time management and monitoring of the interactions between digitized objects and their physical equivalent, creating new scenarios for efficient digital processes.

According to the UK Center for Digital Built Britain, Digital Twins are useful for assets, processes or technical systems in a built or natural environment, and if combined with machine learning methods, they may lead to predictive analytics resulting in digital decision-making support systems optimizing and automating processes.

Digital Twin information systems and workflows in fact involve the use of computing technologies in building processes, applying lean construction[4] approaches to the management of the entire lifecycle, prioritizing the achievement of smooth production flows, minimizing the variation and waste of resources[5].

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innovating processes, products and services in all economic sectors of human activity.

[4] Lean construction paradigms refer to modern management techniques in building processes which prioritize the achievement of smooth production flows with minimal variation and thus minimal waste of resources.

[5] Forbes L.H. and Ahmed S.M. (2011) *Modern Construction: Lean*

Consequently, by introducing the increasing potential of Artificial Intelligence and Machine Learning systems in a Digital Twin-based construction process, it becomes possible to optimize and automate the operation and maintenance phases with the acquisition and continuous processing of data streams from different sources, allowing to perform analysis, evaluating alternative scenarios using what-if analysis approaches[6] and promptly responding to unexpected events in an increasingly accurate way over time[7].

From a technological point of view, it can be pointed out that commercial applications of monitoring technologies are still involved in the construction process but often for specific purposes, such as laser scanning for 3D Reality Capture[8] and construction status recording, computer vision with video and 360° images for safety/security or production progress monitoring, as well as smart sensors for indoor air quality or safety monitoring.

In this framework, it seems relevant to underline the absolute need to achieve an integrated holistic approach

Project Delivery and Integrated Practices. CRC Press, Boca Raton, FL, USA; Forbes L.H. and Ahmed S.M. (2011) *Modern Construction: Lean Project Delivery and Integrated Practices*. CRC Press, Boca Raton, FL, USA.

[6] What-if analysis is the basic level of data-driven predictive analytics. as a tool able to elaborate different scenarios to offer multiple possible results. In contrast to advanced predictive analysis, *what-if analysis* has the advantage of requiring only a few input data to be processed.

[7] Koskela L (1992) *Application of the New Production Philosophy to Construction* (Technical Report # 72). Center for Integrated. Facility Engineering, Department of Civil Engineering, Stanford University, Stanford, CA, USA.

[8] 3D Reality Capture is the process of scanning and capturing sites, plants, buildings, into a 3D digital model, combining measurements and visual information.

Frequency of monitoring	ICT-based approach	Enabling technologies
REAL-TIME MONITORING	Remote sensing for real-time and predictive monitoring	BIM, GIS, Cloud computing, Laser scanning, GPS, computer vision, IoT devices, WiFi ultra-wideband, machine learning.
DAILY PERFORMANCE MONITORING	AI software for early detection	
PERIODIC (WEEKLY-MONTHLY) ANALYSIS	Agent-based simulations	
LONG-TERM/PROJECT DURATION PLANNING	Machine learning improving future scenarios	

Tab. 1 Enabling technologies for building monitoring systems.

combining different technologies and merging data from multiples sources with a consistent project database, as a useful support system for delivering specific actions and implementing efficient management strategies[9]. From this perspective, table 1 lists various ICT approaches to monitoring, according to type and frequency, all of which correspond to the enabling technologies.

Cyber-Physical systems for facility management and construction monitoring

The effective value of such “data-centric” monitoring systems for construction and facility management consists of the production of relevant awareness about Building

[9] Seo J., Han S., Lee S. and Kim H. (2015) *Computer vision techniques for construction safety and health monitoring*. Advanced Engineering Informatics 29(2), 239–251; Fang W., Ding L., Zhong B., Love P.E. and Luo H. (2018) *Automated detection of workers and heavy equipment on construction sites: a convolutional neural network approach*. Advanced Engineering Informatics 37, 139–149.

Managers activities, making construction and facility management processes gradually more proactive than reactive[10].

In fact, Digital Twins must virtually contain and represent physical information in both predicted and real states, reflecting physical reality as it evolves over time. When occurring a change in the physical world, real-time updates are needed to re-monitoring or re-measuring, as the virtual replica of physical information will no longer represent the actual physical reality.

If Machine and Deep Learning[11] techniques combined with automatic reasoning mechanisms are involved in the Digital Twin-based building management process, they allow to strategically leverage such a large amount of real-time available information through features for the elaboration of heterogeneous data streams, including:

- Prediction of phenomena, particularly of failures;
- Profiling of users' behaviors and operating states of machinery;
- Optimized planning of material supplies and processing shifts;
- Real-time monitoring of systems and infrastructures;
- Multidimensional analysis of information.

Production management as well as supply chain performances, construction safety and labour productivity

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[10] Sacks R., Brilakis I., Pikas E., Xie H. S., Girolami M. (2020) *Construction with digital twin information systems*. Data-Centric Engineering.

[11] *Machine learning* is the domain of Artificial Intelligence that investigates automatic learning capacity of a system basing on data inputs analysis. *Deep learning* is a specific form of machine learning involving the use of artificial neural networks to process information in a non-linear manner, simulating the cellular behaviour of the human brain.

are also enriched by the use of Digital Twins thanks to the availability of large-scale, reliable and accessible databases representing a complete evolution of proactive building management systems, where data are contained in Digital Twin Models (DTM), along with associated performance simulation results. Thanks to artificial intelligence systems DTMs can be used as a knowledge-based predictive system, providing a source of labelled (tagged) data supporting machine learning application training, leading to learning and classification[12] processes.

Digital Twin and Artificial Intelligence for predictive maintenance: a residential district in Rome

The project developed in 2020 by the CITERA Interdepartmental Center for Territory, Construction, Restoration and Environment of the Sapienza University of Rome explores the application of digital tools and methods in order to obtain a three-dimensional information district-model integrated with Artificial Intelligence (AI) systems, defining predictive maintenance approaches for Building Management.

These potentials are examined in relation to a residential area called Rione Rinascimento III[13] consisting of a total

[12] *Classification* is a Machine Learning technique based on predicting the "class" (called targets/labels) of given data points. Classification predictive modelling is the approximation of a mapping function finding specific relationships in the input data that make it possible to produce correct outputs.

[13] Rinascimento III in Rome is configured as a building intervention characterizing an energetically almost self-sufficient (nZEB) new portion of the city, integrated as much as possible with the surrounding areas in terms of urban planning and services. The total area is about 85,000 m^2 consisting of 16 eight-floor buildings with 911 apartment units and 2,500

of 40 units, built in 2008 and located in the Monte Sacro district in Rome, next to a large public park.

Predictive maintenance is a methodology based on condition-monitoring techniques to track performance levels during the operations, aiming at identifying and resolve anomalies in a timely way before they give rise to failures. In comparison, with corrective/ reactive maintenance, repairs are carried out only after a malfunction or failure has occurred, and preventive or scheduled maintenance interventions are implemented on the basis of the time or intensity of use of a given asset.

In addition to the ability to reduce downtimes and improve productivity, predictive maintenance can be used to extend the lifecycle of assets, reducing the costs and complexity of repairs, optimizing inventories of materials and spare parts, and complying with relevant regulations and compliance standards.

Thus, the development of Digital Twins for predictive maintenance of the built environment begins from the configuration of a building information model connecting three-dimensional objects (Figure 1) to specific information about the planned maintenance of individual components, as well as collecting input data from different sources (IoT, alarm systems, operators data sheets etc.), gradually powering self-learning capabilities with artificial intelligence and machine learning techniques, analysing data and comparing expected and unexpected rates of maintenance interventions.

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inhabitants.

Fig. 1. Rinascimento III BIM digital information model.

The configured BIM-AI integrated model is based on an automatic reasoning system, allowing the digital control of scheduled maintenance activities through the dynamic definition of rule-based algorithms for the recognition of malfunctioning scenarios, aiming at the progressive reduction of breakdown interventions.

As defined, the BIM model is the core-system of the DTM-based predictive maintenance process, combining machine learning systems and rule-based methods (such as data mining and association rule mining[14]) with the 3D physical/spatial information model containing operation and maintenance data layers, optimizing specific activities and interventions on such a complex building system thanks to the as-built geometric virtual representation provided by the BIM model.

Based on the collected data, Digital Twin-based building predictive models are structured to allow the optimization

[14] Data mining is a set of techniques and methodologies aimed at extracting useful information from large amounts of data through automatic or semi-automatic methods. In data mining, association rules are one of the methods to extract hidden relationships between data.

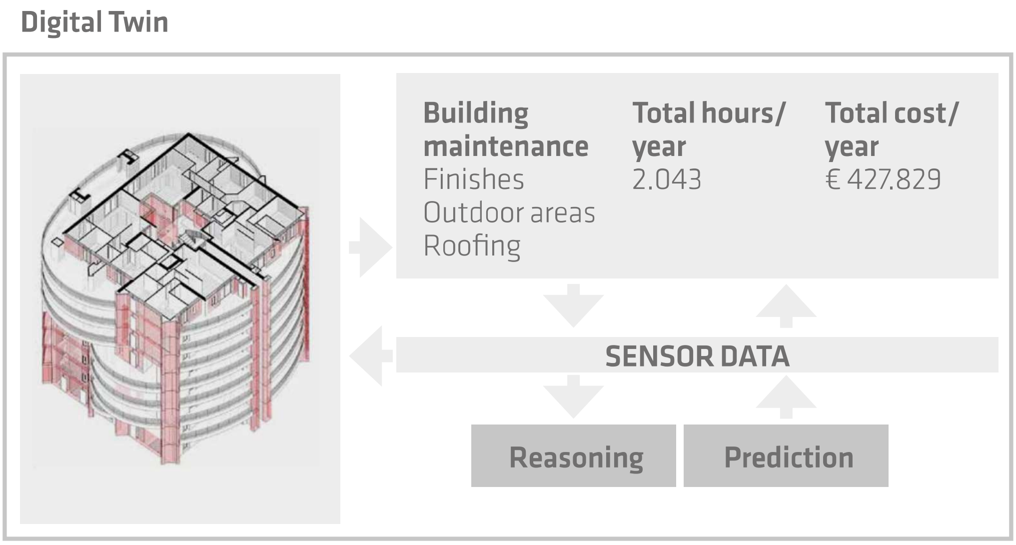

Fig. 2. Digital Twin-based machine learning system for predictive maintenance

of maintenance strategies (Figure 2) through the interaction of AI and data coming from sensors with 3D objects containing data layers about specific maintenance activities in terms of (a) type of activity, (b) description of activities for each phase (verification, restoration, repair), (c) total consistencies, (d) frequency, (e) employees, (f) time employed to perform the planned activities.

Then, the BIM functional/spatial data model combined with data coming from sensors and integrated with artificial intelligence systems becomes the control and monitoring centre for the operations and maintenance phases on building systems as well as on mechanical, electrical, and HVAC plants, supporting decision-making processes.

In fact, Digital Twin Models for predictive maintenance may indicate both that the current programs and practices are ideal and do not need to be changed, or that there is the urgent need to avoid a breakdown, even postponing a costly intervention if the component does not need it.

Thus, integrating Artificial Intelligence systems into Facility Management processes implies the use of software to make decisions and solve problems autonomously through deduction and reasoning processes, thanks to the collection and analysis of large amounts of real-time data supporting decisions and providing in-depth information, even identifying and eliminating routine and repetitive tasks that could be easily automated.
Therefore, Facility Management using AI-systems takes advantages of automating activities such as scheduled maintenance and critical inspections, achieving greater efficiency as machine learning makes the system capable to learn autonomously and become smarter gradually over time, as it increases amount of data analyzed.
Leveraging the advantage offered by AI as well as the support of information and data for decision-making, it is also essential to manage resources more efficiently, operating in a strategic and optimized integrated way.
In fact, the progressive diffusion of IoT (Internet of Things) devices and applications, together with the availability of advanced analytical tools using Artificial Intelligence and machine learning technologies, now make it possible to integrate different kind of sensors into industrial machinery, connecting such equipment to a structured network, in order to continuously monitor its operating status.
In this perspective, the more data is captured from sensors, the more machine learning algorithms can learn about the history and condition of building systems and machines, continuously improving maintenance methodologies.

The configuration of such a Building Management system aimed at optimizing the maintenance activities allows therefore considerable savings on the operating costs to be charged to the single owner, providing the opportunity to identify a fixed fee for the annual maintenance program according to the real needs and conditions of the assets.

In addition, through the identification of tasks and activities that could be potentially assigned to advanced TVCC sensors, the use of computer vision for image recognition[15] analysis with drones and video-surveillance systems provides a significant optimization of costs and resources for maintenance activities.

In fact, with regard to the security requirements of the building complex, cameras could take day and night images even in closed or inaccessible areas, and they could represent a source of useful data for a machine learning/computer vision system, processing and comparing the variation of chromatic ranges, as well as decreases in the performance of lighting fixtures, or the state of conservation of elements/components (roofs, facade elements, etc.) even for operation and maintenance purposes.

In this perspective, drones and advanced cameras implemented in the district for high-performance security

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[15] Computer vision, or artificial vision, is an interdisciplinary research field that deals with the study of computer processing, understanding how digital systems can reproduce processes and functions of the human visual apparatus. Therefore, it is not only referred to acquiring static or moving images (even beyond the spectrum of natural light), but also to their identification and recognition, extracting useful information to make decisions. Image Recognition is in fact only a part of computer vision, which is mainly based on neural networks able to identify, classify and recognize images.

levels could be used even for operation and maintenance control and monitoring activities using computer vision and image recognition systems on external areas as well as for monitoring the state of conservation of building finishes.

The configuration of such a DTM-AI-based construction and urban digital management ecosystem aims at optimizing decision-making processes integrating technologies for different purposes, implementing predictive tailor-made strategies based on the analyses performed, configuring a scalable and replicable methodological approach for different contexts from industrial to building assets.